Succession of Food Forests

An open source functional plant characteristics database and decision-making framework for the design of food forests in the Netherlands

Name: Jordy van Eijk

Reg. nr: 950807234130

Thesis Supervisor: Prof. dr. Frans Bongers

Chair-group: Forest Ecology and Forest Management

Thesis nr. AV2021-11

Date: 7 july 2021

Preface

When I started this research my supervisor Frans Bongers told me I had 3 PhDs floating in my head. Despite often cursing myself for the complexity and boundarylessness I nonetheless voluntarily emerged myself in, I believe this turned out to be for the better.

"I would define biodiversity as the amount of connections"

Most scientists will probably find this statement from one of the designers that participated in this study rather vague, but when all different definitions of biodiversity are boiled down this quote is what might remain. In reflection on what I have learned, what this thesis and perhaps life is about, my conclusion in two words would be connection and diversity. Diversity of plant characteristics, diversity of ecosystems, diversity of genes, diversity of the people I have interviewed, diversity of values across plant characteristics, diversity across space, diversity across time… and how all of these relate to each other.

I have a strong love-hate relationship with science. I love details, facts, patterns. I hate narrow-mindedness, deadening repetition, research that is far from useful for the urgent change that is to be made and the illusion of control. My human brain likes to put things into boxes, but my spirit also sees their shortcomings.

As one permaculturist once explained, living systems are not complicated, but complex systems. A plane is a complicated system that can be taken apart and put together with the according knowledge, so that it will fly again. The amount of particles and their relatedness has limits. A bird is a complex system. A bird can be taken apart and somewhat put together, but the bird will not fly anymore. The life of the bird is taken out, because the amount of particles and their relations is practically infinite and subject to continuous change. We live in the illusion that with enough research, we know exactly what to do, but this moment will never come. Then what will all the boxes, tables, figures and lists in this thesis be worth for science and practice? If we learn to trust complexity and use self-organisation, complexity will increase, and with that the health and resilience of each system. As Sir David Attenborough stated:

"Humans have to move from being apart of nature to being a part of nature."

And for that, scientific knowledge can also play its part when done right. For me this also means transparency and connecting to practice. I like to think of myself that I am generous in sharing knowledge and an important motive for doing this research is breaking through the fragmentation and privatisation of data on food forests and start building together on a holistic, dynamic, open source knowledge platform, supporting and supported by the movement in practice. The urgency for change is too large.

Thanksgiving

First of all, I would like to express my gratitude to my supervisor Frans Bongers. Thank you for all your trust, freedom, open and motivating guidance and feedback on structuring and making explicit the main results. Next, my thanks to St. VBNL for understanding my vision with this work and providing me a unique opportunity to conduct a thesis research that will not remain words in a report, but will be collaboratively brought into practice as an open-source participatory plant database. In particular, my thanks to Evelyn Derksen and Marc Buiter for working together parallel to this research on all the non-content related aspects necessary for establishing the database. The relevance of making an actual impact with this open-source platform increased my perseverance to finish this work and hopefully allows me to reciprocitate the gifts of the many experts I interviewed.

Moreover, I would like to thank Louise van der Stok for her mental support and her company during some of the visits to other experts as part of the data collection. Besides, my thanks to Martijn Aalbrecht, Niek Engbers, Kees van Veluw, Sebastiaan Kuiper and Tim Shen for reviewing the draft texts of this study and providing valuable feedback. Thanks to Madelon Lohbeck for sharing her scientific rigour that improved the proposal and methodology of this thesis. Also, thanks to all my colleagues who did pioneering research as students on food forests, Wendy Jenkins, Pablo van Neste, Luka Burhomistrenko, Suzy Rebisz, Niek Pepels, Kay van Kernebeek, and all others, the academic food forest movement stands on your shoulders.

Finally, I am grateful to all of those who were willing to participate as experts in this study. I wish to acknowledge that, in attempting to create this report, I have not done justice to the diversity of experience and the depth of insight reflected in the interviews I conducted with you. For this I apologize in advance. My sincere hope for reciprocity is that you, my readers, will be inspired, intrigued or irritated by what you do find here, to also become catalysts of this regenerative, existential movement.

Abstract

Food forestry is one of the most novel, complex and arguably nature-driven forms of agroforestry for integrating and reinventing modern western agriculture and forestry systems that is exponentially gaining attention in the Netherlands. However, the existing knowledge about these systems in temperate climates is almost exclusively the result of personal anecdotal experience of practitioners in young food forest systems. Consequently, the design and in particular research on design of these systems is poorly understood and developed. In this study I propose that the development of a decision-making framework linked to an open-source functional plant database, unpinned by academic theory and experiential knowledge from practice, has the potential to form an evidence-based foundation for the design of food forests in the Netherlands and help mature food forestry as a science and practice. To do so, I chose an explorative and participatory action research approach, combined with principles from integrative research, to interview 26 experts from a large diversity of backgrounds through semi-structured interviews. The problem framing, boundary setting and data collection, processing and evaluation developed iteratively and together with these participants. The research outcomes suggest that design steps and their corresponding maps, lists, plans and actions are key elements for designing the spatial and temporal composition and structure of living and non-living elements, especially vegetation, in food forests in the Netherlands. In evaluation with practitioners the decision-making framework was regarded to contain the minimal required elements for place-based designs, reflect the cyclic and iterative nature of food forest design and emphasize the continuous feedback loop between decisions in theory and practice. However, each food forest designer and project dynamics are unique without single silver bullet design solutions. Consequently, practitioners agreed that designing complex agroforestry systems always goes further than mindlessly taking over prescribed choices and a decision-making framework for food forests can never be put in stone. Furthermore, the results indicate that functional plant characteristics of plant species, cultivars, hybrids, rootstocks and scion-rootstock combinations, underpinned with dynamic sourcing on author, date and place are essential, relational elements in an open-source plant database that can underpin the decision-making framework. Functional targets, current and future environmental conditions, successional gradients, ontogenetic variations, harvest practices and project scales emerged as key design criteria and were applied for the identification of the functional plant characteristics and plant entities. In particular mimicry of natural succession was a central temporal design consideration and I explored 'starting', 'transition' and 'final' stadia to analyse, predict, imagine, visualize and adapt to multiple scenarios in successional food forest design. Based on these criteria I propose a diagram of 80 key functional plant characteristics and a list of 100 promising food forest species, including the relevance of zooming in to cultivars, hybrids and rootstocks for these species. Moreover, exemplify that there is a need to assess which functional plant characteristics are relevant on the cultivar and rootstock level per individual (group of) species. The database elements utilize the explored diversity in functional targets and project dynamics among food forests as well as the diversity in personal perspectives of the interviewees. Still, the selections of key functional plant characteristics and promising species should not be regarded as a holy grail since designing for diversity arguably remains the most important narrative in food forest design. Like the decision-making framework, the key functional plant characteristics and promising species list I present in this explorative study can serve as inspiration and guidance for decision-makers in practice and offer directions for future research to scientists. I conclude this paper by providing a blueprint for future directions to assess and advance the decision-making framework and open-source plant database elements for and in connection with practice.

Keywords: *Decision-making Framework; Food forest Design; Food forests; Functional Ecology; Functional plant characteristics; Open-source Plant Database; Participatory Action Research; Perennial crops; Succession*

Table of contents

Lists of abbreviations, tables, figures, boxes and drawings

List of abbreviations

AGFORWARD	AGroFORestry that Will Advance Rural Development (EU Project)
MCA	Multi Criteria Analysis
EURAF	European Agroforestry Federation
FAO	Food and Agricultural Organization of the United Nations
ICRAF	International Centre for Research in Agroforestry
NMVB	Nationaal Monitoringsprogramma Voedselbossen
PAR	Participatory Action Research
RVO	Rijksdienst voor Ondernemend Nederland
SAF	Successional Agroforestry
St.VBNL	Stichting Voedselbosbouw Nederland

List of tables and boxes

List of figures and drawings

1 Introduction

1.1 Broad context

‘Agriculture’ and ‘forestry’ have long been perceived as strictly different land use practices among modern western culture, farmers, foresters, science and law. However, integration opposed to separation of forestry and agriculture offers solutions to tackle the complexity of entangled sustainability issues that can be mindful of the ecological, the social, the cultural, the economic and the ethical, and the way these dimensions interrelate (Asbjornsen et al., 2014). A promising land use system for integrating and reinventing modern western food and forestry systems is known as agroforestry. Agroforestry is broadly defined as agriculture containing trees, often in combination with annual crops or animals (ICRAF, 2020). One of the most complex, novel and arguably nature driven types of agroforestry is food forestry.

In the Netherlands, interest in food forests has experienced an exponential growth, in particular among citizens (St.VBNL, 2020). The planning and establishment of over a 1000 food forests in the last 3 years exemplifies how fast the movement is gaining momentum (Van Eck, 2020). Recently, the Dutch government signed the Green Deal Voedselbossen, thus identifying the practice of food forestry as part of the path towards “green growth” (RVO, 2017; p.2). Despite the attention food forests receive, there is little consensus on what can be defined as a food forest and how food forests are nested within the broader context of agroforestry. Several criteria can be used to classify and group agroforestry systems (and practices). The most commonly used ones are the system's composition and structure (arrangement of components), its function, its socio-economic scale and level of management, and its ecological spread (Tab. 1.1.1 in Annex 1). It is hard to classify food forests within one of the classes of agroforestry, since food forests show a tremendous variation in each of these aspects (Rebitz, 2018).

Food forests are also often related to concepts such as multi-strata systems, homegardens, permaculture, analog forestry, etc (Crawford, 2010; Limareva, 2014; Nair, 2014). According to Crawford (2010) a food forest, or edible forest garden, can be described as a land use system mimicking the structure and functioning of a natural forest, with plants (in)directly useful for people, that are most of the time edible (Crawford, 2010). Moreover, in principle, a food forest generally starts at nature’s end of the agriculture-nature continuum and attempts to increase yields while maintaining all of nature's desirable qualities instead of the other way around (Jacke and Toensmeier, 2005). Therefore, a food forest could even be defined as principles or human values. The history of food forests in temperate climate as a recent movement initiated by Robert Hart in the 1970’s (Hart, 1996) that was adopted by a handful of pioneering individuals only several decades ago (Riolo, 2019). Most currently existing food forests are only a few years old, while it can take decades before a forest ecosystem develops and many perennial woody crops come into full production (Crawford, 2010). Therefore, the existing knowledge about these novel systems is almost exclusively the result of personal anecdotal experience of practitioners in the field (Pilgrim et al., 2018).

Besides the diversity, novelty and complexity of food forests, a myriad of reasons can explain why design, management, research and specifically research on the design and management of these systems is still hardly developed and understood. Although some books exist to help practitioners making choices on designing a food forest (Crawford, 2010 ; Jacke and Toensmeier, 2005), there is currently no systemized, standardized framework for decision-making that integrates the experiential evidence accumulated over the years and novel interdisciplinary research in the fields of ecology and agronomy. As a result, many practitioners base species selection on self-assembled categorical tables of habitat requirements, uses and ecosystem functions. That food forest designers originate from a wide range of backgrounds introducing perspectives, knowledge and principles of permaculture, agroecology, landscape architecture and forestry to the novel field of food forestry (Park et al., 2019), complicates the development of methods for design. Furthermore, ICRAF has mainly carried out research on agroforestry systems in the tropics, subtropics, arid and semi-arid regions since 1978. In comparison, there is limited research into temperate agroforestry systems. Only in 2011 the EURAF was formed. Finally, science as a reductionist approach in contrast to the holistic and intuitive approach in practice has been a hindrance for conducting classical scientific research on food forests.

A broad approach to exploring the design of these complex and novel systems is necessary. Nevertheless, I propose ecology and in particular the relatively recent scientific fields of functional ecology and successional agroforestry can serve as a central theme for inspiration in this research (Martin and Isaac, 2018 ; Young, 2017). Biomimicry of natural processes for increased ecosystem health and self-maintenance has huge implications for design and management of any forestry or agricultural systems. For applying natural processes food forests are tightly linked to the mechanism of ecological succession. Succession can be described as the consecutive sequencing of plant communities. In conventional agriculture of annual crops, farmers continuously disturb the succession to the first stage of bare soil and let succession go forward by only one year. Under these conditions understanding succession seems unimportant, the control of the outcome of the practices is large. To apply ourselves intelligently to intentionally designing and managing directed succession beyond that stadium is relatively unfamiliar territory in modern, temperate agriculture (Jacke and Toensmeijer, 2005). Several studies testing mimicry theories on successional agroforestry systems in the tropics showed that similar structural and functional attributes can be achieved with an imitation of natural succession using different species (Ashton and Ducey, 2000 ; Young, 2017). However, the findings of these studies echo other studies that warn to acknowledge the challenges of designing ecologically intensive agroecosystems due to the necessity of in-depth knowledge of biological processes, tree species survival, growth, and other dynamics (Alvim and Nair 1986; Malézieux, 2011 ; Perera and Rajapakse 1991).

A decision-making framework, linked to a functional plant characteristic-based plant database, underpinned by academic theories, concepts and empirical research, has the potential to form an evidence-based foundation for the design of food forests and help mature food forests as a science. Besides scientific research, personal empirical experience of pioneering food forest practitioners in the Netherlands is seen as valuable local knowledge. A framework consolidating and structuring advances already achieved in practice accelerates the process of identifying which plant characteristics and species are relevant for the Dutch context and increases the chances of the framework ultimately becoming operationally usable for practitioners in the field again. Farmers in multifunctional agroecological systems already implicitly base their decisions on functional traits of crop and non-crop species adding to the potential to unify practical decision making and ecological theory through a functional trait framework (Damour et al., 2017).

Problem statement

For evidence-based ecological design of Dutch food forests there is a large need for a practicable decision-making framework, linked to a functional plant characteristic database, both supported by evidence based on scientific research and local experiential knowledge.

Hindrances for developing such a tool (Fig. 1.1.1) are the:

- ➢ Novelty of existing food forests in the Netherlands while forests take time to grow
- ➢ Complexity and place-based character of food forests
- ➢ Reductionist approach in science in contrast to the holistic and intuitive approach in practice
- ➢ Focus of ecologists on natural systems and species instead of managed systems with food objectives
- ➢ Ecologist attention to agroforestry focusses on tropical systems and undervalues temperate agroforestry
- ➢ Lack of explicitly applying succession as mechanism in complex agroforestry system design
- ➢ Disconnect between academic agronomic and ecological functional traits
- ➢ Disconnect between science and practice

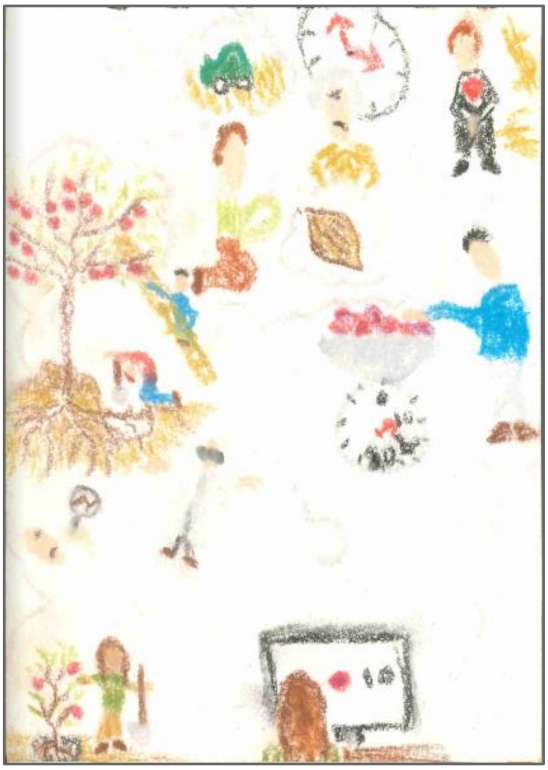


Figure. 1.1.1: Impression of the challenges and opportunities of data collection in science and practice for developing a food forest plant database and decision-making framework.

1.2 Research objectives and questions

The purpose of this MSc thesis research is to help advance the food forest movement in the Netherlands, whereby the advance needs to be based on evidence from science and practice, and bridge the gap between both. This thesis research aims, in connection with the movement in practice, to discover relevant functional plant characteristics, species, cultivars, rootstocks, targets, successional gradients, and other elements that need to be included in a relational, synergized plant-database and decision-making framework for the design of food forests in the Netherlands. In service of this evidence-based, interlinked plant-database and decision-making framework the following main research question was formulated:

What elements need to be consolidated in a plant-database and decision-making framework for the design of food forests in the Netherlands and how do these elements relate to each other?

Five corresponding sub-research questions were generated using a participatory action research (PAR) approach:

1. *What are key elements and steps applied during the design process of food forests in the Netherlands?*
2. *What are key functional plant characteristics for the design of food forests in the Netherlands based on the most important 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) harvest practices and 6) project scales?*
3. *What are 100 promising plant species for food forests in the Netherlands based on the selected key functional plant characteristics and overall complementarity of inter-species variation?*

4. *What is the similarity between the key functional plant characteristics on species level compared to key characteristics for cultivars and rootstocks for the design of food forests in the Netherlands?*
5. *What are the relations between the elements selected for the plant database and those of the decision-making framework?*

Scope

The transdisciplinary, novel and complex context of this thesis research, extensive data collection and time constraints, would arguably demand a sharp demarcation narrowing down the scope of the thesis research. However the integrative research principles discussed in the methods that guide sustainability research and action research demanded a scope that iteratively developed over the course of the thesis research. Therefore, the thesis was a constant feedback loop of problem framing, boundary setting, data collection and evaluation. Examples of this iterative process are given in Tab. 1.2.1 in Annex IV. Furthermore, due to the iterative development of this study, time constraints, action imperative and schemes of the structure and scope of the results provided in Chapter 3, I did not choose to compose a conceptual framework. However, Box 1.2.2 in Annex III lists the definitions of the keywords that emerged throughout this study.

2 Methods

The thesis research has an explorative, comparative and reflective nature. The elements that need to be contained in the database and decision-making framework are explored and comparisons are done on the variation, overlap and relation between design criteria, plant characteristics, species, cultivars, rootstocks and expert groups. In practice, exploration, comparison and reflection constantly followed each other in acknowledgement of the science of transformative learning (source). A PAR approach was chosen for the potential of generating data driven research questions, linking theory to practice, collecting both qualitative and quantitative data, having clear objectives to achieve and value creation with and for stakeholders (Brydon-Miller et al., 2003).

Moreover, integrative research principles served as guidelines for the design and implementation of this thesis research. Integrative research is here defined as "research in the context of complexity, with an action imperative". Taking an integrative approach has long been integral to sustainability science and a fundamental to the co-design of research and co-production of knowledge (Van Kerkhoff, 2013). The four principles of integrative research used for conducting the research were to embrace uncertainty, engage stakeholders, be transdisciplinary and have a learning orientation.

The implications of these methods for reliability, replicability and validity were explicitly considered. The above mentioned principles of integrative and action research in explorative, regenerative science reject the possibility that another thesis research done with the same starting point would result in the same research outcomes. Science, historically, has tended to favour homogeneity over heterogeneity, the single 'silver bullet' solution to a problem rather than many solutions (Van Kerkhoff, 2013). The theory of PAR, integrative research and research by design, counteracts this view, regarding variation and difference as positive and desirable. In the novel and complex research field of food forest design, predictability is limited, so there will always be unexpected outcomes from any intervention or change.

2.1 Expert interviews

A total of 26 experts were interviewed during the MSc thesis. In order to approach the topic from a transdisciplinary perspective a classification of multiple expert groups was made. Potential respondents were categorized into the main groups; ecologists, agronomists, food forest designers, food forest farmers, nursery growers and data scientists. For zooming in on specific topics one chef, two business economists and a decision-making scientist were interviewed. Experts could fall into multiple categories. A full overview of all experts that participated in the thesis research, their affiliation, corresponding expert group(s) and vision on food forests can be found in Tab. 2.1.1 in Annex IV.

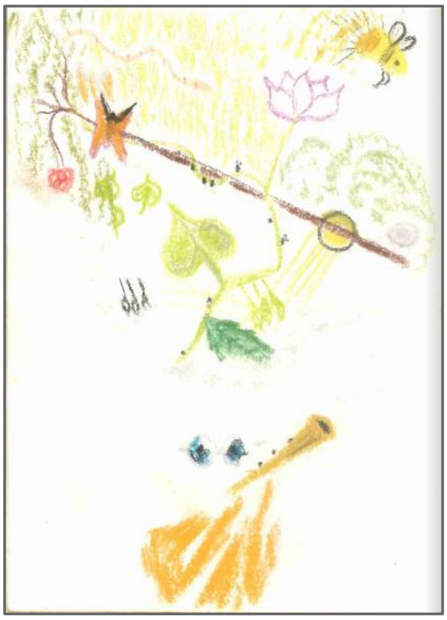


Figure 2.1.1: Impression of the content and progression of a semi-structured expert interview.

Semi-structured interviews were conducted composed of standardized questions, questions tailored to certain expert groups and specific follow-up questions to obtain deepening knowledge per expert on important topics. The questions were articulated in a non-suggestive, open way, customized to fit the experts expertise and word use. Follow-up questions were sometimes prepared in advance and other times asked spontaneously and intuitively during the interviews following the integrative research principle to embrace uncertainty. The main survey format used during the first round of data collection can be found in Box 2.1.2 Annex IV. Interviews took on average 2,5 hours per expert. The interviews took place digitally or physically while respecting the Covid-19 regulations. All interviews were recorded with consent of the respondents. Afterwards, the recordings were transcribed and aggregated into a collective excel sheet. Data processing included structuring data and translation from Dutch to English.

As a consequence of the participatory action research approach the survey format developed as a result of a reflection after each interview, reconsidering the scope and direction of the thesis research. Questions were added, modified and dropped over the course of the data collection as a result of an increased understanding of the elements relevant for the database and decision-making framework, the way these elements interrelate and contradictory perspectives and knowledge that was found about these topics among the different experts. When an expert of a certain expert group did not answer all relevant questions during the interview, for example due to time-constraints or development of the survey format, the expert was contacted to provide answers on these specific questions via mail in hindsight. Moreover, this approach was chosen to engage participating experts as stakeholders to come to a collaborative desired output, build relationships and value for the experts.

Despite continuous development of the data collection process, a rough division can be made between a first and second round of interviews. Furthermore, a distinction can be made between experts interviewed for either the database, decision-making framework or both. The different expert groups were interviewed equally distributed over the thesis research in order for all expert groups to have representatives for each stage of the data collection in which they were relevant.

The first round of interviews focussed on sub research questions 1, 2 and 4; identifying the most relevant plant characteristics, plant species, functional targets, successional gradients, and other elements that need to be included in the plant-database and decision-making framework, the relation between these elements and an appropriate structure for the database and decision-making framework. 17 experts were interviewed on the subject of the plant database with backgrounds in ecology (5), agronomy (2), design (5), nursery growing (2), farming (3), databases (3) and business management (1). Simultaneously, 4 designers were questioned directly related to the steps and elements of the decision-making framework. The input resulting from the questions on the database indirectly served as input for the elements of the decision-making framework as well. A '100 top plant species list' was constructed following two approaches that are elaborated on in Box 2.1.3 in Annex IV. The second round of interviews emphasized collecting data on RQ 3-5 and featured two parallel interview pathways that are elaborated on in Box 2.1.3 in Annex IV as well.

3 Structure of the Results

The results are structured in three parts, Chapter 4, 5 and 6. In Chapter 4 the elements of the decision-making framework, in Chapter 6 the elements of the database and chapter 6 the synergy between the framework and database are explored. Consequently, Chapter 4 explores RQ1, Chapter 5 explores RQ2-4 and Chapter 6 explores RQ5. All result Chapters are enriched with drawings that illustrate insights from an artistic perspective as well as quotes that emphasize the interrelatedness of design aspects, structure of the collected qualitative data and personal expert perspectives.

Decision-making framework

The key explored elements of the decision-making framework present in Chapter 4 were the design steps and their corresponding design elements; plans, maps and lists as shown in Fig. 3.1.1. These elements have their own sub-chapter. The striped feedback arrows emphasize the cyclic and iterative nature of food forest design. The feedback loops are discussed in the sections of each step. The orange coloured center ring of the framework visualizes step 0, surrounded by a multi-coloured second ring of steps 1 to 5. The third ring shows the most relevant design elements of each step, mainly plans, maps and lists. Specific elements nested in the plans, maps and lists are extended in the fourth ring.

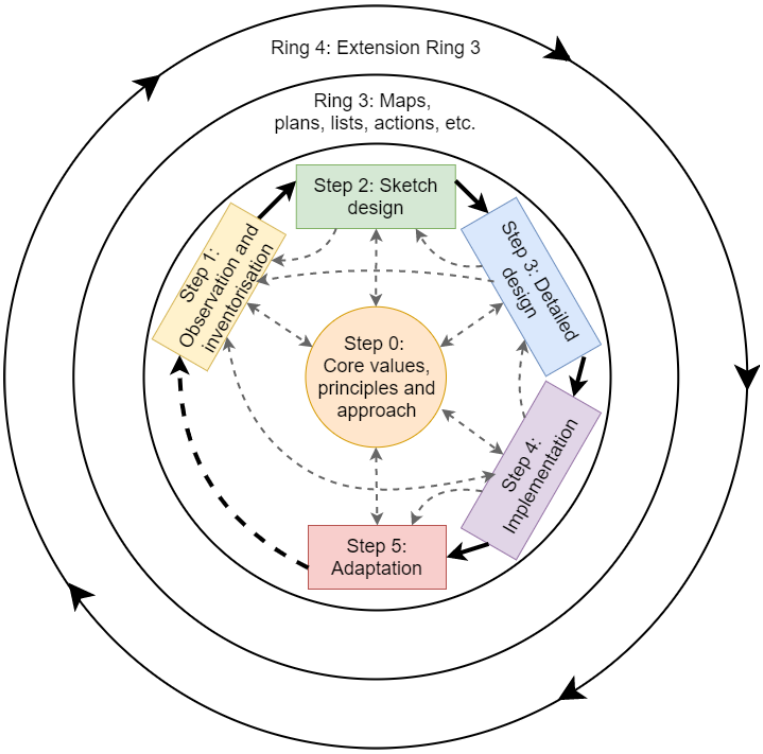


Figure 3.1.1: Simplified decision-making framework for the design of food forests in the Netherlands.

Open-source Plant database

Chapter 5 presents the exploration of the key database elements. Plant characteristics were considered the foremost elements for an open source plant database for designing food forests in the Netherlands. Plant characteristics had a central role in linking systems and targets to concrete design variables like species, temporal and spatial vegetation arrangement and management practices. Other important elements were the plant entity (species, cultivar or cultivar-rootstock combination), standardized classes derived from the plant characteristics values and the data source (author, date and place).

Each of the design criteria mentioned in sub-research question 2 is presented as 6 sub-chapters, including the most discussed themes, their related plant characteristics and considerations for plant entities and spatial and temporal vegetational arrangement. While many functional plant characteristics were considered in relation to many criteria, most plant characteristics are mainly elaborated on as part of the criteria that they were mostly referred to during the interviews. Fig. 3.1.2 shows the six sub-chapters and their relation to the vegetation composition and structure via the functional plant characteristics.

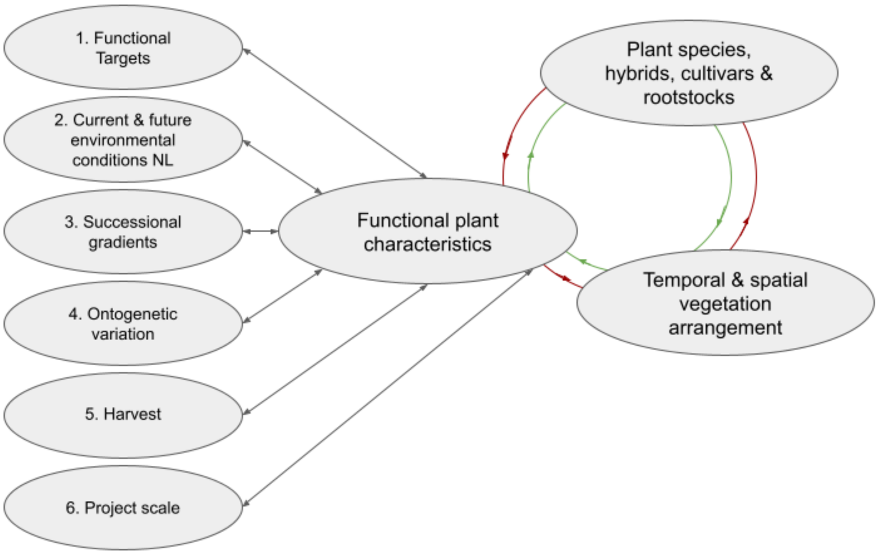


Figure 3.1.2: The setup of part two of the results in order to present the linkage of important design criteria (from functional targets to system dynamics) via functional plant characteristics to plant entities and temporal and spatial vegetation arrangements.

The 6 sub-chapters build up to a seventh 'aggregation sub-chapter' that is divided in 3 sections; 5.7.1 presents a complete extended scheme of the plant characteristics nested in the categories of figure x, 5.7.2 a 100 top species list and 5.7.3 database elements for enhancing traceability and transparency of the data source. Besides aggregating the results presented in sub-chapters 5.1-5.6, sub-chapter 5.7 provides supplementary justifications for selecting plant characteristics and species.

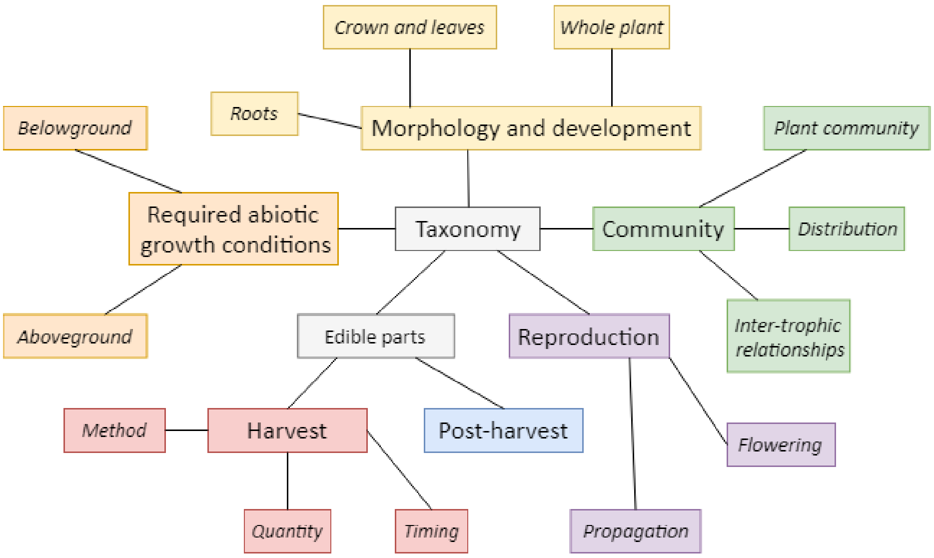


Figure 3.1.3: A simplified overview of the explored plant characteristic categories where each color represents a group of plant characteristics and multiple subcategories are nested within a set of main functional plant characteristic categories. E.g. flowering period would be a functional plant characteristic within the flowering subcategory which is nested in the reproduction category.

The design criteria in Fig. 3.1.2 roughly correspond with the categories in Fig. 3.1.3. The required abiotic growth conditions are mainly covered in sub-chapter 5.2, the community plant characteristics in sub-chapter 5.3, those nested in morphological and development in sub-chapter 5.4, harvest related characteristics in sub-chapter 5.5, post-harvest related characteristics in sub-chapter 5.6 and characteristics nested in reproduction in the ecology section of sub-chapter 5.1. However, most categories hold (in)direct relations to all sub-chapters and the other way around.

Synergizing the Plant Database and Decision-making Framework

The relations between the elements selected for the plant database and those of the decision-making framework are explored in Chapter 6. Here, mainly the explored key plant characteristics are matched with the decision-making elements of all rings and steps.

4 Decision-making framework

RQ1: What are key elements and steps applied during the design process of food forests in the Netherlands?

4.1 Elements and structure

The explored key elements of the framework were the steps with their corresponding plans, actions, maps and lists in ring 3 and 4 (Fig. 4.1.1). The steps are iterative and cyclical. Each of the elements and their interrelatedness is elaborated on in this chapter.

Figure 4.1.1: The iterative, cyclic decision-making framework for designing food forests in the Netherlands. The explored key elements of the framework were the steps in ring 1 and 2 with their corresponding plans, actions, maps and lists in ring 3 and 4. The steps are iterative and cyclical, visualized through the dotted arrows. The center ring of the framework visualizes step 0, surrounded by a second ring of steps 1 to 5. The third ring shows the most relevant design aspects of each step. These aspects are elaborated in another surrounding fourth ring. As the design progresses the amount of detail increases concerning plant species selection, designing the spatial and temporal orientation of the vegetation on the maps as well as the concrete elaboration of the succession and management plans. In practice sometimes a step is moved back, which is indicated through the dotted feedback arrows.

4.2 Steps

The centre ring of the framework visualizes step 0, surrounded by a second ring of steps 1 to 5 (Fig. 4.1.1). The third ring shows the most relevant design aspects of each step. These aspects are elaborated in another surrounding fourth ring. The cyclic structure and feedback arrows emphasize the cyclic and iterative nature of food forest design. As the design progresses the amount of detail increases concerning plant species selection, designing the spatial and temporal orientation of the vegetation on the maps as well as the concrete elaboration of the succession and management plans. One designer mentioned thinking of the process as a meditative process of zooming in and out. In practice sometimes a step is moved back, that is covered in the model.

The 6 steps of the framework are:
0) Core values, principles and approach
1) Observation and inventorisation
2) Sketch Design
3) Detailed Design
4) Implementation
5) Adaptation

During the interviews the pattern emerged that there were several options for how the decision-making is organised between involved persons during the design process. Most designers design a food forest alone for most of the projects, but three designers mentioned working together with other designers and dividing the contribution to design phases, based on personal skills, knowledge and interests. Two designers were found to actively involve stakeholders, by mentoring persons or communities in shaping their own food forest designs. Who is involved in the decision-making of a food forest design had implications for the elements of each of the design steps.

4.2.1 Step 0

Step 0 represents the core of the designer. One designer called this step in Dutch the 'Grondhouding', translating roughly into both 'earth attitude', or 'fundamental attitude'. Through step 0, food forest design is acknowledged as inherently relational with the identity of the designer. This step is responsible for the designer's values, principles, approach and attitude towards food forests, the world and society. Respondents were asked for their ideas on what an optimal agriculture and forestry system should encompass and what role food forests have in this optimal future. An overview of the expert's answers can be found in Tab. 4.2.1 in Annex I. These answers provided a first insight in the values of the respondents and their attitude towards food forests. When there are multiple designers, for instance in the case of a participatory design process with a farmer, step 0 represents the core of each individual designer. One designer mentioned the permaculture ethics of earth care, people care and fair share as guidelines during the whole design process. These are depicted in the fourth ring of step 0.

Five collectively shared principles among designers are depicted in the fourth ring as well:

- ➢ understand the unique context of the place
- ➢ create many elements to support one function and many functions for each element
- ➢ create local circularity
- ➢ design with and for flexibility (see Tab. 4.2.2 in Annex I for examples)
- ➢ design from large to small patterns

During all consecutive steps that follow, designers consciously or intuitively check if his or her decisions are in line with his or her personal step 0. The interaction of the designer with all elements during the following steps also shapes the fundamental attitude of the designer in return. This reflection is visualized by the grey dotted two way arrows. For instance, one designer mentioned how he put his own motivation beneath the motivation of the initiative taker of the food forest projects he designs as illustrated in the quote. The quote also illustrates how he approaches the design with flexibility, dives deeper to understand the unique context of the place and reflects if this is in line with his own values.

"I try to make an objective inventory of all the stakes and dive deeper than the question at hand. As a designer you register what the initiative taker wants and try to see the underlying goal so that you can explore from different perspectives the routes towards that goal. And the goals of an initiative taker are not sacred from the start. If an initiative taker does not find biodiversity important, but I do I can still try to get it in."

4.2.2 Step 1

The goal of step 1 is to observe and assess the contextualized dynamics between all relevant stakeholders to make an overall estimation of what is potentially desired and possible and how this could be achieved. The step is summarized as the inventorisation and observation. Combined with step 0, step 1 guides all aspects of the design,from site preparation to species selection, patterning and management. This step can help designers decide to leave the site be and adapt to it, modify it to conducive growing conditions for desired plant species or use a combination of different strategies for different patches or zones. Designers often distinguished two main design elements nested in this step, but varied in defining both. Applied categorizations were the human and ecological dynamics, wishes & demands and site survey or the client interview and landscape interview. The latter indicates that designers often design for a specific stakeholder, generally the landowner and / or farmer. One designer spoke of this step as simply the stakeholder analysis. The framework features the human and landscape dynamics as categorization. Here, dynamics imply that these elements are interrelated and subjected to continuous change. Landscape implies that the designer should observe and assess these elements not only for the project area, but the surrounding landscape as well.

Human dynamics

To understand the human dynamics, designers try to identify the relevant human stakeholders, their wishes and demands and means for carrying out the design, implementation and management. During interviews, designers can ask the initiative taker of the project and other stakeholders questions such as;

"Who will be the consumer? Who will be the manager? What are plannological and juridical constraints? What are the wishes from the stakeholders? What are potential available product chains?"

The discussed functional targets can be allocated to the main groups food production, ecological and social and educational. These are elaborated on in chapter 1 of part 2. One designer mentioned that the goals of the food forest can be focussed within the project area, but also by providing benefits for the surrounding landscape. Laws and regulations, especially plannological and juridical constraints, were thought to be important prerequisites. However, one expert also argued the importance of challenging these constraints, corresponding to the approaches of step 0, as demonstrated below.

"You have a landscape that translates itself in people living there, a history, policies. If there is a juridical or plannological constraint that is not just an annoying rule. There are stakeholders for this rule. You want to start a sustainable project and save the planet. If you emphatically connect to these rules you try to understand why they are there in the first place and you can see if you can find a way around it."

Landscape dynamics

The landscape dynamics emphasize the non-human stakeholders. These consist of living, natural, abstract and artificial elements. Discussed elements shaping the landscape dynamics were the soil and water conditions, in and outflows of wind, temperature, light, chemicals, sound, nutrients and water, the flora and fauna, project size, geographical orientation, patterns through the season and climate and artificial objects. Additionally, the historical land use can provide insight in the current landscape dynamics. All these elements can be observed and assessed by visiting the place, collecting maps, taking soil samples or making a base map. Considering the potential implications of climate change for developing a food forest in the contextualized landscape was mentioned as a crucial observation element by several designers. Artificial objects such as bridges, buildings and underground cables were noted to provide additional dynamics, especially in urban areas.

Interrelatedness among dynamics and with other steps

One designer mentioned that the socio-economic human context completely shapes the constraints and comes chronologically before the ecological and technical possibilities should be assessed. Therefore the first is shown in 1A and the latter is 1B in the decision-making framework in Fig. 4.1.1. Moreover, the distinction between landscape and human dynamics can be perceived as mainly pragmatic since human stakes and impacts are interrelated with the landscape.

Each of the elements of step 1 were found directly or indirectly interrelated. Designers make one big estimation on what is there and what is achievable and stated that how they do this cannot be captured in any framework. Therefore step 1 provides users with the key themes, elements and patterns that should be considered when designing but does not prescribe a linear or systematized order for the decision-making process within each step.

In practice this step overflows with elements nested in later steps of the framework and step 0. Three examples from designers are given here. For designing commercial food forests, the initiative taker might reason from a specific product. Then the designer can choose to zoom in to what is needed to create that specific product. This can be a specific cultivar that would otherwise be selected during step 3. Second, in a participatory design process with many stakeholders involved, the core of each stakeholder contributes more explicitly to the design. Finally, as the quote below demonstrates, designers may already apply design concepts of step 2 in multiple intricate feedback loops with step 1 before largely moving to the next step.

'I see how a forest edge would fit. You are already making mental notes for the next phase. These I sometimes make visible in the form of theme maps, these also serve the purpose of inviting the initiative taker I am designing for to start a dialogue and share his opinion. So step 1 and 2 are overflowing and sometimes you temporarily jump some steps to explore specific topics. You just can't wait to start designing when you are making an analysis of the site."

4.2.3 Step 2

Based on the inventory of the human and landscape dynamics a sketch design can be made. The sketch design includes map(s), plans and list. The sketch design focuses on the rough spatial and temporal structures and patterns that the designer wants to make a transition towards. The designer chooses a point in time till when the design is made. One or multiple sketch maps generally include the vegetation structure, main paths, water elements, edges, zones and open spaces of the 'final' stadium of the food forest. The 'final' stadium here implies that designers tend to design towards a temporal horizon, while in reality no food forest design is fixed and designing towards a final stadium is mostly a practicality. The framework takes the sketch and a definite design together, while one designer mentioned explicitly making a distinction between those when the sketch design consists of multiple potential scenarios.

Parallel to the sketch maps the total list of workable species is reduced to a species longlist. Species can be crossed off when they do not correspond with the wishes, demands and ecological constraints. Moreover this step explores a general plan for the succession, water, landscape building, management, harvesting and potential available product chains. These are explained later on in this chapter. The grey dotted feedback arrow indicates the reflective action to check if the sketch map(s), plans and species list correspond with the elements of step 1 (Fig. 4.1.1). This reflection can take place both internally during the design process and while discussing the sketch model among stakeholders of the project.

Step 3

Step 3 is the detailed design. For the detailed design numbers and planting distances within all vegetation layers worked are out in maps. An overall map can also be combined with the planting scheme, discussed in step 4. Circumstantially it may be necessary to visualize maps for multiple moments in time. When applying succession this can include phased implementation maps of the vegetation. For instance, plants can be planned to be introduced 3 times over the course of multiple years, resulting in a separate planting scheme for phase 1, 2 and 3 of implementation. All plans of step 2 are specified. For instance, an initial maintenance plan of the herb layer can be worked out in detail as part of the overall management plan. The species longlist is further reduced to a species shortlist, based on the specific project context.

4.2.5 Step 4

The implementation step can be summarized as bringing the conceptual design (maps, plans and lists) into practice. The main implementation activities are circumstantial site preparations such as earthworks, adding external inputs, collecting plant material and thinning followed by introducing the planting material by planting and circumstantially sowing seed. When earthworks, thinning, soil cultivation or external inputs are part of the implementation, these activities may require circumstantial detailed, technical maps as well. For instance, earthworks often require a map with profiles necessary to communicate to a crane machinist what he is supposed to do. For introducing plants a planting scheme to set out the design in the field, for example with picket posts, is important. This map can include GPS coordinates, reference points in the landscape such as gates or buildings and planting grids to accurately translate the map to the field. Besides earlier mentioned implementation activities this step includes collecting and introducing the available planting material. In practice the strategies for collecting planting material and the execution during the design process vary widely among designers and between the scale, targets and means of projects.

