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Harvesting efficiency in Complex Agroforestry Systems



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Foreword

I would like to express my sincere gratitude to my supervisors, Arni Janssen and Jordy van Eijk, for their continuous support and for giving me the opportunity to explore the fascinating field of Complex Agroforestry Systems. Arni, thank you for thinking along with me on this journey and for the valuable feedback you consistently provided. Jordy, I greatly appreciate your willingness to dedicate time to this thesis despite your already full schedule.

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Abstract

The industrial food system is built on unsustainable practices, making it an important driver of the current environmental problems. Alternative food systems, such as complex agroforestry systems (CAS), can address some of these challenges. While CAS do well in environmental and social sustainability, they often underperform economically due to the trade-off between system complexity and the resulting labour required for their management. Therefore, this thesis developed and evaluated different design and low-tech management scenarios for complex agroforestry systems (CAS) that enhance harvesting efficiency and align with farmers' objectives of economic feasibility, environmental sustainability and social well-being. The design method, Reflexive interactive design (RIO), guided this process. Semi-structured interviews were conducted with CAS practitioners and farmers cultivating fruits, nuts, and herbs, providing insights into the issues related to labour demand in CAS and potential harvesting solutions. This information, combined with a literature review, was then used to generate two design and low-tech harvesting scenarios for the case study Het Middenbos: the bulk scenario and biodiversity scenario. These scenarios were evaluated by farmers and researchers, the case study farmer and through a self-conducted evaluation. Overall, both scenarios scored high in relation to farmers' objectives; however, their performance varied across objectives. While both scenarios demonstrated a significant improvement in harvesting efficiency compared to manual harvesting, the bulk scenario outperformed the diversity scenario, achieving 1.7 times greater efficiency. Additionally, while both scenarios rated reasonably high in terms of economic feasibility, the bulk scenario moderately outperformed the diversity scenario. In contrast, the diversity scenario excelled in environmental sustainability and social well-being. The results demonstrate that the trade-off between system complexity and labour requirements could be reasonably overcome, highlighting that, even within complex systems, there is considerable potential to improve harvesting efficiency.





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1 Introduction

The industrial food system is built on unsustainable practices, making it an important driver of the current environmental problems. It contributes to the exceedance of the ecological planetary boundaries, including global warming, nitrogen cycle disruption, land use change, and species extinction (Björklund et al., 2019). Dependency on fossil fuels, mineral fertilisers, and chemical pesticides add to this issue (Rembiałkowska et al., 2016). Further, economic inequalities across the value chain and adverse effects on human health can be observed (Albrecht & Wiek, 2021; Stichting Regeneratie, n.d.). This shows that the focus should not solely be on production, but rather shifted to one that equally values regenerative practices (Björklund et al., 2019).

Alternative food systems, such as complex agroforestry systems (CAS – often referred to as food forests), can address some of these challenges. They have the potential to regulate and support the environment, produce healthy food, and provide sociocultural services such as spaces for recreation, education, and community building (Albrecht & Wiek, 2021).

CAS are commonly practised in indigenous and traditional production systems in the tropics and subtropics, and are probably among the oldest forms of agriculture practised by humanity (Kumar & Nair, 2004; Pilgrim et al., 2018). However, in temperate climates, CAS emerged in the 1970s (Hart, 1996) and only shifted more into focus in recent years (Stichting Regeneratie, 2025). Since CAS take decades to fully develop and come into production, it is only logical that there is not much scientific knowledge of the functioning of such systems in temperate climates.

As indicated by the name, CAS are the most complex form of agroforestry (van Eijk, 2021). Agroforestry is the umbrella term for land-use systems that grow trees together with crops and/or animals (Rebisz, 2019). Complex agroforestry systems combine nature and food production (Pilgrim et al., 2018) and can be described as a multifunctional biodiverse agroforestry system (Albrecht & Wiek, 2021). CAS are designed on the structure of young natural woodland (Crawford, 2010), meaning they consist of several plant layers (see Figure 1) of different heights, including trees, shrubs and groundcover (Albrecht & Wiek, 2021). CAS mainly use perennial plants, all planted to grow together in beneficial mutualism (Crawford, 2010).