4.2.6 Step 5

Step 5 is termed evaluation and adaptation. At any moment in time after implementation the designer can observe the realised human and landscape dynamics, compare these to the past dynamics and targets of step 0 and 1 and reflect upon the development of the food forest. If the realised development is not in line with the predicted development the designer can, in agreement with all stakeholders, both adapt the initial targets and/or start redesigning. One designer stated the cyclical decision-making process recognizes the infinity of food forest design as a result of the continuously changing human and landscape dynamics, in particular as a result of succession.

Another designer noted the importance of staying involved during the whole cycle as a designer, mentioning that the novel character means that there is a large need for feedback of performance for designers. Moreover, staying involved as a designer creates the opportunity for adequately adapting the system, management or targets. The designer emphasized that there are increasingly more food forest designers, but that most are very inexperienced, increasing the risk of designs that in practice do not turn out to make sense.

4.3 Maps

The nature of sketch and detailed maps were discussed earlier in this chapter. Here dynamic and technical implementation maps are described further.

4.3.1 Dynamic maps

Making multiple maps for planning and visualising the development of the food forest at different moments in the future is what food forest designers call a dynamic design. For example, if the vegetation structure will be designed with the prediction of how the food forest looks 25 years from now, it can be relevant to make an additional map of the vegetation structure and composition after 3, 5 or 10 years. According to the interviewed designers visualizing a dynamic design can have multiple benefits. First, these maps can give insight on how to spatially and economically bridge the gaps with smaller plants with an earlier start of their productive life span till slower growing larger vegetation matures. Second, they can give an insight of phased introduction of plants. Some plants are only suitable for introduction when the right environmental conditions are created over time. This is of particular interest when the starting conditions of the food forest are an open, exposed landscape or when the former land use severely degraded the soil. Then the first planting scheme could consist of only densely spaced pioneer species in grids, randomly scattered or in hedges. Dense pioneer planting is further explained in chapter 3 of part 2. Furthermore, to only map the end stage may give too little security, explained one designer. Since uncertainty of the vegetation developing the way it is predicted to develop increases over time, a map showing the vegetation in 10 years will have a higher chance of reflecting the realised vegetation in the future compared to a map of the vegetation in 25 years. A dynamic design may already be included as part of the detailed design or already in the sketches of step 2. The in-between year vegetation can be included in the sketch phase, for example as theme maps, when it visualizes important concepts like succession as part of communicating between designers as part of the narrative to the initiative taker or external stakeholders like municipalities at an early stage of the design process.

4.3.2 Additional technical implementation maps

The detailed maps zoom in on the sketch design, both spatially and temporally. Earthworks and planting schemes were considered the most common implementation maps. Additional circumstantial detailed maps were thought especially relevant in a more urban context. For instance these could serve for dimensioning impenetrable layers, water engineering objects like bridges, culverts or locks and other artificial objects like cables or concrete posts.

4.4 Plans

"Plans are the substitution of error for chance."

The succession plan was considered the foremost ecological element in the decision-making framework for a regenerative design of food forests in the Netherlands. Plant development through life stadia and seasons were important temporal design considerations as well. The management and business plan was considered the foremost agro-economical element. The third plan is the explicit consideration of the water management of the food forest. The landscape building plan can be an additional plan for explicitly embedding the food forest into the surroundings. Circumstantially specific other plans may be relevant.

4.4.1 Succession plan

The succession plan focuses on the planned temporal and spatial vegetation arrangement. This plan was thought to be interrelated with the management plan. It prescribes when, where and how plants are introduced and removed, including the required management practices, for guiding the plant community development. The succession plan also implicitly or explicitly includes the designers prediction on how the environmental gradients and communities of other kingdoms will change over time through the design. The plan can describe how the vegetation both responds to these gradients and affects these gradients in intricate feedback loops. The succession plan is elaborated on in sub-chapter 5.3.

4.4.2 Management and (post-)harvest plan

This plan was defined differently by designers, as management, harvesting and marketing plan, management and (post-)harvesting plan or in the commercial context as business plan. Site preparation, general maintenance, harvesting, processing, distribution, consumer and monitoring can be important parts of this plan. One designer mentioned that this plan was exceptionally important for large scale, commercial food forests.

"I always think from the 80-20 percent rule. What is the biggest precondition to take into account? What you sell and harvest makes a lot of difference for what cultivars you are going to use, what your planting distances are, etc. The rest is all within the margin. And that is the danger of food forests. Many people start food forests based on the plants and the love for plants, but that is just one of your elements."

4.4.3 Water management plan

As one designer stated water is the basis of all designs. Designers take moisture into account on all scales across time and space. In practice this plan includes the capture, storing and cycling of water and groundwater regulation based on the site conditions, water elements & management. On the project scale soil moisture gradients can be the basis for determining a zonation within the food forest. Furthermore, the water management plan is developed in consideration of the interaction between water requirements and the development of the food forest through the years. This plan could constitute large modifications in the landscape to manipulate water cycling in, out and through the system. These are often one time interventions, reflected in the earthwork maps. The earthwork maps can include water elements like ponds, drainages or raised terraces. The water management plan also relates to the management plan. For instance, there can be short term management practices in the first years to get the food forest plants established under drought conditions by mulching or irrigation.

4.4.4 Landscape building plan

A landscape building plan prescribes how the food forest will add as a landscape element to the surrounding area and how different zones or vegetation structures contribute to each other and the food forest as a whole. It prescribes the positive contributions of a food forest to the surroundings, but also the other way around. For instance, designing a hedge or a waterway in the food forest that connects to an existing hedge or waterway adjacent to the food forest increases faunal and floral movement in both directions. This plan also helps in telling the narrative to the outside world, both when explaining that a perceived negative effect of the food forest on the surrounding area is negligible or how large the positive contributions are. A landscape building plan perceives a food forest not as an isolated piece, but integrated in a landscape.

4.5 Lists

Designers varied in the frequency, content and naming of the developing plant material lists during the design process. In the decision-making framework four different stadia of the list are linked to each of the steps 1 to 4. Both the landscape and human dynamics were mentioned for moving from the starting list to the longlist and from the longlist to the shortlist. The order and importance of one of the two dynamics as selection criteria depended on the project objectives and personal preference of the designer. Besides the names of the plant entities, the lists often also include the exact or rough numbers of plants for each species or cultivar.

4.5.1 Species starting list

The starting list is formulated in the decision-framework as the species 100 top list for the purpose of this thesis research (elaborated on in Chapter 6). Some designers have a documented self-assembled list of food forest species that can be considered their starting list or their longlist.

"I like to work with a list of plants of which I know the advantages and disadvantages. It is very hard for a designer to know from 100 species times the amount of variable rootstocks, for example 3, times the amount of cultivars, for example 5, so 1500 plants, how they grow and what they need. More is close to impossible. You have to simplify."

Downsides mentioned by three practitioners to start with a list of 100 species is the little comparative experience with all potential species in a food forest context, subjectivity due to personal preference and environmental variation across the Netherlands. Most designers use a percentage of species and cultivars they have no experience with yet to build up their knowledge and total planting material collection.

4.5.2 Species longlist and shortlist

During the development of the species longlist and shortlist species are deselected based on the overall and prioritized context of the place. Designers generally agreed on this selection procedure. However, species may be assessed as temporarily inapplicable or undesirable in large quantities while they could be regarded suitable on the long term or in low abundance as illustrated in Box 4.5.1. Therefore, also a distinction could be made between a long term and short term list.

Box 4.5.1. Complications of narrowing down species candidate lists.

Q: How do you narrow down species to get a species longlist?

A: I wouldn't cross out too many species based on current environmental conditions. Everything is creatable and is also somewhere on the palette. If someone says a plum doesn't belong on a sandy soil, I think that if you create beneficial light conditions and organic matter builds up, it may be suitable later. Growth conditions are influenceable, for some species you just may need to wait 2 years, for others maybe 15 years. Also management practices influence this. If you do not want to irrigate at all, more species are dropped, but you can also think about irrigating the first years till the plants are well established.

Q: And based on the business plan?

A: A farmer may want all his species in production after 10 years for an economic return, so you could drop species based on that, but you don't have to make 100 percent of the food forest in production after 10 years, perhaps 70 percent is enough. I would see if I could convince him that in the long term his business model is stronger like this.

Rootstock and cultivar list

The final planting scheme(s) is/are accompanied with a list of rootstocks and cultivars. In practice the strategies for collecting planting material, and consequently zooming in to the level of cultivars and rootstocks, vary widely among designers and between the scale, targets and means of projects. There are designers that:

- collect part or all of the planting material during earlier steps in the design process
- check as soon as step 1 what is available on the market
- propagate, graft, nurse and use their own stock
- discuss with a nursery the plants and volumes beforehand
- use a combination of any of the above mentioned methods

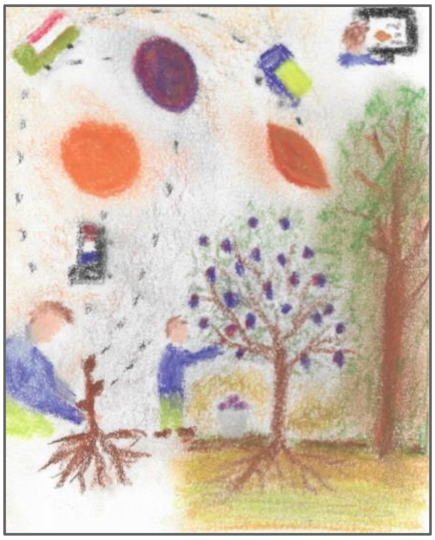


Figure 4.5.1: A practitioner ordering planting material of various *Prunus* hybrids and cultivars from eastern and southern europe to graft himself on the specific rootstocks suitable for the growth conditions of his food forest.

An important factor responsible for the different strategies for the collection of plant material is the availability, especially of cultivars with the right rootstock combination. The drawing on the right shows one practitioner ordering planting material of various *Prunus* hybrids and cultivars from eastern and southern europe to graft himself on the specific rootstocks suitable for the growth conditions of his food forest. In this scenario, the cultivars and hybrids are selected for their compressed growth season. Plant species with a short growth season can avoid damage from droughts and frost in spring and need less heat and light for sufficient ripening. The practitioner expects these plant characteristic values to be crucial for adaptation to climate change. However, the required plant material is scarcely or not available in the Netherlands.

5 Open-source plant database

5.1 Functional targets: Visions for the future

The main functional targets of food forests in the Netherlands mentioned during the interviews were clustered into the following sections:

1. ecology
2. food production
3. education and social

For each of these targets experts noted specific sub-targets. The relation between (multiple) targets and food forest scale, vegetation structure, species richness and notable plant characteristics is exemplified in Fig. 5.1.4 at the end of the chapter.

5.1.1 Ecology

A wide range of ecological functional targets was addressed by experts including creating wildlife habitat, landscape diversity, stimulation and maintenance of biodiversity, carbon sequestration and storage, water regulation, reducing pollution, self-regulation and climate resilience. Diversity was emphasized on the scale of the landscape, species and genes. Genetic diversity was found important by auto-ecologists.

"It always functions very complicated and subtle everywhere, and we don't understand much about it yet, I think, but it is a fascinating world and if you sometimes start to see a little bit how an organism or mechanism works then you are completely surprised how unlikely ingenious it is, with a flower that is just a millimeter longer that an insect can or cannot reach."

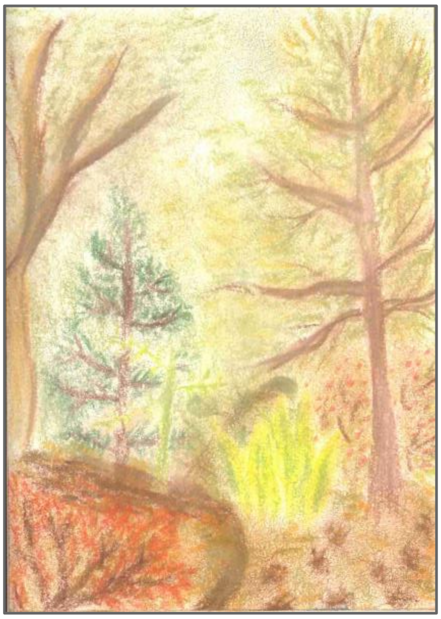


Figure 5.1.1: Impression of a romantic, multi-layered food forest.

The quote above was derived from the question to pinpoint specific characteristics for increasing biodiversity and exemplifies the intricate feedback loops and specific, seemingly infinite plant characteristics contributing to associated biodiversity. According to one ecologist, at least all plant characteristics related to light, decomposition, soil formation, water and associated biodiversity (pollination, seed dispersal, trithropic relations, etc.) are relevant for stimulating biodiversity. Often, practitioners were found to apply a high diversity of plant species for stimulating overall biodiversity as an intuitive strategy without conscious consideration of specific plant characteristics. Plant species that provide many ecosystem services for the ecological health of the food forest system besides food were identified through the food forest practitioners and are further on in this thesis research collectively categorized as 'system plants'. The main corresponding plant characteristics of system plants as identified during the data collection are further elaborated on through the themes; Carbon sequestration and storage, nectar and pollen provisioning, invasiveness and indigeneity, integrated vertical vegetation layers, water regulation, reducing pollution and nitrogen fixation. A romantic food forest integrating all of these themes is drawn in Fig. 5.1.1.

Carbon sequestration and storage

Carbon sequestration and storage was discussed as an important climate change mitigating ecological functional target. To a lesser degree carbon sequestration is also discussed in relation to succession (Chapter 3) with rapid nutrient cycling and netto biomass increment of the food forest as succession continues.

During identification of relevant plant characteristics and values for mitigating climate change a trade-off emerged between carbon sequestration rate and long term storage. Acquisitive plant characteristics such as a fast growth rate and rich leaf composition, often corresponding to an early plant successional status, increases netto sequestration. In particular, acquisitive values stimulate storage within highly active soil biota. On the contrary, long lifespan, high tree volume (height, crown diameter, root depth) and conservative whole plant and leaf characteristics such as wood density and leaf composition, often corresponding to a late plant successional status, contribute to long term storage in biomass. One practitioner stated simply being perennial and preferably tree-based in general is a first priority plant characteristic for agriculture. Another stated that both acquisitive or conservative litter are no indication of becoming stable soil organic carbon in the system after total decomposition.

Much is unknown about how roots affect carbon sequestration, thick roots that decompose over a long time or fibrous roots that decompose fast can be two ways leading to the same result. Furthermore, for a practitioner these traits are hard to observe since excavation damages the roots and is labour intensive. If there is plant species diversity, total root biomass is higher so carbon is higher.

Design propositions of experts were to either mix a diversity of plants with acquisitive and conservative values or start with acquisitive and later add conservative values (following the gradients of succession). In the timeline relevant for management, fast carbon sequestration is often favored over long-term storage in biomass by practitioners.

Nectar and pollen provisioning

Encouraging an extended, continuous and/or abundant nectar and pollen provision for stimulating biodiversity was mentioned by 7 experts during the interviews. Both the peak and length of the flowering period as well as pollination vectors and the quality and quantity of nectar and pollen were identified as corresponding plant characteristics. Species vary in flowering period year round and while some species only flower for a few days others can flower for months. A temporal consideration is to combine species for consecutive flowering where flowering starts early and continues till late in the season. One expert stated there are not so many very early and late flowering food producing food forest species, but there are systemplants that can extend the nectar and pollen provision. Genetically native species were thought to be particularly suitable for their long term symbiosis with indiginous pollinators by one expert. Grouping these species into hedges that also provide other ecosystem services was a common spatial vegetation arrangement applied by designers.

Figure 5.1.2: A flowering calendar of plant species with consecutive, long, nectar rich flowering. The calendar starts at the top and continues clockwise. In winter and early spring, Cornus mas, Chaenomeles japonica and Salix caprea flower even before coming into leaf. In April, many fruit crops from the Rosaceae family flower, such as Prunus avium. For May to Juli, Myrrhis odorata is drawn, as a representative from the Apiaceae family, together with Castanea sativa. Malus moschata, Frangula alnus and Symphytum officinale flower the entire summer and continue into fall, followed by Helianthus tuberosus flowering in October and November.

Moreover, attracting pollinators with early flowering system plants before important crops both in the food forest and circumstantial surrounding agricultural systems start flowering was seen as a strategy for increasing agrobiodiversity. For instance, bumble bees already become active in February. Herbaceous plants of the *Apiaceae* family were considered good general nectar plants in the understory. The drawing shows a flowering calendar of plant species with consecutive, long, nectar rich flowering (Fig. 5.1.2).

Invasiveness and indigeneity

Invasiveness and indigeneity of plants cut into the tension field between the functional targets of food production and biodiversity stimulation and were also identified in relation to both the topics of environmental conditions (5.2) and succession (5.3). A division was perceived between practitioners and ecologists regarding the use of potentially invasive species and exotics. The narrative of several ecologists was that genetically autochthonous plants are well adapted to the Dutch environment, associate to large biodiversity and are regulated by natural enemies so have a smaller chance of becoming invasive. Besides the known functional benefits, one ecologist advocated the introduction of exotic genes is also an ethical question. The native *Quercus robur* in Box 5.1.1 serves as an example of the high associated biodiversity of native plants. Moreover, this box exemplifies the complexity of the plant characteristics responsible for this functioning and inconsistency of plant characteristics for predicting stimulation of biodiversity. Plant characteristics such as a heavily textured bark were identified to contribute to associated biodiversity reasoning from the *Quercus*, while not being mentioned by any expert during the interviews reasoning from the perspective of taking the criteria or plant characteristics as a starting point.

Box 5.1.1: *Quercus robur,* associated biodiversity and responsible plant characteristics.

Quercus robur was discussed with two auto-ecologists as the native tree with the highest associated biodiversity. *Quercus robur* offers a wide range of niches in time and spatially in terms of food and habitat. A general diversity of morphological structures provides diverse microhabitats. *Quercus robur* can grow in a lot of directions as compared to pine trees that grow straight with horizontal branches. Furthermore, the bark is very textured. Moreover, when the plant gets older new morphological structures provide new niches. Thus, a long lifespan can reinforce associated biodiversity. *Quercus robur* offers a diversity of edible products, with a mast of acorns of importance to birds and mammals and the gals attracting many insects compared to other native species like *Fagus sylvatica*.

Quercus robur does not score well on leaf composition that increases understory plant biodiversity, since their leaves provide some nasty acids, while for example *Tilia cordata* does have rich leaves and increases undergrowth biodiversity.

Most practitioners argued that the current agriculture, forestry, city trees and ornamental plants mainly introduce exotic species in the landscape and that without reliance on exotic species there would be an insufficient quantity and diversity of food to sustain a large human population. In regard to successional status, most food forest species are not pioneers so do generally not rejuvenate fast and abundantly, especially not on the common early successional agricultural monocultures of the Netherlands. Practitioners do however cautiously consider specific species that could spread aggressively in a certain place. *Vaccinium corymbosum*, *Vaccinium macrocarpon* and *Aronia spp* or *Rosa rugosa* and *Lycium barbarum* can behave aggressively in peat soils and coastal dunes respectively. Therefore regionally certain species could best be avoided in specific biotopes. Moreover, exotic cultivars from native species in collections of Arboreta can also diversify the total gene pool.

Integrated vertical vegetation layers

Designing multiple, integrated vertical strata of vegetation was thought to increase wildlife habitat diversification and encourage movement of species between food forest layers. Designers classified a range of 4 to 9 vertical layers. The most simplified categorisation consisted of a canopy, shrub, ground and climber layer. The most extensive classification included canopy, in between, shrub, climbers, herb, soil surface, fungi, root and water. Climbers were explicitly mentioned by one ecologist for connecting different layers. Identified promising food forest species of the climbing layer were *Actinidia spp, Apios americana, Hablitzia* *tamnoides, Humulus lupulus, Schisandra simulans* and *Vitis vinifera*. The plant characteristic layer is further explored in sub-chapters 5.3 and 5.5.

Water regulation

Water regulation was by several experts considered a local ecological functional target that enhanced climate change resilience. One design consideration was to mix deep and shallow rooting species for increased moisture, capture, storage and (re)use. Plant characteristics and species related to moisture are further explored in sub-chapters 5.2, 5.3 and 5.4.

Reducing pollution

Reducing pollution was a regenerative functional target that was not explicitly considered by most experts, but perceived as an inherent regenerative property of food forests. Wintergreen plants are used for filtering air or placed along boundaries for blocking detrimental air pollutants from entering the food forest. Phytoremediation plants could be used for heavy metal uptake, although no expert voiced experience or specific plant characteristics.

Nitrogen fixation

An often discussed function of system plants considered by practitioners was fixation of atmospheric nitrogen. This was not mentioned as a functional target in itself unlike the above themes, but as a means of self-regulation of the system. Most practitioners place nitrogen fixing plants around food producing species for passive nitrogen support. One ecologist named nitrogen as an important component for accelerating nutrient decomposition, stimulating more plant-available nutrients for plants in the topsoil. Another practitioner placed nitrogen fixing plants on the south west so the dominant prevailing south-western wind in the Netherlands blows nitrogen rich leaves as fertilizer into the food forest. There were also experts that were sceptical about the use of nitrogen fixing plants, advocating the passive nitrogen deposition through the air and excess nitrogen in the ground water leached from agricultural fields provides sufficient nitrogen for a fully productive food forest. Identified promising, nitrogen fixing species were *Alnus spp, Caragana arborescens, Elaeagnus spp* and *Hippophae rhamnoides*.

5.1.2 Food production

All experts mentioned food production as a functional target of food forests. There was however a large variation between perceptions of the importance and potential of food production in food forests, as well as the underlying and specific goals of food production. With 'food production', experts could refer to the quantity, quality or diversity of food supporting agrobiodiversity, commercial interests, public health, food security or food sovereignty on a global to local scale. Moreover, food production for non-human beings and for telling the narrative of the food forest were acknowledged as fundamental food production targets which are further elaborated on in the first and third part of this chapter.

"I want the system to produce food. If we believe that we can sustain the world with agroforestry systems, among those food forests, then it has to produce food, otherwise it will never be a substitute for conventional agriculture."

Design considerations

Key functional plant characteristics explored for designing in service of food production targets were; edible plant part, nutritional value, productivity (start and peak), productive lifespan (start, peak and length), harvest period (start, length and uniformity), culinary appreciation, suitable harvesting methods, processability, storability, markets and consumption and future demand. Specified food production targets were discussed strongly in relation to the project scale and harvest. Thus, an in-depth exploration of the corresponding functional plant characteristics and related design considerations for food production targets is continued in chapter 4 and 5 to reduce redundancy.

Commercial food production is highlighted and elaborated on here and further on in chapter 6 since this was a central theme to many experts. Reduction of labour and starting at the product end of the supply chain were the most mentioned design considerations by experts when designing a commercial food forest. Designers can plan the quantity and diversity of harvestable food throughout the season and years. Initiatives such as Heerenboeren have a demand for an amount of apples or nuts that need to come out of the system and those are the numbers the designers of these systems will be judged upon in the future. When aiming for commercial food production for self-sufficiency not for all food forest designers this means all food of a farm has to be plant-based or produced solely in a food forest context. Some of the newly designed Heerenboeren farms have a zonation plan with one part food forest, one part less complex agroforestry, one part annual stripcropping and one part animal systems to compose a complete diet that Dutch people are familiar with. Tab. 5.1.2 and Tab. 5.1.3 in Annex I provide a complete overview of the plant characteristics, desired values and promising food forest species explored in relation to small and large commercial food production.

"I start at the product side of the chain and ask the experts in that market what they look for in a product. With walnuts, I went to someone that makes walnut oil and asked him what he finds important in walnuts. He knows that walnut cultivars differ in oil concentration so looks specifically for those cultivars. As a farmer I can then choose cultivars for this reason."

5.1.3 Education and social

Education (experiencing, discovering, learning), social regeneration (cohesion, connection) and to a lesser degree recreation (mental health) were mentioned as the third large set of functional targets of food forests by most experts. According to some experts, this target can also be summarized as the restoration of the relationships of humans with the land, nature, food and each other.

"Building social capital is the short term yield of most projects. Relations are established, volunteers get involved, people get motivated, bond, have a common goal, it gives energy. It speaks to people of all age classes."

One practitioner stated that important plant characteristics during excursions depend entirely on the target audience, the message the guide wishes to tell and the creativity of the guide to use plant characteristics to get the message across. The drawing on the right gives an example of a social and educational food forest-like design for children (Fig. 5.1.3). Consequently, for food forests with educational and social targets and less emphasis on the commercial aspects, there is also a less sharp demarcation of the species that are suitable. This is exemplified by the conversation highlighted in Box 5.1.4.

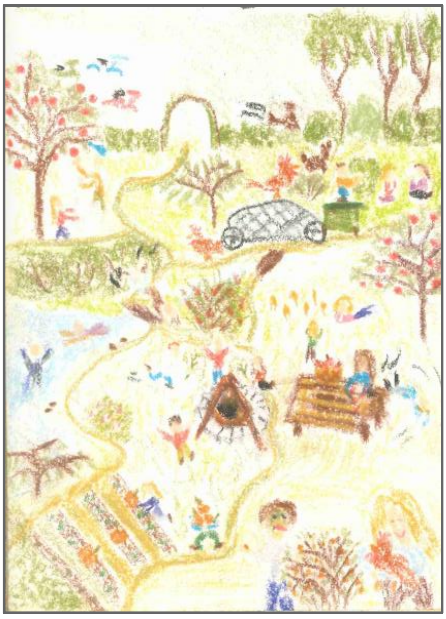


Figure 5.1.3: Impression of an educational food forest for children.

Box 5.1.4: Telling the narrative of food forests in relation to plant species and characteristics.

Q: What are important functional targets of food forests in the Netherlands?

A: Many people start a food forest for food production, but in practice other implicit goals turn out to be more important. … Food forests give a concrete solution to how we can relate to and experience nature through all our senses. That is also possible if you take a walk through a forest, but this appeals more because food is important to everyone, it is the perfect bridge between humans and nature. If I let people taste something during an excursion my story comes across 10 times better. So the food is important, but more as a bridge to tell the story. Chefs play an important part in this. They make the translation between a vague conceptual system with weird plants to a tasteful meal on your plate. Food forest recipes facebook groups are growing exponentially.

Q: how does using food as a bridge for connecting people to nature translate to concrete design considerations for species selection?

A: Here in the Overtuin the place is incredibly accessible for people year round. We give an excursion once every month so you would want something to experience each month and choose species that stimulate people's senses over the year. However, here it is also important to show what a diversity of species is around in the first place that provide interesting properties, so here it is almost the goal to plant as many species in a way that is ecologically possible and allowed … Also because this food forest is part of an Arboretum that holds the function of demonstration of different species.

Nevertheless, culinary appreciation, start of the harvest period, familiarity to the Dutch consumer, nutritional value, lifespan and suitable harvest methods were highlighted here for telling the narrative of the food forest. Species with an extraordinary or unusual taste were mentioned for stimulating the human senses mentioned by one practitioner were *Amelanchier alnifolia, Asimina triloba, Toona sinensis, Leycesteria formosa, Ribes uva-crispa* and *Viburnum lentago. Prunus armeniaca* was mentioned as an example of fruits that gain a superior taste when left ripening on the tree. As one practitioner described, many commercially grown fruits were picked before fully ripening since harder fruits are easier to transport and store. Social and educational food forests without commercial interest can let these products ripen further and make humans experience them in their best condition. The boy in the drawing on Fig. 5.1.3 demonstrates how even unpleasant tastes, such as a fresh *Hippophae rhamnoides* berry, add to the experience of food. *Hemerocallis spp* and *Hosta spp* exemplify plants that are regularly planted in ornamental gardens in the Netherlands, but unknown in Dutch culture as edible. *Juglans ailantifolia, Juglans cinerea, Juglans nigra, Juglans regia* and *Pinus koraiensis* were mentioned as interesting for educational and social food forests by one expert because of the rare cultivars, hard processability and late start of the productive lifespan that makes these plants less attractive to commercial growers.

One practitioner mentioned telling the story about healthy food during excursions, including the importance of a complete diet and how conventional agriculture gets less nutritious over time. *Aronia spp, Elaeagnus multiflora, Elaeagnus umbellata, Hippophae rhamnoides* and *Vaccinium corymbosum* were named explicitly and illustrate the healthy properties of small fruit. In native american thanksgiving *Fragaria spp* is thanked as the leader of fruits, ripening already in june. The plant characteristic "start of harvest period" can teach people that a good leader is the first to share his or her gifts. When people care for a tree for generations this connects an individual person not only to this tree, but to each other, the land, future and past generations. This is captured by the plant characteristic lifespan. Finally, species suitable for harvest by hand were considered suitable for a self-harvesting system that encourages an intimate relationship of humans with food, nature and the land.

Tab. 5.1.2 in Annex I provides a complete overview of the plant characteristics and desired values explored in relation to food production for educational purposes as opposed to food production for commercial targets. The table indicates how in food forests with educational and social targets, a wider range of plant characteristic values is suitable compared to food forests with commercial targets and how all different edible plant parts are perceived to be easy to integrate in the food forest.

Figure 5.1.4: Impressions of (from left to right) a romantic, multi-layered food forest, 'Heerenboeren' farm with a food forest integrated with other food production systems and educational food forest for children, to illustrate how the vegetation structure and composition of food forests are highly dependent on the desired targets of the place and project scales.

5.2 National, regional, local and future environmental conditions

In this chapter temperature, moisture and "urban context" are highlighted as essential environmental design criteria both in the spatial (national, regional, local) and temporal (climate change, seasonal) context of food forest design, with corresponding relevant plant characteristics and promising food forest species. Temperature is further divided into winter hardiness, susceptibility to spring frost and heat requirement.

5.2.1 Spring frost

Spring night frost was perceived as one the key design criteria for food forests in the Netherlands and was the second most mentioned environmental condition during the interviews. The only two experts that did not refer to spring night frosts had no experiential knowledge with growing fruit crops. Spring night frost could be translated to the compound plant characteristic susceptibility to late night frost, combining the characteristics edible plant part, flowering time, minimum tolerated temperature by the flowers, height of the flowers from the soil and to a lesser degree frost susceptibility of other plant parts, with leafing out indicating the end of dormancy.

Due to the northern, maritime location of the Netherlands late night frosts are common up till may. Moreover, late night frosts also differ greatly within the Netherlands on a regional scale, with less late night frost close to the sea and directly adjacent to the IJsselmeer. The Netherlands also provides relatively little opportunity for avoiding local late night frost due to selecting a food forest location on a regional scale. Since the Netherlands are flat, cold air does not drain properly at most places. Expert opinions differ on whether damage from late night frost will decrease or increase in the future due to climate change. Some experts replied that species will start their growth season earlier through softer winters while the late night frosts themselves will stay the same, increasing the risk of late night frost damage. Other experts replied that in theory night frosts will occur less and less severely in spring due to climate change, while others replied this is a big question, without passing judgement.

Species and cultivar variation

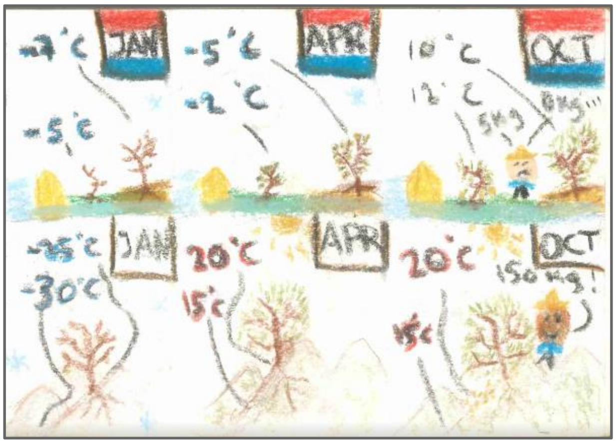


Figure 5.2.1: Effect of seasonal temperature gradients in a maritime versus a continental climate and planting distance from the coast on the productivity of *Juglans regia*.

Some plant species are very resistant to late night frost. For instance, *Lonicera caerulea* and *Cornus mas* both flower early in spring, but their flowers tolerate minimum temperatures of -8 degrees. Other species flower relatively late in the season and escape late night frost even though the plant may be vulnerable to low overall minimal temperatures. Plants from continental and southern climates are especially susceptible to late night frost, as exemplified in Fig. 5.2.1. In the dormant stage many species originating from continental climates on the same latitude tolerate minimum temperatures below -20 degrees when dormant, but hardly tolerate any frost after coming out of dormancy. Late night frost is most problematic for species where the edible product is a reproductive organ (flower, fruit, seed, nut). *Actinidia arguta* was the most mentioned example (5 experts) and may lose their crop three in five years. Traditionally many fruits were cultivated in the Dutch coastal provinces such as Friesland and Zeeland. Sprinkling flowers with water can create a protective thick ice layer on the flowers. This management practice is one of the main reasons traditional and modern conventional orchards are located along the large Dutch rivers (Rijn, Waal, Maas), emphasizing the importance of this climatic condition for fruit cultivation. Tab. 5.2.1 lists promising food forest species that were considered either vulnerable to late night frost or nut and fruit crops that are very resistant despite early flowering and possible conflicting expert opinions on the plant characteristics values of these species. Practitioners experienced and suspect a large intra-species variation in vulnerability on the cultivar scale. Therefore, the interviewed practitioners explicitly choose and experiment with specific cultivars or hybrids (Tab. 5.2.1). Diversifying on flowering periods of cultivars can spread the risk of damage and late flowering cultivars have a general lower risk.

Table 5.2.1: Spring frost vulnerability for promising food forest species, the availability of improved cultivars (cv) and conflicting expert experiences.

Nr.	Plant species	Spring frost vulnerability	Improved cvs/hybrids?	Conflicting expert experiences
1	Actinidia arguta	very vulnerable	Yes	
2	Actinidia chinensis	Vulnerable	Yes	
3	Castanea sativa	very resistant / vulnerable	Yes	x
4	Crataegus spp	medium - vulnerable	Yes	
5	Diospyros kaki	Vulnerable	Yes	
6	Juglans regia	Vulnerable	Yes	
7	Malus domestica	Vulnerable	Yes	
8	Morus alba	Vulnerable	Yes	
9	Morus nigra	medium / very vulnerable	No	x
10	Pinus koraiensis	Vulnerable	no data	
11	Prunus armeniaca	very vulnerable	Yes	
12	Prunus avium	very resistant / vulnerable	Yes	x
13	Prunus domestica	Vulnerable	Yes	
14	Prunus dulcis	very vulnerable	Yes	
15	Prunus persica	very vulnerable	Yes	
16	Pyrus communis	Vulnerable	Yes	
17	Quercus robur	Vulnerable	no data	
18	Toona sinensis	medium - vulnerable	No	
19	Vitis vinifera	Vulnerable	no data	
20	Chaenomeles cathayensis	very resistant	-	
21	Chaenomeles japonica	very resistant	-	

22	Cornus mas	very resistant	-	
23	Corylus avellana	very resistant	-	
24	Lonicera caerulea	very resistant	-	

Spatial and temporal design considerations

For vulnerable species, designers can choose specific favourable local microclimates. Designers can put vulnerable plants out of reach of direct morning sun in spring. Morning sun can accelerate the ice on flowers to melt resulting in distorted flowers. Moreover, suitable microclimate can be encouraged by placing plants on terraces and along ponds for cold air drainage. Larger plants, for example on vigorous rootstocks can escape late night frost since temperatures considerably increase further away from the ground.

5.2.2 Heat requirement

There are negative consequences if a plant gets too much or too little heat in summer. Summer heat strongly influences moisture use and photosynthesis rates. When a plant gets too much summer heat, evaporation exceeds the moisture supply rate and plant parts dry out. When a plant gets too little summer heat this can result in insufficient flowering, fruit or nut ripening and hardening of wood. Some experts mentioned explicitly considering an increase of summer heat in the Netherlands due to climate change.

Species and cultivar variation

Species from northern climates, with high moisture requirements, vulnerable large leaves or naturally occur in a late successional understory were thought to have a low heat tolerance. On the other hand, species from warmer (Mediterranean or subtropical) and continental (e.g. China) climates have a certain heat requirement for which a deficiency of Dutch summer heat is problematic for cultivation.

Promising food forest species from warm and continental climates that may have trouble getting enough summer heat for sufficient fruit or nut ripening were *Carya illinoinensis, Castanea mollissima, Castanea sativa (x crenata), Diospyros kaki (x virginiana), Prunus armeniaca* and *Pyrus pyrifolia*. Cultivars with a shorter growth period are generally relatively early ripening and need less summer heat. Suitable early ripening cultivars were identified for each of the above species, except *Castanea mollissima*. For some species like *Castanea sativa (x crenata)* only the very late ripening cultivars were considered suitable for the Dutch climate, for others like *Diospyros kaki (x virginiana)* only early ripening cultivars may be suitable. In the chapter harvest using the phenological plant characteristic harvest period as indicator for summer heat requirements is further explored.

Spatial and temporal design considerations

Designers can consider heat requirements during the spatial and temporal vegetation arrangement. They create microclimate in food forests for species with a high heat requirement by placing these plants in full southern and western sun. A heat trap can be designed by placing heat requiring species in a horse shoe shaped surrounding vegetation. When the food forest does not have the required microclimate, these can be created while plants demanding or susceptible to heat can be planned for introduction at a later stage.

5.2.3 Soil moisture

Soil moisture recurred as a central theme during the interviews and was perceived as an essential environmental design criteria among all experts. Soil moisture was explored on both spatial (regional and local) and temporal (seasonal, ontogenetics and climate change) levels. In the Netherlands there are two problem areas that were considered either too wet or too dry. The first problem area is the low elevated peat colonies and clay polders in the west of the country with an additional heavily human controlled high groundwater table. The second area refers to the higher elevated sandy soils in the middle and east of the country which are especially prone to drought. Zooming in to the local scale, the vertical soil layer where the drought occurs was seen as a factor impacting different plants. If drought occurs in the top layer the small plants without a deep rooting system are gone fast, while deep tap roots enable deep water retrieval. In contradiction however, finely branched roots of many smaller plants were mentioned by one expert to increase drought tolerance in the topsoil due to efficient water acquisition. On the horizontal local scale, elevations in the landscape were experienced to result in high gradients of moisture availability and groundwater levels.

The last three consecutive years practitioners experienced dry springs and summers due to low rainfall. One practitioner mentioned high mortality rates on the dryer soils for the last four years due to these seasonal patterns. High seasonal fluctuations of the groundwater table were experienced as another detrimental pattern, tolerated by only a few wild plant species and even fewer food forest crops. The question whether a tree would be more or less susceptible to drought during different life stadia led to conflicting experiences and interpretations. Young plants were generally believed to be more susceptible to drought since the rooting system has to establish and extend (see also sub-chapter 5.4). Several practitioners called this the most problematic current aspect for the starting phase of food forests. However, other experts said that the largest trees are hit hardest by drought, because of hydraulic physiological limitations and relatively high evaporation. Moreover, while mortality rates of young plants were thought to be higher, younger plants were also perceived to recover faster after rain compared to older plants. As a consequence of climate change, both scientists and practitioners expect extremes and unpredictability of the weather conditions in the near future that result in extended droughts and peak rainfall.

Soil moisture tolerance was mentioned as the relevant overall compound plant characteristic applied by practitioners. An overview of the identified plant characteristics that can contribute to soil moisture tolerance is given in Fig. 5.2.2 in Annex II. However, designers advocated it is more important to know how the plant performs under these conditions, since they need to know how to apply the plant instead of knowing why the plant has these tolerances. As one designer put it; “It is interesting, but not applicable for the movement. Besides, for most plants we don’t know why they have these tolerances”. Another identified plant characteristic was the highest ground water table tolerance.

Species variation

Tab. 5.2.2 lists identified promising food forest species with experienced tolerances to extreme moisture conditions (drought, wet, inundated soils) and little rooting depth (<50 cm). Moreover, the table includes species that were thought to demand a relatively low groundwater table (>50 cm). *Alnus spp*, *Amelanchier lamarckii*, *Aronia spp*, *Betula spp*, *Chaenomeles cathayensis*, *Chaenomeles japonica*, *Crataegus spp*, *Mespilus germanica*, *Prunus cerasifera, Quercus robur* and *Salix caprea* were mentioned by practitioners to tolerate both wet and dry soils. A wide spectrum of soil moisture tolerances was thought to also predict suitability for soils with heavy groundwater fluctuations, future extreme weather conditions and exposed early successional systems (sub-chapter 5.3). Only 3 genus were identified to tolerate inundated soils.

Table 5.2.2: Soil moisture and highest groundwater tolerances for promising food forest species.

Nr.	Soil moisture tolerance				Highest groundwater table	
	Drought	**dry**	**wet**	**inundated**	**< 50 cm**	**> 50 cm**
1	Amelanchier lamarckii	Alnus spp	Amelanchier lamarckii	Alnus spp	Actinidia arguta	Asparagus officinalis
2	Castanea mollissima	Amelanchier alnifolia	Arctium lappa	Betula spp	Alnus spp	Castanea sativa (x)
3	Castanea sativa (x)	Apios americana	Aronia spp	Salix spp	Aronia spp	Crambe maritima
4	Chaenomeles cathayensis	Armoracia rusticana	Asimina triloba		Asimina triloba	Dioscorea polystachya
5	Chaenomeles japonica	Aronia spp	Carya illinoinensis		Betula spp	Juglans regia
6	Crambe maritima	Asimina triloba	Chaenomeles cathayensis		Carya illinoinensis	Pyrus communis
7	Ficus carica	Betula spp	Chaenomeles japonica		Corylus avellana	Zingiber mioga

8	Foeniculum vulgare	Caragana arborescens	Crataegus spp		Hosta sieboldiana	
9	Frangula alnus	Cornus mas	Heracleum spp		Petasites japonicus	
10	Hippophae rhamnoides	Corylus avellana	Hosta sieboldiana		Prunus cerasifera (x)	
11	Lycium barbarum	Crataegus spp	Juglans nigra		Ribes nigrum	
12	Mespilus germanica	Diospyros virginiana (x)	Mespilus germanica		Ribes rubrum	
13	Prunus cerasifera (x)	Myrrhis odorata	Myrica gale		Rubus idaeus	
14	Quercus ilex	Prunus avium	Myrrhis odorata		Salix spp	
15	Quercus robur	Ribes uva-crispa	Petasites japonicus			
16	Rosa rugosa	Rumex acetosa	Prunus cerasifera (x)			
17	Scorzonera hispanica	Rumex acetosella	Quercus robur			
18	Sorbus aucuparia	Salix caprea	Ribes nigrum			
19	Ziziphus jujuba	Sambucus nigra	Ribes rubrum			
20	*Mediterranean herbs*	Stellaria media	Vaccinium corymbosum			
21	*Native dune herbs*	Tilia cordata	Vaccinium macrocarpon			
22		Vitis vinifera				

Spatial design considerations

Concerning spatial arrangement on the scale of the project area, one designer mentioned that local gradients in moisture levels are one of her guiding criteria for designing the rough vegetational arrangement during the sketch phase. Zooming in to the spatial plant-plant interactions, one practitioner mentioned designing high and low moisture demanding crops in the same vertical strata, while placing high demanding crops horizontally away from each other. On dryer soils, one designer mentioned choosing wider planting distances to reduce competition for water between crops. Regarding the potential of belowground niche partitioning through the combination of species with differing rooting depths the interviewed functional root ecologist answered the following:

"*I can imagine that if there is more variation in species you will have more possibilities to use more of the soil and have a higher chance to get niche partitioning. However, trees also have most roots in the top layer. You can not afford not to be in the top layer as a plant since that is where the rain infiltrates.*"

Pruning was experienced by one practitioner as an effective management practice to shift the above and belowground biomass ratio in favour of the root systems. This management had a direct influence on his planting distances. Designing terraces or drainages for species that require sufficient rooting space was a common design element in the context of high water tables.