In the Netherlands, Wouter van Eck pioneered the food forestry movement in 2009 when he first set up his educational food forest in Groesbeek (Swart, 2022). The interest in this concept has risen significantly (de Groot & Veen, 2017). In 2017, the Dutch government signed the Green Deal of Food Forests, acknowledging the concept of food forests being part of "green growth" (Green Deal Voedselbossen, 2020).

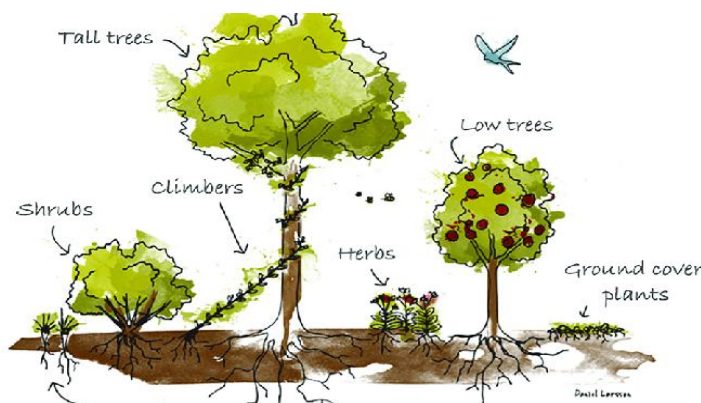


Figure 1: Layers of a Complex Agroforestry System (Stolz & Schaffer, 2018)



While CAS do well on the environmental and social pillar of sustainability by providing healthy food and environmental services, they often underperform in the economic one (Albrecht & Wiek, 2021; Stichting Regeneratie, n.d.). To make CAS economically viable and implement them on a wider scale, more research on the design, implementation, and management of CAS is needed. (Van Eijk & Van Der Stok, 2022). The organisation 'Stichting Regeneratie' conducts research to enhance knowledge for professionalising small-scale complex agroforestry. They aim to answer how CAS can be designed into productive, profitable, and socially attractive ecosystems with a high natural value. Therefore, they are setting up five pilot projects, which they design and implement, while documenting the process and making it openly accessible (Stichting Regeneratie, n.d.-b). The design process is participatory and scientifically embedded in the Engineering Doctorate of Jordy van Eijk at Wageningen University and Research (Stichting Regeneratie, n.d.-b).

As indicated before, the economic viability of CAS is not a given. This is partly due to the trade-off between the complexity of the system and the resulting labour required for its management (J. Steinfeld, 2018; J. P. Steinfeld, 2024; J. Van Eijk & Van Der Stok, 2022). On one hand, complexity in terms of multiple vegetation layers, a high diversity of plants and non-linear spatial arrangements can lead to environmental and social benefits (Albrecht & Wiek, 2021a; Netwerk voedselbosbouw, n.d.; Van Eijk & Van Der Stok, 2022). On the other hand, this complexity also increases the complexity of the management of the system (Björklund et al., 2019; The Center for Agroforestry, 2024). Currently, most CAS operations are done manually (Burhomistrenko, 2020). Conventional agricultural machinery is aimed at delivering maximum efficiency in homogeneous row crops (Steinfeld, 2024) making it unsuitable to operate in CAS (Björklund et al., 2019; Burhomistrenko, 2020). Hence, it is essential to develop innovative technologies suited for managing these diverse and complex systems (Björklund et al., 2019).

When one talks about innovation in the agricultural world, one tends to go towards connected farms, drones, robots, and big data. These digital technologies and robotics are supposed to solve the current ecological challenges in agriculture. There are, however, voices that challenge this way of thinking about innovation. Marie Mardon, co-manager of L'Atelier Paysan, a collective that supports the unique approach of low-tech, voices the following critique: "We must take back the land from machines, which are ever more disproportionate, powerful, complex, and difficult to repair yourself. To be profitable, they require increasingly large areas. Hence the spiral of debt. The dependence of farmers. We want to give them back technological sovereignty. Support peasant agroecology, agriculture on a human scale." (Meyer, 2022).

The CAS movement is characterized as a small-scale, human-inclusive form of agriculture (Netwerk Voedselbosbouw, n.d.-b). Furthermore, its inherent species diversity leads to the need of a wide range of technologies. Therefore, this production system does not match with the use of expensive high-tech farming solutions. Low-tech farming solutions provide a better fit since they prioritize three main principles: Useful, Accessible and Sustainable. Useful in terms of meeting the essential needs of an individual or a community. Accessible in terms of affordable price and simple handling. Sustainable in terms of the optimization of the environmental and social impacts linked to using this technique, at all stages of its life cycle (from design to end of life) (Martin et al., 2022).



A study by Burhomistrenko, 2020, focusing on two CAS, analysed that from the total labour required, approximately 70% was needed for harvesting. Therefore, low-tech harvesting methods need to be explored to increase harvesting efficiency in CAS. There is no comprehensive overview of currently available machinery or equipment adapted by practitioners that is potentially suitable for CAS. Hence, it is unclear how this machinery would influence the spatial arrangement and species selection of CAS, and the harvesting efficiency within the system.

This thesis aims to explore low-tech harvesting methods suitable for CAS, how these methods influence CAS design, and which additional factors should be considered when designing to optimise harvesting efficiency. The goal is to develop design and low-tech management scenarios that align with the farmer's future vision. Based on this, the following main research question was formulated:

How do different CAS design and low-tech management scenarios perform in relation to achieving farmers' objectives, specifically harvesting efficiency?

To answer the main research question, three corresponding sub-questions were formulated:

1. What are the main challenges in complex agroforestry systems regarding harvesting efficiency?
2. Which harvesting methods are most suitable in relation to farmers' requirements?
3. How can complex agroforestry systems be designed to improve harvesting efficiency?



2 Background

This chapter defines complex agroforestry systems in relation to other terminology used. More detailed information on (complex) agroforestry policy, size of the sector and classification of agroforestry systems can be found in Appendix I.

2.1 Complex agroforestry systems

2.1.1 Definition

As the name suggests, CAS are one of the most complex forms of agroforestry (van Eijk, 2021). Currently, there are several terms to describe this system used in the temperate context. An overview of the terms encountered during this study can be seen in Appendix II. These systems have in common that they are polycultures with multiple vegetation layers that function in synergy with each other (van Eijk, in press). In the European context food forestry (or translations of the term into the corresponding language) is the most commonly used term. The Green Deal Voedselbossen formulated a distinct definition of this farming concept:

"A food forest is a human-designed productive ecosystem based on the model of a natural forest, with a high diversity of perennial and/or woody species, parts of which (fruits, seeds, leaves, stems, etc.) serve as food for humans.

With presence of:

- a canopy layer of taller trees;
- at least three of the other niches or vegetation layers of lower trees respectively, shrubs, herbs, ground cover, underground plants and climbers; a rich forest floor life.
- A food forest has a robust size, i.e. an area of at least 0.5 hectares in an ecologically rich environment; in a severely impoverished environment, a minimum area of up to 20 hectares is required." (Green Deal Voedselbossen, 2020)"

In essence, food forests are a form of agriculture that mimics natural processes and, therefore are, closest to natural systems (Rebisz, 2019) (see Figure 2).