5.2.4 Urban or rural

Four experts mentioned the importance of urban or rural conditions adjacent to the food forest. For pest management, rural conditions may hold large habitat large enough for large predators for natural pest regulation. Another expert stated that due to a larger population density, there is a larger audience to reach in urban areas and therefore a high potential for food forests with education and social targets. The third expert mentioned how the urban environment asks for specific abiotic design considerations. For instance, shelter or local wind bursts through high buildings or raised overall temperatures due to the concrete.

5.3 Succession: Community development over the years

In this sub-chapter successional stadia and gradients as design criteria, their according plant characteristics (including values) and design considerations (spatial and temporal vegetation arrangement, species and management) are explored. Tab. 5.3.1, 5.3.2 and 5.3.3 in Annex I provide overviews of the explored relevant plant characteristics concerning succession in a food forest context, how the relevant values of each plant characteristic relate to different successional stadia, the amount of experts that mentioned each plant characteristic as relevant (with a distinction made between academic ecologists and practitioners) and which plant species and management practices were found relevant in each successional stadium.

5.3.1 Stadia

The same course of succession for natural forest succession applies for food forests with a division into three (and in some cases four) main successional stadia. Most practitioners described the phases of the food forest as "pioneer", "thinning/underplanting" and "mature", referring to an early, early or mid and mid or late successional stage respectively. Early successional stadia were perceived by food forest practitioners as open landscapes with a former land use of pasture, annual crops or simply fallow land. According to practitioners these were the most common starting conditions for food forests in the Netherlands. The mid successional stadium was also referred to as "young woodland" or "forest edge", providing a direct reference to the envisioned vegetational spatial arrangement. Several practitioners referred to "mature food forest" as a mid successional system. The late stadium was also described as "climax", simply "forest" or "closed canopy". This stadium could be both a starting stadium and final stadium for food forests.

5.3.2 Gradients

Through the course of succession, several biotic and abiotic gradients were identified concerning light, soil characteristics, wind, temperature, vegetation and fauna. Each of the gradients and the corresponding plant characteristics are described below. The vegetation both responds to these gradients and affects these gradients, corresponding to the distinction termed as 'response traits' and 'effect traits' in functional ecology. As one practitioner put it, the effect and response plant characteristics are often the same plant characteristics, but with different occurring and desired characteristic values on the spectrum. While temporal patterns are explored, local abiotic conditions and for instance natural storage and inputs of the system play a role for the contextual succession stadia and gradients in practice. How both apply to concrete design elements (species, spatial patterns and temporal patterns) for food forests according to the interviewed experts is discussed in the paragraph design considerations.

Light

Respondents unanimously agreed on light reduction in the understory as a relevant successional gradient for the design of food forests in the Netherlands, with several experts explicitly stating the light environment as the most important gradient. In the tropics there is more light of higher intensity, higher in the sky compared to the Dutch temperate conditions. Long shadows casted by high vegetation and reduced light availability in lower food forest layers create a strong horizontal and vertical light gradient. Both the response on and effect of the light gradient was explicitly considered by practitioners. Relevant response plant characteristics were light preference and shade tolerance for growth and specifically for productivity in shade, mentioned by 3, 5 and 9 experts respectively.

The interviewed ecologists apply a very broad range of plant traits, especially leaf economic traits, in trait-based research on forest succession. Food forest practitioners apply a smaller range of characteristics, mainly the effect of the canopy crown on the understory (crown density and diameter) and shade tolerance (growth and productivity) of the understory, while they generally discarded the characteristics proposed by ecologists with various arguments. First, the characteristics needed to be applicable in the field (recognizing, monitoring, etc.), while they regarded many of the light related functional traits identified during interviews with ecologists as hard to interpret and far from practice. Second, species successional status sufficiently indicates the desired leaf, root and whole plant traits according to practitioners. Lastly, as one designer stated, food forest designers do not have the time to consider all these traits during a design due to the limited budget of their clients, large amount of other plant characteristics to be considered and their work schedule.

Soil nutrients, structure, fauna, fungi, acidity, oxygen and moisture

Within the soil environment experts named an increase in soil organic carbon, improvement of soil structure, increase in soil life diversity and abundance (especially fungi) as successional gradients. Carbon builds up coming in from the air and other nutrients come in from soil and rain. Ecologists perceived a shift from acquisitive to conservative plant characteristics as a major gradient responding to and affecting succession in relation to the soil environment. For example, acquisitive root dimensional characteristics were thought to increase soil porosity and provide nutrients for soil fauna while conservative leaf dimensional characteristics correlate to low leaf decomposition rates. Leaf composition, in particular, was mentioned by three experts as an important acquisitive or conservative effect trait on both soil organic matter, acidity and moisture. Other plant characteristics that could drive soil nutrient cycling in an acquisitive or conservative manner according to the interviewed ecologists were leaf nitrogen content, leaf dry matter content, leaf mass per area and wood density.

In consequence of improving soil structure and soil organic matter building up, soil moisture is regulated by improved surface infiltration and storage as succession continues. The mediation role of the food forest results in a more even distribution of water over the season. Most practitioners perceived soil acidity and fertility as relatively unimportant gradients to consider for food forest design, due to the ability of most shrubs and trees to mediate their own pH around the rhizomes and organic matter building up over time naturally. One practitioner stated literature is too strict on soil fertility and acidity tolerances. On the contrary, ecologists generally mentioned soil fertility and acidity tolerance of plants as relevant characteristics. Multiple experts stressed that opposed to natural forests, an increasing amount of nutrients are taken out of a food forest by harvesting as the food forest grows, countering the natural gradient of increased soil organic matter.

Identified plant characteristics to respond to these gradients were tolerances to soil acidity, compaction, fertility and moisture with important values for these characteristics during early succession with tolerances to extreme soil acidity (high or low), extreme moisture levels (wet or drought), poor and compacted soils. Identified plant characteristics driving (and to lesser degree responding to) these gradients were high mycorrhizal type and occupation, leaf characteristics (biomass, dry matter, fibers, life span, lignin, specific leaf area, nitrogen, composition, decomposition rate, size), root characteristics (decomposition rate, biomass, growth rate) and whole plant characteristics (relative growth rate, wood decomposition rate). During early successional stages designers chose for plants with a diversity of mycorrhiza types and high mycorrhizal occupation and mainly aquisitive leaf, root and whole plant characteristic values.

Wind

Several experts mentioned a reduction of wind speed as a successional gradient, especially in the understory of the food forest. Moreover, reduction of wind speed was thought to indirectly facilitate and accelerate vegetation growth and soil related successional gradients. While wind speed generally decreases as succession within the food forest area continues, one expert argued that the wind gradient may be dependent more on natural or artificial elements surrounding the food forest, for example an adjacent forest or buildings in an urban context. The main response characteristic identified in relation to this gradient was wind stress resistance.

Temperature

Only one expert explicitly mentioned the mediation of both air and soil temperatures as a successional gradient, with frost vulnerability explicitly mentioned as a plant characteristic, with high frost resistance as a relevant value during an early successional state.

Vegetation and fauna

As succession continues, biomass of the vegetation increases, the canopy layer increases in height, niches increase and in consequence species diversity. The responses/effects of a plant driving and driven by all above described abiotic biotic and abiotic gradients could collectively be summarized as the plant characteristic; successional status. Besides shade tolerance (productivity) and layer, successional status was the most applied and discussed plant characteristic during interview conversations on succession. The quote below illustrates the relation of a plant's successional status to a broad spectrum of other plant characteristics;

"There is big literature on ecophysiological basis with shade tolerance matching up with species successional status. This points to leaf traits as primary drivers of plant successional statuses. We know that early vs late species differentiate in terms of leaf economics traits and this is where I would start. Those scale up specifically to relative growth rates and mortality rates as whole plant traits. What comes along with that are wood characteristics. Wood density is a strong correlate of relative growth rate. Mortality rates are a bit harder, early successionals should have higher mortality rates and lower lifespans."

In addition to the plant characteristics mentioned in the quote, plant characteristics mentioned in relation to plant successional status were height, layer, competitive strength and edible plant part, leaf photosynthesis rate and leaf respiration rate. Other explored plant characteristics were dispersion, productive lifespan (length), rooting depth, resprouting, vegetation strategy and vegetative propagation. The desired values for these plant characteristics during multiple successional stadia are discussed at the design consideration paragraphs below. Stem diameter, specific leaf area and wood density were mentioned by ecologists.

5.3.3 Design considerations

The difference between natural forest succession and food forest development is that food forest designers disturb, guide, mimic and accelerate succession by planting, thinning and other management practices. For instance, certain successional stages can be jumped over by planting certain species. Therefore, compared to natural forest succession, food forests undergo a heavily guided succession, even though interviewed food forest practitioners do embrace spontaneous vegetation establishment and (planned) natural environmental filtering of species by the system. The most common spatial structures discussed in relation to succession were hedges, edges and dense pioneer planting. The main temporal design considerations discussed can be described as ' instant successions', 'phased introduction' or 'relay plantings' and 'shifting mosaics'. Fig. 5.3.1 visualizes the successional schemes of the explored starting, transition and 'final' stadia applied and envisioned by experts. These are discussed below.

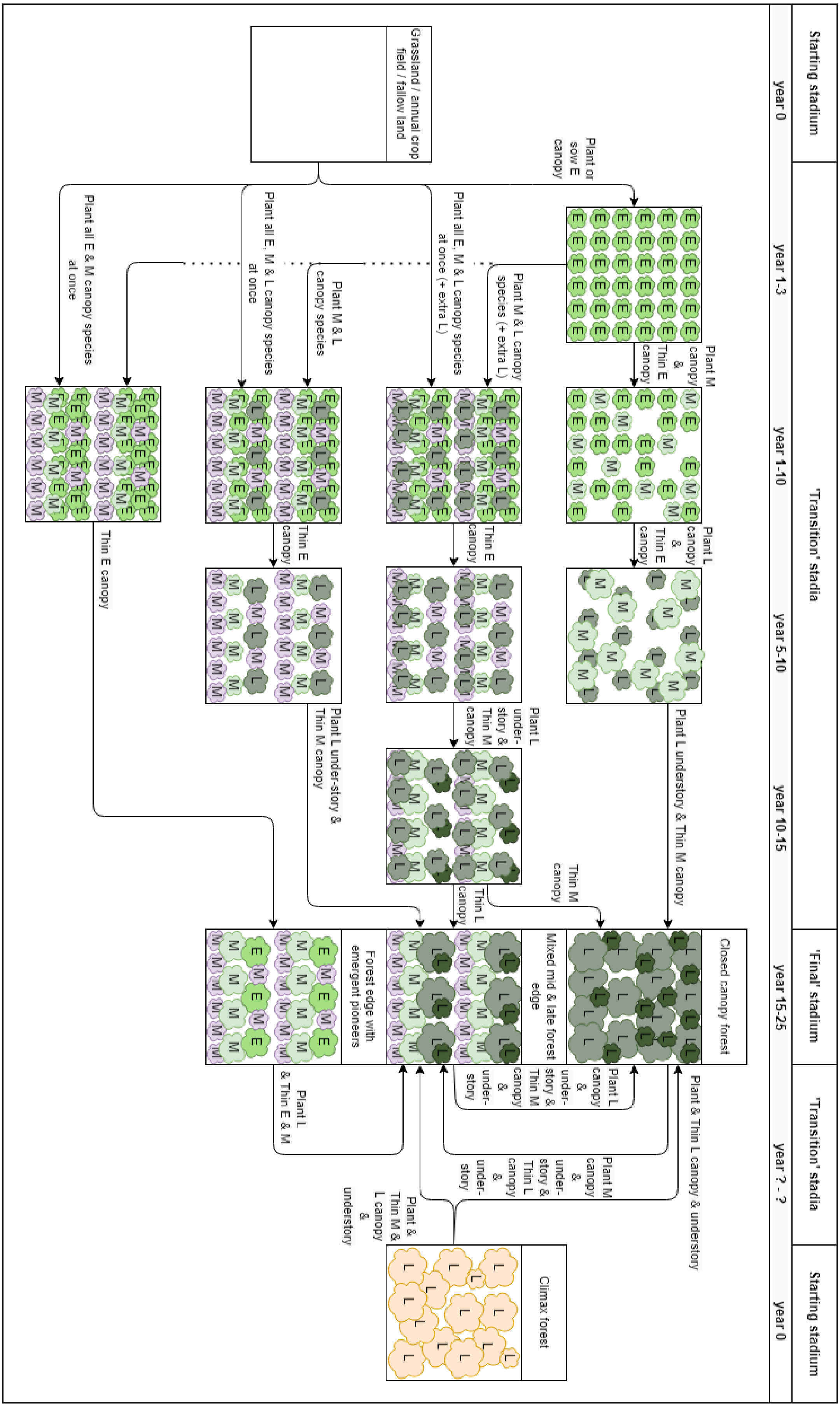


Figure 5.3.1: Main explored scenarios for the 'starting', 'transition' and 'final' stadia in successional food forest design (E=early, M= mid and L=late plant successional status).

Starting from early successional systems

With grassland or poorly developed soil as a starting condition, practitioners select species with a pioneer successional status, for a high competitive strength in this phase and compared to the grasses, while moving the system to the next successional state and building up soil health with acquisitive plant characteristics and values. On the contrary, mulching litter with predominantly conservative values of later successionals could be more effective for grass suppression so some experts also advised a mixture of these plant characteristic values. The interviewed functional root ecologist suggested that species with deep rooting and a lot of mycorrhizal associations can accelerate forest succession and decrease competition of the more vulnerable species with the grasses, but also mentioned traits for competition with grass remain very context dependent. As a management practice the competition pressure could also be reduced by breaking open and turning the grass root mats. Besides competitive strength and effect characteristic values, early successionals are selected for general high tolerance of low temperatures, wind-stress, browsing, frozen soils, compacted soils and low soil organic matter. Hedges and dense pioneer plantings were the most used spatial patterns to guide food forests from early to mid succession, in particular by reducing wind speed, providing shade and improving soil health.

In most food forests, nurse trees / pioneers are simultaneously introduced with later successional crops (see Fig. 5.3.1). This strategy can be referred to as 'instant succession'. However, designers recently acknowledged and more frequently applied what is termed by several practitioners as the concept of 'phased introduction' or 'relay planting'. Instead of planting the whole food forest at once, only pioneer plants are planted, while later successional food crops are only introduced once their required conditions are met (Fig. 5.3.1). Practitioners mentioned this design consideration is highly dependable on other contextual factors besides successional stage. For example, one expert said he would probably wait 2-3 years on dry, poor sandy soil before also planting the more mid and late successional production crops while feeling more inclined to plant all species at once at an already sheltered clay soil. Often most pioneer trees are planned to be thinned out within a few years, mainly in the context of creating enough light in the understory after creating sufficient wind speed reduction. Other designers explicitly plan at least part of the early successional system plants as long term nurse plants. For instance, some designers were found to introduce *Alnus spp* in the bottom successional scenario of Fig. 5.3.1 as long term emergent pioneers on the north side of fruit trees, providing nitrogen for decades.

Starting from late successional systems

Starting from a natural closed canopy climax forest, setting back succession through thinning part of the trees and underplanting with edible species is thought to be fundamental by several food forest designers and ecologists. From there on, the food forest could be developed again towards a closed canopy forest with edible species or kept in a forest edge or young open woodland structure. While some practitioners visited these food forests, none of the interviewed experts voiced personal experiential knowledge on how to guide this transition in more detail.

'final' stadia

For the 'final' successional stage, multiple scenarios were thought to be possible. Practitioners recognize that all current food forests were too young to base conclusions on the optimal successional stage and this is highly contextual. Nevertheless, most experts envision mid successional systems as the most promising 'final' stages for food forests. A recurring argument was to prevent a fully closed canopy, common among late successional systems, since this controls shade lower down and in consequence the productivity of all the lower layers. Most promising food forest crops, especially fruit species, are adapted to grow and produce best in mid successional systems in temperate climates. Besides light and species availability, the (a)biotic gradients described at the start of the paragraph were mentioned for favouring mid successional systems.

In particular, mid successional ecosystems were thought by ecologists to exhibit the greatest netto biomass production and adequate storage, conservation and cycling of these nutrients. However, inclusion of annuals or a high percentage of desired late successional crops could result in different designs and successional stadia.

A repetitive pattern of forest edges, as shown in Fig. 5.3.1, was the most commonly envisioned spatial vegetation arrangement for food forests with commercial food production objectives. This mid successional system could still include late successional plants as highest canopy species and in the understory. The main justification given by practitioners for the forest edge pattern was optimizing photosynthesis capture and harvest efficiency. One expert mentioned the limited room for experimentation and exploration in the exponentially growing and commercializing food forest movement as an argument to stick to this approach for now. Other practitioners designed an open woodland spatial structure with gaps left in the full size canopy. Experts both from practice and science agreed that they will probably keep the food forest edge system intact in the same mid successional stage in most situations since in the Netherlands the light intensity is thought to be too low for a food forest to remain productive in multiple vertical strata if succession passes into the climax stage where the crowns shade the entire understory and netto biomass production decreases. As one designer put it;

"*The story of ever increasing yield does not exist.*"

Some experts stressed the future will need to tell what the required energy is to keep food forests in this stage and how this trade-off balances out the benefits. Especially in regard to nutrient cycling, experts admitted that in practice it needs to be experimented how much can be harvested and what other management practices might be worth it for keeping the nutrient balance neutral in this stadium. One designer mentioned designing food forests in a way that as an intuitive rule of thumb more organic matter from the canopy returns to the soil compared to organic matter harvested to encourage a neutral nutrient balance of the system. Several experts voiced they at least expect that keeping a mid successional food forest edge would be most practical to manage by circumstantial thinning and pruning.

Several other experts stressed the importance of a diversity of successional stadia between and within food forests, in particular for ecological values such as diverse wildlife habitat. One designer concluded it will be possible to have multiple succession stadia in one food forest location, for instance when the highest crown species form a closed canopy forest while the lower canopy and understory is designed as an edge or by spatial zonation of multiple target vegetations. Both practitioners and ecologists envisioned that the mid successional food forest edge stadium could be rotated on a larger scale for commercial and high food production, while for increasing nature values it may be more beneficial if a certain area of food forest can pass beyond the young woodland phase. Another expert perceived this as less of a problem, since the food forest edge systems nonetheless diversify the national landscape significantly since it currently consists mainly of early and late successional monocultures of annual crops, grassland and forest. The quote below illustrates how designers were found to design for flexibility (Tab. 4.2.2 in Annex I and Fig. 5.3.1) and for a diversity of successional stages between food forest projects as exemplified by the quote below:

"*At some locations we interplant with more nuts, in a few decades we can choose if we want to let the system develop into a closed canopy nut food forest. Many mid succession crops don't get that old or are phased out as light decreases so you can choose then. Also because you have a lot of different projects so that you can keep a diversity in the successional stages of the different projects.*"

One ecologist envisioned a cyclical mosaic of successional stadia on the scale of the landscape and food forest site as opposed to maintaining any permanent 'final' stadia. These landscapes combine all successional stages, with different patches at different stages, all cycling through in concert. At a landscape scale, a relatively stable state is maintained, because the proportions of the forest, and corresponding crops, at various stages remain stable.

Species variation

This paragraph summarizes and extends upon the discussed species relevant in each food forest succession stadium (Tab. 5.3.2 in Annex I). During early succession, pioneer trees are often planted. Multiple practitioners experienced that it is often too much labour to introduce and maintain herb species in the early successional stadium since they will lose the competition with the herb layer species that establish at the food forest naturally. Naturally established common wild, native edible herbs on the other hand have potential according to several practitioners. Mid successional shrubs such as *Lonicera caerulea* and *Aronia spp* can be already introduced at the early successional stadium for relatively high plant height and competitive strength compared to many other mid successional shrubs. Most fruit species produce best on the edges because of the Dutch light climate and general light requirement of these species for flowering and fruit ripening. Food forest designers found it very exciting to find out what plants remain productive in a climax understory in the Netherlands. Several fruit shrubs were mentioned, but mainly vegetables were identified. Nuts were considered promising main food producers of late successional systems in the canopy layer. Remarkable was that 'effect' plant characteristics applied by practitioners were often not explicitly linked to specific species, but more to inherent general characteristics of perennials (especially trees) for the development of a food forest on a system level.

5.4 Ontogeny: Plant development through life stadia

While succession refers to the consecutive order of plant communities following each other up through a feedback with the environment, ontogeny is the developmental history of one organism within the own lifetime. Together with phenology and succession, ontogeny was the main identified temporal vegetation consideration in food forest design. For the design of food forests the seed stage is jumped over, since most plants are propagated in by nursery growers and planted in the sapling phase. For the purpose of simplicity, only a difference was explored between saplings, occasionally an intermediate phase and the mature plants. Three categories of plant characteristics that change throughout ontogenetics were distinguished:

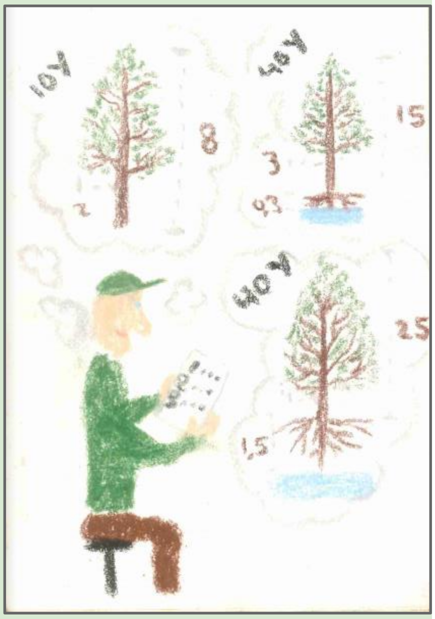
1. above and belowground architecture
2. environmental tolerances
3. productive lifespan

5.4.1 Above and belowground architecture

The above and belowground architectural development of perennial plants changes completely over their lifetime. These changes are genetically embedded, but also highly plastic and context dependent as described in Box 5.4.1. Practitioners voiced a variation in aboveground growth rate between life stages that was in line with the plant successional status. They explained this by the strategy of many climax species to first invest in root biomass prior to aboveground biomass (Box 5.4.1). The above paragraphs emphasize responses of the vegetation to the environment, but morphological development through life stadia also correspond to 'effect traits' that designers use to influence the successional gradients in the previous chapter.

Combining scions and rootstocks with different ontogenetic stadia can manipulate the morphology and development of the new plant further. Grafted plants with biologically older scions start investing in reproductive organs sooner, at the cost of investment in height and crown diameter so these plants stay smaller. As one practitioner noted, while *Castanea sativa* or *Juglans regia* seedlings can get 20 - 25 meters high, grafted ones often only reach a maximum of 12 meters or take much more time to reach that height.

Box 5.4.1: Relevant plant characteristics for the morphological development through life stadia and their contextualized plant characteristic values.



The drawing shows a Forest ecologist with many decades of field experience, assessing the morphological development of a namesake pioneer, the alder tree, following the standardized format of the second phase of data collection. Morphological plant characteristics that can be derived from the drawing are tree height when full grown, crown diameter when full grown, tree age when full grown, tree height after 10 years, crown diameter after 10 years and rooting depth.

These plant characteristics are modified through environmental preferences and tolerances, in the drawing this is soil moisture preference and the quotes below illustrate the influence of nutrient and light preference.

"Tree roots go where there are nutrients and water. The depth and width of the rooting system in turn shape the size and growth rate of the above ground architecture."

The architecture of the rooting system is highly dependent on the soil characteristics. In this example the black alder goes as deep as the water table in summer (and tolerates fluctuations). If the water table is 30 cm below the surface a tree may reach a 15 meters height eventually. If the water table is 1,5 meter below the surface the tree forms a developed rooting system and a tree may get up to 25 meters.

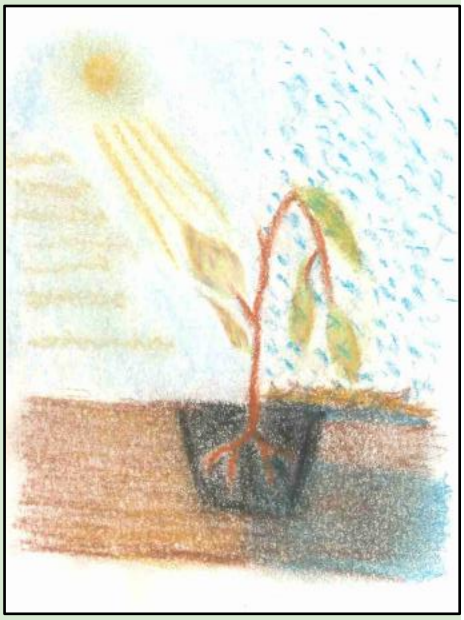
"The crown keeps growing as long as there is a gap in the canopy left"

The eventual height and width also depends on the availability of light in the canopy. While the growth curve flattens over the life of a tree, there is no absolute point where a tree is full grown. Furthermore, light requirements and planting distance influence the size and age of full growth. It does not make sense to give an absolute single value for a tree on these characteristics, but a band width is needed. A food forest designer needs to make a place-based prediction of the future size and development of a specific tree species.

5.4.2 Environmental tolerances

Tolerances to shade, moisture and frost (whole plant, flowers and leaves) were identified to change as a plant matures as described in Box 5.4.2.

Box 5.4.2: Gradients in environmental tolerances throughout life-stadia with the corresponding plant characteristics in bolt.



In general, plants are more vulnerable to the environment in early life stadia (seed and sapling) compared to an intermediate and mature stadia.

Shade
In theory **shade tolerance** reduces as a plant matures. As a young plant needs less light on maintenance compared to an old plant, the total resource balance can be kept in place longer. Many later successional canopy species, such as Tilia cordata are observed to wait in the understory for years till a gap in the canopy appears. Full sun may even damage young plant leaves through photon destruction.

Moisture
The interviewed experts differed in opinion on whether **drought tolerance** increases or decreases as plants mature. When a young plant has not developed a proper root system yet the plant is very susceptible to drought. A mature tree with a lot of biomass transpires a lot, so has a harder time to keep a neutral or positive water balance.

Frost
Finally, **susceptibility to frost**, both of the **whole plant** as the **flowers and leaves**, was frequently mentioned to decrease during later life stadia. For the whole plant, increasing bark thickness over time was thought to be an important factor. Damage to leaves or flowers is reduced when the plant increases in height, putting the leaves at a greater distance to the air frost that is colder closer to the ground.

5.4.3 Productive lifespan

The start, length and end of the productive lifespan was a very important ontogenetic gradient for practitioners for making a four dimensional design of the vegetation and business model. Similar to morphological development, these characteristics are dependent on the environmental growth conditions. For instance, forest plants naturally have to wait in the understory for years till light is available, delaying the start of the productive life-span. In the case of vegetative edible plant parts, both groups of characteristics may correspond. When the reproductive plant parts are the intended main harvest, the plant should reach sexual maturity as a condition before the start of the productive lifespan. The start, length and peak of the productive lifespan of the reproductive plant part is further complicated by the environmental conditions. Paradoxically a plant starts reproducing under stress, but also when the conditions are suitable for reproduction. In general, a plant can invest energy in growth, maintenance and reproduction. The balance between these energy flows changes during the plant's life stadia. Box 5.4.3 illustrates the development of the plant throughout life stadia and the interrelatedness with the productive lifespan, based on the expert interviews.

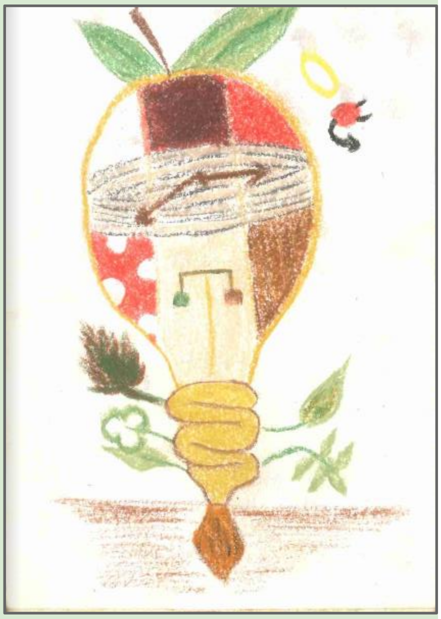
Box 5.4.3: Development of an imaginary tree through life stadia and the gradients in the values of the related plant characteristics.

The tree germinates from seed and starts growing, the leaves taking a different shape and composition through life. This may be important for leaf crop cultivation, for the changing culinary appreciation and nutritional value through life. Therefore, many vegetables are artificially propagated after a certain timespan.

The annual ring clockwork symbolizes the increment in biomass throughout the years. The weighing balance symbolizes the changing trade-off between investment in growth, maintenance and reproduction. As long as the balance is positive a plant can afford to keep growing or put energy in reproduction (in this case a red apple like fruit). As the devil and angel indicate, paradoxically a plant starts reproducing under stress, but also when the conditions are suitable for reproduction.

As the tree gets larger and older, maintenance costs increasingly more energy (for example through higher evaporation). At one point the balance shifts. The reproduction, the yield, starts reducing. The fruits undergo a different ripening process and get another taste and nutritional value. Eventually the quantity of the yield is so low the fruit is not worth harvesting anymore and, if the plant is not rejuvenated, naturally or through human intervention, the end of the productive lifespan is reached.

Finally, the plant is decomposed by a red fungus with white dots. (actually the Vliegenzwam symbolizing the decomposition by fungi is a mycorrhiza instead of a saprotrophic fungi so is not entirely correct for symbolizing death and degradation).



The start, length and end of the productive lifespan is further complicated by several factors. Propagation by cuttings or grafting biologically older scions on top of rootstocks are commonly applied strategies for manipulation of the productive lifespan. The scion or cutting is usually already in the reproductive life stadium. This results in a precocious start of the productive lifespan of the plant. As mentioned in box x the pruning regime can prolong the productive lifespan. Finally, there was a complication identified concerning the subjectivity of productivity. The yield is high enough depending on the food forest practitioner's business model, for instance, the available time for labour, cost of harvesting and market price of the product.

Designers considered species with a later start of the productive lifespan to be harder to fit into a commercial business model. However, these were also the species that generally keep producing for a long time and can therefore be important for projects with long term food production targets.

5.5 The Honorable Harvest

This sub-chapter covers all plant characteristics nested in the (post-)harvest aspects of a food forest design. It explores *what* can be harvested *when*, *where* and *how* in a food forest.

"*The canon of indigenous principles that govern the exchange of life for life is known as the Honorable Harvest. They are "rules" of sorts that govern our taking, so that the world is as rich for the seventh generation as it is for us.*"

5.5.1 What?

For the purpose of this thesis research the focus is on edible plant parts for human consumption. Fungal and animal food sources for humans, as well as plant-based food sources for non-human organisms (e.g. livestock) and secondary products (fibers, medicines, dye, etc.), are not discussed in this chapter although these potential harvestable products from food forests were mentioned by several experts during the interviews. The plant characteristics, edible plant part, toxic plant part and plant part size are discussed below.

Edible plant part

Edible plant part was an undisputed functional plant characteristic for the design of food forest for all experts. During the interviews three patterns emerged. The first was that all (post-)harvest plant characteristics (and in consequence temporal and spatial vegetation arrangement, species choice and management) relate directly to the edible plant part instead of the plant species as a whole. The second pattern observed was that the relevant plant characteristics (and related design considerations) differed between certain categories of edible plant parts. Some plant characteristics were found only relevant for the harvest of specific edible plant parts, while other plant characteristics were found relevant in relation to all edible plant parts.

The third pattern observed was that in classifying edible plant parts there is little consensus among the interviewed experts and the general public between how edible plant parts can be distinguished, mainly botanically and culinarily. For instance, there are fruits that are used as vegetables and vegetables that are used as fruits. Small fruit was by some experts regarded as a relevant sub-category within fruits due to the size of the edible plant part and consequences for mainly the harvest. This pattern complicates the second. The four plant dynamics successfully applied in functional ecology served as inspiration to systematise and standardize the general categorisations used by practitioners. Thus, this categorisation was followed for exploring, analysing and presenting the harvestable edible plant parts as depicted in Tab. 5.5.1.

Table 5.5.1: Categorisation and classification of edible plant parts (behind brackets is the number of identified plant species for which these plant parts were considered the main harvest).

Reproductive (143)	*Green (103)*	*Belowground (17)*	*Other (43)*
flowers (7)	growing shoots (2)	bulbs (0)	bark (0)
fruits (109)	leaves (85)	roots (8)	gum (0)
nuts (21)	leaf stalks (5)	tubers (9)	sap (4)
seed pods (0)	spear shoots (11)		none (39)
seeds (4)	emerging shoots incl. leaves (1)		
unopened flowerheads (2)			

Finally, since many functional plant characteristics were found related to the edible plant part, the optimal relative distribution of main plant parts within a 100 top food forest species list emerged as a recurring theme during the interviews and these results also elaborated on below.

Reproductive plant parts

The main reproductive plant parts for food forests were fruits and nuts, based on the number of identified promising species and the criteria discussed in the other chapters. Secondary edible reproductive plant parts were flowers, seedpods, seeds and flowerheads. As already explored in previous chapters, susceptibility to spring frost and productivity in the shade are of significant relative importance for obtaining a yield of reproductive plant parts. Other specific key plant characteristics for reproductive plant parts, apart from edible flowers, were pollination vector, plant reproductive fertility, optimal distance for cross pollination and staying on the plant after ripening.

The largest number of identified species provide fruits as the main harvestable edible plant part. This was 109 out of all 306 identified species. The 'starting' top 100 species list provided by food forest pioneer Martin Crawford contained 47 fruit species compared to 47 species providing other edible plant parts and 6 system plants. Fruits were also the most abundantly selected by practitioners as promising food forest species. When exploring promising species with assessments from the perspective of the species, culinary appreciation was nearly always given as part of the justification. Two experts that were asked for promising species for commercial large scale food forests marked 77% (17/22) and 80% (33/41) of all species with fruits as their main harvestable edible plant part.

"There will be a market for it, for the second part of this century they are important food producers and the importance of large trees and nuts in our diet and landscape is very large. But because of the late starting productive lifespan they are hard to fit in an agricultural business. If in 20 years a farmer needs to have everything up and running most are crossed off the list... ...there is hardly any experience, the food forests are too young."

Nuts were highly regarded by practitioners mainly due to their long lifespan, low maintenance requirements, general system functions, suitability for later successional systems, fairly easy mechanized harvesting, good storability, high nutritional value, good flavour and growing market demand. *Castanea spp* were mentioned as a sustainable alternative to annual carbohydrate crops and oily nuts as plant-based protein substitution to meat. There were 22 identified species with nuts as their main crop. Fig. 5.5.1 gives an impression of the wide diversity in color, shape and size of nuts from promising food forest species. On the cultivar level there is little breeding done for most nut species. Most nuts with little cultivation history have a low productivity. Moreover, the combination of nuts with a high groundwater table is considered hard compared to other crops as previously explored in sub-chapter 5.2. In food forests with a commercial food production target, nuts were found harder for practitioners to fit in a business model due to the relatively long time before the plants come into bearing. Since nuts are harvested from the ground this may limit the implementation of a understory crops due to damage to these plants and inefficient nut harvesting. Lastly, very little experience has been gained with nuts, both in comparison to other edible plant parts from species with generally shorter lifespans and in comparison to the historical cultivation in other perennial systems, especially in the Netherlands.

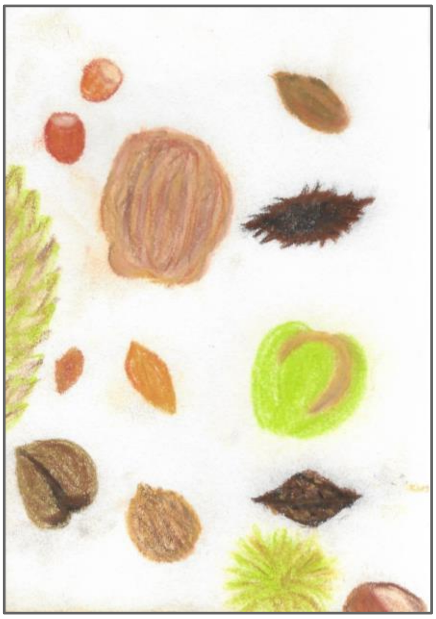


Figure 5.5.1: Impression of the wide diversity in color, shape and size of nuts from promising food forest species.

Of the remaining edible reproductive plant parts, flowers were the most discussed. Still, the statements in this paragraph are largely based on singular expert opinions. For flowers, the same key plant characteristics apply as for fruits and nuts, except for those that contribute to pollination and ripening. Edible flowers were mainly mentioned for the special niche market or food forests without commercial targets. Low productivity, high vulnerability to damage, low harvest uniformity and short shelf-life contributed to the perceived low overall potential for food forests. For *Hemerocallis spp, Sambucus canadensis* and *Sambucus nigra* the flowers were mentioned as a promising main yield for food forests by at least 4 practitioners. However, most promising food forest species only had edible flowers as secondary yield. Examples are *Allium ursinum, Chaenomeles spp, Malva moschata, Schisandra chinensis, Taraxacum officinale, Viola odorata* and *Zingiber mioga.* Others, like *Tilia cordata* and *Rosa rugosa, had flowers that* were mentioned primarily for tea instead of actual consumption. The herbs *Hyssopus officinalis, Lathyrus tuberosus, Oxalis acetosella* and *Monarda fistulosa* were only mentioned by one expert as promising flower crops.

There were several promising species with edible seeds and unopened flower heads that were identified during the interviews when practitioners were asked to name promising species. These are highlighted here, but concrete correlated plant characteristics and design considerations were too scarcely discussed. *Chenopodium bonus-henricus, Pinus koraiensis* and *Urtica dioica* make many, large edible seeds. *Cynara cardunculus subspp scolymus* and *Staphylea pinnata* were mentioned by two experts for their culinary valuable, productive unopened flowerheads.

Green plant parts

The main classification between green plant parts are leaves and shoots. Of certain leaf crops, like *Rheum spp* only the stalk is edible. Between shoots a distinction can be made between young shoots emerging from the ground and growing shoots growing from existing stems. Young shoots without leaves are called spear shoots. As one practitioner stated, there is a huge number of leaf crops, confirmed by the 85 identified plant species with leaves as a main crop. Many leaf crops have growing shoots as secondary yield. The other way around, of some plants the small leaves are harvested all together with the main young shoots. Species like *Hablitzia tamnoides* offer young shoots with young leaves in spring and large leaves and small growing shoot tips later in the growth season. The key relevant plant characteristics identified for green edible parts were layer, competitive strength, shade tolerance (productivity), successional status, culinary appreciation, markets and consumption and harvest period. Productivity, indigeneity, dispersion, start and length of the productive lifespan, transportability, storability and propagation method are also mentioned below. The drawing in Fig. 5.5.2 reflects the diversity of green edible plant parts, their functional plant characteristics and variation in expert opinions which are elaborated on below.

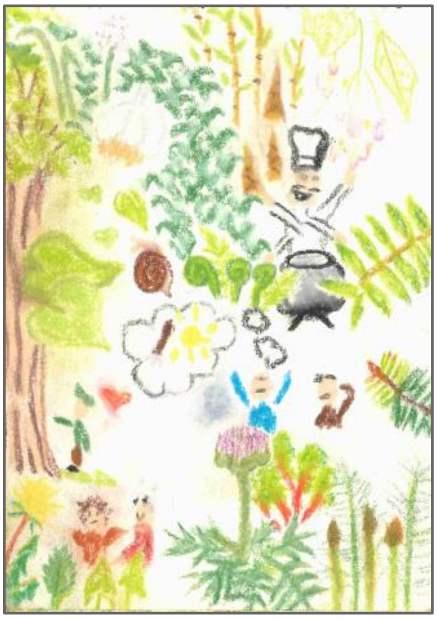


Figure 5.5.2: The diversity of green edible plant parts, their functional plant characteristics and variation in expert opinions.

Most species providing green edible parts are understory plants, especially from the herb layer. The challenges in relation to this layer in extensively managed, multi layered systems are already explored in sub-chapter 5.3, but further elaborated on here. Leaf crops can react to shade by increased leaf size and perennials that can avoid competition with the higher food forest layers, mainly for light, by emerging before the overstory leaves out and collecting their resources early in the growth season. The nursery grower specialized in vegetables stated that fewer plant characteristics were needed for green plant parts compared to species with reproductive plant parts or woody life forms, especially trees. Moreover, the practitioner stated that contrary to other edible parts, growth in shade equals productivity in shade.

Shade tolerant, late successessional green edible plant parts were considered exceptionally promising by most experts. The relevance of competitive strength increased the earlier the successional stadium of application. Still, the experiences of some practitioners were that planted herb layer vegetables will lose the competition with the herbs that establish at the food forest naturally, except when excessive weeding was considered as an affordable management practice. In that regard, several practitioners noted the potential of edible wild plants that establish spontaneously and plants that self-sow freely. Moreover, 4 practitioners agreed about rectifying the underappreciated cultural status of common wild edible herbs, like *Urtica dioica, Heracleum spp* and *Rumex spp* and would highlight these species for public education and awareness. These different viewpoints on the potential of vegetables among practitioners are illustrated in the drawing of Fig. 5.5.2.

"*Everything that comes up spontaneously in the herb layer is much stronger.*"

Winter leaf crops, like *Claytonia sibirica*, and especially (spear) shoots that emerge in spring were mentioned to avoid resource competition with the overstory. Moreover, the early harvest period was considered beneficial for providing green vegetables complementary in time to most annual green vegetables that are harvested later in the year. Therefore, they were thought to hold potential for food security, self-sufficiency, the undeveloped market of spring vegetables and spreading labour. Promising understory species with spear shoots as the main harvest in spring are listed in Box 5.5.2.