Figure 2: Agriculture and forestry systems adapted from Stichting Voedselbosbouw, n.d.-b

This report uses the term complex agroforestry system instead of food forestry as it is a contribution to the engineering doctorate of Jordy van Eijk, who chose this term for his research. The term CAS fits within the framework of international research on agroforestry systems (Stichting Regeneratie, n.d.-b). Further, by choosing this term, it is possible to allow variations on the concept of food forestry, such as including annuals and animals in the system. In summary, all food forests can be considered complex agroforestry systems. However, not all CAS are food forests.



3 Materials and Methods

3.1 Reflexive interactive design

The whole thesis process is guided by the design method reflexive interactive design (RIO). RIO is a systematic design approach integrating innovation and policy sciences with more technically oriented methods. It aims at generating feasible solutions for new socio-technical systems, sparking niche experiments in the near future, while contributing to structural reform in the long term. It takes the needs of central actors as a starting point and then further translates them into a set of requirements on which the generation of solutions is based on. RIO is iterative, meaning that its three cycles of activity (see Figure 3) do not necessarily follow a chronological order but are connected through feedback loops. However, as the project progresses, the focus shifts from the first to the last cycle (Bos et al., 2009). This thesis focuses on steps A-H throughout the whole thesis project.

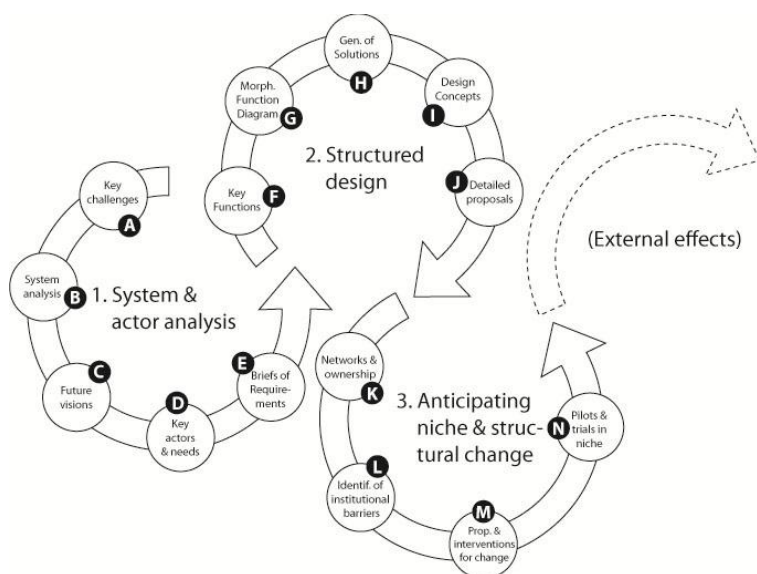


Figure 3: Overview of three cycles of activity of Reflexive Interactive Design (Bos et al., 2009)

3.1.1 Case study farm Het Middenbos

In order to apply the reflexive interactive design process a case study farm was selected. As this research is part of Jordy van Eijk's engineering doctorate, in which five CAS pilot projects are developed and implemented, one of these projects was chosen as a case study. The farm "Het Middenbos" was selected since its scale is large enough (4.5 ha) to consider investing in harvesting technology, making labour efficiency especially important. Additionally, the spatial layout had not yet been defined, allowing it to be informed by the requirements of suitable harvesting methods.

3.1.2 Key challenges

To explore the key challenges related to low harvesting efficiency in CAS, a literature review was conducted. Search engines such as Google Scholar and Scopus were used to gather scientific literature. Additionally, (grey) literature from organisations and individuals active in the (complex) agroforestry was also reviewed. Since current research on CAS focuses on ecological benefits and the design of such systems, more data was needed. Therefore, semi-structured interviews with CAS practitioners were conducted. These interviews provided insight into the farm context, tasks, and responsibilities of people working on the farm, as well as the current harvesting methods' drawbacks and benefits. Furthermore, reasons for choosing these methods and why other options were considered but deemed unsuitable were explored. Additionally, qualitative data on the most time-consuming



operations and how practitioners prioritize these was gathered. In essence, it provided a better understanding of how CAS practitioners currently operate and the most prominent issues they encounter. Most interviews were conducted in person to gain a better understanding of the system in question. However, due to time constraints of some interviewees, a few were conducted online via Microsoft Teams or Zoom. Interviewees were located in the Netherlands and countries with similar climate and context, namely France and Austria. To ensure significant results, a total of ten CAS practitioners were interviewed. Interviewees selected have several years of practical experience in the field, and some also provide consultancy services, courses or books on the topic. Potential interviewees were identified via online research. The snowball method was applied, where consulted experts were asked to connect the student with relevant experts they are in contact with. The interview questions were adapted and refined throughout the process based on new information. The final interview guide can be found in Appendix III.

A root cause analysis, based on the practitioner interviews and literature review, was conducted to identify key challenges related to low harvesting efficiency in CAS. The case study farmer gave feedback on these key challenges to determine their relevance for the design process of the case study. This led to the identification of key challenges that have the potential to be adapted in order to increase harvesting efficiency in CAS and were used as input for the subsequent steps in the reflexive interactive design process.

3.1.3 System analysis

In the system analysis, the case study farm and its system boundaries were explored. Information was obtained through interviews with the case study farmer and background data from Stichting Regeneraties database. Based on this, the background of the farm, size, context and soil characteristics were described. Additionally, a map was created to illustrate different elements and farming systems present within the project.

3.1.4 Future vision

Prior-defined key challenges were used as a basis to create a future vision which overcomes these challenges and defined what needs to be achieved. As this future vision has to work within the system's boundaries, the system analysis was then used to contextualise it for the case study. Additionally, further interviews with the case study farmer were conducted to gain a deeper understanding of the pilot farmers' perspectives and ensure even better alignment with the case study's context and the farmer's needs. This was then used to create a tree of objectives.

3.1.5 Key actors

An inventory of key actors relevant to the case study farm was compiled. Data were obtained from interviews with the case study farmer, the database from Stichting regeneratie, and a literature review on actors involved in the research, design, and development of complex agroforestry systems in the Dutch context.

3.1.6 Brief of requirements

Requirements for the future system were defined based on the previously established objectives. To specify and quantify these requirements in more detail, both qualitative and quantitative data were obtained from all interviews conducted. Additionally, relevant literature was consulted to refine specific requirements further. The resulting brief of requirements was organised into a table, outlining each requirement alongside its corresponding overall objective, sub-objective, and a description. Lastly, the evaluation of the design scenarios led to a further specification of the requirements.



3.1.7 State-of-the-art, key functions and morphological diagram

State-of-the-art harvesting methods in commercial farms and their potential application in complex agroforestry settings were explored during semi-structured interviews with herb, fruit and nut producers. These interviews were conducted in the same manner as CAS practitioner interviews. To ensure significant results, a total of ten farmers were interviewed. The final interview guide can be found in Appendix III.

Harvesting methods already applied in CAS were compiled during CAS practitioner interviews. During these interviews, data on the benefits and drawbacks of these harvesting methods, as well as which methods are most challenging and time-consuming, and the restrictions these methods pose to the system, were gathered. As all interviews were carried out simultaneously, harvesting methods encountered during interviews with herb, fruit and nut producers were presented to CAS practitioner interviewees in order to gain more information on how and why such a machine could work in CAS conditions, as well as the challenges they might encounter. Furthermore, a literature review on this topic was conducted, drawing on scientific literature but also exploring companies producing harvesting methods and organisations focusing on spreading low-tech harvesting methods. All data combined was then used to identify potential suitable harvesting methods for CAS.

Then, a function analysis was carried out by deriving the functionality of the harvesting methods found in the state-of-the-art exploration. That led to the identification of key functions essential to realising the system's objectives while meeting the requirements. Consequently, a morphological diagram was created, where various working principles for all key functions were defined.