Box 5.5.2: Promising understory species with spear shoots as the main harvest in spring.

1. *Aralia cordata*
2. *Aralia elata*
3. *Asparagus officinalis*
4. *Crambe maritima*
5. *Hosta montana*
6. *Hosta sieboldiana*
7. *Humulus lupulus*
8. *Ornithogalum pyrenaicum*
9. *Phyllostachys vivax*
10. *Polygonatum biflorum*

Concerning scale and commercial targets, green plant parts were considered mainly for the small scale and short chain niche market. Several practitioners, including one chef, mentioned the demand of restaurants for exclusive and highly culinary appreciated plants like *Aralia cordata, Phyllostachys spp* and *Zingiber mioga.* Other practitioners mentioned their experience with directly sold fresh products, based on the high culinary appreciation and niche market values of fresh products like *Brassica oleracea 'Ramosa'.* Since the transportability and storability of these products is generally low, competition can be avoided with larger businesses with a general indirect product chain (chapter 6). One practitioner stated that since the herb layer comes into production earlier this could be beneficial for small scale farms and that there is the possibility for more intensive management, while for larger food forests the required planting material and potential additional labour could be unaffordable. Relatively easy propagation by cuttings can make it doable for small scale growers to propagate their own plants for obtaining the required quantity of planting material and rejuvenating plants at the end of their productive lifespan.

For self-sufficiency one practitioner mentioned planning consecutive harvest periods of 15 to 20 leaf crop species throughout the season and deciding upon the number of plants for each species based on the productivity and number of people relying on the food forest. Easy propagation decreases reliance on external parties for plant material and consequently food.

Tab. 5.5.3 in Annex I shows the 20 species with the highest total score and the variation between expert opinions. There were many possibilities for species with edible leaves as main yield. Corresponding to the differences in expert opinions on the design of the potential of these plant parts, mainly in the herb layer, were the mixed opinions on promising species. 77 of the 103 species with green plant parts as main yield were proposed as top 100 food forest species by only one of the interviewed experts indicating the division in expert opinions. Moreover, many species including *Mentha spp, Allium spp, Hosta spp, Rheum spp,* *Hemerocallis spp, Phyllostachys spp* and *Heracleum spp* within the genus, kitchen herbs in general and leaf crops in general were thought to be interchangeable.

Belowground plant parts

The belowground edible plant parts constitute bulbs, roots and tubers. The initial top 100 list provided by Martin Crawford included 5 species with bulbs and 2 species tubers as one of their main edible parts. Out of the 6 experts explicitly asked for the potential of belowground crops in food forests, 5 saw little and 1 saw much potential.

Tubers and roots were mentioned by 3 experts as important for food production targets including a complete diet and self-sufficiency due to their nutritional value. Additional perceived benefits of tubers and root crops were an overall early start of the productive lifespan and high productivity.

Figure 5.5.3: Impression of harvesting tuber crops. Tubers can be very productive, but the harvesting is often labour-intensive and disturbing the soil.

However, harvesting belowground plant parts in a food forest risks ecological detrimental effects and management impracticalities. Digging up belowground crops in food forests can damage soil structure, roots of other crops and mycorrhizal networks and harvesting belowground crops by hand is inefficient and labour intensive (Fig. 5.5.3). Moreover, most tubers and root crops are early successionals. Their successional status matches up with high light requirements. Besides light, one expert also mentioned a general high resource requirement for water and nutrients and therefore potential need for external inputs, which is often not desirable in food forests. As early successional plants, most tubers and roots have a short productive lifespan and are cultivated as annuals with the negatively perceived yearly labour of (re)planting. One expert mentioned the cultivation as annuals also results from high pest pressure of rodents in winter and low winter hardiness for many species. Another reason is that plants like *Helianthus tuberosus* are replanted every year on the same plant density to get uniform thick tubers. Furthermore, the harvesting generally means the end of the life of the plant. Finally, a negative effect of many tubers is that as climbers they can suffocate trees when grown spatially together.

Spatial separation from other food forest plants in rows or plots was mentioned by 3 experts to avoid damage to other plants during the harvest and enable efficient mechanized harvesting. A temporal consideration is to implement these rows and patches especially during the first years of the food forest when starting from an early successional vegetation so that there is still sufficient light in the food forest understory. While most experts disregarded frequent soil disturbance in food forests, one practitioner argued that frequently disturded soil on the small scale is easily colonized and regenerated by soil life, for example when cultivating thin strips of 1 meter wide. Concerning species, *Apios americana* and *Dioscorea polystachya* were highlighted as perennially cultivated tuber and root crops respectively with extensive drought resistant root systems, receiving the highest overall expert count as promising top 100 species together with *Helianthus tuberosus* among the roots and tubers. One expert mentioned dispersal by self sowing or vegetative propagation as important plant characteristics for roots and tubers in extensive systems. Besides the 3 species mentioned above, *Arctium lappa*, *Pastinaca sativa* and *Scorzonera hispanica* may also be able to disperse easily in a food forest context. When designing rows of annuals and potential external inputs or a zoned perennial vegetable garden plot, the range of promising tuber and root species would increase significantly. *Allium spp* were the main promising food forest bulbs and many were considered interchangeable.

Other edible plant parts

Bark, gum and sap were identified as other edible plant parts, but no considerations for temporal and spatial vegetation arrangement or promising species were discussed during the interviews.

Toxic plant part or relative

Multiple experts mentioned the responsibility of mentioning toxic plant parts or toxic related plant species in the database for safety measures. For one expert this characteristic was important enough to dismiss potential promising species such as *Polygonatum Biflorum*. In food forests with many uneducated visitors or private food forests of households with young children plants with toxic plant parts may be least suitable. However, in specific contexts toxic plants can also be planted on purpose for educational targets like creating the awareness that not everything in nature is edible.

Edible plant part size

Edible plant parts differ in their size, shape, colors, weight, texture, aroma, etc. Of all these morphological and chemical properties, only edible plant size was selected as relevant to explicitly define, classify and discuss in the database since knowledge of size can be applied very widely in a food forest design. This characteristic was mentioned during the interviews by plant growers, food forest designers and managers, 1 forest ecologist and the chef. The size of the edible plant part can strongly relate to both the quantity, quality and harvest efficiency. Edible plant part size showed a high inter- and intraspecies variation, and circumstantially large or small edible plant parts can be preferable as explained in Box 5.5.4.

Box 5.5.4: Considerations for inter and intraspecies variation of edible plant part size.

Why big?
Small size was emphasized as one of the main reasons for the labour intensive hand harvesting of soft fruit, especially as compared to what are traditionally called the hard fruits, like *Malus domestica* and *Pyrus communis*. The edible plant part size was a deciding factor for experts to decline a promising food forest species for the 100 top species list. For example, *Caragana arborescens* was disregarded by one expert, because he found the peas too small to bother. Edible plant part size was mentioned by experts as a good reason for choosing cultivars over wild relatives. One expert mentioned the significant increase in fruit size of *Lonicera caerulea* and *Hippophae rhamnoides* compared to the wild species. Also the variation in fruit size within *Lonicera caerulea* and *Hippophae rhamnoides* cultivars was viewed as a deciding factor for cultivar selection. The large difference between cultivars can contribute significantly to the culinary appreciation, as was explained by one expert through the public enthusiasm for giant walnuts.

Why small?
The other way around, species and cultivars with smaller edible plant parts can be regarded superior culinary and nutritionally for concentrated taste and nutrients respectively. In England, the small nuts of *Corylus avellana* "Kentish Cob" are appreciated highly for their superior flavor compared to large sized common cultivars. This can also mean that wild plants with small plant parts can be culinary preferable to cultivars. The taste of the small fruits of the wild strawberries, *Fragaria moschata* and *Fragaria vesca* are considerably more intense than those of the larger fruited *Fragaria x ananassa* cultivars. Furthermore, the smaller wild *Asparagus officinalis* are viewed with higher culinary appreciation than the cultivars. Relative edible plant part size can also influence storability. For instance, the earlier mentioned giant walnuts have a shorter shelf life than smaller ones.

Contextual influences
The size of the edible plant part of the same cultivar can be highly dependent on age of the plant and external factors. One expert mentioned the size of the *Castanea sativa x crenata* nuts steadily increasing as the tree matured. Insufficient heat during a specific ripening stadia can result in 2 times smaller nuts of *Juglans Regia* cultivar "Dyonym". Other experts mentioned how over-pollination especially in *Prunus spp* and *Pyrus spp* can significantly decrease fruit size. The edible plant part size is less relevant, when not the whole plant part is edible. For example, with nuts and stone fruits, it is the kernel-shell and stone-fruit ratio respectively that forms an important determinant for the actual edible yield.

Quantity

The start and peak productivity refer to the quantity of food at the start and peak of the productive lifespan. With perennial species, there is generally a large division between these yields. Peak productivity was considered a plant characteristic that singlehandedly could degrade a plant species as a promising food forest candidate. A complication for measuring productivity is that many yield numbers need a correction factor to get to the actual consumable edible yield. For example via the flesh:stone ratio or kernel:shell ratio the actual yield can be determined for stone fruit. Species with high productivity are referenced throughout other chapters, mainly chapter 5.6.

Quality

Culinary appreciation and nutritional value were the main identified compound plant characteristics representing the quality of edible plant parts. Regardless of the functional target, culinary appreciation was a crucial criteria for assessing the potential of food forest species for most experts. When asked whether a species would be promising enough to be part of the top 100, culinary appreciation was the most applied plant characteristic for justification. However, experts refrained from defining and classifying culinary appreciation and acknowledged this characteristic is highly dependent on personal preference, cultural context and processing of the edible plant part. Plant characteristics that were identified to contribute to culinary appreciation included taste, texture, color, aroma, shape, size, nutritional value, whether processing was required for consumption, processability, the place in a dish or the course, exclusivity and eating efficiency. Moreover, a wide range of plant characteristics like traditional uses, origin and the name of the plant can contribute to the narrative of the plant responsible for culinary appreciation. Plant characteristics specific for certain species(groups) can be covered by this compound variable as well. For instance, for *Prunus armeniaca*, *cerasifera* and *domestica* this is the ease with which the fruit comes free from the stone.

Nutritional value was a fundamental aspect, with an emphasis on complementarity to obtain a healthy and complete diet. Multiple experts mentioned a balanced distribution of nutritional values within the species top 100 when assessing the list as a total. Similar to culinary appreciation, experts had difficulty defining and classifying this into a systamized or applicable set of plant characteristics.

5.5.2 When?

The harvest period is a compound variable that covers the phenological traits of the desired edible plant part. Flowering period is the underlying main phenological trait when flowers are the main edible part to be harvested, the harvest of green edible parts relates to the growth period and when fruit is the main yield fruit ripening is the responsible plant trait determining the harvest period. The harvest uniformity was mentioned by most practitioners, referring to the proportion of the total yield that can be harvested at once and the times the harvester needs to separately come back for harvesting the total crop. The importance of the harvest uniformity for commercial food production is elaborated in chapter 5.6.

Design considerations

The harvest period is important for planning to spread or concentrate the harvest. For food forests that sell fresh products directly to consumers, in particular via self-harvest, it can be beneficial to offer cultivars with consecutive harvest periods to offer the same species over an extended period to customers. Large scale commercial food forests may also intently spread the harvest of a species to consistently offer a species over a longer period to a fixed buyer.

Within rows or even zones, it can be beneficial to concentrate the harvest period so that the food forest owner or manager can clearly explain to harvesters which plants can be harvested that day, reducing the chance of uneducated self-harvesters harvesting the wrong plant or plant part. Concentrating harvest can also be a strategy to saturate pests, preventing that nothing will be left to harvest.

Large scale, commercial food forests, may strategically concentrate the harvest in order to efficiently get many food out of the system at once. Besides a higher harvesting efficiency this strategy limits the amount of times a harvest should be organised. Concentrating the harvest can also be beneficial when the food forest manager also has time-bound labour for another activity. For example for a pumpkin grower, it is beneficial to plan the harvest before the labour of the pumpkins reaches a peak.

The harvest period can also indicate the values of other phenological plant characteristics. Just before the harvest period a plant often needs most resources, giving opportunities to reduce resource competition of species in the same vertical layer. This can give opportunities to combine plants vertically growing under each otherwise that would otherwise have the same harvesting location. For example, *Allium ursinum* can be grown under *Juglans regia*. The first uses the light before the other is in leaf and is harvested up till June before retreating underground, leaving a clean forest floor so that the nuts of *Juglans regia* can be harvested from the ground later in the season. Box 5.5.5 illustrates design considerations for phenological plant characteristics.

Box 5.5.5: Designing along the four seasons.

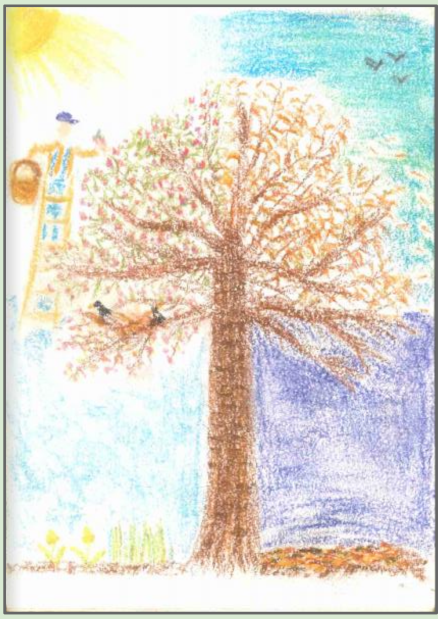
The drawing shows the cyclical phenological phenomena of a cherry tree and herbaceous understory vegetables during the four seasons in four quadrants, starting in the bottom left.

In spring the cherry is in flower (1) and leafing out (2) while the understory (3) vegetables (4) get in leaf earlier, using the reserves in their roots and can grow before it gets too dark. Spring is the harvest period (5) of the vegetables in the understory. In summer the cherries ripen and can be harvested, followed by leaf fall (6) in autumn. In winter both the cherry and understory are dormant, with implications of their aboveground architecture (7).

Phenological plant characteristics: flowering period, leafing out, harvest period, leaf fall, height, crown diameter, crown density
Non-phenological plant characteristics: layer, edible plant part

Phenological design considerations:

1. mixing layers with separate leaf phenology for resource partitioning
2. spreading harvest periods for seasonal fresh food and reduced labour
3. ensuring year-round soil cover by fallen leaves and groundcover for erosion control, water regulation and preventing nutrient leaching



For a self-harvesting food forest it can be beneficial to spread the edible products as wide over the season as possible so that consumers have fresh food forest products year round. Therefore, species that are harvested exclusively early or late in the season can be important. Multiple experts named the earlier harvesting period of many perennial food forest vegetables important as complementary to the later annual vegetables.

On a cultivar level, it may be necessary for designers to choose early harvestable cultivars for fruits or nuts to ripen well. The natural occurrence can provide an indication of the required solar light and heat for ripening as explored in chapter 5.2. Besides cultivar selection, spatially arranging plants originating from continental and southern regions in a warm microclimate was noted by practitioners. Several experts mentioned there is little experiential experience and scientific research done on this. The local microclimate of the plant also influences the harvest period, since the more in the shade a plant is located the later its fruit can be harvested.

Choosing cultivars with an early harvesting season also can have market benefits, avoiding competition on the market with other fresh products of larger conventional or even organic markets that may be able offer the same species for a much lower price otherwise. *Vaccinium Corymbosum* and *Prunus armeniaca* examplify species with cultivars that can consecutively offer fruits, to offer the same species over an extended period to customers. Moreover, choosing a cultivar with a specific harvesting period can be applied for avoiding the life cycle of a relevant pest or disease. Both *Prunus avium* and *Sambucus nigra* were mentioned by different practitioners as severely damaged by Suzuki fruit fly and separately came to the solution to use cultivars which ripen early when the Suzuki is still in the first life cycle of the season and the population is still small.

5.5.3 How?

Harvest efficiency was the best proxy for harvestability. Both are compound variables. The drawing on the right (Fig. 5.5.4) provides examples of the responsible explored plant characteristics:

- ➢ harvesting location and staying on the plant. A ladder is needed for harvesting the top fruits of full grown *Asimina triloba*.
- ➢ vulnerability to damage during harvest, harvest method and markets and consumption. *Rubus idaeus* are soft and perishable, they need to be harvested carefully by hand when meant for fresh consumption. The perceived market
- ➢ thorns, single or bundles and length of stig. *Hippophae rhamnoides* (top of drawing) with its many, large thorns and single fruits close and tight to the wood take longer to harvest compared to berries of *Aronia spp.* (bottom of drawing) having no thorns, growing in bundles on a stig.

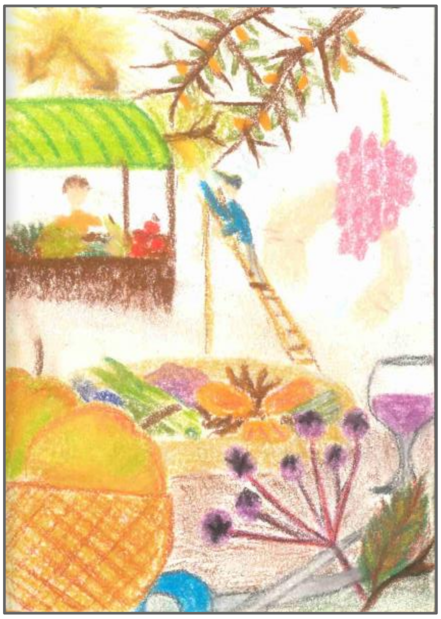


Figure 5.5.4: Examples of functional plant characteristics that contribute to harvest efficiency. Besides the accessibility, the perceived post-harvest market and consumption also influences the harvest.

How to harvest was not only seen as a process to optimize, but also as receiving gifts in a respectful and sustainable manner. This is illustrated by the principles of the honorable harvest in Box 5.5.6.

Box 5.5.6: Principles of the honorable harvest.

Principles of the honorable harvest

- Ask permission of the ones whose lives you seek. Abide by the answer
- Never take the first. Never take the last
- Harvest in a way that minimizes harm.
- Take only what you need and leave some for others.
- Use everything that you take.
- Take only that which is given to you.
- Share it, as the Earth has shared with you.
- Be grateful.
- Reciprocate the gift.
- Sustain the ones who sustain you, and the Earth will last forever.

5.6 Project scales

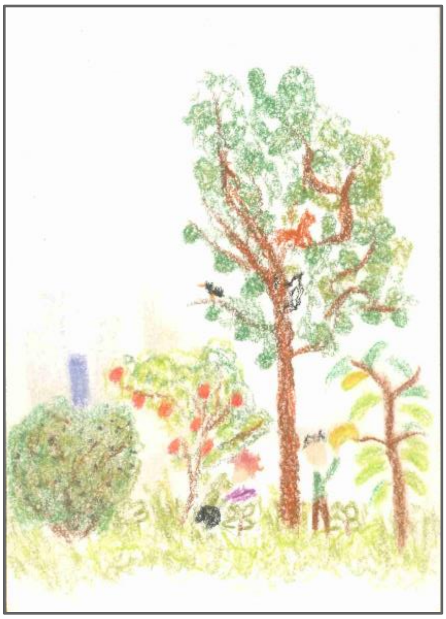


Figure 5.6.1: Impression of awareness, connection, experiencing and the narrative of food forests in a small scale urban food forest.

Large versus small scale food forestry was of high importance for experts. Therefore, project scale was already added after the second interview as an independent criteria. There was no general consensus among experts on how to classify small (0,01 - 5 ha) and large (2 - 50 ha) food forests. The main patterns dividing small and large scale food forests were their interrelatedness with functional targets, management (harvest in particular) and the vegetation structure and composition (Fig. 5.1.4 in sub-chapter 5.1). Moreover, experts differed strongly in their opinion on the potential of scaling up food forests in general.

Scaling up was accompanied in expert experiences by increasingly commercial food production targets opposed to the more ecological, social and education oriented functional targets in smaller projects. In smaller food forests, awareness, connection, experiencing and the narrative of food forests were found easier to pursue (Fig. 5.6.1). Larger food forests risk the disappearance of what one expert named the 'human measure'. Both large and small scale food forests hold the potential trade-off of decreased nature values when also striving for commercial, social and educational targets. While large scale food forests were often found more commercial food production oriented at the cost of nature value, in small scale food forests the highly concentrated disturbance caused by high human activity was harder to prevent. In relation to private food forests with the target of self-sufficiency, a small scale was found sufficient for producing a relevant amount of plants for a household for most nutritional requirements.

There was a large variation between the perceived overall potential of large scale commercial food forests among experts. Some experts expressed there is not enough knowledge in the short term or expressed how crucial a knowledge rich and curious farmer is for managing such a complex and unsecure system. Others think the food volumes and prices large scale food forests can offer will also on the long term not be able to compete with the existing industrial markets. As another expert wondered:

"Perhaps optimizing 1 hectare is more effective for a farmer compared to these 5 hectare projects, also because of risk spreading and easier harvesting. There can be more labour in these systems and maybe that is worth it."

Another expert advocated that while not being against large food forests, the strength of food forests lay in the small, local context with the functional targets of education, recreation and connection. Other experts envision a large part of agriculture in the future to be simplified, large scale food forests consisting of mechanically harvestable rows and occasional integration with annual crops and animals (Fig. 5.6.2 on next page). Some experts say these food forests are complex agroforestry systems that fall outside of the definition of a food forest.

5.6.1 Design considerations

Tab. 5.1.2 in Annex I provides a complete overview of the plant characteristics and desired values explored in relation to both large and small scale food production under either commercial versus social and educational targets. The plant characteristics markets and consumption (7), start of the productive lifespan (7), harvest methods (6), culinary appreciation (5), future demand (5), processability (4), edible plant part (4), harvest uniformity (4), storability (4), peak productivity (4), start of the harvest period (4) and staying on the plant after ripening (3) were mentioned most often by experts in direct relation to both scale and functional targets. How experts translate these plant characteristics to design considerations for spatial and temporal vegetation arrangement and species selection is discussed below.

Harvest method and efficiency

The optimisation of harvesting to reduce workload, including increased consideration of mechanical harvesting, was one of the most discussed design considerations among experts for commercially scaling up. For smaller projects hand harvest was found easier due to the lower volumes. Self-harvesting was thought to be an important element for reaching educational and social targets. Placing the vegetation in rows was regarded as important for enabling mechanical harvesting in large scale commercial systems and organizing hand harvesting in small scale commercial systems. Other design considerations and plant characteristics related to harvest efficiency and methods are previously discussed in sub-chapter 5.5.

Markets and consumption

Markets and consumption was composed as a compound variable, combining the plant characteristics suitability for fresh vs processed and bulk vs niche consumption. Food production for fresh or processed marketing and consumption was mentioned as one of the focal plant characteristics by all expert groups. For a food forest designer and manager it is important to know the suitability for fresh or processed consumption to fit the product in the desired management and marketing. For on farm processing, materials and labour can be necessary. This labour needs to be planned in the schedule of the manager. It offers opportunities if the required processing materials and facilities are already present, or the financial means for investment in these.

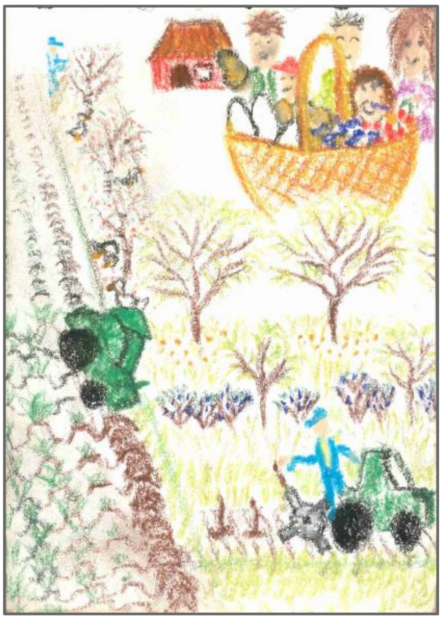


Figure 5.6.2: Impression of a large-scale 'Heerenboeren' farm with a food forest integrated with other food production systems.

Fresh products have the advantage of offering food with a high fresh culinary appreciation, also adding to the market value. In particular, this advantage offers opportunities in self harvesting systems and short, local product chains. These chains reduce the risk of nutrient loss, directly connect people to food, have a lower environmental footprint, decrease or completely cut out costs of harvesting labour and machinery and minimize or cut out the margins of the retail. Moreover it can be a larger hurdle for people to consume food forest products that require complicated or time consuming processing at home, especially those they are not yet familiar with.

A major advantage of processed food is that the quality of the edible product can be lower. For example, it matters less to the consumer if apples for juice, sauce or cider had an unattractive shape, color and size or were damaged through fruit-fall, pests and diseases or insensitive harvesting. This can have positive implications for harvest efficiency and the usable total yield. Another advantage of products is that transportability and storability is generally increased through processing. This way consumers may store the product, use it over a larger window whenever they prefer to consume it and waste less food. Processing can also be applied as a way of upgrading the culinary appreciation and sometimes even for increasing the nutritional value of the product, in consequence increasing the market value.

Edible plant parts that are suitable for both the fresh and processed consumption and market are called dual purpose products and the plants are called double doers. A food forest designer can choose double doers in order to increase flexibility and decrease risk. Often the post-harvest chain is still unclear at the moment of designing the food forest. Moreover, the market may develop differently than expected in the future, influencing the market value of either fresh or processed products or providing new insights and opportunities for the post-harvest chain. Tab. 5.6.1 summarizes the potential benefits of fresh, processed and dual purpose edible plant parts and illustrates the interdependence of this plant characteristic with other (post-)harvest related plant characteristics.

Table 5.6.1. Benefits of fresh, processed or dual purpose edible plant parts and interrelatedness with other plant characteristics.

Fresh	Processed	Dual
higher market value	higher market value	all advantages of fresh and processed
higher culinary appreciation	higher culinary appreciation	risk management and flexibility
sometimes have good natural storability	higher storability	
suitable for hand harvesting, sometimes for machine harvesting	suitable for machine harvesting, sometimes for hand harvesting	
preventing nutrient loss during processing and storage before reaching consumer	sometimes increasing nutritional value	

When designing for the bulk or niche market and consumption, a wide variation of interrelated plant characteristics should be assessed according to practitioners. Bulk products can be sold at the marketplace while niche products can be more suitable to catering industry, for example restaurants. Plants with easy processability, high storability, high productivity and high harvestability were mainly considered for the bulk market.

"If we are talking about a food forest, or a food forest-like vegetation, you should forget the industrial market and machinal crackability, because you will never get the tonnages that such a company is interested in. So then it is the market for selling the nut directly to the consumer. And then I think that it is interesting that a nut is easy to crack and comes well out of the scale. If from the 40 to 50 cultivars that I harvest I should fish one out of a basket that I like to quickly fill my yoghurt, I go first for Big and Easy, despite not being the most productive, not self-fertile and having quite some walnut blight."

Storability

There is a difference between the natural storability of the edible product and storability of the processed edible product. Since many products can be processed in many different ways, with each their own shelf life, here for simplicity the natural storability is discussed. Storability relates strongly to the market and consumption. Edible plant parts with a short shelf life can be explicitly relevant for the short product chain or indicate the necessity for direct processing. Storability is interdependent with the suitability for the fresh or processed, niche or bulk and short or long chain markets. as well as the desired harvesting method. Storability varies widely among promising food forest species (groups) and cultivars. In general edible leaves and flowers have a short natural storability. Fruits differ greatly in storability, ranging from storable for not even a day to storable for more than a year. Most nuts are storable quite well with natural drying.

Species and cultivars

An overview of all species mentioned by experts as suitable for large and small scale food forestry is given in Tab. 5.2.3 in Annex I. Specific species for small scale food forests with educational and social targets are already discussed previously in sub-chapter 5.1. Therefore, these paragraphs focus on comparing species for small and large scale commercial food forests. In general, respondents found a short product chain fitting to small scale food forests and a longer product chain fitting for larger food forests and envisioned a higher emphasis on fresh products with a short chain. Therefore, depending on scale designers can favour species suitable for fresh, processed or dual purpose consumption. Two experts noted the higher general potential of vegetables and flowers on a small scale due to a general high fresh appreciation and short natural storability.

The important plant characteristic values for large scale commercial food forests were largely identified through the species that were dropped for large scale commercial due to lacking these values. Many experts thought a high peak productivity and harvest efficiency, in particular due to a high ripening uniformity, were crucial determinants of species suitability for large scale commercial food forests. *Leycesteria formosa* and *Viburnum lentago* were declined by certain aspects for large scale commercial food forests due to low ripening uniformity. For other species such as *Morus spp, Amelanchier alnifolia* and *Ribes rubrum* ripening uniformity differed among cultivars. Species with a late start of the productive lifespan, such as *Asimina triloba*, *Phyllostachys spp, Pinus koraiensis, Juglans cinerea* and *Carya spp*, where thought to be harder to fit in a business model according to some experts when commercially scaling up. However, other experts advocated combining species that come early and late into production effectively spreads the yield, labour and income in time.

Some species declined for the large scale commercial food forestry due to unsuitability for the indirect product chain or mechanical harvestability may be of special interest for small scale commercial food forests. Besides the earlier mentioned vegetables and flowers, *Prunus armeniaca*, *Rubus idaeus, Morus spp* and *Fragaria spp* have vulnerable plant parts with a low natural storability, transportability and are unsuitable for mechanical harvesting, but have a high culinary appreciation and market value for direct fresh consumption. Therefore, these species can be selected for targeting the niche markets in small scale projects. Furthermore, on the small scale additional practices such as mulching and weeding were experienced to be easier to maintain, increasing the suitability for herb layer species. *Allium ursinum, Aralia cordata, Asparagus officinalis, Brassica oleracea, Fragaria spp, Hemerocallis spp, Matteuccia struthiopteris, Polygonatum biflorum, Rheum x cultorum* and *Zingiber mioga* were emphasized by practitioners as commercially interesting herb layer species to consider for small scale food production.

For 9 species and most plant part groups, experts differed in their opinions on suitability for large scale commercial food forests (Tab. 5.1.3 in Annex I). Moreover, multiple experts voiced that a lot more experimentation is necessary before species can be labelled suitable for large scale commercial food forestry. Species marked by practitioners as suitable for large scale commercial food forests, without conflicting opinions from other experts, based on a high and stable peak productivity, efficient harvestability, good culinary appreciation, high processability, and high market demand were; *Aronia spp, Castanea sativa (x), Corylus avellana, Elaeagnus multiflora, Elaeagnus umbellata, Ficus carica, Hippophae rhamnoides, Lonicera caerulea, Malus domestica, Prunus domestica (x), Pyrus communis, Pyrus pyrifolia, Rheum x cultorum, Ribes nigrum, Ribes rubrum* and *Vaccinium corymbosum*.

There was consensus between experts on a large difference in the designed overall species diversity between small and large scale food forests. One expert mentioned choosing four to five production species to create an economic basis for the large scale projects. In smaller projects there is much more room for production species diversity and complexity, for instance due to opportunities for additional labour, direct marketing to the consumer and lower emphasis on commercial targets.

5.7 Aggregation and selection of database elements

5.7.1 Functional plant characteristics

RQ2: What are key functional plant characteristics for the regenerative design of food forests in the Netherlands based on the most important 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) management practices, 6) project scale and 7) temporal and spatial vegetation arrangement?

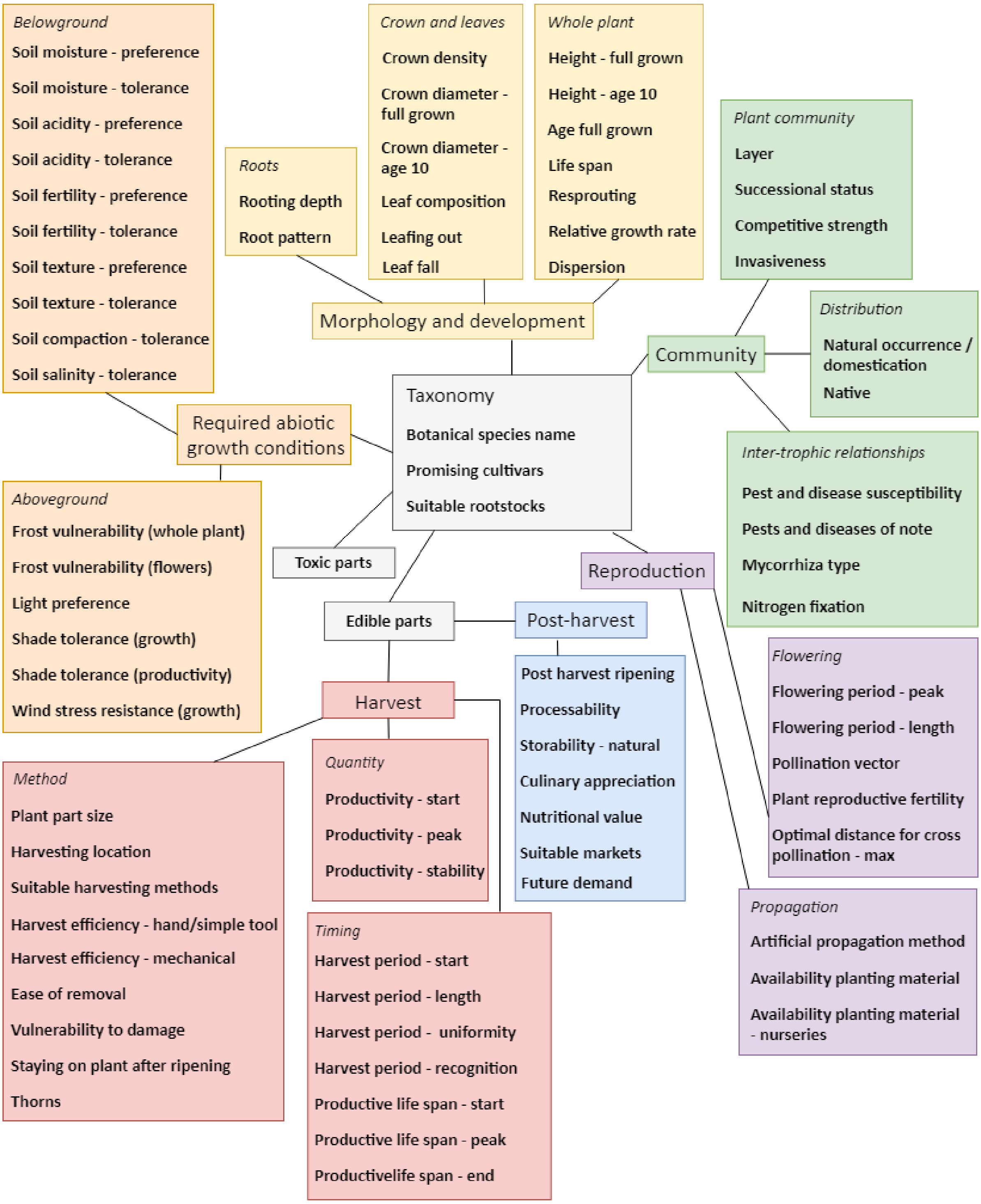


Figure 5.7.1. Key functional plant characteristics as database elements for design of food forests in the Netherlands. The characteristics are nested in the categories morphology and development, community, required abiotic growth conditions, reproduction, harvest and post-harvest. This scheme applies to food forest species with fruit as the main harvest.

There were 234 identified functional plant characteristics of which the 80 key plant characteristics are depicted above in Figure 5.7.1. Each of the selected plant characteristics is already explicitly discussed in relation to one or multiple criteria during the past 6 chapters. Besides the relation of a plant characteristic to a design criteria, other selection criteria identified, explored and applied are shown in Box 5.7.1.

Figure 5.7.1 illustrates one of the many perceptions for grouping the relationships of the plant characteristics to each other. These groups are based on a combination of plant dimensions adapted from functional ecology and the design criteria of chapter 1 to 6. For promising food forest species without reproductive edible plant parts, ripening and the agronomic pollination related plant characteristics can be deselected. For system plants without relevant edible plant parts, (post)harvest related plant characteristics can be dropped. The functional plant characteristics are nested within category groups. 5 general characteristics are allocated to taxonomy (3) and plant parts (2). 15 plant characteristics from the crown and leaf, root and whole plant dimension are nested in the morphology and development category. 10 belowground and 6 aboveground plant characteristics are selected in relation to required growth conditions (16). These are all response characteristics, but also indicate how to apply a plant to have an effect on the system. 8 plant characteristics refer to the relation of the plant to the living community, with a distinction between plant community (4), distribution (2) and inter-trophic relationships (4). Reproduction included flowering (5) and artificial propagation (3). Harvest included method (9), timing (7) and quantity (3). 7 Post harvest functional plant characteristics were selected.

Box 5.7.1. Explored selection criteria for the functional plant characteristics.

1. **amount of experts** that mentioned the characteristic as important for the design of food forests based on one of the 7 criteria
2. being mentioned as relevant characteristic for the design of food forests, based on **multiple criteria (chapter 1 to 6)**
3. **influence** of the plant characteristic value on other plant characteristics
4. practical **applicability**, potential for citizen science **monitoring** and scientific classification. For example, the harvest period is easy to measure and place specific. In northern Great Britain the same plant can ripen 3 weeks later than in the south. Therefore information about the Dutch context is needed. What complicates this characteristic is that it can differ depending on the season and may permanently change due to climate change. A scientific classification can be given through a standardized range of dates.
5. **plasticity** of the plant characteristic to contextual factors. For instance, optimal distance for cross pollination was thought to be vary so widely, depending on contextual factors, by one expert that no applicable value could be given
6. being a **compound variable**, whether a characteristic was an indication for the values on other important plant characteristics, for a user friendly database, to increase fast decision-making, zooming in on specific characteristics is always possible in specific contexts and for reducing redundancy of selected plant characteristics. Some packages are a consequence of a myriad of characteristics that will be hard to interpret by practitioners (and often even scientists) for these, no data on the underlying characteristic is available at the front of the database (could always be included at the back) but schemes are given to exemplify the complexity and give a suggestion of involved characteristics.
7. **complementarity** by high inter-species variation within a plant characteristic

Assessing all plant characteristics systematically on all these criteria goes far beyond the scope of this thesis research and is impossible with the existing experiential knowledge of performance of these species on these plant characteristics in a food forest context. However, based on the collected data an overview for 22 major plant characteristics is shown in Tab. 5.7.2 in Annex I for demonstration.

Table 5.7.3 in Annex I also provides a complete overview of the standardized classes for all promising plant characteristic values. Additionally, Fig. 5.7.2 in Annex V gives a first impression of the potential presentation of the functional plant characteristics for one of the 100 top promising food forest species, in this case Juglans regia, in the open-source database, developed in collaboration with St. VBNL, based mainly on the preferences for applicable classifications and visualisations of the functional plant characteristics identified with the interviewees.

5.7.2 Promising food forest species, cultivars and rootstocks

RQ3: What are 100 promising plant species for food forests in the Netherlands based on the selected key functional plant characteristics, overall complementarity of inter-species variation and availability of promising cultivars, rootstocks and hybrids?

During the interviews 306 plant species were discussed. Based on the functional plant characteristics explored in previous chapters and the continuously developing species list, the species were narrowed down to a list of 100 promising plant species for food forests in the Netherlands (Tab. 5.7.4). The overall distribution of the main edible harvestable plant parts was; 43 fruit, 21 leaf, 11 nut, 8 shoot, 3 flower, 3 root, 2 tuber, 2 seeds, 1 leafstalk and 1 unopened flowerhead. 5 plant species offered no significant edible plant parts, but were selected for their ecosystem services as system plants.

Table 5.7.4: 100 promising plant species for food forests in the Netherlands with their main edible plant part, expert score and relevance of zooming in on cultivars (Cv), rootstocks (Rs) and hybrids (H) in the database.

	Taxonomy			Zooming			
Nr.	**Botanical name**	**English species name**	**Main edible part**	**Cv**	**Rs**	**H**	**Expert score**
1	Actinidia arguta	Hardy kiwi	fruits	x			6
2	Actinidia chinensis	Kiwi	fruits	x			4
3	Allium ampeloprasum	Wild leek	leaves	x			4
4	Allium fistulosum	Welsh onion	leaves				3
5	Allium tuberosum	Chinese chives	leaves				4
6	Allium ursinum	Wild garlic	leaves				6
7	Alnus cordata	Italian alder	none				3
8	Alnus glutinosa	Black alder	none				6
9	Amelanchier alnifolia	Saskatoon	fruits	x		x	5
10	Apios americana	American groundnut	tubers				4
11	Aralia cordata	Udo	spear shoots				6
12	Armoracia rusticana	Horse radish	roots				2
13	Aronia melanocarpa	Black aronia	fruits	x		x	6
14	Asimina triloba	Pawpaw	fruits	x			7
15	Asparagus officinalis	Asparagus	spear shoots				4
16	Berberis koreana	Korean berberis	fruits				2
17	Brassica oleracea	Perpetual kale	leaves	x			3
18	Caragana arborescens	Siberian peashrub	seeds				3
19	Carya illinoinensis	Pecan	nuts	x	x	x	3
20	Carya laciniosa	Kingsnut	nuts	x	x	x	3
21	Castanea mollissima	Chinese chestnut	nuts	x	x	x	3
22	Castanea sativa	Sweet chestnut	nuts	x	x	x	9
23	Chaenomeles cathayensis	Chinese quince	fruits				4
24	Chaenomeles japonica	Japanese quince	fruits				5
25	Chenopodium bonus-henricus	Good king henry	leaves				4
26	Claytonia sibirica	Siberian purslane	leaves				3
27	Cornus mas	Yellow dogwood	fruits	x	x		6
28	Corylus avellana	Hazelnut	nuts	x	x		7
29	Crambe maritima	Sea kale	spear shoots				4
30	Crataegus mexicana	Mexican hawthorn	fruits		x		3
31	Crataegus schraderiana	Blue hawthorn	fruits		x		3
32	Cydonia oblonga	Quince	fruits	x	x		2
33	Dioscorea polystachya	Japanese yam	roots				3
34	Diospyros kaki	Kaki	fruits	x	x	x	8
35	Diospyros virginiana	Persimmon	fruits	x	x	x	6
36	Elaeagnus multiflora	Autumn olive	fruits	x			4
37	Elaeagnus umbellata	Goumi	fruits	x			5

38	Ficus carica	Fig	fruits	x			4
39	Fragaria moschata	Hautbois strawberry	fruits				3
40	Fragaria vesca	Alpine strawberry	fruits	x			4
41	Frangula alnus	Alder buckthorn	none				5
42	Hablitzia tamnoides	Caucasian spinach	young shoots (incl. leaves)				2
43	Helianthus tuberosus	Jerusalem artichoke	tubers				3
44	Hemerocallis lilioasphodelus	Yellow day lily	flowers	x		x	7
45	Heracleum sphondylium	Common hogweed	leaves				2
46	Hippophae rhamnoides	Sea buckthorn	fruits	x			6
47	Hosta sieboldiana	Sieboldiana hosta	spear shoots				7
48	Humulus lupulus	Hop	spear shoots				3
49	Juglans ailantifolia	Heartnut	nuts	x	x	x	6
50	Juglans cinerea	Butternut	nuts	x	x	x	3
51	Juglans nigra	Black walnut	nuts	x	x		5
52	Juglans regia	Walnut	nuts	x	x		8
53	Lonicera caerulea	Honeyberry	fruits	x			4
54	Lycium barbarum	Goji	fruits	x			3
55	Malus domestica	Apple	fruits	x	x		6
56	Malva moschata	Musk mallow	leaves				2
57	Matteuccia struthiopteris	Ostrich fern	leaves				5
58	Melissa officinalis	Lemon balm	leaves				3
59	Mentha suaveolens	Apple mint	leaves				4
60	Mespilus germanica	Medlar	fruits	x	x		7
61	Morus alba	White mulberry	fruits	x	x	x	4
62	Morus nigra	Black mulberry	fruits	x	x		5
63	Myrrhis odorata	Sweet cicely	leaves				4
64	Phyllostachys vivax	Vivax bamboo	spear shoots				6
65	Pinus koraiensis	Korean pinenut	seeds	x	x		3
66	Polygonatum biflorum	Solomon's seal	spear shoots				4
67	Prunus armeniaca	Apricot	fruits	x	x	x	6
68	Prunus avium	Sweet cherry	fruits	x	x		5
69	Prunus cerasifera	Cherry plum	fruits	x	x	x	3
70	Prunus domestica	Plum	fruits	x	x	x	6
71	Prunus dulcis	Almond	fruits	x	x		3
72	Pyrus communis	Pear	fruits	x	x	x	8
73	Pyrus pyrifolia	Nashi pear	fruits	x	x	x	7
74	Quercus ilex	Holly oak	nuts				2
75	Quercus robur	Pedunculate oak	nuts				2
76	Rheum x cultorum	Rhubarb	leaf stalks				5
77	Ribes nigrum	Black currant	fruits	x		x	6
78	Ribes rubrum	Red currant	fruits	x			7
79	Ribes uva-crispa	Gooseberry	fruits	x			4
80	Rosa rugosa	Rugosa rose	fruits				3
81	Rubus idaeus	Raspberry	fruits	x			8

82	Rubus phoenicolasius	Japanese wineberry	fruits				2
83	Rumex acetosa	Sorrel	leaves				5
84	Salix caprea	Goat willow	none				3
85	Sambucus canadensis	Canadian elderberry	flowers	x			3
86	Sambucus nigra	Common elderberry	flowers	x			5
87	Scorzonera hispanica	Scorzonera	roots				2
88	Sorbus domestica	Service tree	fruits	x	x		2
89	Staphylea pinnata	Bladdernut	flowers (unopened)				2
90	Symphytum officinale	Comfrey	none				3
91	Taraxacum officinale	Dandelion	leaves				4
92	Tilia cordata	Small leaved lime	leaves				8
93	Toona sinensis	Chinese cedar	leaves				7
94	Urtica dioica	Stinging nettle	leaves				6
95	Vaccinium corymbosum	American blueberry	fruits	x			7
96	Viola odorata	Sweet violet	leaves				3
97	Vitis vinifera	Grape	fruits	x	x		4
98	Zanthoxylum simulans	Szechuan pepper	fruits				2
99	Zingiber mioga	Myoga ginger	leaves				5
100	Ziziphus jujuba	Jujube	fruits	x	x		2

The 15 highest scoring species were mentioned by 7 to 9 experts and had no experts that were doubting or negative towards a place in the 100 top species list. The distribution of the main edible harvests of the 15 highest scoring species was 8 fruits, 3 leaves, 3 nuts and 1 flowers. 7 species were categorized within the low tree / large shrub layer, 3 species in the canopy layer, 3 species in the low shrub layer and 2 in the ground cover / herb layer. No climbers or belowground crops were represented among the 15 highest scoring plant species.

Experts named a balanced overall distribution within the species top 100 on the plant characteristic values of edible plant part, layer and harvest period as the top 3 plant characteristics. For 50 species the experts thought it would be relevant to zoom in to the cultivar level in the database. 32 species were commonly grafted on a rootstock and for 19 species multiple options could be relevant as rootstock. 18 species were identified to have relevant hybrids. The 19 species that were deselected during the final selection and did not make this list are presented in Tab. 5.7.5 in Annex I.

RQ4: What is the similarity between the key functional plant characteristics on species level compared to key characteristics for cultivars and rootstocks for the regenerative design of food forests in the Netherlands?

The main identified functional plant characteristics that experts regarded as relevant for zooming in to the cultivar level in the database were:

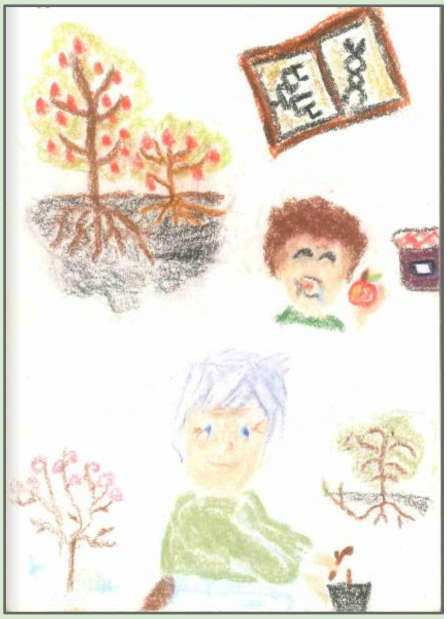
- ➢ variation in suitability for fresh and processed consumption
- ➢ variation in harvesting period and uniformity
- ➢ variation in pest and disease resistances
- ➢ requirements for specific compatible pollinator cultivars or flowering groups
- ➢ number of available cultivars, hybrids and subspecies
- ➢ cultivation history and experience

- ➢ reduced susceptibility to species specific weak points (spring frost, summer heat requirement, etc. (see also sub-chapter 5.2)

A key plant characteristic on the cultivar level that was not a key plant characteristic on the species level was compatibility for cross pollination. The key specific plant characteristic identified for scion and rootstock combinations was the reciprocal compatibility. The main plant characteristic for rootstocks mentioned by all practitioners was growth vigour, which was considered as a proxy for a wide range of other functional plant characteristics. Box 5.7.6 below and the casus studies for *Juglans regia* and *Cornus mas* in Boxes 5.7.7 and 5.7.8 Annex VI provide examples for relevant plant characteristics and design considerations on the cultivar and rootstock level.

Box 5.7.6: Considerations of the nursery grower for which scion and rootstock to combine.

Genetics (upper right corner)
When combining scions and rootstocks a nursery grower thinks about the genetic compatibility and a diversity of plant characteristics. A rule of thumb for genetic compatibility is that closer relatives are better compatible. There are also families and genera in which compatibility is in general higher. For instance, several *Prunus* spp are compatible with each other.



Vigour (upper left corner)
Important characteristics when choosing a rootstock are the manipulation of the size and productive life-span of the scion, as well as influencing suitable growth conditions in relation to soil, wind exposure and frost. Low vigour rootstocks, nowadays used in most commercial Dutch fruit orchards, start early with their productive life-span and stay smaller. This can be beneficial for getting a fast return on yield and easy accessibility during harvesting. However, while starting their productive life-span earlier, the length of the productive life-span is also greatly reduced. Moreover, these dwarfing rootstocks generally need more inputs of nutrients and water and are more susceptible to wind stress, pests and diseases due to their less developed root system. Vigorous rootstocks have the opposite effects and characteristics. It takes longer till plants come into bearing, but plants keep producing for many more years. This aspect in combination with better nutrients and water acquisition in combination with anchorage against wind stress and better pest and disease resistance makes vigorous rootstocks in general more suitable for extensively managed, long term systems such as food forests.

Frost and suckers (bottom left and right corner)
Frost is more severe close to the ground. Species vulnerable to late night frost may escape frost on a vigorous rootstock which is further removed from the ground. Another aspect related to the compatibility is the tendency of rootstocks to form suckers, this can occur when combining a highly vigorous rootstock with low vigour scion.

Markets and consumption (middle right)
The nursery grower is considering if the fruit is meant for direct, fresh consumption or processing, in this case into jam.

5.7.3 Sources

The **author, coordinates** and **date** were considered relevant source related elements of the database. All database experts considered dynamic information (linked to a time and place) as much more valuable than stationary data. These elements increase traceability and transparency of the data, elementary for open source databases. Moreover, place and time based data can contextualize plant characteristic values. As one agronomist explained about productivity:

> *"A yield measurement in itself is not so useful. These numbers always need to be given in a comparative context. The soil conditions seem to be the most important comparative factors for determining these yield numbers. Another important comparative condition is the neighbour plant belonging to a different species."*

Similar statements were made during the interviews by ecologists, agronomists and practitioners concerning the values of plant characteristics within the plant morphology and development category.

6 Synergizing the Plant database and decision-making framework

RQ5: What are the relations between the elements selected for the plant database and decision-making framework?

For the central role of functional plant characteristics in translating functional targets and characteristics of the landscape into design considerations for the vegetation composition and structure and to a lesser degree management, this chapter demonstrates the applications of the functional plant characteristics during the steps, plans, lists and maps of the decision-making framework. This chapter emphasizes which functional plant characteristics can be relevant in which phase of the decision-making and how they connect the design process to the selection of species, cultivars and rootstocks. A summary is provided in Tab. 6.1.1.

Table 6.1.1: The elements of the decision framework in row 1,2,3,4 (depending on ring) and their related (groups of) plant characteristics (colors correspond to steps of decision-making framework).

Ring 1: Step	**Ring 2: Steps**	**Ring 3: Plans, lists, maps, actions**	**Ring 4: Plans, lists, maps, actions**	**Emphasized (groups of) plant characteristics**
0: Core values, principles and approach	1: Observation and inventorisation	Human dynamics	Human stakeholders	-
			Ecological targets	Morphology and development, community status, inter-trophic relationships
			Food production targets	Harvest and post harvest
			Social and educational targets	Harvest period - start, culinary appreciation, nutritional value
			Future (potential) management, product-chains and consumer	Edible part, harvest period - start, productive lifespan - start, markets, processability, storability - natural, harvest methods, future demand
			Means	Layer, harvest methods
			Laws and regulations	Height - full grown, invasiveness, indigeneity
		Landscape dynamics	Geographical orientation in landscape	Frost vulnerability (whole plant and flowers), natural occurrence
			Soil and water conditions	Root depth and pattern, soil moisture, texture, fertility, acidity, compaction and salinity
			In and outflows	Shade tolerance, wind stress resistance, frost vulnerability (whole plant)
			Project scale	Interdependent with targets
			Climate change	Root depth and pattern, natural occurrence, (spring) frost vulnerability (whole plant and flowers), soil moisture tolerance
			Seasonal patterns	Leafing out, leaf fall, frost vulnerability (whole plant and flowers), flowering period - peak and length
			Flora and fauna	Layer, successional status, competitive strength, pollination vector, mycorrhiza type
			Access routes	-
			Artificial elements	Required abiotic growth conditions
		Species 100 top list	-	Latin species name

	2: Sketch design	Sketch maps	Target vegetation structure 'final' stadium	Layer, successional status
			Zones and edges	Edible plant part, successional status, natural occurrence, wind stress resistance
			Main paths	-
			Water elements	Soil moisture tolerance
			Open spaces	-
		Plans	Succession	Edible plant part, layer, successional status, competitive strength, height - full grown, height - age 10 and full grown, age - full grown, crown density, crown diameter - age 10 and full grown, dispersion, resprouting, relative growth rate, leaf composition, wind stress resistance, shade tolerance (productivity), mycorrhiza type, nitrogen fixation, soil moisture, acidity, fertility, compaction, productive lifespan - start and length
			Management, harvesting and marketing	Harvest and post-harvest, layer, competitive strength, soil fertility tolerance
			Water management	Soil moisture tolerance and root depth
			Landscape building	Layer, successional status, invasiveness, indigeneity, height - full grown, crown diameter - full grown, flowering period (peak and length), pollination vector
		Species longlist	Canopy and higher shrub layer species and rough nrs	Latin species name, layer
			All species matching targets and project context	Latin species name
	3: Detailed design	Detailed maps	Shrub layer design(s)	Layer, successional status, shade tolerance (productivity)
			Ground layer design(s)	Layer, successional status, shade tolerance (productivity)
			Vegetation structure 'transitional' stadia	Layer, successional status, crown diameter and height - age 10, relative growth rate, productive lifespan - start and end
			All relevant natural, living and artificial elements	-
		Plans	See 2B	-
		Species shortlist	Cultivars and rootstocks	Cultivar name, rootstock name
			Shrubs and ground layer species and nrs	Latin species name, layer
	4: Implementation	Implementation maps	Planting scheme	Layer, crown diameter - full grown, plant reproductive fertility, optimal distance for cross pollination, pests and disease susceptibility, pests and diseases of note, harvest location of edible plant part
			Earthwork map(s)	-
			Additional technical maps based	-

			on site preparations	
		Site preparations	Thinning	Morphology and development and required abiotic growth conditions
			Soil cultivation	Required abiotic growth conditions
			Initial inputs	Competitive strength, soil fertility tolerance
			Earthworks	-
		Planting material	Collecting	Availability plant material, nurseries, propagation method
			Introducing	-
	5: Adaptation	Realized vegetation structure and composition year x	Harvesting	-
			Other management practices	-
			Ecosystem development	-
			Establishment spontaneous vegetation	-
		Human & landscape dynamics year x	See step 1	-
		Reflect and react	See step 1	-

6.1 Plant characteristics during Step 1

6.1.1 Human dynamics

The relevant plant characteristics of the human dynamics depend largely on the identified human stakeholders. As individuals and communities they emphasize functional targets. The main functional targets discussed in part 2 chapter 1 correspond to those in the decision-making framework. The future (potential) management, product-chains and consumer relates strongly with the post-harvest characteristics discussed in part 2 chapter 5 and 6. Edible part, harvest period - start, productive lifespan - start, markets, processability, storability - natural, harvest methods and future demand are highlighted as the key characteristics identified in chapter 6 for the strong relation between project scale and product-chain.

The means, including the (potential) availability of money, knowledge, time labour and materials, has a wide variation of implications for the design. Highlighted here are the plant characteristics layer and harvest methods. The availability of human labour or machines relates directly to accessing suitable harvest methods. Several designers noted that in practice the complexity and detail of the design depends on the available budget. If there is little time a design often becomes simplified, staying in the earlier phases. Since designers first design the woody layers they may only design the herb layer when there is enough budget and time.

Laws and regulations can hold restrictions on the maximum height of vegetation. In a large area of the Netherlands, an open landscape is plannologically desired, mainly due to cultural historical appreciation and meadow bird conservation. Potential invasiveness and exotic origin of species may provide additional juridical constraints on the introduction of species.

6.1.2 Landscape dynamics

During the inventory of landscape dynamics designers can observe which plant characteristics are demonstrated by the present flora and assess how specific plant characteristics would respond to and affect the landscape elements. Emphasized plant characteristics are those discussed in part 1 chapter 1, 2 and 3, in other words, the plant characteristics nested in the categories morphology and development, required abiotic growth conditions and community. Frost vulnerability of the whole plant and flowers and leaves in spring were strongly related to the geographical location of the food forest on a national, regional and local scale as discussed in part 1 chapter 2. Natural occurrence can provide an indication of the climatological requirements of the plants.

Soil and water conditions relate to plant root depth and pattern and tolerances for soil moisture, texture, fertility, acidity, compaction and salinity for the present and future vegetation. In and outflows of aboveground natural elements such as light, temperature and wind relates directly to the required shade, wind stress and frost vulnerability The project scale can specify relevant specific plant characteristics further and is often interdependent with targets and their related plant characteristics. Plant characteristics for climate change adaptation and mitigation were discussed in part 1 chapter 2. These were root depth and pattern, natural occurrence, (spring) frost vulnerability (whole plant and flowers) and soil moisture tolerance.

Seasonal patterns that are observed in the landscape can indicate relevant phenological plant characteristics to consider. For example, exposure to a cold northeast wind in spring could indicate the relevance of spring frost vulnerability. Also the existing flora in the landscape can initiate seasonal patterns through phenological characteristics. For example, evergreen trees in or adjacent to the project area provide year round shelter and shade. Moreover, the flowering periods of the current vegetation already indicate the current nectar and pollen provisioning throughout the year. Besides phenological characteristics, observing the current flora in the project area and the surroundings provides information on the temporal and spatial vegetation structure and composition. For instance, the layer, successional status and competitive strength. Observing the flora can also provide insights into the pollinators and mycorrhiza present in the food forest.

Finally, artificial objects can influence the abiotic growth conditions. Especially adjacent buildings in urban contexts can influence the local temperature, light conditions and shelter in the food forest and provide insight of relevant plant characteristics for the design such as shade tolerance and wind stress resistance.

6.1.3 Starting list

The 100 promising species listed in figure x can form the starting list of the decision-making framework.

6.2 Plant characteristics during Step 2 and 3

The plant characteristics linked to the landscape and human dynamics of step 1, and more implicitly step 0, can guide the design considerations for the spatial and temporal vegetation arrangement and composition and the management practices that are consolidated in the maps, lists and plans of the sketch and detailed design. For example, for a large-scale food forest is susceptible to drought and set predominantly commercial food production targets, related plant characteristics like soil moisture tolerance, root depth, mechanical harvest efficiency, suitability for bulk market and high natural storability will continue to be applied in shaping the maps, lists and plans. Furthermore, certain plant characteristics and their values can be emphasized during either the sketch or detailed design.

6.2.1 Maps

Since the sketch maps visualize rough temporal and spatial structures, concepts and themes while the detailed maps zoom in to specific plant interactions, the lower food forest layers and cultivars there are differences between the relative importance of certain plant characteristics and their values. Concerning layers, step 2 generally places an emphasis on higher layers with larger plant height and crown diameter and step 3 emphasis on lower layers with smaller plant height and crown diameter. Besides layer, plant successional status of the target vegetation structure's 'final' stadium is important.

During the interviews examples were identified of zones with different themes that correspond to specific plant characteristics. Edible plant parts can be a theme for zonation when targeting specific markets, natural occurrence with zones for plants of different continents for telling the narrative of the importance of growing exotic species and soil moisture tolerance was used as a key plant characteristic for zonatiation because of large soil moisture gradients in the food forest. Wind resistant plants, often pioneers, are highlighted for their frequent use in hedges at the edges of the food forest. However, the plant characteristics responsible for the zonation and edges ultimately depend on the overall assessment during previous steps and the way designers interpret these concepts.

6.2.2 Plans

For the succession plan designers can draw upon the key plant characteristics discussed in part 1 chapter 3 of the results. To reduce redundancy, these are not elaborated here, but summarized in table x. The plant characteristics nested in the harvest and post-harvest categories, described in part 1 chapter 5 and 6, can be applied for shaping the management, harvesting and marketing plan. Layer, competitive strength and soil fertility tolerance are highlighted for the initial maintenance plan of the competitively strong ground layer present in the starting conditions of many food forests. Practitioners experienced young plants to establish better in poor soils with low competition of the existing herb layer in the first years of the food forest. The water management plan may focus on practices such as irrigation, import of water holding mulch or large modifications to the landscape with earthworks, but also includes the feedback loop of the soil and vegetation. Therefore, the moisture related plant characteristics described in part 1 chapter 2 can be considered in the water management plan. For the development of the landscape building plan a wide set of contextualized plant characteristics can be considered. Highlighted in table x are plant characteristics nested in the plant morphology and development as well as the categories community and inter-trophic relationships since these determine the vegetational structure driving the overall habitat and the inflow and outflow of flora and fauna between the food forest and the surroundings. The emphasized plant characteristics related to circumstantial site preparation activities can already be considered during the plans.

6.2.3 Lists

The development of the list depends on the previously selected relevant plant characteristics. Plant species and their numbers are matched via the plant characteristics to the observed human and landscape dynamics.

6.3 Plant characteristics during Step 4 and 5

For collecting planting material the availability of plant material in general and at nurseries as well as the suitable propagation methods can support the collection of planting material during step 4 as discussed in part 1 of the results. Several plant characteristics are mentioned in table x that are relevant during the implementation of specific site preparation activities. However, since step 4 does not focus on designing, but on implementation, actual consideration of these plant characteristics occurs already as part of the plans.

The relevant plant characteristics to consider during the evaluation and adaptation of step 5 would follow from the contextualized, unique development of the landscape and human dynamics of the place.

7 Discussion

7.1 Methodological considerations

The development of the problem definition and research design was an iterative process due to the explorative, action-oriented and participative nature of the study as exemplified in Tab. 1.2.1 in Annex IV. Still, the research directions were predominantly academic-led which may limit the degree to which the production of bottom–up knowledge is produced in a rigorous ethically acceptable way for action research (Pain and Francis, 2003). Representatives of each participant group were equally spread throughout the study to iterate research outcomes and evaluations back to the same participant group. Examples during phase 2 of data collection were testing the knowledge availability and applicability of the selected plant characteristics with 2 case studies (Tab. 5.7.7 and 5.7.8 in Annex V) and evaluating the steps, elements, overall structure, applicability, strengths and weaknesses of the framework with four food forest designers. Participants should have been feeded back processed data of preliminary research outcomes for discussion (Pain and Francis, 2003). Inviting the same participants of the first phase of data collection consistently in the reflection of the second phase as well could have reduced the probability of data being effectively interpreted by the author, strengthened involvement after the study and provided additional discussion. In PAR methodology such a feedback is often included, for increased validity and to bridge cultural, social and personal differences between the researchers initiating the study and other participants. However, time was a constraint for this feedback round due to the duration of the study and schedules of the participants.

Participants of the study are not per se users of the database or decision-making framework. Participants did informally mention the value created by the study for them, such as the integration of the decision-making framework in their design courses and practitioners widely appreciated that nursery growers would be linked to other practitioners to match supply and demand of planting material. Moreover, most participants felt sympathetic towards the open-source knowledge sharing to a broader community than their own personal gain and even mentioned the intention for creating an open-source knowledge platform as an important motivation for participation. However, planned systematized questions could have been included in the study to get a better idea about the perceived direct value created for participants. PAR and the inclusive objective of an open source plant database has the potential to connect fragmented initiatives working parallel on food forestry to share and learn from each other, both in terms of monitored data and their values and perspectives and acknowledge both areas of commonality and of controversy among experts. For instance, the study connects the viewpoints of practitioners affiliated with St. VBNL, individual food forest farmers, designers. These potential desirable value creation for participants should receive more conscious attention in designing future action research methodologies on food forestry.

The expert pool engaged representatives with background in a wide variation of sciences (ecology, agronomy, databases, decision-making) and practices (designing, farming, nursery growing, business management, gastronomy). The results indicated sub-groups within expert groups that hold different perspectives, knowledge and values. For instance, the results indicate differences between designers with origins in gardening, permaculture, landscape architecture or agroforestry. None of the contacted decision-making scientists had time to participate in the second phase of the data collection. Inclusion of decision-making scientists as participants in the later part of the study could have offered the possibility to identify, compare and reflect on the strengths and limitations of the decision-making framework from their personal perspectives and embed the structure of the framework in scientific decision-making theory and concepts. For instance, decision-making scientists could offer their perspectives on concepts and theories for complex decision-making frameworks with cyclic, iterative, qualitative, action-oriented, participatory and non-deterministic properties, comparisons to existing scientific, conceptual frameworks and developing a participatory action research methodology for testing the effectiveness of the application of the design framework in practice. It was outside of the scope of this study and the data was too limited to base conclusions on comparisons, but future research should take the variation of disciplines within account when interviewing food forest designers and also actively pursue the engagement of all relevant expert groups during research design.

The skills, attitudes and understanding of the field researcher are critical for conducting action research (Pain and Francis, 2003). During the iterative data collection and processing in this complex, transdisciplinary, novel context it may have enriched this thesis results to have been able to consciously and freely apply my own knowledge. For processing and interpreting all this data I wonder if I could have come to conclusions not tightly linked to my own worldview. Action research rejects the notion of an objective, value-free approach to knowledge generation and that personal values and commitment should not be avoided to bring about change as part of the research act (Brydon-Miller et al, 2003). My own expert knowledge served in shaping a methodology and I understand I would not have been able to come to these results in the first place without all the prior knowledge I had that enabled me to search out the appropriate experts, deepen in on specific topics, collect more data till I knew I could draw from my results a context that was satisfyingly balanced and complete to my liking. It seems not within human capacity to write all entangled considerations, mingling of what I suspect, found during my research and already knew, out on paper. At the least, in order to research complex, urgent sustainability issues, personal biases should not be discarded as weakness for valid research outcomes. On the contrary, where prior experience as food forest designer and manager contributed to the understanding of the study content, no prior developed personal skill as action researcher or social scientist may have had implications for the academic rigour and reliability of the methods. Mackenzie et al., (2005) also ascribe the sensitivity of relationships between the researchers and participants as one of their key factors for successful action research. First-person action research unfolds a process of self-transformation (Burgess, 2006). Therefore, my future engagement in the practice of action research would develop the required skills, attitude and understanding as an action researcher to strengthen methodologies and consequently research outcomes.

A major objective during the interviews was to collect predominantly personal experiential knowledge. However, it turned out to be hard to confirm or distinguish between what statements resulted from personal observation and what statements did not. Furthermore, it was not asked, and probably would have been impossible to recall for participants, on how many observations, locations and frequencies statements were based. This limits the traceability and thus validity of the thesis results. Furthermore, the open questions of the interview may have left room for missing the collection of relevant elements and relationships, because the experts may have assumed the data was common knowledge, or already discussed it during a previous question. Many characteristics not explicitly mentioned, for example when they may have been perceived as common sense. Other implications of the semi-structured data collection were that answers and follow-up questions often did not directly relate to the question topic, but also to other questions in the interview. Moreover, the explorative character of complex, novel systems with a broad, transdisciplinary scope resulted in a large amount of data to be communicated between me and the experts. For instance, knowledge transfer of a few cultivars and rootstocks for 2 species (Tab. 5.7.7 and 5.7.8 in Annex V) for all selected plant characteristics took four hours during one interview. However, this is inherent to explorative, qualitative research with semi-structured interviews and should be recognized and embraced in future action research.

7.2 Results

In this sub-chapter, the main results are discussed on their implications, limitations, relevance and directions for future research. The structure is based on result chapters 4, 5 and 6 and the sub research questions to which these chapters relate, RQ1, RQ2-4 and RQ5 respectively. The discussion of each research question starts with a general paragraph, is followed by one or multiple paragraphs corresponding to a (sub-)chapter and ends with a summarizing paragraph. The core message of each paragraph is highlighted in bold for increased readability.

Chapter 4: Decision-making framework

RQ1: What are key elements and steps applied during the design process of food forests in the Netherlands?

Interpretation of general results

The **key explored elements of the decision-making framework were the design steps and their corresponding design elements; plans, maps, lists and actions (Fig. 4.1.1 in Ch. 4.1)**. Designing a food forest was found to be an iterative process. This can be translated to making an analysis and testing each next step to the analysis and circumstantially consciously and unconsciously jumping to elements positioned later in the framework. The framework captures the overall cyclical nature of food forests, rooted in the acknowledgement of continuous change of the ecological dynamics, with succession as a primary mechanism and driver. The framework also contains continuous feedback loops between the identified elements and steps. The results build on existing evidence in other studies on agroforestry system design where **cyclical and iterative aspects emerged as an essential and welcome part of the design process** as well (Cardoso et al, 2001 ; Pinners and. Balasubramanian, 1991).

Step 0

The results indicate that **designers consciously or intuitively check if their decisions are in line with their core values, principles and approaches, summarized as step 0**. This step can be seen as the lense through which designers perceive the world and their underlying motive for decision-making. Therefore, for food forest design, step 0 might be the most important and complex step. In permaculture, this step is also described as the inner landscape that can be perceived as the nuclei of design (Holmgren, 2017). A diversity of ethics and principles were identified to guide the design. **All the explored principles of step 0 can be perceived as one the 10 and 12 design principles that respectively Bill Mollison and David Holmgren**, the founders of permaculture, proposed as inherent to any permaculture design (Holmgren, 2017 ; Mollision, 1997). Creating local circularity, many elements to support one function and many functions for each element show direct overlap with Mollison's principles while designing with and for flexibility, designing from large to small patterns and trying to understand the unique context of the place each fit with one or more of Holmgren's principles. It was beyond the scope of this study to confirm which underlying values are applied by food forest designers in practice. The explored ethics are inspired by the permaculture ethics and may indicate a direction for the fundamental attitude or values required for a regenerative food forest design.

Step 1 to 5

The observation and inventorisation step serves for designers to get a holistic overview of the human and landscape dynamics and make one big estimate on what is possible and how this could be achieved. The framework distinguished a sketch and detailed design. The sketch design functions to create large patterns (rough spatial structures, concepts, themes, etc.) by linking systems and targets, via functions, to the potential spatial and temporal arrangement of elements. A sketch design should generally include one or multiple sketch maps, plans (landscape building, succession, water management and management, harvesting and marketing) and a species longlist. A detailed design was found to zoom in to smaller patterns, detailed maps, further developed plans, narrowed down the plant entity lists and preparations for implementation. Management practices during the implementation aim for impacting site conditions and the vegetation composition and arrangement. The adaptation step completes the cyclical design process reflecting the cyclical nature of food forestry.

The six steps of the decision-making framework are supported by the design and management process described in the pioneering work on food forestry by Jacke and Toensmeier (2005). They distinguish six fundamental, interrelated design steps containing Goals articulation, Site analysis and assessment, Design concept development, Design, Implementation and Evaluation. The first two are united in step 1 of the framework, observation and inventorisation. Their third and fourth correspond to the sketch and detailed design of the results. The implementation of the design on the ground overlaps directly between frameworks. The evaluation step of Jacke and Toensmeier occurs in the decision-making framework as the ongoing reflective action during each step to check if ideas and decisions align with those made during previous steps, indicated by the grey dotted feedback arrows in fig. x. Jacke and Toensmeier left out the values of the designer, but explicitly recognized this as a relevant field of inquiry when the designer is not the same person as the client. The adaptation step of the framework is not explicitly stated by Jacke and Toensmeier to close the design cycle, but discussed as a significant part of the management, maintenance and coevolution. Thus, **the steps of the decision-making framework in this thesis research add scientific, evidence-based grounding to the existing pioneering work on food forest design from practice**.

Reconciling practice and theory

The framework also emphasizes the importance of the bridge and continuous feedback loop between theory and practice. Practical knowledge, skills and actions were applied mainly during the steps for inventorisation, implementation and adapting to the development of the project. Practice was sequenced with theory of various disciplines, patterns and concepts are used during species selection, drawing and analysing maps and writing the management, landscape building, water and succession plans. Pursuing a participatory decision-making process with practitioners may prove an effective approach for the design of food forests. Other researchers of agroforestry system design describe collective decision-making processes as appropriate for analysis of stakeholders' perceptions, identifying suitable systems, monitoring and evaluating agroforestry systems (Cardoso et al. 2001 ; Laroche et al. 2019 ; Pinners and Balasubramanian 1991). Results from Laroche et al. (2019) show that social factors seem to have more impact than biophysical factors on the decision to integrate agroforestry systems in agricultural landscapes and that the relative value given to decision factors varies greatly across stakeholders' categories. For continual learning for agroforestry system design a dynamic participatory learning process was even found essential, based on modifications as work progresses, farmers learn, and family and economic circumstances change.

Decision-making in complexity

The framework considers the complexity of the design process, although how to make decisions should be emphasized as a central research theme in further research. Designers agreed that a framework for directly and completely linking each element directly to all relevant other elements, deterministically coming to an optimal design, would not be achievable. The applied complexity and relations of elements of the food forest design process was found to strongly vary, based on the designer and unique context of the project. Each designer has his or her own style, based on his or her values, profession of origin and knowledge level. The absence of a deterministic decision-making prescription within each step embraces the reality that a decision-making framework for food forests can never be set in stone since all elements are interrelated and dynamic place-based systems are desirable. Furthermore, a more explicitly deciphered design process can have a higher risk of being regarded as truth. If that truth becomes the basis for decision-making, it may be used without critical reflection on that information. Therefore, there is a large need for understanding how designers make decisions for developing the system further as opposed to what decisions are made, for instance so additional design approaches and principles can be included in the framework as guidelines. Bennet and Bennet (2008) argue that as complexity builds upon complexity, decision-makers at the point of action must increasingly rely on their intuition and the challenge becomes the ability to holistically integrate logical processes, experiences and intuition.

Conclusion

The framework was regarded by designers as giving a quite complete and practically accessible context of food forest design as well as containing the steps and elements designers personally most frequently used and suggest the minimal requirements for making a food forest design. **However, designing complex agroforestry systems always goes further than mindlessly taking over prescribed choices** and future research should focus more on how decisions are made while applying the design elements in practice.

Chapter 5: Open source plant database

RQ2: What are key functional plant characteristics for the regenerative design of food forests in the Netherlands based on the most important 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) harvest practices, 6) project scales and 7) spatial arrangement?

General findings

During this study 234 functional plant characteristics were identified of which 80 key characteristics were selected (Fig. 5.7.1 in Ch. 5.7). The explored key functional plant characteristics are first discussed in relation to the main themes of each design criteria, followed by a general discussion of the plant characteristics.

Functional targets

The main functional targets were clustered into the categories of ecology, food production and education and social functional targets. The results suggest biomimicry for pursuing ecological targets in food forests can be summarized as creating self maintaining systems and providing ecosystem services for the surroundings. The findings that self-maintaining systems are characterized by resilience and resistance and aiming for biodiversity on multiple scales was found to contribute to this stability fit with the findings of global biodiversity research (EC and JRC, 2016). Applicable considerations for the design of the vegetation structure and composition as well as food provisioning were identified. Explicitly discussed **key plant characteristics for maintaining and stimulating intra and interspecific floral and faunal diversity were plant layer, successional status, indigeneity and aboveground architectural properties, especially height**. Additionally, **consecutive flowering** periods (length and peak) provide food for beneficial pollinators during the entire growth season. **Genetic diversity** was of special importance according to auto-ecologists. The positive role of each of the above functional plant characteristics in conserving and enhancing biodiversity in temperate agroforestry systems is supported by research in the fields of agroforestry, agroecology and functional ecology (Jose, 2012 ; Gliessman, 2017 ; Martin and Isaac, 2015). However, authors advocate associated biodiversity remains too complex to be captured by several plant characteristics (Jose, 2012).

Current and predicted future environmental conditions

Temperature and moisture emerged as the most important environmental conditions during the interviews, relevant and considered during all scales across space (national, regional, local) and time (future, ontogenetic, seasonal). **Spring forest resistance, overall winter hardiness and soil moisture tolerance were identified as key related plant characteristics** for the design of food forests in the Netherlands. In agroecology these characteristics are regarded as essential for crop growth as well (Gliessman, 2014). In horticulture freeze injury still accounts for greater losses of fruits and vegetables than any other environmental or biological hazard (Rodrigo, 2000). Literature reviews support that especially damages on fruit trees are produced in buds, flowers and developing fruits after dormancy and that in general yield losses due to frosts during bloom are more severe than losses due to low winter temperatures (Rodrigo, 2000). The contradictory predictions from the interviewee in this thesis research on the increased or decreased probability of spring frost damage on trees in The Netherlands due to climate change can be compared to climate change models. Results from such models indicate that the probability of spring frost damage may increase due increased temperature variation, but may decrease due to increased mean temperature (Rigby and Porporato, 2008).

Furthermore, the thesis research results indicate that **urban food forestry requires additional environmental design considerations with a wide range of corresponding plant characteristics**. The influence of an urban environment on the appropriate design of food forests is suggested by studies which name abiotic growth requirements, social, educational, regulation functions and food security that can be established through considering site-specific functional plant characteristics (Park et al. 2019 ; Riolo, 2019).

Successional gradients

Experts envisioned mid successional systems as most promising for food forests (Fig. 5.3.1 in Ch. 5.3). **The forest edge was proposed as very promising mid successional spatial patterning of the vegetation and most experts would maintain the food forest in this stage in most situations.** A recurring justification was that mid successional systems provide most targeted species in food forests and are possibly the most productive systems in terms of netto biomass production and edible plant parts in our climate. This can also be found in literature as Jacke and Toensmeier (2005) describe mid successional systems as the aggregation phase of nutrient cycling. Moreover, other experiences suggest that natural mid-successional forests and forest edges contain most useful shrubs and trees for humans, while they are often the peak in forest productivity and species diversity (Crawford, 2010).

However, experts also argued for the importance of maintaining diversity of successional stadia and spatial structures within food forests and on a landscape scale. Some mentioned letting food forests advance into late successional systems, but only one expert voiced a cyclical design and management of food forests on a food forest and landscape scale. It is unknown how much energy (labour and inputs) are required to keep food forests in these stages. Most other agroforestry and arable farming systems are maintained at a desired state (or worked towards a particular stage), often before reaching an ecological climax. Such forms of maintenance can involve large amounts of energy and resources to prevent such ecological evolvement (Conforti & Giampietro, 1997; Pimentel et al., 1973; Smith et al., 2008). This can lead to a greater discussion as to which food forestry is more or less sustainable or regenerative (Park et al., 2018).

The cyclical shifting-mosaic systems illustrated in Fig. 7.2.1 and 7.2.2 in Annex II as proposed by Jacke and Toensmeier (2005) can broaden the possibilities for cyclical, multi-stadia temporal sequencing of vegetation stadia and **through the additional diversity and complexity it may increase the potential benefits, especially related to food forest sites and zones with more ecologically oriented targets,**

of applying successional designs compared to the practices commonly voiced and applied by experts interviewed during this thesis research. At a landscape scale, a relatively stable state is maintained, because the proportions of the forest remain stable at various stages as well as their corresponding crops. It is questionable what desirable proportions of early, mid and late successional stadia throughout the landscape would be in the Netherlands on national, regional and local scales for optimal health and self-maintenance of an overall ecosystem that offers high diverse yields of resources. Literature on shifting mosaics indicates the importance for biodiversity conservation and nutrient cycling for these dynamic systems in the Netherlands (Olff et al., 2008). Moreover, based on succession theories, pollen investigations, historical texts, research into spontaneous succession in forest reserves and the ecology of the tree species that formed the climax vegetation in prehistoric times in the Netherlands Vera (1991) proposed that in prehistoric times, the natural vegetation in the lowlands of Central and Western Europe was a park-like landscape with cyclical patch dynamics. Besides designing for more temporal vegetation arrangements and forfeiting permanent successional stadia, more mid successional spatial patterning may be promising than discussed with the experts. Mid successional structures, habitats or patches besides forest edges and open woodlands Jacke and Toensmeier (2005) propose include thickets, shrubland, oldfield mosaics and coppice systems.

For designing along the successional gradients a broad range of plant characteristics was proposed by all expert groups, but the findings indicate shade tolerance (productivity), vegetation layer and plant successional status as key functional characteristics (Tab. 5.3.1 in Annex I). Ecologists were found to apply the highest abundance of plant characteristics compared to other expert groups, mainly defined as functional traits, and mentioned traits related to leaf economics as most important effect and response traits in relation to forest succession. Productivity of harvestable edible plant parts in the shade was mentioned by most practitioners and scientists as relevant functional plant characteristic for the design of food forests in the Netherlands with food production objectives, mainly due to the low frequency and intensity of light for maintaining productive understory layers in temperate climates. Therefore shade tolerance (productivity) was strongly linked to the vegetation layer within the community. Very little information seems available in literature on the relevance, classification and species values for both of these plant characteristics. This can partly be explained by the fact that multi-strata agroforestry systems, especially with more than two distinct vegetation layers, remain relatively unexplored in modern science and practice, in particular in temperate climates (Froufe et al., 2020 ; Martin and Isaac, 2015). Furthermore, the terminology of these characteristics, their normative definition and relation to yield of edible products is not applied in fields such as functional ecology. For instance, the TRY database only defines species tolerance for growth in shade and distinguishes between species understory and overstory (TRY, 2021). Nevertheless, CABI reports suggest that for fruit crops that naturally occur in forest understories productivity can even increase with a 25-50% reduction of light availability, depending on climate (Retamales and Hancock, 2018). Therefore, these thesis findings provide new insights in relevant, contextualized plant characteristics when considering succession in food forest research and design.

Plant successional status was identified as a third key functional plant characteristic for the successional design of food forests in the Netherlands. Plant successional status was perceived as a compound variable that matches up with acquisitive versus conservative trait values for leaf composition, relative growth rate, aboveground architecture and tolerance to abiotic stresses such as wind and temperature. Litterfall and decomposition are the two major processes that replenish the soil nutrient pools and endow sustainability to multi-strata successional agroforestry systems (Vezzani, 2020 ; Froufe et al., 2020 ; Das and Das, 2010). Therefore, while the identified functional plant characteristics leaf composition and leaf decomposition rate both relate strongly to plant successional status both may not be covered sufficiently for the successional design of food forests by plant successional status and these functional plant characteristics may require inclusion and research as separate key elements. In general these findings suggest that the effect traits for designing along successional gradients may be the same traits as the response traits, while the values are located on the opposite side of the spectrum.

Harvest practices

Edible plant part was the foremost plant characteristic when considering the future harvest practices. The other identified key plant characteristics for designing what, when, how and where to harvest, such as start, length and uniformity of the harvest period, harvest method, harvest efficiency, harvest location and start of productive lifespan link directly to specific edible plant parts instead of the whole plant. Food forests offer a wide diversity of edible plant parts, but the potential and limitations showed strong variation among the classified edible plant part groups.

Fruits were arguably the most prominent edible parts in the food forest, followed by leaf and nut crops. Culinary appreciation, market value and suitability for mid successional systems were identified as important underlying functional plant characteristics for the relatively large interest of interviewee in fruit crops in food forests. However, crop pattern modelling for an ecologically sustainable diet that can adequately feed 10 people on 1 ha of Dutch food forest shows that fruit crops only need to cover 10 to 20 percent of the food forest land area as opposed to 40 percent of nuts and 20 to 50 percent of green vegetables (Jenkins, 2020).

Nuts were highly regarded by practitioners mainly due to their long lifespan, low maintenance requirements, general system functions, suitability for later successional systems, fairly easy mechanized harvesting, good storability, high nutritional value, good flavour and growing market demand. Potential limitations the interviewees perceived for implementing nuts in food forests are low breeding history of most species and hence low overall productivity, incompatibility with lower vegetation layers due to harvesting from the ground and low tolerance to high and strongly fluctuating groundwater tables in the Netherlands. Indeed, most of the beneficial functional plant characteristics ascribed to nut cultivation and consumption in these thesis findings are increasingly promoted in international dietary guidelines for the development of sustainable dietary patterns and reflected in Dutch market and consumption trends (EFSA, 2018 ; FAO and Food Climate Research Network, 2016). Moreover, research by Pepels (2018) on fertilizer needs of food forests dominated by nuts suggests that nut crops can continue bearing nuts for centuries without considering any input apart from occasional nitrogen input, depending on natural nutrient uptake mechanisms in food forests. Based on these thesis findings and the lack of experience in food forest contexts, **future research on the harvest practicality of implementing nuts when designing multi-strata systems is necessary as well as setting up breeding programs for improved cultivars**.