3.1.8 Generation of solutions

Two distinct design and low-tech management scenarios were created. First, scenario-specific targets were established. These targets were defined based on input from the case study farmer and Jordy van Eijk. Second, a spatial layout of the system and selection of species and cultivars were made. This was done in collaboration with the Stichting Regeneratie team. Simultaneously, the author of this report selected the most suitable working principles for each key function, based on objectives, requirements, and scenario-specific targets, to determine suitable harvesting methods. These two aspects influenced each other and were therefore adapted a couple of times before coming to a final advice.

As the focus of the case study farm is bulk production of nuts, special attention was given to selecting a suitable harvesting method. There are many different nut harvesting methods available on the market from small non-powered tools, powered hand-operated machines and self-propelled machines. All have different harvesting capacities and price ranges. To select a suitable harvesting method for the case study farm, a nut harvesting method selection tool was developed, considering the specific context of the farm. Labour needed to perform the whole nut harvest with a specific harvesting method and investment costs of the harvesting method were considered the most essential aspects and are therefore considered in this tool. The Flanders Research Institute for Agriculture, Fisheries and Food developed a tool to help make choices for which Nut harvesting method can be applied in an agroforestry context. However, this tool assumes that only one tree species is used. Therefore, their calculations were adapted to take various different species and cultivars into account. Data on yield was obtained from the Rekentool. The Rekentool is an Excel-based calculation tool used for designing and estimating the profitability of an existing CAS. The tool contains data on around 200 commonly used plant species (Voedselbosbouw, n.d.). A detailed explanation of the calculations taken to estimate the labour requirements and how this output was then visualised to be able to select a suitable harvesting method can be found in Appendix IV.



Evaluation

The design and low-tech management scenarios were evaluated to gather feedback on how the proposed solutions meet requirements and objectives, and to identify any weaknesses that can be further improved. The evaluation was carried out in three consecutive phases (see Figure 4). In the first phase, feedback on the proposed design and management scenarios was gathered from both researchers and farmers. Nine agroforestry researchers were contacted, of whom four provided feedback. Additionally, nine previously interviewed farmers were approached, with two ultimately responding. This led to a total of six responses. In this phase, the scenarios were presented in video form, accompanied by a feedback form (see Appendix V). This was then sent via email to the participants to do in their own time and provide written feedback. In the second phase, the scenarios were evaluated by the case study farmer. First, an in-person presentation was held to explain the scenarios in detail and allow space for verbal feedback. The requirements were simplified into sub-objectives, which are specific enough to elicit feedback but broad enough to allow the case study farmer to provide meaningful input. This was then used to create an evaluation form, where scenarios could be scored from one to four, with one representing that the solution does not meet the sub-objective and four representing that it fully meets the sub-objective. Additionally, a section was included to describe why a score was chosen. The farmer then evaluated the scenarios using this evaluation form. Based on these scores, a spider graph of objectives was created, highlighting the overall score of each scenario on the main objectives. In the third phase, a self conducted evaluation was carried out, where objective level input from the case study farmer was linked to the prior defined requirements and expert feedback from the first phase was analysed. During this step, the harvesting efficiency for both scenarios was calculated for the proposed solutions and manual labour (for detailed calculations, see Appendix VI). Based on the data obtained, a spider graph was created where the overall objectives were scored to highlight each scenario's strengths and weaknesses. Input from all three evaluations was then used to come to a final advise by developing a final scenario.