Perennial (spear) shoot and leaf crops emerging from the ground early in spring were valued by interviewees for holding potential to enhance food security, self-sufficiency and resource partitioning, target the undeveloped market of spring vegetables and spread labour. A recent global meta-analysis revealed the distinct relevance of perennial vegetables as a resource for biodiversity, carbon sequestration, and nutrition (Toensmeier et al, 2020). Nevertheless, asparagus is the only perennial shoot crop commonly grown and consumed in the Netherlands (Gilissen, 2020) and only annual leaf crops are widely grown and consumed as green vegetables, while consumption of perennial leaves is restricted to the limited consumption of wild edible greens (Fleischhauer et al., 2014).

The use of edible flowers as vegetables was limited mainly by the perishability and low productivity. Also belowground edible plant parts seemed particularly difficult to fit in multi-strata crop patterns, mainly due to the harvest complications and growth requirements. However, interviewees did offer specific design considerations for including flowers and belowground crops in food forests. Food forests without commercial food production objectives or serving short chain, specialty markets and alley cropping systems were belowground crops are horizontally and vertically spaced away from other vegetation layers may provide opportunities for integrating respectively flowers and belowground crops in a food forest. Despite their desirable functional characteristics, perennial vegetables receive little attention in the scientific literature and only occupy 6% of world vegetable cropland (Toensmeier et al, 2020). Therefore these thesis findings build upon the emerging evidence that perennial vegetables, especially leaf and shoot crops, seem an underrepresented, undervalued and underutilized class of crops in the current food system, cuisine and scientific research.

Project scale

The scale of the project site emerged as a design theme that exposed many opposing opinions among experts concerning the opportunities and limitations for scaling up food forests in the Netherlands. Moreover, there was a strong relationship between the functional target, harvest practices and project scale of food forests, with implications for the plant characteristics relevant for designing species choice, richness and spatial and temporal arrangement as well as management practices. A potential limitation perceived by interviewees of large scale compared to small scale food forests was the orientation on commercial food production at the cost of ecological, social and educational functional targets. Furthermore smaller food forests may be optimized for commercial food production more effectively by a farmer compared to large scale food forests, due to a higher labour availability. For instance, more management in the understory could optimize an early economic return of plants that start early with their productive life time. Moreover, small scale food forests were suggested to be more suitable to short-chain marketing of products in which farmers cut all margins of the retail and can ask for higher prices. Self harvesting systems hold the additional benefit of omitting labour for harvesting. Finally, since these are novel, long term systems, transforming a large part of their farm may be too costly and the insecurity of economic return too high for farmers, while adapting food forestry as a small piece of a farm may diversify income. Several of these arguments fit with findings of recent case studies on business models for both a small and a large scale food forest in the Netherlands. The model suggested large scale food forests demand increased labour, higher initial negative cash flow and decreased opportunities for short chain sales (Doomen et al., 2019).

However, the current conventional large scale food systems may be less suitable due to their ecological footprint so by comparison a transition to large scale food forests may be a more sustainable alternative. Moreover, Björkland et al. (2018) conclude in their action research study that if forest garden approaches to food production should contribute to more than local self-sufficiency, the systems need to increase in scale. In the study by Doomen et al. (2019) step by step transitioning of existing farms was proposed for upscaling food forestry. Finally, the variation in opinions on project scale in this thesis research could possibly be explained by the lack of experience with large scale food forests in practice and consequently literature (Doomen et al., 2019 ; Pilgrim et al., 2018). The design of the food forest can be considered a major factor in relation to project scale.

These findings are a first contribution in food forestry for approaching the opportunities and limitations of project scale explicitly and primarily via the selection of key functional plant characteristics. Specifically, markets and consumption, start of the productive lifespan, harvest methods, culinary appreciation, future demand, processability, edible plant part, harvest period uniformity, storability, peak productivity, start of the harvest period and staying on the plant after ripening were explored as key functional plant characteristics for designing the along the project scale of food forests.

Conclusion

Based on this explorative study, **functional plant characteristics form a bridge** linking considerations for plant species composition, temporal and spatial vegetation arrangement, functional targets, environmental conditions, successional gradients, plant development through life stadia, harvest practices and project scale. Through functional plant characteristics designers can both respond to and drive ecological, socio-economic and socio-cultural dynamics on multiple spatial and temporal scales for pursuing complex multifunctional targets. Specific key plant characteristics and plant species were identified and further research is necessary to explore their relevance for the design of food forests.

RQ3: What are 100 promising plant species for food forests in the Netherlands based on the selected key functional plant characteristics and on overall complementarity of inter-species variation?

The 100 promising species derived from the 80 key functional plant characteristics in Fig.5.7.1 in Ch. 5.7 and from overall complementarity of inter-species variation, in particular variation in edible plant parts, **are depicted in Tab. 5.7.4 in Ch. 5.7.**

The list utilizes the explored diversity in functional targets and project dynamics among food forests as well as the diversity in personal perspectives of the interviewees. Therefore, users of this plant species list can inform themselves of species, based on the functional plant characteristics of their project context and personal preference. Nevertheless, the variation in suitability scores of the explored species and amount of experts with which these species were discussed remains low. For instance, 33 species had a net positive score of 2 experts. 13 species were selected from those 33 to complete the 100 top species list, while the promising food forest species that were deselected during the final selection round (Tab. 5.7.5 in Annex I) may prove better candidates with more data collection. More experiential knowledge is required on both the performance of the selected as well as the deselected species and their key functional plant characteristics to increase the probability of a 100 species' overall suitability for food forests in the Netherlands.

Still, it is a risk if practitioners and researchers regard this list as a holy grail since designing for diversity should arguably remain the most important narrative in food forest design, with the right plant at the right place at the right time. For instance, the overall 100 top species list may provide representative species of the diversity in values and food forest systems, but the large pool of species candidates, diversity in food forest systems and values of interviewees and consequently only partial overlap among species lists (Tab. 5.1.3, 5.2.1, 5.2.2 and 5.3.2 in Ch. 5.1, 5.2 and 5.3 respectively) emphasize that based on specific functional targets, environmental conditions, successional gradients, ontogenetic life stadia, harvest practices and project scales unique 100 top species lists can be formed. For instance, a 100 top species list can be made for food forests on wet soils that may have a proportionally small overlap of species with this list.

RQ4: What is the similarity between the key functional plant characteristics on species level compared to key characteristics for cultivars and rootstocks for the design of food forests in the Netherlands?

Frost resistance, market and consumption, peak productivity, pest and disease resistance, start of the harvest period, size of the edible plant part, storability and nurseries at which planting material is available might be key functional plant characteristics that are relevant for both species and most cultivars. This can be explained by most of these characteristics as major focus areas of plant breeding. However, none of these key functional characteristics were identified as relevant for each species on a cultivar level and zooming in to the functional plant characteristics of cultivars would only be appropriate for species with available cultivars (Tab. 5.7.4 in Ch. 5.7). Moreover, the findings, especially the case studies, suggest a major variation on the cultivar specific relevance of certain plant characteristics per species (Tab. 5.2.1 in Ch. 5.2, Tab. 5.7.6 in Ch. 5.7 and Tab. 5.7.7 and 5.7.8 in Annex V).

Furthermore, functional plant characteristics concerning **compatibility for cross pollination emerged as predominantly relevant on the cultivar and not on the species level**. Finally, the findings suggest specific characteristics relevant on the cultivar level for specific species groups such as stig length and stone free in small fruit and stone fruit respectively. Therefore, **future research should focus on identifying relevant functional plant characteristics for cultivars per individual species or species group.** In this research, challenges posed for reconciling normative classifications of the same functional plant characteristics between species and cultivars should be taken into consideration. For instance, when comparing the case study species, a *Juglans regia* resistant to spring frost may be very susceptible compared to a *Cornus mas*.

For rootstocks little data was collected, but **the findings indicate an intricate interaction between scion and rootstock that may influence many functional plant characteristic values,** ranging from plant morphology and development to required abiotic growth conditions and from inter-trophic relations with pests, diseases and pollinators to (post)harvest related characteristics. Compatibility between rootstocks and respectively species and cultivars was identified as relevant characteristics in addition to the explored characteristics on species level.

The findings suggest growth vigour as additional relevant rootstock specific functional plant characteristics with wide implications for other functional plant characteristics (Tab. 5.7.6 in Ch. 5.7). **Strong vigour rootstocks may be preferable in extensive farming systems such as food forests.** Little experience is available on the performance of rootstocks for species besides apples, pears and plums in the Netherlands and only some anecdotal experience in a food forest context. This suggests a major knowledge gap that should be the focus of attention in further research and the need for breeding programs that explore the potential of vigorous rootstocks.

Chapter 6: Synergizing the Plant database and Decision-making framework

RQ5: What are the relations between the elements selected for the plant database and those of the decision-making framework?

Plant characteristics work for linking the living, natural, abstract and artificial elements of the place, observed during step 1, to decisions on vegetation composition and structure through space and time. Furthermore, the plant characteristics are used for observing the specifying targets in the early phase of design, creating maps, plans and lists during the design process, obtaining planting material and for evaluating the developed human and landscape dynamics to the targets after implementation (Tab. 6.1.1 in Ch. 6.1). However, the validity of the linkage between specific key functional plant characteristics and elements in the framework was limited through high uncertainties and context-dependency. These linkages are largely based on comparative data analysis by me instead of through consultation with the experts. Besides the plant characteristics, other database elements, specifically the plant species, cultivars and rootstocks connect to the lists of the decision-making framework. An additional element for synergizing the framework and database element could be the inclusion of a list of plant characteristics as part of step 2. Such a list, based on observation and inventorisation, can serve as an explicit bridge for developing a species longlist, sketch map or any plans.

7.3 Conclusion

The main research question that emerged during the study was the following:

What elements need to be consolidated in a plant-database and decision-making framework for the design of food forests in the Netherlands and how do these elements relate to each other?

Steps, plans, lists and maps were identified as key elements in a framework for designing the spatial and temporal composition and structure of living and nonliving elements, especially vegetation, in food forests in the Netherlands. Each of these elements was found interrelated in an iterative, cyclical design process whereas it is desirable to acknowledge the process and elements as unique in each context without single silver bullet design solutions. Still, mimicry of natural succession was identified as a central temporal consideration when designing maps, plans and plant lists. Moreover, the framework as a whole and as individual elements emphasizes the importance of the bridge and continuous feedback loop between theory and practice. Project scale may prove a critical design criteria and posed an exceptionally large dissonance among food forest experts.

The thesis research outcomes suggest that **functional plant characteristics of plant species, cultivars, rootstocks and cultivar-rootstock combinations, underpinned with dynamic sourcing on author, date and place are essential elements in a relational, open-source plant database that can underpin the decision-making framework.** In particular, the explored functional plant characteristics were found to contribute as an approach and bridge for translating design criteria such as functional targets, environmental conditions, successional gradients, management practices and project scale into a vegetational composition and structure for food forests. Specific key plant characteristics and plant species were identified and further research, with and for practice, is necessary to explore their relevance for the design of food forests.

A participatory action research approach, combined with principles from integrative research, was found effective to 'design the design process' of food forests. Not earlier were as many as 26 experts from different backgrounds sharing their knowledge and perspectives in an academic study on food forest design in the Netherlands. Consequently, the first decision-making framework for the design of food forests in the Netherlands was developed that integrates key elements, structures and functions reflecting the experiential evidence accumulated over the years and novel interdisciplinary research in the fields of ecology and agronomy into a systematized design process. An exploration for database elements relevant to support the design of food forests in the Netherlands did not exist either. **This broad, explorative study can inspire practitioners and scientists in their decision-making during food forest design and research on design respectively and can inspire practitioners, scientists, policy makers and the general public alike to contribute to the succession of food forests as a practice and science.**

8 Recommendations

This chapter provides a blueprint for a research agenda for the succession of food forests with and for practitioners and scientists, based on the findings and reflections of this explorative study. Methodological considerations to consciously take into account during future participatory action research, based on the strong points as well as the limitations of this thesis research are 1) active practitioner participation during research design and iteration of findings back to participants for discussion, 2) value creation for the participants, 3) personal biases of the field researcher and 4) specific sub-groups within and new groups besides the expert groups of above study.

8.1 Succession of Decision-making Frameworks for food forest design

The decision-making framework should be tested and improved upon in collaboration with practitioners, especially designers. Future research on this topic should assess the practical applicability of the framework for making a design for food forests in the Netherlands. Topics of the framework that I recommend for testing and further exploration in practice are:

1. The cyclic and iterative nature of food forest design
2. The continuous feedback between practice and science
3. The underlying personal values, design principles and approach of participants that shape the design process and content. This includes assessing the flexibility of the framework to leave room for designers to follow their own style.
4. The integration of succession into the framework during the different steps, maps, plans and actions. For researching how to analyse, predict, imagine, visualize and adapt to relevant successional gradients and stadia in the decision-making framework, later studies can also draw upon the findings in Fig. 5.3.1 and the discussed cyclic shifting-mosaic in Fig. 7.2.2 in Annex II. In general, both practitioners and scientists are suggested to focus more specifically on exploring possibilities for temporal and spatial patterns across systems, since food forests are such a novel phenomena and offer so many possible benefits.
5. The integration of functional plant characteristics into the framework during the different steps, maps, plans and actions. The explored relations between specific plant characteristics and specific elements of the decision-making framework should be further assessed. For synergizing the open-source plant database to the decision-making framework I recommend researching the role of functional plant characteristics in linking functional targets, landscape dynamics and personal values to food forest systems and systems to species, hybrids, cultivars and rootstocks composition and arrangement.
6. The completeness for designing a large variation of place-based food forest systems as well as other complex perennial food systems, for instance by testing which elements in the decision-making framework specifically feed elements of next steps and whether all later steps are fed sufficiently by the previous step in different food (forest) systems.
7. The integration of more planological, social, economic and educational focussed design considerations
8. How to make decisions in complexity. In particular, I recommend further research on the integration of experience, logical processes and intuition when holistically considering the design elements and process of the framework. These findings can be included in the framework as guidelines and heuristics for additional design approaches and principles during step 0

Specific methodological considerations for testing and improving upon the decision-making framework building upon those voiced at the start of this chapter are to 1) present food forest case studies to a wide pool of participants, especially designers, asking them to make a food forest design and comparing their design process and elements to the framework or 2) present food (forest) system designers the framework and reflect collectively on the framework in comparison to earlier food (forest) projects they designed. Relevant sub-groups within the designers identified in this study are landscape architects, permaculturists, practice-oriented agroecologists. However, for transdisciplinary, integrative and inclusive research on food forest design where each discipline can contribute experiences from his or her own background a much broader range of participants should be involved to assess and improve the framework. This includes industrial designers, artists, accountants, climatologists, sociologists, teachers, managers, children, students and more.

8.2 Succession of Open-source Plant databases for food forest design

For the succession of the open-source plant database the suitability of the explored functional plant characteristics and species for food forest design should be systematically tested and potentially substituted by more desirable alternatives. Contextualized data should be collected about functional plant characteristic values for the 100 promising food forest species, their cultivars, rootstocks and scion-rootstock combinations. **Exploring appropriate future data collection, analysis and sharing should develop iteratively with and for practice and science.**

Further research as well as filling in the database requires setting up standardized, systematic monitoring of key plant characteristics in a food forest context. For contextualized data the growth and productivity of species should be monitored as well as the key (a)biotic site conditions. Filling in the database would provide the opportunity to perform a Multi Criteria Analysis (MCA) for systematic assessment and evaluation of overall potential of the 100 listed species based on the relative importance of all selected key functional plant characteristics and the complementarity of functional plant characteristic values. Assessing the inter-species variation can identify gaps in the overall complementarity of the plant characteristic values of the 100 promising species and consequently the need for substituting species. Moreover, MCAs could aid designers in predicting suitability of species for specific functional targets, environmental conditions, successional stadia, harvest systems and project scales during food forest design. For instance, when a large proportion of the 100 promising species list turns out to have a low drought tolerance, early flowering in spring, applicability for the climbing layer or native occurrence, species with those plant characteristic values could be promoted in substitution of a species lacking these values. These analyses can also initiate the composition of target- and place-specific lists of promising species.

Exploring the potential of promising plant species, by filling in the database through action research will provide insight in both the applicability in practice and scientific grounding of the explored classifications for each plant characteristic so these can be iteratively improved. For this, Fig. 5.7.2 in Annex V provides a starting point for research on the presentation of the functional plant characteristics of the 100 top promising food forest species in the open-source database. The way knowledge is shared in the database should also be fed back to future users for discussion on practical applicability, scientific rigour and potential lacking relevant database elements.

For future plant characteristic based cultivar, rootstock and hybrid selection I recommend the separate assessment of relevant key plant characteristics for each species. The identified availability of promising cultivars, rootstocks and hybrids as depicted in Tab. 5.7.4 and the general relevant functional plant characteristics discussed in Box 5.7.6 can serve as a starting point. Furthermore, I recommend caution with limiting the diversity of cultivars in food forest design and any open-source database. Since different plants of the same cultivar have the same genetics, there is a risk of food forests becoming rich in species, while being genetic monocultures. Furthermore, limited use of cultivars and rootstocks increases the risk of overlooking other promising cultivars and through decreased demand for plant material and consequently decreased propagation of these genes in nurseries. Therefore I advise designers that aim to use the open-source database to experiment with cultivars, rootstocks and hybrids not presented in the database. Finally, there is a large need for breeding new cultivars, hybrids and rootstocks for guaranteed diversity and improved performance on species specific key functional plant characteristic values. Breeding programs for strong vigour rootstocks seem underrepresented while these rootstocks seem especially promising for extensively managed food forest contexts.

Finally, I suggest specific research directions that link functional plant characteristics to each explored design criteria which are depicted in Tab. 8.2.1.

Table 8.2.1: Research directions on critical design criteria, based on key functional plant characteristics.

Design criteria	Key functional plant characteristics	Research topic
Functional targets	flowering period, layer, inter-tropic characteristics	relation between biodiversity and designing a flowering calendar, multiple layers, indigeneity and inter-tropic characteristics
Environmental conditions	temperature requirements, soil moisture tolerance	relation of plant characteristics to spatial vegetation arrangement, climate adaptation and urban dynamics
Successional gradients	shade tolerance productivity, layer, crown density, leaf composition, competitive strength	productivity of lower layers in different light climates, plant-soil feedback through leaf composition and competitive strength of lower layers in early successional stadia
Ontogenetic variation	height and crown diameter after x years, light, temperature and soil moisture tolerance	growth and productivity through life stadia in different growth conditions (temperature, drought, shade)
Harvest practices	edible plant part, start, length and uniformity of the harvest period, harvest method, harvest efficiency, harvest location and start of productive lifespan	relation of edible plant part to values of other key characteristics to apply their strengths and overcome their limitations
Project scale	markets and consumption, start of the productive lifespan, harvest methods, culinary appreciation, future demand, processability, edible plant part, harvest period uniformity, harvest efficiency, storability, peak productivity, start of the harvest period, staying on plant after ripening	relevant plant characteristics and their values for small and large scale commercial food production food forests

9 Literature

Anderson, C. R., Bruil, J., Chappell, J. M., Kiss, C., & Pimbert, M. P. (2020). *Agroecology Now!: Transformations Towards More Just and Sustainable Food Systems* (1st ed. 2021 ed.). Palgrave Macmillan.

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., et al. (2014). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renew. Agric. Food Syst.* 29, 101–125. doi: 10.1017/S1742170512000385

Barstow, S. (2015). *Around The World in 80 Plants: An Edible Perennial Vegetable Adventure for Temperate Climates* (Illustrated ed.). Permanent Publications.

Bennet A., Bennet D. (2008) The Decision-Making Process in a Complex Situation. In: Handbook on Decision Support Systems 1. International Handbooks Information System. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-48713-5_1

Brydon-Miller M, Greenwood D, Maguire P. Why Action Research? *Action Research*. 2003;1(1):9-28.

Burgess, J. (2006). Participatory action research: First-person perspectives of a graduate student. *Action Research*, *4*(4), 419-437.

Cardoso, I. M., Guijt, I., Franco, F. S., Carvalho, A. F., & Neto, P. F. (2001). Continual learning for agroforestry system design: university, NGO and farmer partnership in Minas Gerais, Brazil. Agricultural Systems, 69(3), 235-257.

Crawford, M. (2010). *Creating a Forest Garden: Working with Nature to Grow Edible Crops*. Green Books.

Das T, Das AK (2010) Litter production and decomposition in the forested areas of traditional homegardens: a case study from Barak Valley, Assam, northeast India. Agrofor Syst 79:157–170.

Doomen, R., Leeuwen, van B., Puhe, L. | *Food Forest Business Models in The Netherlands* | HAS Den Bosch | 2019

European Food Safety Authority. Scientific topic: Dietary reference values | European Food Safety. (2018). Available at: http://www.efsa.europa.eu/en/topics/topic/dietary-reference-values.

European Commission & Joint Research Centre. (2016). *Global Soil Biodiversity Atlas*. UTB.

FAO & Food Climate Research Network. Plates, pyramids, planet. (2016). doi:ISBN 978-92-5-109222-4

Fleischhauer, S. G., Guthmann, J., Spiegelberger, R., de Kort, M., Oosterhuis, L., van der Woude, D., & Uslu, H. (2014). *Eetbare wilde planten*. Schildpad Boeken.

Froufe, L. C. M., Schwiderke, D. K., Castilhano, A. C., Cezar, R. M., Steenbock, W., Seoane, C. E. S., ... &

Gilissen, L. J. (2020). Food, nutrition and health in the Netherlands. In *Nutritional and Health Aspects of Food in Western Europe* (pp. 85-108). Academic Press.

Gliessman, S. R. (2014). *Agroecology: The Ecology of Sustainable Food Systems, Third Edition* (3rd ed.). CRC Press.

Holmgren, D. (2017). *Permaculture: Principles and Pathways Beyond Sustainability (Revised Edition)* (Revised Edition). Melliodora Publishing.

Jacke, D., & Toensmeier, E. (2005). *Edible Forest Gardens, Vol. 1: Ecological Vision and Theory for Temperate Climate Permaculture*. Chelsea Green Publishing.

Jacke, D., & Toensmeier, E. (2005). *Edible Forest Gardens, Vol. 2: Ecological Design And Practice For Temperate-Climate Permaculture* (Illustrated ed.). Chelsea Green Publishing.

Jenkins, W. (2020) A Ground Up Approach to Designing Diet: Using Modeling to Maximize Nutritional Output in The Droevendaal Food Forest.

Jose, S. (2012). Agroforestry for conserving and enhancing biodiversity. *Agroforest Syst* 85, 1–8. https://doi.org/10.1007/s10457-012-9517-5

Kimmerer, R. W. (2013). *Braiding sweetgrass: Indigenous wisdom, scientific knowledge and the teachings of plants.* Milkweed Editions.

TRY (2021) Functional traits. Retrieved at April 2021, from https://www.try-db.org/TryWeb/Prop023.php

Kitsteiner, J. (2013). Nine Layers of the Edible Forest Garden (Food Forest) | Temperate Climate Permaculture. Retrieved March 2, 2018, from http://tcpermaculture.com/site/2013/05/27/nine-layers-of-the-edible-forest-garden/

Kreitzman, M., Toensmeier, E., Chan, K., Smukler, S., & Ramankutty, N. (2020). Perennial staple crops: yields, distribution, and nutrition in the global food system. *Frontiers in Sustainable Food Systems*, *4*, 216.

Li, Wenhua. Agro-ecological farming systems in China. Paris UNESCO, 2001.

Mackenzie, J., Tan, P. L., Hoverman, S., & Baldwin, C. (2012). The value and limitations of participatory action research methodology. *Journal of hydrology*, *474*, 11-21.

Martin, A., & Isaac, M. (2015). REVIEW: Plant functional traits in agroecosystems: a blueprint for research. Journal Of Applied Ecology, 52(6), 1425-1435

Mollison, B. (1997). *Introduction to Permaculture* (Revised ed.). Ten Speed Pr.

Mollison, B. (1988). *Permaculture: A Designers' Manual.* Tagari Publications.

Nair, P. K. Ramachandran, Viswanath, S., & Lubina, P. A. (2017). Cinderella agroforestry systems. Agroforestry Systems, 91(5), 901–917. https://doi.org/10.1007/s10457-016-9966-3

Nair, P. K.R. (1985). Classification of agroforestry systems. Agroforestry Systems, 3(2), 97–128. https://doi.org/10.1007/BF00122638

Nair, P.K.R. (1993). An Introduction to Agroforestry Kluwer Academic Publishers. Retrieved from http://www.worldagroforestry.org/Units/Library/Books/PDFs/32_An_introduction_to_agroforestry.pdf?n=161

Nair, P.K.R. (2014). Agroforestry: Practices and Systems. In Encyclopedia of Agriculture and Food Systems (pp. 270–282). https://doi.org/10.1016/B978-0-444-52512-3.00021-8

Olff, H., Vera, F. W., Bokdam, J., Bakker, E. S., Gleichman, J. M., De Maeyer, K., & Smit, R. (1999). Shifting mosaics in grazed woodlands driven by the alternation of plant facilitation and competition. Plant biology, 1(2), 127-137.

Pain, R., & Francis, P. (2003). Reflections on participatory research. *Area*, *35*(1), 46-54.

Pilgrim, E. S., Osborne, J., & Winter, M. (2018). Evaluating the multiple benefits of multi-layered agroforestry systems. IJAM 7 (2) 4-16 https://doi.org/10.5836/ijam/2018-07-04

Retamales, J. B., & Hancock, J. F. (2018). *Blueberries (Crop Production Science in Horticulture, 27) (2nd ed.).* CABI.

Rigby, J. R., & Porporato, A. (2008). Spring frost risk in a changing climate. *Geophysical Research Letters*, 35(12).

Rodrigo, J. (2000). Spring frosts in deciduous fruit trees—morphological damage and flower hardiness. *Scientia Horticulturae*, 85(3), 155-173.

RVO (2017) Green Deal Voedselbossen.

St. VBNL (2019). Food Forest: Land Use. Retrieved September 26, 2019, from https://d2od87akyl46nm.cloudfront.net/cms/2019/08/5d52db38dd269_INFOGRPAHIC_WEB.jpg

St. VBNL (2020) Food forest locations in the Netherlands. Retrieved May 19, 2020, from .https://www.voedselbosbouw.org/voedselbossen-in-nederland

Toensmeier E, Ferguson R, Mehra M (2020) Perennial vegetables: A neglected resource for biodiversity, carbon sequestration, and nutrition. PLoS ONE 15(7): e0234611. https://doi.org/10.1371/journal.pone.023461

Vera, F. W. (1997). Metaforen voor de wildernis: eik, hazelaar, rund en paard. Vera.

Vezzani, F. M. (2020). Nutrient cycling from leaf litter in multistrata successional agroforestry systems and natural regeneration at Brazilian Atlantic Rainforest Biome. AS, 94(1), 159-171.

Violle, C., Navas, M. L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., & Garnier, E. (2007). Let the concept of trait be functional!. Oikos, 116(5), 882-892.

10 Annex I: Tables

Table 1.1.1: Categorization of agroforestry systems (Nair, 1988).

Categorization of systems (Based on their structure and function)			Grouping of systems (According to their spread and management)	
Structure (Nature and arrangement of components, especially woody ones)		Function (Role and/or output of components, especially woody ones)	Agro-ecological/ environmental adaptability	Socio-economic and management level
Nature of components	Arrangement of components			
Agrisilviculture (crops and trees incl. shrubs/trees and trees) Silvopastoral (pasture/animals and trees) Agrosilvopastoral (crops, pasture/animals and trees) Others (multipurpose tree lots, apiculture with trees, aquaculture with trees, etc.)	*In space* (Spatial) Mixed dense (e.g.: Home garden) Mixed sparce (e.g.: most systems of trees in pastures) Strip (width of strip to be more than one tree) Boundary (trees on edges of plots/fields) *In time* (Temporal) Coincident Concomitant Overlapping Sequential (separate) Interpolated	*Productive function* Food Fodder Fuelwood Other woods Other products *Protective function* Windbreak Shelterbelt Soil conservation Moisture conservation Soil improvement Shade (for crop, animal, and man)	*Systems in/for* Lowland humid tropics Highland humid tropics (above 1,200 m a.s.l; e.g.: Andes, India, Malaysia) Lowland subhumid tropics (e.g.: savanna zone of Africa, Cerrado of South America) Highland subhumid tropics (Tropical highlands) (e.g.: in Kenya, Ethiopia)	*Based on level of technology input* Low input (Marginal) Medium input High input *Based on cost/benefit relations* Commercial Intermediate Subsistence

Table 4.2.1: The overall potential of food forests according to different experts.

Joop Schaminee - Ecologist	I think food forests can have a very large meaning in the small scale, local context. If you are talking about scaling up that is not the thing that we immediately need to do, although I am not against it, but I see its worth in the common involvement. If we meet each other in a food forest and you show me a pawpaw I am happy for 3 days. It is being involved with food on a real, human level and that is entirely different from the supermarket. In our municipality we accept much more from each other because we have a shared vegetable garden and the atmosphere in our neighbourhood is increased. I don't care that I eat a lot of tomatoes or beans for 3 weeks. It is also the realisation that food is not to be taken for granted. I come from a farm and it was not nice if you get a few bad years and have a bad yield, but this realisation is important. It is about enjoying biodiversity, esthetics, awareness and experience.
Sjef van Dongen - Food Forest Designer and Manager	Food forests have to offer a full alternative to conventional agriculture with an as high as possible ecological value, but not the other way around. With that you get that a food forest should be mechanically harvestable, so not only hand labour. Otherwise you cannot extract reasonable amounts of food from a system fast enough. We cannot harvest the whole Netherlands by hand. We simply don't have the people for that.
Frans Bongers - Forest Ecologist	Food forests can be defined as agriculture and forestry. Both think that food forests are 'spielerei'. I think food forests are a serious development that gets attention and is used in all parts of the world, especially the tropics. The question that is always asked is if we can feed the world with food forests. The answer is no. Does it need to do that? No. Can we feed a number of people with it? Yes. Can we make people happy with it? Yes. Can you influence other things we want? Yes. Diverse landscapes? Yes. Improve livelihoods? Yes. Store carbon? Yes. These simplistic models calculating if the world can be fed with food forests I find less and less interesting. It is a good development. Greening the landscape, connecting people to food again and as a bonus providing some food. We need a diversity of agricultural and forestry systems for different functions at specific areas that are suitable for those goals. This also includes systems that are efficient, but not entirely circular. This also includes systems like food forests where there is a lot of complexity and where we have to allow that a lot of mistakes will be made.
Martin Crawford - Food Forest Designer, Manager and Nursery Grower	The optimal agricultural system must store carbon (1st priority) and must include Trees or Perennials or both. In fact if it is storing carbon then many things follow including being tree-based or perennial-based.
Micha Wieland - Food Forest Nursery Grower	I never thought about what would be an optimal agricultural system. I have no idea. With only perennials you won't get there. A diversity of systems. That's a good question. Most optimal is if it is organic, but I don't know if that will happen. I don't know how far we get without chemical fertilizers. Short chain I am for. Circularity in the long term, I don't know if that is possible. The soils in the Netherlands have some buffer through our former land use. I don't know if a production food forest where you harvest so much works on the long term. You should adapt your production targets to your soil. I don't know well how to answer this question.
Max de Corte - Food Forest Designer	What a food forest must be I leave to the owner. I think food forests are in theory able to replace part of agriculture and give a good indication of the direction we have to go in. We have to research what we can get away with without damaging ecology too much.
Dirk van Apeldoorn - Agronomist	I think the future should follow the idea of regenerative agriculture. This is for me highly connected with society, how we create places again that are happy instead of miserable. Food forests can contribute to

	this, for example by creating a place that is pleasant to visit and where the farmer feels appreciated for what he does.
Danae Rozendaal - Ecologist and Agronomist	If a food forest wants to show it can produce food it will need to be compared to other systems and all reasons for and against the establishment of a food forest will need to be quantified, also in pest management and other ecosystem services. I like food forests, but are sceptical on how feasible they will be commercially, partly because of the reaper investment. With a priority on ecosystem services and recreational function I see a lot of potential for food forests.
Maarten Jacobs - Vegetable Nursery Grower	I am perfect for ecological gardening. I find a food forest a very nice system in an ecological context, but in a self-sufficiency, food producing context there are a few things in there that will limit the yield and diversity of food in a way that I find a shame. For instance, soil cultivation is not insurmountable. If it is about a hectare it is not good, but on strips of a few meters wide microorganisms will recolonize the soil from the edges in weeks.
Leo Goudzwaard - Forest Ecologist	Food forests are a nice development, agroforestry a nice inclusion of the Dutch forests. The Dutch forests need to become way more diverse instead of monocultures. That is becoming more evident with the droughts and diseases of the last years.

Table 4.2.2: Identified examples of risk spreading by designing flexibility in food forests.

Species diversity	Species diversity in general increases the chance that one species performs poorly one year the yield of another is high that year.
Dual purpose products	Double doers or dual purpose products are plants that yield plant parts that can be used for multiple products which leaves farmers the opportunity to choose later on.
On-farm propagation	A nursery as part of the food forest so farmers can propagate plants that perform well to replace plants that perform poorly to fill the gap to adapt better to the uncertain, place-based, pioneering circumstances.
Income differentiation	Farmers can have multiple yields from food production or facilitating social and educational activities or from food produced by other food systems on the farm. The latter is something inherently created by establishing a food forest on an existing farm.
Final successional stadia	Interplanting with extra later successional species with long productive lifespans, leaves the option open, if the farmer wants to let the system develop into a closed canopy nut food forest in a few decades or thin them to stay in a mid successional open woodland phase.
Spring frost avoidance	By spreading flowering periods of species and cultivars susceptible to damage by late night frost the risk increases that at least some species will have a yield.

Table 5.1.2: All plant characteristics and values explored in direct relation to varying project scale and functional targets for food production, including the number of experts that explicitly mentioned these interrelatednesses.

Nr.	plant characteristic	large scale commercial	Small: commercial	Small: educational and social	experts
1	Markets and consumption	fresh and processing, mainly indirect chain	mainly fresh, niche and direct chain	mainly fresh, direct chain	7
2	Productive lifespan - start (yield)	late harder to fit in business model	late harder to fit in business model	all	7
3	Suitable harvesting methods	mainly mechanical	mainly hand or simple tool	hand	6
4	Culinary appreciation	Good	extraordinary	extraordinary, exotic, stimulating all senses	5
5	Existing and predicted market demand processed	l to grow, avoid competition with bul			5
6	Processability	mainly high	variable	all, also plants unfit for commercial processing	4
7	Edible plant part	flowers hard, leaves if processed directly after harvest, market demand for nuts is growing	all, incl. leaves for direct fresh consumption	all	4
8	Harvest uniformity	High	mainly high	all	4
9	Storability (natural)	High	variable	all	4
10	Existing and predicted market demand fresh	l to grow, avoid competition with bul			4
11	Productivity (peak)	High	mainly high	all	4
12	Harvesting period - start	spread or concentrate	mainly spread	mainly spread	4
13	Staying on plant after ripening	mainly yes	mainly yes		3

14	Harvesting location of edible part	fruit, preferably elbow height with hand harvest	eferably elbow height with hand		2
15	Nutritional value - relatively high	yes, market is growing	yes, market is growing	yes, for telling the narrative	2
16	Shade tolerance (productivity)	important for understory	important for understory		2
17	Productive lifespan - end (age)	general design consideration			2
18	Frost vulnerability (flowers)	Resistant			2
19	Frost vulnerability (whole plant)	very resistant			2
20	Leafing out	Late			2
21	Crown diameter - full grown	general design consideration			2
22	Height - full grown (age)	general design consideration			2
23	Suitable rootstocks	Vigorous			2
24	Familiarity Dutch consumer	mainly familiar	both	unfamiliar	2
25	Competitive strength	High	mainly high		1
26	Edible plant part size	mainly large	variable	all	1
27	Layer	herb layer harder to fit in	herb layer easier to fit in	all	1
28	Pests and diseases of note	Few			1
29	Pest and disease susceptibility	Resistant			1
30	Optimal distance for cross pollination - max	general design consideration			1
31	Compatible fg / spp / cv	general design consideration			1
32	Plant reproductive fertility	general design consideration			1
33	Crown diameter - age 10	general design consideration			1
34	Height - age 10	general design consideration			1
35	Height - full grown	general design consideration			1
36	Prize	High	high	all	1
37	Transportability	High			1
38	Harvest efficiency (hand/simple tool)	High	mainly high	all	1
39	Easily removed from plant	Yes			1
40	Vulnerability during harvest	No			1
41	Available processing infrastructure	Present			1
42	Harvesting period - end	general design consideration			1
43	Harvesting period - length	general design consideration			1
44	Flowering period - start	general design consideration			1
45	Flowering period - length	general design consideration			1
46	Yield consistency	High			1
47	Root inundation tolerance	general design consideration			1
48	Flowering period - end	general design consideration			1
49	Soil salinity tolerance	general design consideration			1
50	Soil acidity tolerance	general design consideration			1
51	Soil moisture tolerance	general design consideration			1
52	Soil texture tolerance	general design consideration			1
53	Wind stress resistance	general design consideration			1
54	Fruit size, on cv level	Large			1
55	Fruit weight, on cv level	High			1
56	Price fresh product market	High			1
57	Price unprocessed	High			1
58	Price product for processing market	High			1
59	Year of maximum size	general design consideration			1
60	Productive - period	general design consideration			1

Table 5.1.3: Promising plant species identified through their plant characteristic values in relation to different functional targets and project scales, with yellow cells indicating conflicting expert opinions and empty cells indicating absence of data.

Nr.	plant species / plant part group	large scale commercial	small		conflict
			commercial	educational and social	
1	Actinidia arguta		x		

2	Actinidia chinensis		x		
3	Allium ursinum		x		
3	Amelanchier alnifolia		x	x	yes
4	Aralia cordata		x		
6	Aronia spp	x		x	
7	Asimina triloba		x	x	yes
8	Asparagus officinalis	x	x		yes
9	Brassica oleracea		x		
10	Castanea sativa (x)	x			
11	Corylus avellana	x	x		
12	Diospyros spp	x	x		
13	Elaeagnus multiflora	x	x	x	
14	Elaeagnus umbellata	x	x	x	
15	Ficus carica	x	x		
16	Fragaria spp		x	x	
17	Hemerocallis spp		x	x	
18	Hippophae rhamnoides	x		x	
19	Hosta spp			x	
20	Juglans ailantifolia		x	x	
21	Juglans cinerea		x	x	yes
22	Juglans nigra		x	x	yes
23	Juglans regia	x	x	x	yes
24	Leycesteria formosa			x	
25	Lonicera caerulea	x			
26	Malus domestica	x			
27	Matteuccia struthiopteris		x		
28	Phyllostachys spp		x		
29	Pinus koraiensis		x	x	
30	Pinus spp		x		
31	Polygonatum biflorum		x		
32	Prunus armeniaca	x	x	x	yes
33	Prunus avium	x			yes
34	Prunus domestica (x)	x			
35	Prunus persica	x			yes
36	Pyrus communis	x			
37	Pyrus pyrifolia	x	x		
38	Rheum x cultorum	x	x		
39	Ribes nigrum	x			
40	Ribes uva-crispa	x	x	x	yes
41	Ribes rubrum	x	x		
42	Rubus idaeus	x	x		yes
43	Schisandra chinensis		x		
44	Toona sinensis		x	x	
45	Vaccinium corymbosum	x	x	x	

46	Viburnum lentago			x	
47	Zingiber mioga		x		
	herbs	x	x	x	yes
	tubers	x	x	x	yes
	small fruit			x	
	nuts	x	x	x	yes
	vegetables	x	x	x	yes

Table 5.3.1: Overview of 1) all explored relevant plant characteristics concerning succession in a food forest context (grouped by selected and non-selected), 2) how the values of each plant characteristic change in different successional stadia and 3) how many experts mentioned each plant characteristic and species as relevant (with a distinction made between academic ecologists and practitioners).

Successional stadium	**early**	**mid**	**late**	**Total**	**Eco**	**Prac**
Plant characteristic						
Competitive strength	high			3	1	3
Crown density				3	1	2
Crown diameter - full grown				3	1	3
Dispersion	self-sows freely, spreading		self-sows freely	3	1	2
Edible plant part		fruit	nut, vegetable	3	1	2
Frost vulnerability (whole plant)	resistant		resistant - vulnerable	1	1	1
Height - full grown				4	3	2
Layer	diversity	diversity	diversity	9	3	7
leaf composition	mainly acquisitive	diversity	diversity	3	2	1
Life span	mainly short	diversity	diversity	4	3	1
Light preference	full sun	diversity	diversity	3	2	1
Productive life span - length (age)	mainly short		diversity	1		1
Relative growth rate	mainly fast		diversity	3	3	
Rooting depth	mainly deep		diversity	1	1	
Shade tolerance (growth)	full sun		fairly deep - deep	5	2	3
Shade tolerance (productivity)	full sun		fairly deep - deep	9	4	6
Soil acidity (tolerance)	debatable		debatable	1	1	
Soil compaction tolerance	tolerant		sensitive	1	1	1
Soil fertility (tolerance)	poor		rich	3	2	2
Soil moisture (tolerance)	tolerance to extremes		moist	3	3	1
Successional status	mainly pioneer	mainly mid	mainly late	6	3	4
Wind stress resistance (growth)	resistant	resistant - medium	diversity	3	2	2
Non-selected plant characteristics						
Browsing tolerance	high			1	1	1
leaf biomass				1		1
Leaf decomposition rate	fast			3	2	1
Leaf dry matter				1	1	
leaf fibers				1	1	
Leaf life span	diverse		diverse	1	1	
Leaf lignin	low		high	1	1	
Leaf nitrogen	high			2	2	

Leaf photosynthetic rate	high			1	1	
Leaf respiration rate	high			1	1	
Leaf size				1	1	
Mortality rate	high		low	1	1	
Mycorrhiza type	diverse		diverse	3	1	2
Mycorrhizal occupation	diverse		diverse	3	1	2
Root decomposition rate	high		low	1	1	
Root biomass	high			1	1	
Root growth rate	fast		slow	1	1	
Resprouting	yes			1	1	
Specific leaf area	diversity			2	2	
Vegetation strategy	other axis	other axis	other axis	1	1	
Vegetative propagation	yes			1	1	
Wind stress resistance (productivity)	high			1		1
Wood decomposition rate	fast		slow	1	1	
Wood density	low		high	1	1	

Table 5.3.2: Overview of promising food forest species (*and groups*) during early, mid and late succession.

Successional stadium	**early**	**mid**	**late**
Plant species			
1	Arctium lappa	Aronia spp	Allium ursinum
2	Armoracia rusticana	Prunus avium	Aralia cordata
3	Aronia spp	Tilia cordata	Castanea sativa (x)
4	Heracleum spp	Urtica dioica	Chaenomeles cathayensis
5	Hippophae rhamnoides	*Most fruits*	Chaenomeles japonica
6	Lonicera caerulea		Hosta spp
7	Lycium barbarum		Juglans ailantifolia
8	Rosa rugosa		Juglans cinerea
9	Rumex acetosa		Juglans nigra
10	Rumex acetosella		Juglans regia
11	Stellaria media		Matteuccia struthiopteris
12			Pinus koraiensis
13			Polygonatum
14			Quercus robur
15			Tilia cordata
16			Toona sinensis
17			Zingiber mioga

Table 5.3.3: Overview of management succession for guiding, accelerating or setting back succession during the early, mid and late stadia (main=m, additional and circumstantial=a).

Successional stadium	**early**	**mid**	**late**
Management practices			
1	Planting (m)	Planting (m)	Planting (a)
2	Thinning / taking out plants (m)	Thinning / taking out plants (m)	Thinning / taking out plants (m)
3	Harvesting (a)	Harvesting (m)	Harvesting (m)

4	-	Pruning (a)	-
5	Breaking open and turning grass root mats (a)	-	-

Table 5.5.3: The 20 promising species with green edible parts with the highest expert score (0 can refer to species that were freely interchangeable with others or experts were not sure to value a species among the species top 100 or not).

Species reference	sum	Aalbrecht	Barstow	De Corte	Crawford	van Dongen	van Eck	Goudzwaard	Jacke & Toensmeier	D. Jacobs	M. Jacobs	Schaminee	van der Staak	Wieland
Tilia cordata	7	1			1		1	1			1	1		1
Allium ursinum	6	1	1	1	1		1				1			
Hemerocallis lilioasphodelus	6	1	0	1	1		1		1		1			
Hosta sieboldiana	6	1	1	1	1		1				1			
Phyllostachys vivax	6	1		1	1		1				1		1	
Urtica dioica	5	1	1				0		1		1		1	
Toona sinensis	6	1			1		1				1		1	1
Aralia cordata	6	0	1	1			1				1		1	1
Matteuccia struthiopteris	5	1	1	1	1				1		0			
Rheum x cultorum	5	0	0		1	1	1		1		1			
Zingiber mioga	5	1		1			1				1			1
Allium ampeloprasum	4	1	1		1		0				1			
Allium tuberosum	4	1	0		1		0		1		1			
Asparagus officinalis	4	-1	0	1		1	0		1	1	1			
Chenopodium bonus-henricus	4	1	0		1				1		1			
Crambe maritima	4	1	0						1	1	1			
Mentha suaveolens	4	1		0	1		1		1		0			
Myrrhis odorata	4	1	0		1				1		1			
Taraxacum officinale	4	1	1						1		1			
Rumex acetosa	4	1			1				1		1			
Allium fistulosum	3	1	0		1		0		1		0			
Caragana arborescens	3	1			1		0		1					
Humulus lupulus	3	1	1		1						0			
Melissa officinalis	3	1			1		0		1		0			
Polygonatum biflorum	3	1		1	1				1					-1
Viola odorata	3	1			1				1					
Claytonia sibirica	3	-1			1		1		1		1			

Table 5.7.4: The 80 selected key plant characteristics including standardized classification and characteristic group.

TID	Plant characteristic	Classification						Characteristic group
1	**Latin species name**							Taxonomy
2	**Cultivar name**							Taxonomy
3	**Rootstock name**							Taxonomy
4	**Edible plant part**	bark	bulbs	flowers	fruits	growing shoots		Harvest (what, where, when, how)
		gum	leaves	leaf stalks	nuts	roots		

		sap	seedpods	seeds	spear shoots	stems		
		tubers	unopened flowerheads	all	none			
5	**Toxic part or relative**	plant part		Latin species name		none		Harvest (what, where, when, how)
6	**Layer**	canopy	low tree / large shrub	low shrub	ground cover	vertical		Community status
7	**Successional status**	early		mid		late		Community status
8	**Competitive strength**	very good	often needs care first years	needs care occasionally	needs some care yearly	bad		Community status
9	**Natural occurrence / domestication**			NESW + Continent				Community status
10	**Native**	native		archaeophyte		exotic		Community status
11	**Height - full grown**			meter				Morphology and development
12	**Height - age 10**			meter				Morphology and development
13	**Height - full grown (age)**			year				Morphology and development
14	**Crown density**	open		half-open		closed		Morphology and development
15	**Crown diameter - full grown**			meter				Morphology and development
16	**Crown diameter - age 10**			meter				Morphology and development
17	**Rooting depth**	deep		medium	shallow	very shallow		Morphology and development
18	**Root pattern**	tap	heart	fibrous				Morphology and development
19	**Life span**	very short	short	medium	long	very long		Morphology and development
20	**Dispersion**	no spreader	slow spreader	fast spreader	self-sows freely	invasive potential		Morphology and development
21	**Resprouting**	many suckers		resprouting after cutting		no		Morphology and development
22	**Relative growth rate**	very slow	slow	medium	fast	very fast		Morphology and development
23	**Leaf composition**	very rich	rich	medium	poor	very poor		Morphology and development
		januari	februari	march	april	may		
24	**Leafing out**	semi-evergreen	evergreen					Morphology and development
		september	october	november	december	evergreen		
25	**Leaf fall**	semi-evergreen						Morphology and development
26	**Flowering period - peak**			start/half/end + month				Reproduction
27	**Flowering period - length**	few days	1 week	2 weeks	1 month	multiple months		Reproduction
28	**Pollination vector**	wind				insects		Reproduction
29	**Plant reproductive fertility**	self-fertile (sf)	sf, higher yield with cross pollination	partly self-fertile		self sterile		Reproduction
30	**Optimal distance for cross pollination - max**	< 25 meter	50 - 100 meter		100 - 200 meter	> 200 meter		Reproduction
31	**Frost vulnerability (whole plant)**	very resistant	resistant	medium	vulnerable	very vulnerable		Required abiotic growth conditions
32	**Spring frost vulnerability (flowers)**	very resistant	resistant	medium	vulnerable	very vulnerable		Required abiotic growth conditions
33	**Light preference**	full sun	light shade	partial shade	fairly deep shade	deep shade		Required abiotic growth conditions
34	**Shade tolerance (growth)**	full sun	light shade	partial shade	fairly deep shade	deep shade		Required abiotic growth conditions
35	**Shade tolerance (productivity)**	full sun	light shade	partial shade	fairly deep shade	deep shade		Required abiotic growth conditions

36	**Wind stress resistance (growth)**	very resistant	resistant	medium	vulnerable	very vulnerable		Required abiotic growth conditions
37	**Soil moisture (preference)**	inundation	wet	moist	dry	drought	all	Required abiotic growth conditions
38	**Soil moisture (tolerance)**	inundation	wet	moist	dry	drought	all	Required abiotic growth conditions
39	**Soil acidity (preference)**	very acidic	acidic	neutral	alkaline	very alkaline	all	Required abiotic growth conditions
40	**Soil acidity (tolerance)**	very acidic	acidic	neutral to slightly acidic	alkaline	very alkaline	all	Required abiotic growth conditions
41	**Soil fertility (preference)**	very rich	rich	medium	poor	very poor	all	Required abiotic growth conditions
42	**Soil fertility (tolerance)**	very rich	rich	medium	poor	very poor	all	Required abiotic growth conditions
43	**Soil texture (preference)**	sand	loam	light clay	heavy clay	peat	all	Required abiotic growth conditions
44	**Soil texture (tolerance)**	sand	loam	light clay	heavy clay	peat	all	Required abiotic growth conditions
45	**Soil compaction tolerance**	tolerant		medium		intolerant		Required abiotic growth conditions
46	**Soil salinity (tolerance)**	very tolerant	tolerant		sensitive	very sensitive		Required abiotic growth conditions
47	**Root depth - min**	deep	medium	shallow	very shallow			Required abiotic growth conditions
48	**Nitrogen fixation**	yes				no		Inter-trophic relationships
49	**Pest and disease susceptibility**	very resistant	resistant	medium	vulnerable	very vulnerable		Inter-trophic relationships
50	**Pests and diseases of note**					none of note		Inter-trophic relationships
51	**Mycorrhiza type**	arbuscular	ecto	ericoid		none		Inter-trophic relationships
52	**Productive lifespan - start (age)**			year				Harvest (what, where, when, how)
53	**Productive lifespan - peak (age)**			year				Harvest (what, where, when, how)
54	**Productive lifespan - end (age)**			year				Harvest (what, where, when, how)
55	**Productivity - start**			kilogram				Harvest (what, where, when, how)
56	**Productivity - peak**			kilogram				Harvest (what, where, when, how)
57	**Yield consistency / stability**	very consistent	fairly consistent	tendency to biennial	often biennial	very inconsistent		Harvest (what, where, when, how)
58	**Harvest location**	belowground	ground - low	around elbow-height	high but within arm's reach	above arm's reach		Harvest (what, where, when, how)
59	**Harvest period - start**			start/half/end + month				Harvest (what, where, when, how)
60	**Harvest period - length**	day - few days	week	few weeks	month	multiple months		Harvest (what, where, when, how)
61	**Harvest period - uniformity**	high		medium		low		Harvest (what, where, when, how)
62	**Harvest period - recognition**	easy, color	easy, drop	easy, taste	easy, hardness	easy, other		Harvest (what, where, when, how)
		hard, color	hard, drop	hard, taste	hard, hardness	hard, no sign		
63	**Harvest methods**	hand		simple tool		mechanical		Harvest (what, where, when, how)
64	**Harvest efficiency (hand/simple tool)**			kilogram / hour				Harvest (what, where, when, how)
65	**Harvest efficiency (mechanical)**	easy		kilogram / hour				Harvest (what, where, when, how)
66	**Ease of removal**	easy				hard		Harvest (what, where, when, how)
67	**Vulnerability to damage**	very resistant	resistant	medium	vulnerable	very vulnerable		Harvest (what, where, when, how)
68	**Staying on plant after ripening**	long		short		no		Harvest (what, where, when, how)
69	**Thorns**	many or large		few or small		no		Harvest (what, where, when, how)
70	**Edible plant part size**	very small	small	medium	large	very large		Harvest (what, where, when, how)
71	**Post harvest ripening**	yes				no		Post-harvest (what, where, when, how)

72	**Processability**	easy		medium		difficult		Post-harvest (what, where, when, how)
73	**Storability - natural**	day	week	weeks	months	year		Post-harvest (what, where, when, how)
74	**Culinary appreciation**			text + grade (1-10)				Post-harvest (what, where, when, how)
75	**Nutritional value - relatively high**	protein	fats	minerals	vitamins	etc.		Post-harvest (what, where, when, how)
76	**Markets and consumption**	niche	bulk		fresh	processed		Post-harvest (what, where, when, how)
77	**Future demand**	none	yes, stays saturated		none, predicted to grow	yes, predicted to grow		Post-harvest (what, where, when, how)
		softwood cuttings	hardwood cuttings	root cuttings	suckers	seed (non dormant)		
78	**Artificial propagation method**	seed (stratification)	seed (scarification)	grafting	layering			Reproduction
79	**Availability planting material**	abundance in NL	limited in NL	elsewhere in Europe	outside of Europe	not known		Reproduction
80	**Availability planting material (nurseries)**							Reproduction

Table 5.7.2: Additionally explored selection criteria exemplified by some of the most relevant functional plant characteristics.

	n related design criteria	**n positive experts**	**Complementary inter-species variation**	**Context dependency**	**Compound variable**	**Strong indicative variable**	**Applicable, measurable, quantifiable**
Harvest period	5		x	x, temperature	x		a, m, q
Flowering period	2		x	x, temperature	x	x	a, m, q
Edible plant part	4		x	x		x	a, m, q
Nutritional value	2		x	x	x, fats, carbs, proteins, vitamins, etc.	x	a, m (but hard), q
Height	6		x	x		x	a, m, q
Root structure				x	x		A
Root depth			x	x			A
Crown diameter				x			a, m, q
Crown density					x, leaf biomass and thickness, branch biomass, etc.		a, m, q
Successional status			x	x	x, leaf economic traits	x, required growth conditions	A
Leaf economics			x		x, contents, morphology, etc.		a, m (but hard)
Culinary appreciation	4				x, taste, texture, aroma, etc.		a, m (but hard)
Growth rate				x, wind, temperature, soil moisture, soil texture, etc.			a, m, q (but hard)

Productivity (peak)				x, light, wind, temperature, soil moisture, soil texture, etc.			a, m (but lot of work), q
Soil moisture tolerance				x, soil texture, wind	x, stomatal closure, root depth, etc.		A
Soil nutrients				x, soil texture			A
Pest and diseases				x, wind, habitat fragmentation, urban land use			A
harvest efficiency				x, spatial vegetation arrangement	x, thorns, vulnerability, size and location plant part, etc.		a, m (but lot of work), q
Leaf composition					x, nitrogen, fibers, tannins, etc.		A
Markets and consumption					x, fresh vs processed, niche vs bulk, expected demand, etc.		A
Invasiveness				X	x		A
Shade tolerance							A

Table 5.7.5: Promising food forest species that were deselected during the final selection round.

1	Achillea millefolium
2	Amelanchier lamarckii
3	Aralia elata
4	Arctium lappa
5	Aronia arbutifolia
6	Carya ovata
7	Cochlearia officinalis
8	Foeniculum vulgare
9	Levisticum officinale
10	Origanum vulgare
11	Prunus persica
12	Prunus tomentosa
13	Rumex scutatus
14	Salix alba
15	Salvia officinalis
16	Schisandra chinensis
17	Sedum telephium
18	Sorbus aucuparia
19	Vaccinium macrocarpon

11 Annex II: Figures

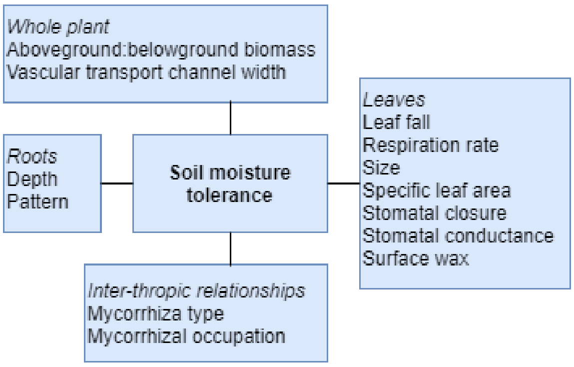


Figure 5.2.2: Identified functional plant characteristics contributing to soil moisture tolerance

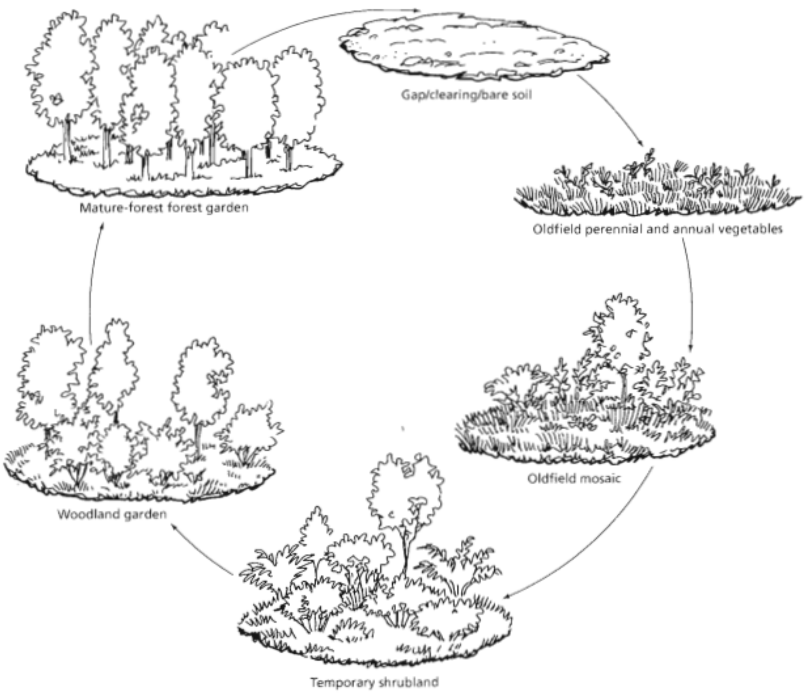


Figure x: A possible cyclical successional pattern for one patch in a food forest. Such a successional round can be the foundation of a shifting-mosaic food forest.

Figure 7.2.2: A shifting-mosaic food forest combines all stages of a successional cycle like that shown in figure x at once, with different patches at different stages, all cycling through in concert (Jacke and Toensmeier, 2005).

12 Annex III: Definitions of keywords

Box 1.2.2: List of definitions of keywords that emerged throughout this thesis research.

Agricultural systems, practices and scientific fields
Agroecology: The ecology of food systems (Anderson et. al, 2020)
Agroforestry: Agriculture containing trees, often in combination with annual crops or animals (ICRAF, 2020)
Agronomy: The theoretical physics of crop production (Anderson et. al, 2020).
Cyclical shifting-mosaic: A system combining multiple stages of a successional cycle at once, with different patches at different stages, all cycling through in concert (Jacke and Toensmeier 2005).
Food forest: A land use system mimicking the structure and functioning of a natural forest, with plants (in)directly useful for people, that are most of the time edible (Crawford, 2010).
Horticulture: Agriculture generally dealing with fruits, vegetables, and ornamentals (Crawford, 2010).
Grafting: Placing a portion of one plant (bud or scion) into or on a stem, root, or branch of another (stock) in a way that a union is formed and the partners continue to grow (Crawford, 2010).
Multi-strata: A perennial cropping system featuring multiple vertical vegetation layers (Young, 2017).
Permaculture: A philosophy and design method for living with nature. (Mollison, 1988).
Successional agroforestry: A complex, multi-strata system composed of species assemblages that resemble native forest structures and mimic mechanisms of natural succession (Young, 2017).

Other scientific fields
Decision-making: Identifying, considering and choosing between alternative courses of action (Bennet and Bennet, 2008)
Functional ecology: An approach to understanding or predicting the causes and consequences of biotic or abiotic species interactions, as a function of the physiological, morphological, chemical or phenological characteristics of organisms (Martin and Isaac, 2015).

Ecological and biological mechanisms and practices
Biomimicry: Learning from an imitating natural features and processes for alternative, often human, purposes (Young, 2017)
Ontogeny: The developmental history of an organism within its own lifetime.
Phenology: Periodic events of seasonal and interannual variations in climate influencing biological life cycles (Rigby and Porporato, 2008).
Succession: The consecutive sequencing of plant communities (Vera, 1979).

Plant properties
Cultivar: A variety of a species that is bred and propagated for desirable functional plant characteristics (Jacke and Toensmeier, 2005).
Effect trait: plant attributes that reflects the effects of a plant on environmental conditions (Violle et al., 2007).
Functional trait: morpho-physio-phenological trait which impact fitness of an organism indirectly via the effects on growth, reproduction and survival, the three components of individual performance (Violle et al., 2007).
Perennial crop: woody and herbaceous crops that are grown for multiple years without replacement (Kreitzman et al., 2020).
Response trait: plant attributes that vary in response to changes in the environmental conditions (Violle et al., 2007).
Rootstock: The base and root portion of grafted plants (Crawford, 2010).

Research methodologies
Integrative research: research in the context of complexity, with an action imperative (Van Kerkhoff, 2017).
Participatory action research: a participatory, democratic practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview (Burgess, 2017).

Other
Open-source: Complete traceability and transparency of the source material of information (Hennekens, 2021).

13 Annex IV: Supplementary information on methods

Tab. 1.2.1 Examples regarding the iterative development of the thesis research.

Topic	Iterative process
Sources for species identification	Species identified during the interviews fell within the scope of the selection process. Books and databases mainly supplemented the selection making process of the species and benchmark statements of experts. However, the books of Stephan Bartstow and Dave Jacke and Eric Toensmeier were also used for identifying species because of the author's extraordinary knowledge on general food forest plants and perennial vegetables respectively.
Management practices	Since food forests generally envision low labour cultivation, management practices besides harvesting were identified and incorporated in the framework, but not extensively explored and consolidated.
Expert source selection	A starting list of experts was composed, but results from the data collection itself also had a feedback on which experts were interviewed next. This was for deepening knowledge on a specific aspect, for example by including a root ecologist, or adding experts with complementary expertise to the interviewed experts. For example, by adding a nursery grower specialized in vegetables and adding a designer focussing on large scale commercial projects with mechanical harvesting. The participating experts were involved in the selection of the follow up participants through their recommendations for future research.
(sub) research questions and interview questions	The main research question and sub-questions developed. Harvesting aspects and future environmental conditions were included in the research after the first interview and added as criteria in sub-research question 1. The interview questions developed, were specified to specific expert knowledge or answers that provoked intuitive follow-up questions.
Plant characteristics about inter-trophic relationships	Plant characteristics representing biotic interactions of plants with organisms from other trophic levels were initially left completely out of the scope of the thesis research for the intricate feedback loops and species specific nature of associated biodiversity. However, during the interview direct interactions, namely with pests and diseases were mentioned by experts so often that these subjects are not entirely excluded from the thesis research and a few plant characteristics are proposed for the database. For the decision-making framework, a cell is included for thinking about the floral and faunal presence in the food forest and the surrounding area, without deepening on the subject.
Plannological, juridical, social and educational design aspects	Despite a regenerative food forest design requiring an understanding of social, educational, spiritual, juridical and plannological aspects the emphasis for discovering the elements of the plant database and decision-making framework remained on ecology as a root perspective, followed by agronomic aspects. However, identified elements identified in relation to all aspects were discussed whenever necessary. For example, during the first criteria, functional targets, educational and social targets are also discussed, while the corresponding plant characteristics and species were purposefully not extensively discussed during follow up questions. Furthermore, plannological and juridical aspects were not extensively discussed as criteria for the database, but during a design process, plannological and juridical constraints are a relevant design aspect for actual realisation of food forests. Therefore, as a cell in a larger web, plannological and juridical constraints are briefly described.
Technical and visual presentation of database elements	Technical issues for operationalizing the database and decision-making framework fell outside of the scope of the thesis. Technical challenges for the development of the database are tackled by an ICT-company partnered with St. VBNL. However, experts were circumstantially asked on preferred data visualization of the plant characteristics.

Table 2.1.1: Expert list with corresponding affiliation, type of knowledge, expert group, specific expertise consulted during the interview and participation phase (P = phase) and topic (D=database, F=framework).

ID	Name	Affiliation	Type of knowledge	Expert group	Specific expertises	P1		P2	
						D	F	D	F
1	Adam Martin	Department of Physical and Environmental Sciences Toronto University	Academic	Ecologist	Functional agroecology	x			
2	Andrew Dawson	Researcher Agroecology and Business Economy Wageningen University	Academic	Agronomist, Business economist	Agroforestry	x			
3	Arie Bruin	Tree Nursery 'De Acht Plagen'	Personal	Nursery grower	Nuts			x	
4	Bastiaan Rooduijn	National Monitoring Program Food Forests, food forest 'Groenlandje'	Academic & personal	Designer, Ecologist, Farmer		x	x		
5	Danaë Rozendaal	Lecturer Plant Production Systems Wageningen University	Academic	Ecologist	Forest ecology, agroforestry	x			
6	Dimitri Jacobs	Fruit nursery 'De Zoetewei'	Personal	Nursery grower	Fruits and tubers	x			

7	Dirk van Apeldoorn	Lecturer and researcher Farming Systems Ecology Wageningen University	Academic	Agronomist	Agroecology, research by design	x			
8	Emile van der Staak	Chef Restaurant 'De Nieuwe Winkel'	Personal	Chef	Food forest products for the special niche market			x	
9	Evelyn Derksen	Designer Stichting Voedselbosbouw Nederland	Personal	Designer	Landscape architecture	x	x		
10	Frans Bongers	Professor Forest Ecology and Management Wageningen University	Academic & personal	Ecologist	Forest ecology, management and economics, agroforestry	x			
11	Fransjan de Waard	Co-founder Stichting Voedselbosbouw Nederland, De Waard Eetbaar Landschap	Personal	Designer	Permaculture, nature education				x
12	Gertjan van Hofstede	Professor Information Technology Wageningen University	Academic & personal	Data scientist	Database design, research by design	x			
13	Jelle Fekkes	Designer 'Fekkes Landschapsarchitectuur'	Personal	Designer	Landscape architecture				x
14	Joop Schaminée	Professor Plant Ecology & Nature Conservation Wageningen University, Westhoff Radboud University Nijmegen, Landelijke Vegetatiedatabank	Academic	Data scientist, Ecologist	Auto-ecology	x			
15	Kees van Veluw	Lecturer Farming Systems Ecology Wageningen University	Academic & personal	Agronomist, Designer	Organic agriculture, agricultural education				x
16	Leo Goudzwaard	Researcher Forest Ecology and Management	Academic & personal	Ecologist	Forest ecology, forest management			x	
17	Liesje Mommers	Professor Plant Ecology & Nature Conservation Wageningen University	Academic	Ecologist	Functional root ecology	x			
18	Maarten Jacobs	Special and forgotten vegetables nursery 'Den Oude Kastanje'	Personal	Nursery grower	Special and forgotten vegetables			x	
19	Martin Crawford	Founder Agroforestry Research Trust, Shumacher Food Forest	Academic & personal	Designer, Farmer, Nursery grower		x	x		
20	Martijn Aalbrecht	Food forest 'Strootman', Designer 'De Voedselboss'	Personal	Designer, Farmer				x	
21	Max de Corte	Designer 'Moestuinman', Designer 'Ondergrond'	Personal	Designer		x	x		
22	Micha Wieland	Food forest nursery 'Arborealis'	Personal	Nursery grower	Food forest plants	x			
23	Sjef van Dongen	Nursery 'Fruitz for Life', Designer 'Fruitz for Life', Food forest 'Fruithof de Brand'	Personal	Designer, Farmer, Nursery grower	Permaculture				x
24	Stephan Hennekens	Researcher Plant Ecology & Nature Conservation Wageningen University, Landelijke Vegetatiedatabank	Academic	Data scientist		x			
25	Stijn Heijs	Manager Stichting Voedselbosbouw Nederland, Food forest 'In 't Holt'	Personal	Business economist	Food forest product chains	x			
26	Wouter van Eck	Co-founder Stichting Voedselbosbouw Nederland, Food forest 'Ketelbroek'	Personal	Designer, Farmer		x			

Box 2.1.2. General survey format used during the first phase of data collection.

SURVEY MSC THESIS: SUCCESSION OF FOOD FORESTS

The aim of this MSc thesis research is to create an evidence-based, open-source plant database and decision-making framework for the ecological design of food forests in the Netherlands. This survey is meant to identify the most relevant traits, species, cultivars, rootstocks, functional targets, successional gradients, and other elements that need to be included in the plant database and decision-making framework, the relation between these elements and an appropriate structure for the database and decision-making framework. This objective is articulated into the following sub-research questions:

RQ1

What are key functional plant characteristics for the design of food forests in the Netherlands based on the most important 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) management practices and 6) project scale?*

RQ2
What are 100 promising plant species, including their cultivars and rootstocks, for food forests in the Netherlands based on the identified functional characteristics?

RQ3
What are key elements and steps in the design process of food forests in the Netherlands?

RQ4
What is an appropriate structure of the interlinked plant-database and decision-making framework for integrating the identified key elements?

*These are hereafter referred to as the 'selection criteria'.

SURVEY TOPICS

I. SELECTION CRITERIA → CHARACTERISTICS → SPECIES → CULTIVARS & ROOTSTOCKS
II. VEGETATION ARRANGEMENT (SPATIAL & TEMPORAL) → CHARACTERISTICS → SPECIES
III. SPECIES ←→ CULTIVARS & ROOTSTOCKS → CHARACTERISTICS & SELECTION CRITERIA
IV. BRIDGING PRACTICE AND SCIENCE
V. DECISION-FRAMEWORK & DATABASE STRUCTURE
VI. FUTURE RESEARCH
VII. IDEOLOGY AND VALUES

I. I. SELECTION CRITERIA → CHARACTERISTICS → SPECIES

Each of these questions is followed by the questions; what plant characteristics are relevant based on this criteria and which plant species exemplify this statement.

A. What are key functional targets of edible forest gardens in the Netherlands?
B. What are common current environmental conditions on a national scale that should be considered when designing edible forest gardens in the Netherlands?
C. What are common regional current environmental conditions that should be considered when designing an edible forest garden across the country?
D. What are predicted future environmental conditions that should be considered when designing an edible forest garden in the Netherlands?
E. What are key successional gradients and distinct relevant successional stages for the ecological design of an edible forest garden in the Netherlands?
F. What are common starting successional stages of an edible forest garden in the Netherlands?
G. What are key ontogenetic gradients and distinct relevant ontogenetic stages for the ecological design of an edible forest garden in the Netherlands?
H. What are distinct spatial project sizes of an edible forest garden in the Netherlands?
I. What aspects are important for harvesting an edible forest garden in the Netherlands?
J. What are the different plant parts that can be harvested from an edible forest garden in the Netherlands?
K. What aspects are important for the management practice of planting in an edible forest garden in the Netherlands?
L. What other practices are fundamental to consider for managing an edible forest garden in the Netherlands?
M. Are there criteria lacking for the identification and selection of the key functional plant characteristics for the ecological design of an edible forest garden in the Netherlands?

II. VEGETATION ARRANGEMENT (SPATIAL & TEMPORAL) → CHARACTERISTICS → SPECIES

Each of these questions is followed by the questions; what plant characteristics are relevant based on this criteria and which plant species exemplify this statement.

A. What are important aspects for the design of the vertical layers in edible forest gardens in the Netherlands?
B. What are important aspects for the design of horizontal planting distances between plants of the same species in food forests?
C. What are important aspects for the design of horizontal planting distances between plants of different species in edible forest gardens in the Netherlands?
D. What are important aspects for the design of horizontal planting distances between plants in a hedge in the Netherlands?
E. What are important aspects for considering the time component when designing an edible forest garden in the Netherlands?
    a. In particular, what are important phenological events when designing an edible forest garden in the Netherlands?

III. SPECIES ←→ CULTIVARS & ROOTSTOCKS → CHARACTERISTICS & SELECTION CRITERIA

*Each of the questions with * is followed by the questions; on what reason is this statement based*

A. What are promising plant species for edible forest gardens in the Netherlands?*
    a. Is there a 'competitor' with similar characteristics that could be even more promising?*
    b. Which promising cultivars exist for this species?*
    c. Which promising rootstocks exist for this species?*
B. What are promising cultivars for edible forest gardens in the Netherlands?*
C. What are promising rootstocks for edible forest gardens in the Netherlands?*
    a. With which plant species scion can this rootstock be combined?
D. What are promising species for edible forest gardens in the Netherlands, because of the availability of improved cultivars?
E. What are promising plants species for edible forest gardens in the Netherlands with a climbing habit?
F. What are promising plant species for edible forest gardens in the Netherlands for their below-ground edible plant parts?

IV. BRIDGING PRACTICE AND SCIENCE

A. Where is a clear overlap between functional traits used in functional ecology and plant characteristics used in practice?
B. What are the opportunities and limitations to bridge the gap between functional traits used in functional ecology and plant characteristics used in practice?
    a. How to bridge the gap between the classifications as standardized, quantitative functional traits as opposed to normative, indicative plant characteristics?
    b. How to integrate 'trait-mean values' and 'trait variation' with plant 'preferences' and 'tolerances'
    c. What are appropriate data measurement scales (nominal, ordinal, interval and ratio) for standardizing the identified functional plant characteristics?

d. What are appropriate classes for categorizing the identified functional plant characteristics?

V. DECISION-FRAMEWORK & DATABASE STRUCTURE

C. What are important design steps for creating edible forest gardens in the Netherlands?
D. What can be the final outputs of a design of an edible forest garden in the Netherlands?
E. What would be an appropriate output of a decision-making framework for the design of edible forest gardens in the Netherlands?
F. What key edible forest garden principles need to be reflected in a decision-making framework for the design of edible forest gardens in the Netherlands?
G. How can the time component be integrated in a decision-making framework for the design of edible forest gardens?
H. How can the database be organized?
I. How can the database highlight interdependencies between characteristics?
J. How can the database highlight characteristics that are disproportionately important for a specific species?
K. How can the database be visualized in a non-tiring way?
L. How can the database be structured in a way that searching works efficiently?
M. What should be the metadata of the database?
N. How can data be linked to citations?

VI. FUTURE RESEARCH

A. What databases hold relevant information as input for the design of the plant database and the decision-making framework?
B. What books hold relevant information as input for the design of the plant database and the decision-making framework?
C. What experts can be relevant to ask for their participation in this research?
    a. Are you able and willing to contribute to establishing contact with named experts?
D. What research topic would you suggest for future research (integration with a topic from another discipline or diving deeper into one of the discussed topics)?

VII. IDEOLOGY AND VALUES

A. What is your idea on what an edible forest garden in the Netherlands should encompass?
B. What does an optimal agricultural system look like to you?
C. What does an optimal forestry system look like to you?

Box 2.1.3: Selection procedures for selecting 80 key functional plant characteristics and 100 promising plant species.

A '100 top plant species list' was constructed following two approaches:

1. promising food forest species were identified via the criteria and plant characteristics in the general survey. See the example below.
2. A species list with the 100 most promising species was requested from food forest pioneer Martin Crawford. Later, food forest practitioners were asked to judge both the potential of the individual species on the list for food forests in the Netherlands and whether they would nominate superior alternatives for each species. Moreover, they were asked to assess the list in total on the relative complementarity or presence of what were according to them important plant characteristic values.

<u>Example</u>
Q1D: What are predicted future environmental conditions that should be considered when designing an edible forest garden in the Netherlands?

A: Drought
Q: What plant characteristics are relevant based on this criteria?
A: Drought resistance
Q: *Which plant species exemplify this characteristic?*
A: Ziziphus jujube and Ficus carica

The two parallel approaches in the second phase of the data collection served to:

1. Discuss and collect experiential knowledge on the selected functional plant characteristics for the selected plant species and explore cultivars, rootstocks and their plant characteristics more thoroughly. During this round seven experts participated with backgrounds in ecology (1), design (2), nursery growing (3), farming (2) and gastronomy (1). The nursery growers were explicitly selected for their complementary expertise on edible products. One specializes in nuts, one in vegetables and the last in fruits. These interviews had the aim to:
    - ➢ complete the species and plant characteristic selection process
    - ➢ test the efficiency and effectiveness of the data collection format for filling in the database with practitioners in food forestry and forest ecology. Species from the *Juglans* genus and native trees and large shrubs in the 100 top list were used as a case study.
    - ➢ get more insight in the inter and intra species plant characteristic values for the selected plant species, cultivars, rootstocks and the way rootstocks and grafts interrelate on the selected plant characteristics. For this purpose J*uglans regia* and *Cornus mas* were discussed with multiple experts as case study species. These interviews also aimed to explore whether the same plant characteristics were relevant on species as on cultivar level. *Juglans regia* was discussed with three nursery growers with an expertise in walnuts. The data collected from the interviews was supplemented and cross referenced using the book "How to grow your own nuts" of food forest pioneer Martin Crawford
2. Improve the decision-making framework by evaluating the steps, elements, overall structure, applicability, strengths and weaknesses of the framework with four food forest designers

When asked for promising species, experts were found to also name the genus, subspecies and hybrids instead, this could happen unconsciously or because they were the species within this genus were interchangeable. The scores of these species were allocated to the 'full' species with the highest score during the construction of the 100 top species list. For example, *Phyllostachys* spp was mentioned as promising on the genus level by 4 experts. *Phyllostachys vivax* was explicitly mentioned by 2 experts, while *Phyllostachys bissetii* was only mentioned by 1 expert. Therefore, *Phyllostchys vivax* received a total score of 6 and made it in the 100 top list.

86 species received a positive score of 3 or higher, meaning that netto 3 or more experts were in favour of placing the food forest plant in the 100 toppers list. 33 species had a netto score of 2 experts. 13 species were selected from those 33 to complete the 100 top species list. This selection was based on balancing the overall distribution of edible plant parts of the 86 species and identified desirable values for a set of relevant plant characteristics. Species with main edible parts other than fruits and leaves were prioritized. Furthermore, drought tolerance, high productivity, high culinary appreciation and system functions were main considerations. For the herb layer this was also competitive strength, easy natural dispersion and shade tolerance (productivity). Additional circumstantial plant characteristic values were high storability, evergreen, high pest and disease resistance, tolerance to poor soil, native origin, high market demand and long productive lifespan. Finally, it was assessed if there were already comparable species in the top 86 or other species with a score of 1 of the same genus. For example, there were multiple *Berberis spp* identified, but none in the top 86, so Berberis koreana was favoured. The other way around, there were already multiple *Carya spp* and *Prunus spp* with comparative or improved qualities of *Carya ovata* and *Prunus persica* in the top 86 so these were declined. The 19 species that did not make the final 100 top species list are found in table x in annex x.

Plant characteristic selection
For the selection of the plant characteristics experts were asked directly if they thought a plant characteristic should be included in the plant database. In addition, the identified selection criteria in box x were applied, although not systematically. For example, plant characteristics were compared and if one was covered sufficiently by another, only one was selected to reduce redundancy. Familiarity to the Dutch consumer was mentioned by 3 experts as a relevant plant characteristic, but was thought to be sufficiently represented by the compound variable Culinary appreciation.

14 Annex V: Development visualization plant database

Fig. 5.7.2. First impression of the potential visualization of the key functional plant characteristics of *Juglans regia* in the open-source database as one of the 100 promising plant species for food forests in the Netherlands (in Dutch).

15 Annex VI: Cultivar case studies

Casus 1: Juglans Regia

"If we are talking about a food forest, or a food forest-like vegetation, you should forget the industrial market and machinal crackability, because you will never get the tonnages that such a company is interested in. So then it is the market for selling the nut directly to the consumer. And then I think that it is interesting that a nut is easy to crack and comes well out of the scale. If from the 40 to 50 cultivars that I harvest I should fish one out of a basket that I like to quickly fill my yoghurt, I go first for Big and Easy, despite not being the most productive, not self-fertile and having quite some walnut blight."

The selected cultivars and plant characteristics are shown in Tab. 5.7.7. The collected relevant functional plant characteristics reflecting particularly relevant intra-species variation for walnut cultivars are discussed below followed by a paragraph on suitable rootstocks and related characteristics.

Table 5.7.7: Functional plant characteristics and cultivars for *Juglans regia*.

Available promising cultivars		**Big and Easy**	**Fernette**	**Fernor**	**Franquette**	**Lange van Lod**	**Nr.22**
Relative growth vigour		N/D	medium	medium	high vigour	low vigour	N/D
Pollination	**self-fertile**	partly self-fertile	partly self-fertile	partly self-fertile	N/D	partly self-fertile	self-fertile (sf)
	pollinator of	Nr.22	Fernor	N/D	Fernette Fernor	N/D	Big and Easy
	pollinated by	Nr.22	Franquette	Fernette Franquette	N/D	N/D	Big and Easy
Frost susceptibility	**whole plant**	N/D	medium	medium	medium	N/D	N/D
	blossom	medium	medium	medium	resistant	N/D	N/D
	leafing out	late (april-late)	late (april-late)	late (april-late)	very late (may - start)	early (april - start)	late (april-late)
Pests and diseases	**general susceptibility**	medium	resistant	resistant	resistant	medium	very resistant
	pests and diseases of note	blight	N/D	N/D	N/D	N/D	none of note
Yield	**harvest period - start**	N/D	october end	october end	october end	september half	october half
	harvest period - uniformity	high	High	high	high	high	low
	productive lifespan - start	average (terminal)	early (lateral)	early (lateral)	N/D	early (lateral) after 3-4	N/D
	productivity - peak	below average (terminal)	high (lateral)	high (lateral)	fairly high (despite terminal)	high (lateral)	fairly high (despite terminal)
Market and consumption	**Suitable markets**	niche	Bulk	bulk	bulk	niche	N/D
		processed	processed	processed	processed	fresh	processed

		fresh					
	Culinary appreciation	large nut, exceptionally easy to crack by hand, kernel neatly removed from scale and pellicle, good taste	large nut	large nut	average to large nut	Dutch cultivar from Steyl, sweet giant nut that comes out of shell in quarters, easy to crack, also consumed fresh in certain cultures	ut, good taste,
Availability planting material (nurseries)		Acht plagen	Acht plagen	Acht plagen	Acht plagen	Acht plagen	Acht plagen
		Smallekamp	Fruitz for Life	Fruitz for Life	Fruitz for Life Smallekamp	Fruitz for Life Smallekamp	Smallekamp

Relative growth vigour

Plant vigour influences the eventual size of the tree. It is of importance for food forest designers to determine planting distances and the amount of plants that can be placed into the food forest. Of the selected cultivars *Lange van Lod* and *Broadview stay* smaller due to relatively low vigour while *Franquette* is relatively vigorous.

Pollination

Flowering time and length can differ when plants have both male and female flowers, so characteristics peak and length of the flowering time could be applied for each flower sex. Long male flowering is a trait of a good pollinator. How well the male and female flowering periods overlap is a large determinant in self fertility and important for choosing compatible cultivars. Walnuts in two flowering groups based on this order of sexual flowering. Some cultivars like *Nr.22 kw* are self-fertile, increasing suitability for smaller projects.

Spring frost susceptibility

Walnuts are usually susceptible to late spring frost. Cultivars with late female flowering have a benefit of less late night frost damage. However, a very late flowering male pollinator is needed as a pollination partner so more care should be given to compatibility when choosing one of these cultivars. Besides blossom damage, cultivars that leaf out late were experienced to be less susceptible to damage. Cultivars differ in flowering time and leafing out for about 30-40 days. Whole plants can also be damaged by low temperatures, depending on the origin of their genes. Especially saplings are susceptible as emphasized by one expert.

"During night frost I scour with a headlight whether the grass is turning white somewhere, then the water goes on it. You have sometimes travelled the world for a piece of wood. That has then become a sacred plant. That he then freezes to death that does not happen to me."

Pests and diseases

In the humid climate of the Netherlands walnut blight and blotch were mentioned as the main serious diseases. Cultivars varied widely in their resistance to these diseases. Martin Crawford distinguishes between resistance of cultivars for these specific diseases.

Harvest period

Both the start of the harvest period and harvest uniformity were selected as relevant plant characteristics. Cultivars differ in harvest period for about 30-40 days. Most cultivars were mentioned to drop nuts over a period of 2 weeks, with shaking as a management practice 2 or 3 times should be sufficient for harvesting. Several cultivars dropped nuts earlier than others and over a longer period, like *Nr.22 kw*. While these cultivars might be less suitable for large scale commercial systems, for the private owner, or food forest with regular visitors and educational purposes, these cultivars can be of particular interest.

Yield

Lateral bearing is important for both precociousness and peak productivity according to both experts. used as a side note in Crawford's book. Apomixis is another factor in peak productivity. Yield stability over consecutive years was also mentioned as an important characteristic with high variation. However, since this is partly covered by blossom resistance to late night frost this characteristic is not taken up in the Tab. 5.7.7.

Market and consumption

Culinary appreciation was one of the top characteristics for all experts. As a compound variable, this plant characteristic covered taste, color, size, uniformity and crackability by hand as well as information about the heritage of the plant. Especially walnuts with red or huge kernels were highly appreciated. Experts differed in their opinion of suitable markets for walnuts, but agreed walnuts with red or huge kernels should be sold directly to consumers. For the huge nuts, this can include the fresh, milky nut that is seen as delicacy in certain cultures.

Availability planting material (nurseries)

This characteristic was found important to enable food forest designers to actually work with the selected promising cultivars.

Rootstocks

All nursery growers graft *Juglans regia* on *Juglans regia* seedlings. Moreover, all growers mentioned this largely out of practical financial reasons since *Juglans regia* seedlings are easily accessible and cheap compared to other possible rootstocks. The clonal rootstock *Paradox* that is often used in North America was not perceived to perform in the Netherlands. *Juglans nigra* was perceived as unsuitable as rootstock for showing delayed incompatibility through blackline disorder after 10 to 20 years. However, one expert mentioned that compatibility between one *Juglans nigra* rootstock and *Juglans regia* scion might be better than it would have been with some *Juglans regia* seedling rootstocks, due to the large genetic variation in *Juglans regia*. With other rootstocks for *Juglans regia* the experts had no extensive experience. The other way around, *Juglans regia* seedlings were regarded as a suitable rootstock for the species J*uglans ailantifolia*, *Juglans cinerea* and *Juglans nigra* without showing any delayed incompatibility.

Casus 2: Cornus mas

Cornus mas was praised by experts during the first round of data collection as a fantastic early flowering plant as part of a flowering bridge with frost resistance (whole plant and flower), consistent yield, a long productive lifespan, no pests and diseases of note and many options with cultivars. An overview of the cultivars and their functional plant characteristic values is shown in Tab. 5.7.8.

Box 5.7.8: Functional plant characteristics and cultivars for *Cornus mas*.

Available promising cultivars		**Elegantnyj**	**Flava**	**P5**
Relative growth vigour		Low	high	low
Pollination	**self-fertile**	sf, higher yield with cross pollination	sf, higher yield with cross pollination	iigher yield with cross pollina

	pollinator of	other cultivars	other cultivars	other cultivars
	pollinated by	other cultivars	other cultivars	other cultivars
Harvest	**harvest period - start**	august start	august half	august end
	harvest period - uniformity	High	high	high
	staying on plant after ripening	Short	Short	short
	natural post harvest ripening	Yes	yes	Yes
Market and consumption	**productive lifespan - start**	Early	early	early
	productivity - peak	high (30 kg)	fairly high	N/D
	Suitable markets	Niche	Niche	niche
		Bulk	Bulk	bulk
		Fresh	Fresh	fresh
		Processed	processed	processed
	Culinary appreciation	excellent sweet taste	very old cultivar, known since the 17th century. Fruit is of average size, shining yellow, intense taste of pine apple aroma	r shaped red fruits with excel
Availability planting material (nurseries)		Zoetewei	Zoetewei	Zoetewei

Available promising cultivars

Elegantnyi, Flava and *P5* were selected.

Relative vigour

While *Flava* was mentioned as a cultivar with high vigour, experts had experienced slow growth from *P5* and *Elegantnyi*.

Pollination

The two consulted experts differed in opinion on pollination requirements of *Cornus mas*. All cultivars are self-fertile, however where one expert was confident *Cornus mas* is entirely self-fertile the other was convinced that cross pollination does further increase fruit set and yields although it did not matter which cultivar was partnered with who.

Harvest period

Start and uniformity of the harvest period were mentioned as important characteristics, the latter in particular for efficient commercial harvesting. The harvest times of the discussed cultivars varied from early to late august. Staying on the plant was mentioned as an important characteristic for Cornus in general since most cultivars tend to drop fruits even before ripening, increasing the chance of loss through fruit decay as well as inefficient harvesting. The selected cultivars are all at least shortly staying on the plant after ripening. Some cultivars ripen naturally post-harvest enabling harvesting before full ripening to prevent fruit fall.

Yield

While none of the experts measured yield, yield for all cultivars were considered to be ranging from average to high.

Market and consumption

While some cultivars are only suitable for consumption, the preferred cultivars by the experts were so-called ‘double doers’ being suitable for fresh consumption as well. Being of an extraordinary taste and of good productivity, the *Cornus mas* cultivars were regarded for both the niche and potentially bulk market since the fruits are a specialty product both simultaneously commercially efficient and effective to harvest under the conditions of uniform ripening and fruit staying on the plant. For both experts culinary appreciation was a decisive characteristic for assessing cultivar potential and both differed in opinion over the most tasteful cultivars.

Available planting material

This characteristic was found important to enable food forest designers to actually work with the selected promising cultivars.

Rootstocks

Cornus mas cultivars were grafted upon *Cornus mas* seedlings to retain cultivar characteristics and stimulate precociousness. The experts had not experienced any (delayed) incompatibility between scion and rootstock.

Epilogue – Elders

"Humans have to move from being apart of nature to being a part of nature." Most of us have seen David Attenborough's documentary where he reflects upon his life and shares his vision for humans on our planet. He is one of our great acknowledged elders in the world. The importance of elders in this research was tremendous. Many experts were above the age of 60. They expressed extraordinary sympathy for my research and were very prepared to make time available, despite their busy schedules. Most even wanted to meet in real life, despite the risks of COVID-19. I felt the urge of these experts to share their decades of experiences. The role of elders in western modern society saddens and concerns me. In indigenous cultures their role was to tell stories sitting in their rocking chair, the younger generations listening with full attention and respect, building upon their knowledge and feeling inspired to take up their own quest. I heard many times during my research of experts that took their knowledge and wisdom with them into the grave, while they are an essential source of empirical, experiential knowledge. In each field of expertise that I explored, agroforestry, plant ontogeny, vegetation community ecology, nursery growing and organic agriculture, the elders paved the way as true pioneers. During their lives they often had very little to build on, except for their values and intuition. Of all people this group touched me most deeply. They are our alders, the trees colonizing the bare environments, making them more appealing and comfortable for

Succession of Food forests

An open-source functional plant characteristics database and decision-making framework for the design of food forests in the Netherlands

Executive summary

1 Introduction

A promising land use system for integrating and reinventing modern western agriculture and forestry systems is known as agroforestry. One of the most complex, novel and arguably nature driven types of agroforestry is food forestry. In the Netherlands, interest in food forests has experienced an exponential growth, while the existing knowledge about these systems in temperate climates is almost exclusively the result of personal anecdotal experience of practitioners in young food forest systems. Mainly due to the diversity, novelty and complexity of food forests, the design, research and specifically research on the design of these systems is still hardly developed and understood.

Research objectives and questions

For this thesis I propose that a decision-making framework linked to an open source functional plant database, unpinned by academic theory and empirical research as well as experiential knowledge of practitioners, has the potential to form an evidence-based foundation for the design of food forests and help mature food forests as a science and practice. In service of this evidence-based, interlinked plant-database and decision-making framework the following main research question was formulated:

What elements need to be consolidated in a plant-database and decision-making framework for the design of food forests in the Netherlands and how do these elements relate to each other?

Five corresponding sub-research questions were generated using a participatory action research approach:

1. *What are key elements and steps applied during the design process of food forests in the Netherlands?*
2. *What are key functional plant characteristics for the regenerative design of food forests in the Netherlands based on the most important 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) harvest practices and 6) project scales?*
3. *What are 100 promising plant species for food forests in the Netherlands based on the selected key functional plant characteristics and overall complementarity of inter-species variation?*
4. *What is the similarity between the key functional plant characteristics on species level compared to key characteristics for cultivars and rootstocks for the design of food forests in the Netherlands?*
5. *What are the relations between the elements selected for the plant database and those of the decision-making framework?*

2 Methods

In order to explore the design and management of these complex and novel systems an integrative, transdisciplinary, participatory approach was necessary. Participatory action research was conducted for the potential of generating data driven research questions, linking theory to practice, collecting both qualitative and quantitative data, having clear objectives to achieve and value creation with and for stakeholders. Moreover, integrative research principles, integral to sustainability research, served as guidelines for the design and implementation of this thesis research. Consequently, the scope iteratively developed over the course of the thesis research. This implied that the thesis was a constant feedback loop of problem framing, boundary setting and data collection, processing and evaluation. To explore the topic from a transdisciplinary perspective expert groups from practice and science were made. A total of 26 experts were interviewed during the study through semi-structured interviews that took on average 2,5 hours. Box 1 in

Annex provides additional methodological information on the scope, expert groups and identification and selection procedure of experts, database elements and framework elements.

3 Decision-making framework

RQ1: The key explored elements of the decision-making framework (Fig. 1) were the design steps and their corresponding design elements; plans, maps, lists and actions. The 6 steps of the framework were 0) Core values, principles and approach, 1) Observation and inventorisation, 2) Sketch Design, 3) Detailed Design, 4) Implementation and 5) Adaptation. As the design progresses the amount of detail increases concerning plant species selection, designing the spatial and temporal orientation of the vegetation on the maps as well as the concrete elaboration of the succession and management plans. Moreover, cyclical and iterative aspects emerged as an integral part of the design process. For instance, the adaptation step implies the cyclical nature of food forest design, designers consciously or intuitively check if their decisions in later steps are in line with their core values and continuously apply design principles and approaches.

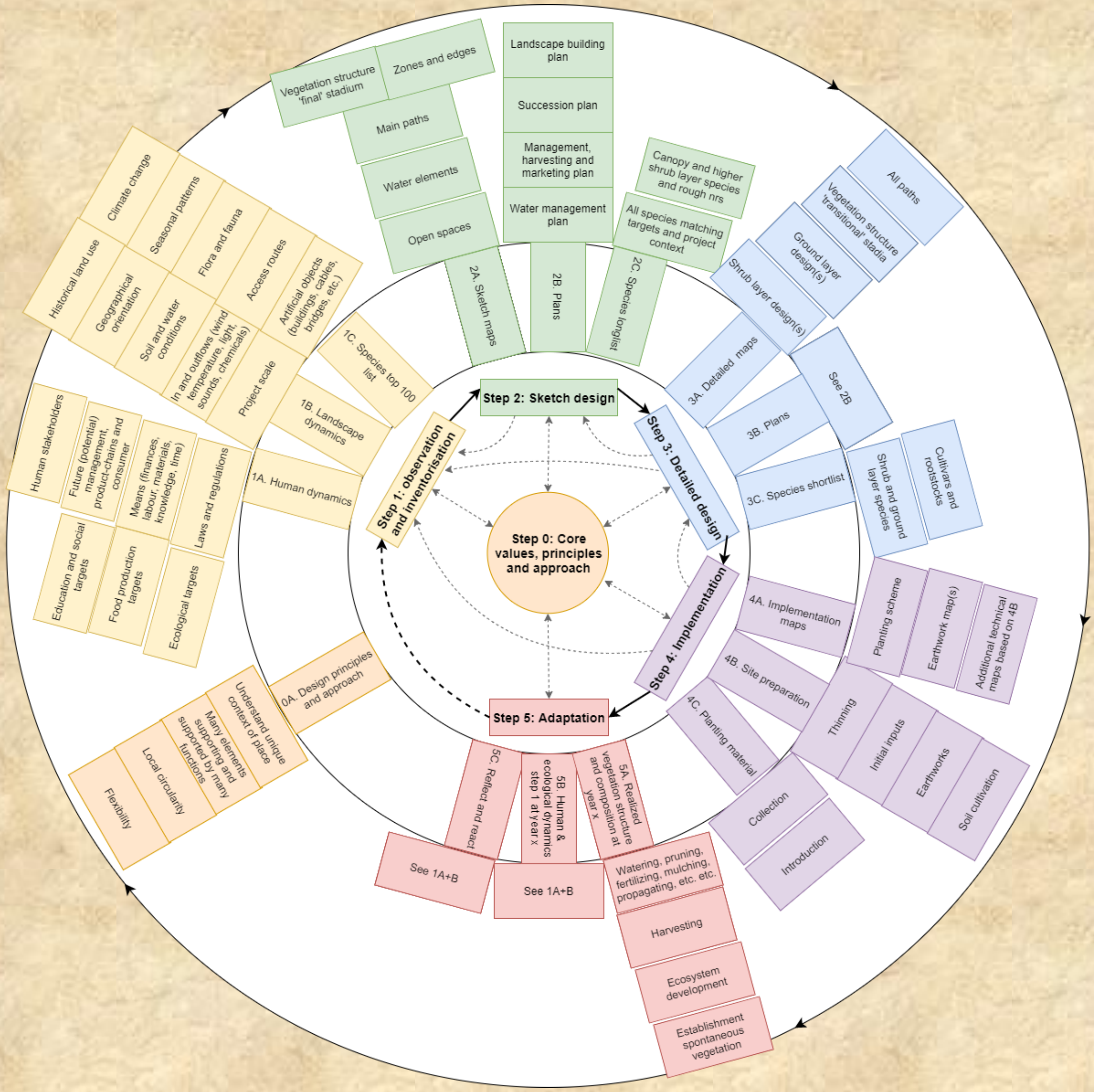


Figure 1. The iterative, cyclic decision-making framework for designing food forests in the Netherlands. The orange centre ring of the framework visualizes step 0. This ring is surrounded by a second ring consisting of steps 1 to 5 with each their own colour. The third ring shows the most relevant plans, lists, maps, actions and other elements corresponding to each step. Elements for each of these are elaborated in another surrounding fourth ring. The design progresses iteratively and cyclical, visualized through the dotted arrows.

4 Open-source plant database

RQ2: The main design criteria for exploring relevant plant characteristics, and consequently vegetation composition and structure, that emerged during the interviews were 1) functional targets, 2) current and predicted future environmental conditions, 3) successional gradients, 4) ontogenetic variation, 5) harvest practices and 6) project scales. Based on these design criteria 234 functional plant characteristics were identified from which 80 key characteristics were selected (Fig. 2). The foremost key functional plant characteristics for each design criteria are presented in Box 2.

Figure 2. The scheme shows relevant functional plant characteristics as elements for a database for the design of food forests in the Netherlands, nested in the categories morphology and development, community, required abiotic growth conditions, reproduction, harvest and post-harvest (see colours). These categories roughly correspond with the 6 design criteria. However, most functional plant characteristics and their categories hold (in)direct relations to all design criteria and the other way around.

Box 2. Descriptions and illustrations of explored key functional plant characteristics for each design criteria.

Functional Targets

The main functional targets were clustered into the categories of ecology, food production and education and social functional targets. The relation between (multiple) targets and project scale, vegetation structure, species richness and key plant characteristics relevant for designing species choice, richness and spatial and temporal arrangement as well as management practices is exemplified in Fig. 3 in Annex. Key functional plant characteristics for maintaining and stimulating intra and interspecific floral and faunal diversity were layer, successional status, indigeneity, flowering period and architectural properties, especially height.

Environmental Conditions

Temperature and moisture emerged as the most important environmental conditions during the interviews, relevant and considered during all scales across space (national, regional, local) and time (future, ontogenetic, seasonal). Spring forest resistance, overall winter hardiness and soil moisture tolerance were identified as the corresponding key functional plant characteristics. Additionally, an urban environment was perceived to require considering a wide range of corresponding plant characteristics.

Successional Gradients

Experts envisioned mid successional systems as most promising for food forests. The forest edge was proposed as very promising mid successional spatial patterning of the vegetation and most experts would maintain the food forest in this stage in most situations. However, experts also argued for the importance of maintaining diversity of successional stadia and spatial structures within food forests and on a landscape scale. Fig. 4 in Annex visualizes the successional schemes of the explored starting, transition and 'final' stadia applied and envisioned by experts. For designing along the successional gradients a broad range of plant characteristics was proposed by all expert groups, but shade tolerance (productivity), vegetation layer and plant successional status were discussed most as key functional plant characteristics.

Ontogenetic Variation

Three categories of functional plant characteristics that change throughout ontogenetics were distinguished; 1) above and belowground architecture, 2) environmental tolerances and 3) productive lifespan. Architectural functional plant characteristics that can be derived from the drawing at the bottom of this box are tree height when full grown, crown diameter when full grown, tree age when full grown, tree height after 10 years, crown diameter after 10 years and rooting depth. In general, plants were considered more vulnerable to the environment in early life stadia (seed and sapling) compared to an intermediate and mature stadium, especially on shade, frost and drought tolerance. Finally, the start, length and end of the productive lifespan was a key ontogenetic gradient for practitioners for making a four dimensional design of the vegetation and business model.

Harvest Practices

Edible plant part was the foremost functional plant characteristic when considering the future harvest practices. The other identified key plant characteristics for designing what, when, how and where to harvest, such as start, length and uniformity of the harvest period, harvest method, harvest efficiency, harvest location and start of productive lifespan link directly to specific edible plant parts instead of the whole plant. Fruits were arguably the most prominent edible parts in the food forest, but nuts were highly regarded by practitioners as well, mainly due to their long lifespan, low maintenance requirements, general system functions, suitability for later successional systems, fairly easy mechanized harvesting, good storability, high nutritional value, good flavour and growing market demand. Potential limitations the interviewee perceived for implementing nuts in food forests were a small breeding history of most species and hence few improved cultivars, incompatibility with lower vegetation layers due to harvesting from the ground and low tolerance to high and strongly fluctuating groundwater tables in the Netherlands. Perennial (spear) shoot and leaf crops emerging from the ground early in spring were valued by interviewees for holding potential to enhance food security, self-sufficiency and resource partitioning, target the undeveloped market of spring vegetables and spread labour. The use of edible flowers as vegetables was limited mainly by the perishability and low productivity. Also belowground edible plant parts seemed particularly difficult to fit in, mainly due to the harvest complications and growth requirements.

Project Scale

The scale of the project site emerged as a design theme that exposed many opposing opinions among experts concerning the opportunities and limitations for scaling up food forests in the Netherlands. Specifically, markets and consumption, start of the productive lifespan, harvest methods, culinary appreciation, future demand, processability, edible plant part, harvest period uniformity, storability, peak productivity, start of the harvest period and staying on the plant after ripening were explored as key functional plant characteristics for designing the along the project scale of food forests.

RQ3: A 100 promising species list was derived, based on the 80 key functional plant characteristics shown in Fig. 4 and on exploring the overall complementarity of inter-species variation, in particular variation in edible plant parts (Tab. 1 in Annex). *RQ4:* Box 3 in Annex provides information on the explored key functional plant characteristics for cultivars, rootstocks and scion-rootstock combinations. Additional elements identified as part of the open source plant database that do not directly connect to one of the sub-questions. The author, coordinates and date were considered relevant open-source related elements of the database. All database experts considered dynamic information (linked to a time and place) as much more valuable than stationary data. These elements increase traceability and transparency of the data, elementary for open source databases.

5 Synergizing the plant database and decision-making framework

RQ5: In this chapter the explored synergy between the elements selected for the plant database and those of the decision-making framework is presented. For the central role of functional plant characteristics in translating functional targets and characteristics of the landscape into design considerations for the vegetation composition and structure and to a lesser degree management, this chapter demonstrates the applications of the functional plant characteristics during the steps, plans, lists and maps of the decision-making framework. Tab. 2 in Annex emphasizes which functional plant characteristics can be relevant in which phase of the decision-making and how they connect the design process to the selection of species, cultivars and rootstocks.

6 Discussion

RQ1: The framework was regarded by designers as giving a quite complete and practically accessible context of food forest design as well as containing the steps and elements designers personally most frequently used and suggest the minimal building blocks for making a food forest design. Steps, plans, lists and maps were identified as key elements in a framework for designing the spatial and temporal composition and structure of living and non-living elements, especially vegetation, in food forests. Each of these elements seem interrelated in an iterative, cyclical design process. Moreover, the framework as a whole and as individual elements emphasizes the importance of the bridge and continuous feedback loop between theory and practice. However, it is desirable to acknowledge the process and elements as unique in each project context and for each designer, without single silver bullet design solutions. Consequently, designing complex agroforestry systems always goes further than mindlessly taking over prescribed choices and a decision-making framework for food forests can never be put in stone. As complexity builds upon complexity, decision-makers at the point of action must increasingly rely on their intuition and the challenge becomes the ability to holistically integrate logical processes, experiences and intuition.

RQ2: The thesis research outcomes suggest that functional plant characteristics of plant species, cultivars, rootstocks and scion-rootstock combinations, underpinned with dynamic sourcing on author, date and place are essential elements in a relational, open-source plant database that can underpin the decision-making framework. In particular, the explored functional plant characteristics were found to contribute as an approach and bridge for translating design criteria such as functional targets, environmental conditions, successional gradients, management practices and project scale into a vegetational composition and structure for food forests.

RQ3: The 100 promising species list utilizes the explored diversity in functional targets and project dynamics among food forests as well as the diversity in personal perspectives of the interviewees. Still, it is a risk if practitioners and researchers regard this list as a holy grail since designing for diversity should arguably remain the most important narrative in food forest design, with the right plant at the right place at the right time.

RQ4: There was little similarity between the key functional plant characteristics on species level compared to key characteristics for cultivars and rootstocks for the design of food forests in the Netherlands. However, the findings suggest specific characteristics relevant on the cultivar level for specific species or species groups. Concerning rootstocks, growth vigour emerged as a central relevant rootstock-specific functional plant characteristics with wide implications for other functional plant characteristics. Strong vigour rootstocks may be preferable in extensive farming systems such as food forests. Compatibility between scion and rootstock was a specific additional characteristic for connecting the two. Moreover, intricate interaction cultivar-rootstock combinations may influence many functional plant characteristic values.

RQ5: The functional plant characteristics and plant entities (species, cultivars, rootstocks) connect to elements during all steps of the decision-making framework. Plant characteristics work for linking the living, natural, abstract and artificial elements of the place, observed during step 1, to decisions on vegetation composition and structure through space and time. Furthermore, the plant characteristics are used for observing the specifying targets in the early phase of design, creating maps, plans and lists during the design process, obtaining planting material and for evaluating the developed human and landscape dynamics to the targets after implementation.

Conclusion

An explorative, participatory action research approach, combined with principles from integrative research, was found effective to 'design the design process' of food forests. Not earlier were as many as 26 experts from different backgrounds sharing their knowledge and perspectives in an academic study on food forest design in the Netherlands. The framework and database elements and their relations presented in this explorative study can guide practitioners and scientists in their decision-making during food forest design and research on design respectively and can inspire practitioners, scientists, policy makers and the general public alike to contribute to the succession of food forests as a practice and science.

7 Recommendations

The decision-making framework should be tested and improved upon in collaboration with practitioners and scientists, especially designers. A blueprint for methodological considerations and relevant topics is provided in the full-length report. For the further development of the open-source plant database I recommend that the specific key plant characteristics and plant species that were identified should be further researched, with the focus on further exploration of their relevance for the design of food forests and developing a monitoring plan for obtaining contextualized functional plant characteristics values for the 100 promising food forest species.

8 Annex

Table 1: Supplementary information on scope, expert categories and procedure for identification and selection of experts, decision-making framework elements and open-source plant database elements.

Scope
Despite a food forest design requiring an understanding of social, educational, spiritual, juridical and plannological aspects the emphasis for discovering the elements of the plant database and decision-making framework remained on ecology as a root perspective, followed by agronomic aspects. This also influenced the selection of the expert groups.

Expert groups
The group(s) experts represented were ecologists, agronomists, food forest designers, food forest farmers, nursery growers, data scientists, chefs, business economists and decision-making scientists. Experts were selected based on my personal prior knowledge of the research field and by asking experts during the interviews for other relevant experts to interview.

Decision-making framework elements
The identified steps and elements during the first half of the interviews were combined into a draft framework, which was later evaluated with four food forest designers on steps, elements, overall structure, applicability, strengths and weaknesses of the framework.

Design criteria for database elements
The interviews started with Functional targets, Environmental conditions, Successional gradients and Ontogenetic variation as design criteria. However, interviewees were asked if any key design criteria were lacking, resulting in the inclusion of Harvest practices and Project scale along the study.

Functional plant characteristics
For the identification of functional plant characteristics interviewees were asked which were relevant based on the above design criteria. For the selection of the plant characteristics experts were asked in a later stage of the study if they thought a plant characteristic should be included in the plant database. Besides the amount of experts and design criteria favoring the characteristics, characteristics were (de)selected based on complementarity, being a compound variable, reducing redundancy, applicability, influence on other characteristics and plasticity, although due to time constraints this was not done systematically. Interviews during the second phase of data collection also aimed to explore whether the same plant characteristics were relevant on species as on the cultivar and rootstock level. *Juglans regia* and *Cornus mas* were chosen as case studies.

Species, hybrids, cultivars and rootstocks
Promising food forest species were identified via the criteria and plant characteristics in the general survey. A species list with the 100 most promising species was requested from food forest pioneer Martin Crawford. Later, food forest practitioners were asked to judge both the potential of the individual species on the list for food forests in the Netherlands and whether they would nominate superior alternatives for each species. Moreover, they were asked to assess the list in total on the relative complementarity or presence of what were according to them important plant characteristic values. Final selection to achieve a 100 top list was based on expert opinions and species performance and complementarity on key functional plant characteristics for the 33 species with a score on the boundary of making the 100 top list. For each species was also the availability of promising hybrids, cultivars and rootstocks identified throughout the interviews..

Figure 3: Impressions of (from left to right) a romantic, multi-layered food forest, 'Heerenboeren' farm with a food forest integrated with other food production systems and educational food forest for children, to illustrate how the vegetation structure and composition of food forests are highly dependent on the desired targets of the place and project scales.

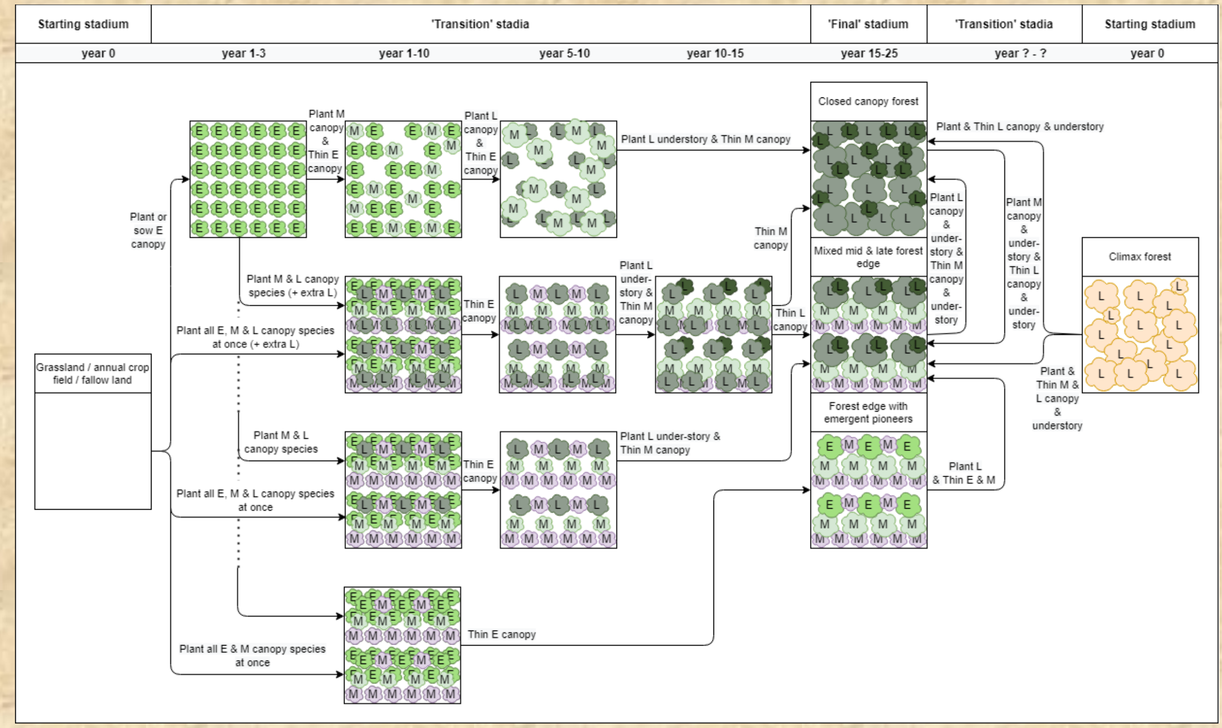


Figure 4: Main explored scenarios for the 'starting', 'transition' and 'final' stadia in successional food forest design (E=early, M= mid and L=late plant successional status).

Table 1: 100 promising plant species for food forests in the Netherlands with their main edible plant part, expert score and relevance of zooming in on cultivars (Cv), rootstocks (Rs) and hybrids (H) in the database.

Nr.	Taxonomy		Main edible part	Zooming			Expert score	Nr.	Taxonomy		Main edible part	Zooming			Expert score
	Botanical name	English name		Cv	Rs	H			Botanical name	English name		Cv	Rs	H	
1	Actinidia arguta	Hardy kiwi	fruits	x			6	51	Juglans nigra	Black walnut	nuts	x	x		5
2	Actinidia chinensis	Kiwi	fruits	x			4	52	Juglans regia	Walnut	nuts	x	x		8
3	Allium ampeloprasum	Wild leek	leaves	x			4	53	Lonicera caerulea	Honeyberry	fruits	x			4
4	Allium fistulosum	Welsh onion	leaves				3	54	Lycium barbarum	Goji	fruits	x			3
5	Allium tuberosum	Chinese chives	leaves				4	55	Malus domestica	Apple	fruits	x	x		6
6	Allium ursinum	Wild garlic	leaves				6	56	Malva moschata	Musk mallow	leaves				2
7	Alnus cordata	Italian alder	none				3	57	Matteuccia struthiopteris	Ostrich fern	leaves				5
8	Alnus glutinosa	Black alder	none				6	58	Melissa officinalis	Lemon balm	leaves				3
9	Amelanchier alnifolia	Saskatoon	fruits	x		x	5	59	Mentha suaveolens	Apple mint	leaves				4
10	Apios americana	American groundnut	tubers				4	60	Mespilus germanica	Medlar	fruits	x	x		7
11	Aralia cordata	Udo	spear shoots				6	61	Morus alba	White mulberry	fruits	x	x	x	4
12	Armoracia rusticana	Horse radish	roots				2	62	Morus nigra	Black mulberry	fruits	x	x		5
13	Aronia melanocarpa	Black aronia	fruits	x		x	6	63	Myrrhis odorata	Sweet cicely	leaves				4
14	Asimina triloba	Pawpaw	fruits	x			7	64	Phyllostachys vivax	Vivax bamboo	spear shoots				6
15	Asparagus officinalis	Asparagus	spear shoots				4	65	Pinus koraiensis	Korean pinenut	seeds	x	x		3
16	Berberis koreana	Korean berberis	fruits				2	66	Polygonatum biflorum	Solomon's seal	spear shoots				4
17	Brassica oleracea	Perpetual kale	leaves	x			3	67	Prunus armeniaca	Apricot	fruits	x	x	x	6
18	Caragana arborescens	Siberian peashrub	seeds				3	68	Prunus avium	Sweet cherry	fruits	x	x		5
19	Carya illinoinensis	Pecan	nuts	x	x	x	3	69	Prunus cerasifera	Cherry plum	fruits	x	x	x	3
20	Carya laciniosa	Kingsnut	nuts	x	x	x	3	70	Prunus domestica	Plum	fruits	x	x	x	6
21	Castanea mollissima	Chinese chestnut	nuts	x	x	x	3	71	Prunus dulcis	Almond	fruits	x	x		3
22	Castanea sativa	Sweet chestnut	nuts	x	x	x	9	72	Pyrus communis	Pear	fruits	x	x	x	8
23	Chaenomeles cathayensis	Chinese quince	fruits				4	73	Pyrus pyrifolia	Nashi pear	fruits	x	x	x	7
24	Chaenomeles japonica	Japanese quince	fruits				5	74	Quercus ilex	Holly oak	nuts				2
25	Chenopodium bonus-henricus	Good king henry	leaves				4	75	Quercus robur	Pedunculate oak	nuts				2
26	Claytonia sibirica	Siberian purslane	leaves				3	76	Rheum x cultorum	Rhubarb	leaf stalks				5
27	Cornus mas	Yellow dogwood	fruits	x	x		6	77	Ribes nigrum	Black currant	fruits	x		x	6
28	Corylus avellana	Hazelnut	nuts	x	x		7	78	Ribes rubrum	Red currant	Fruits	x			7
29	Crambe maritima	Sea kale	spear shoots				4	79	Ribes uva-crispa	Gooseberry	Fruits	x			4
30	Crataegus mexicana	Mexican hawthorn	fruits		x		3	80	Rosa rugosa	Rugosa rose	Fruits				3

31	Crataegus schraderiana	Blue hawthorn	fruits		x		3	81	Rubus idaeus	Raspberry	Fruits	x			8
32	Cydonia oblonga	Quince	fruits	x	x		2	82	Rubus phoenicolasius	Japanese wineberry	Fruits				2
33	Dioscorea polystachya	Japanese yam	roots				3	83	Rumex acetosa	Sorrel	Leaves				5
34	Diospyros kaki	Kaki	fruits	x	x	x	8	84	Salix caprea	Goat willow	None				3
35	Diospyros virginiana	Persimmon	fruits	x	x	x	6	85	Sambucus canadensis	Canadian elderberry	flowers	x			3
36	Elaeagnus multiflora	Autumn olive	fruits	x			4	86	Sambucus nigra	Common elderberry	flowers	x			5
37	Elaeagnus umbellata	Goumi	fruits	x			5	87	Scorzonera hispanica	Scorzonera	Roots				2
38	Ficus carica	Fig	fruits	x			4	88	Sorbus domestica	Service tree	Fruits	x	x		2
39	Fragaria moschata	Hautbois strawberry	fruits				3	89	Staphylea pinnata	Bladdernut	flowers (unopened)				2
40	Fragaria vesca	Alpine strawberry	fruits	x			4	90	Symphytum officinale	Comfrey	None				3
41	Frangula alnus	Alder buckthorn	none				5	91	Taraxacum officinale	Dandelion	Leaves				4
42	Hablitzia tamnoides	Caucasian spinach	shoots & leaves				2	92	Tilia cordata	Small leaved lime	Leaves				8
43	Helianthus tuberosus	Jerusalem artichoke	tubers				3	93	Toona sinensis	Chinese cedar	Leaves				7
44	Hemerocallis lilioasphodelus	Yellow day lily	flowers	x		x	7	94	Urtica dioica	Stinging nettle	Leaves				6
45	Heracleum sphondylium	Common hogweed	leaves				2	95	Vaccinium corymbosum	American blueberry	Fruits	x			7
46	Hippophae rhamnoides	Sea buckthorn	fruits	x			6	96	Viola odorata	Sweet violet	Leaves				3
47	Hosta sieboldiana	Sieboldiana hosta	spear shoots				7	97	Vitis vinifera	Grape	Fruits	x	x		4
48	Humulus lupulus	Hop	spear shoots				3	98	Zanthoxylum simulans	Szechuan pepper	Fruits				2
49	Juglans ailantifolia	Heartnut	nuts	x	x	x	6	99	Zingiber mioga	Myoga ginger	Leaves				5
50	Juglans cinerea	Butternut	nuts	x	x	x	3	100	Ziziphus jujuba	Jujube	Fruits	x	x		2

Box 3: Considerations of the nursery grower for which scion and rootstock to combine.

Genetics (upper right corner)
When combining scions and rootstocks a nursery grower thinks about the genetic compatibility and a diversity of plant characteristics. A rule of thumb for genetic compatibility is that closer relatives are better compatible. There are also families and genera in which compatibility is in general higher. For instance, several *Prunus* spp are compatible with each other.

Vigour (upper left corner)
Important characteristics when choosing a rootstock are the manipulation of the size and productive life-span of the scion, as well as influencing suitable growth conditions in relation to soil, wind exposure and frost. Low vigour rootstocks, nowadays used in most commercial Dutch fruit orchards, start early with their productive life-span and stay smaller. This can be beneficial for getting a fast return on yield and easy accessibility during harvesting. However, while starting their productive life-span earlier, the length of the productive life-span is also greatly reduced. Moreover, these dwarfing rootstocks generally need more inputs of nutrients and water and are more susceptible to wind stress, pests and diseases due to their less developed root system. Vigorous rootstocks have the opposite effects and characteristics. It takes longer till plants come into bearing, but plants keep producing for many more years. This aspect in combination with better nutrients and water acquisition in combination with anchorage against wind stress and better pest and disease resistance makes vigorous rootstocks in general more suitable for extensively managed, long term systems such as food forests.

Frost and suckers (bottom left and right corner)
Frost is more severe close to the ground. Species vulnerable to late night frost may escape frost on a vigorous rootstock which is further removed from the ground. Another aspect related to the compatibility is the tendency of rootstocks to form suckers, this can occur when combining a highly vigorous rootstock with low vigour scion.

Markets and consumption (middle right)

The nursery grower is considering if the fruit is meant for direct, fresh consumption or processing, in this case into jam.

Table 2: The elements of the decision framework in row 1,2,3,4 (depending on ring) and their related (groups of) plant characteristics (colors correspond to steps of decision-making framework).

Ring 1: Step	**Ring 2: Steps**	**Ring 3: Plans, lists, maps, actions**	**Ring 4: Plans, lists, maps, actions**	**Emphasized (groups of) plant characteristics**
0: Core values, principles and approach	1: Observation and inventorisation	Human dynamics	Human stakeholders	-
			Ecological targets	Morphology and development, community status, inter-trophic relationships
			Food production targets	Harvest and post harvest
			Social and educational targets	Harvest period - start, culinary appreciation, nutritional value
			Future (potential) management, product-chains and consumer	Edible part, harvest period - start, productive lifespan - start, markets, processability, storability - natural, harvest methods, future demand
			Means	Layer, harvest methods
			Laws and regulations	Height - full grown, invasiveness, indigeneity
		Landscape dynamics	Geographical orientation in landscape	Frost vulnerability (whole plant and flowers), natural occurrence
			Soil and water conditions	Root depth and pattern, soil moisture, texture, fertility, acidity, compaction and salinity
			In and outflows	Shade tolerance, wind stress resistance, frost vulnerability (whole plant)
			Project scale	Interdependent with targets
			Climate change	Root depth and pattern, natural occurrence, (spring) frost vulnerability (whole plant and flowers), soil moisture tolerance
			Seasonal patterns	Leafing out, leaf fall, frost vulnerability (whole plant and flowers), flowering period - peak and length
			Flora and fauna	Layer, successional status, competitive strength, pollination vector, mycorrhiza type
			Access routes	-
			Artificial elements	Required abiotic growth conditions
		Species 100 top list	-	Latin species name
	2: Sketch design	Sketch maps	Target vegetation structure 'final' stadium	Layer, successional status
			Zones and edges	Edible plant part, successional status, natural occurrence, wind stress resistance
			Main paths	-
			Water elements	Soil moisture tolerance
			Open spaces	-
		Plans	Succession	Edible plant part, layer, successional status, competitive strength, height - full grown, height - age 10 and full grown, age - full grown, crown density, crown diameter - age 10 and full grown, dispersion, resprouting, relative growth rate, leaf composition, wind stress resistance, shade tolerance (productivity), mycorrhiza type, nitrogen fixation, soil moisture, acidity, fertility, compaction, productive lifespan - start and length
			Management, harvesting and marketing	Harvest and post-harvest, layer, competitive strength, soil fertility tolerance
			Water management	Soil moisture tolerance and root depth
			Landscape building	Layer, successional status, invasiveness, indigeneity, height - full grown, crown diameter - full grown, flowering period (peak and length), pollination vector
		Species longlist	Canopy and higher shrub layer species and rough nrs	Latin species name, layer

			All species matching targets and project context	Latin species name
	3: Detailed design	Detailed maps	Shrub layer design(s)	Layer, successional status, shade tolerance (productivity)
			Ground layer design(s)	Layer, successional status, shade tolerance (productivity)
			Vegetation structure 'transitional' stadia	Layer, successional status, crown diameter and height - age 10, relative growth rate, productive lifespan - start and end
			All relevant natural, living and artificial elements	-
		Plans	See 2B	-
		Species shortlist	Cultivars and rootstocks	Cultivar name, rootstock name
			Shrubs and ground layer species and nrs	Latin species name, layer
	4: Implementation	Implementation maps	Planting scheme	Layer, crown diameter - full grown, plant reproductive fertility, optimal distance for cross pollination, pests and disease susceptibility, pests and diseases of note, harvest location of edible plant part
			Earthwork map(s)	-
			Additional technical maps based on site preparations	-
		Site preparations	Thinning	Morphology and development and required abiotic growth conditions
			Soil cultivation	Required abiotic growth conditions
			Initial inputs	Competitive strength, soil fertility tolerance
			Earthworks	-
		Planting material	Collecting	Availability plant material, nurseries, propagation method
			Introducing	-
	5: Adaptation	Realized vegetation structure and composition year x	Harvesting	-
			Other management practices	-
			Ecosystem development	-
			Establishment spontaneous vegetation	-
		Human & landscape dynamics year x	See step 1	-
		Reflect and react	See step 1	-

About the Author: I am a graduate student at Wageningen University with a Masters in Forest and Nature Conservation. As a freelancer I focus on design, implementation, management and education of food forests in the Netherlands, I am co-founder of St. Re-generatie which aims to contribute to a regenerative food system by bridging the gap between science and practice and I collaborate with St. Voedselbosbouw Nederland to realise an open-source plant database for food forests in the Netherlands.

Acknowledgements: I would like to express my gratitude to my thesis supervisor Prof. dr. Frans Bongers, i.r. Madelon Lohbeck, St. VBNL and in particular Evelyn Derksen and Marc Buiter and all experts who were willing to share their wisdom in this study. My sincere hope for reciprocity is that you, my readers, will be inspired, intrigued or irritated by what you do find here, to also become catalysts of this regenerative, existential movement.

Contact: Further copies of this publication, the full-length report and more information on this subject can be obtained via telephone or email.
Tel: +316 36532762
Emails: jordyvaneijkinspire@gmail.com

Citation: Eijk, Van, J.H.G. (2021). Succession of Food forests: An open-source functional plant characteristics database and decision-making framework for the design of food forests in the Netherlands. Executive summary.