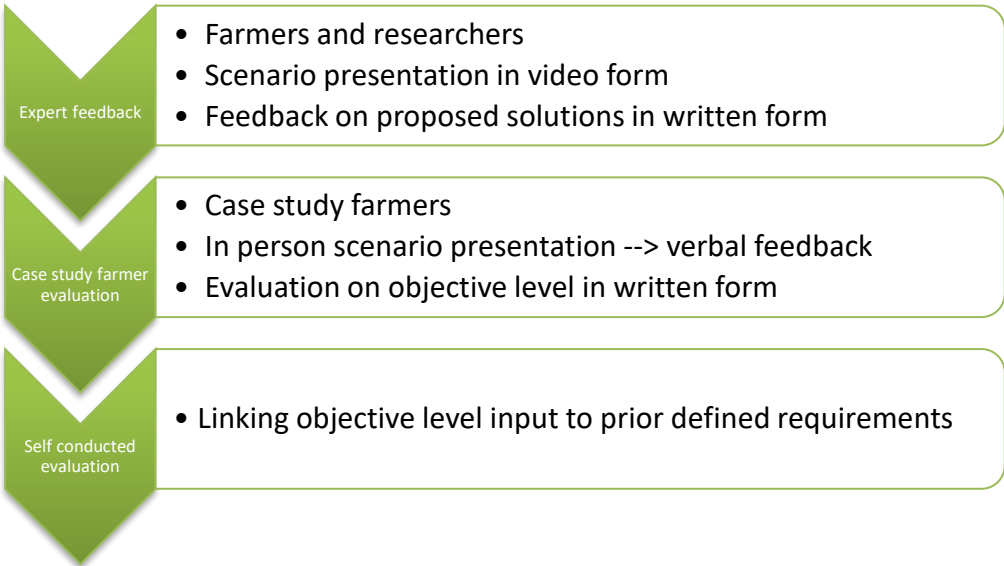


Figure 4: Three phase evaluation



4 Results

This chapter presents the results obtained during the Reflexive interactive design process. Each step of the design process, from key challenges to solution concepts and evaluation, will be addressed. This is followed by a chapter that focuses on the factors to be considered when designing and selecting harvesting methods to enhance harvesting efficiency.

4.1 Key challenges

The Root cause analysis (RCA) (see Figure 5) shows underlying factors contributing to inefficiencies in harvesting performance and highlights aspects that need to be addressed to improve on this aspect. The challenges surround four main topics, which are described in more detail below.



4.1.1 High system complexity

High species diversity, multiple vegetation layers and an irregular planting scheme are inherent characteristics of CAS. Due to these characteristics, a successful harvest operation is only possible with specialised knowledge and observation. This causes difficulties in instructing workers, a high risk that not all crops will be harvested and missing the optimal harvest window. Further, multiple vegetation layers increase the difficulty of not damaging surrounding plants during harvest and accessing plants for maintenance and harvest. High species diversity also leads to less investment power for specialised machines and tools, as this means that, per species type, fewer plants are present and therefore lower total yields are obtained. Lastly, the irregular planting scheme results in increased transportation times. Therefore, this thesis aimed to identify system design options and communication pathways to overcome knowledge barriers and increase accessibility for maintenance and harvest.

4.1.2 Physically challenging and time intensive work

Harvest operations in CAS are physically challenging and time-intensive due to the manual harvesting and transportation process. Practitioners often face the challenge that currently available machines are unsuitable in a complex agroforestry setting. There are various reasons for this, which are shown in detail in Figure 5.

4.1.3 Use of alternative crops

Complex agroforestry systems explore the use of alternative crops to increase diversity and widen the range of locally produced food. As these crops did not undergo as much breeding effort, fruit sizes tend to be smaller, leading to an increased effort when harvesting. Furthermore, there is limited information available regarding the needs and care of these plants, resulting in suboptimal yield levels. Therefore, this thesis explored innovative ways of harvesting such crops to increase harvesting efficiency. Gathering data and information on alternative crops suitable for CAS is out of the scope of this research. However, given its relevance, this highlights an opportunity for further research efforts.

4.1.4 Inaccessibility of paths

Inaccessibility of paths can be another issue in CAS. Non-flat terrain, meandering, narrow, and overgrown paths make the transport of tools and crops more challenging, increase the distances that need to be covered, and make access for observation, maintenance, and harvesting difficult. Therefore, designing for accessible paths is a crucial consideration in this thesis.



4.2 System analysis

This chapter provides an overview of the context of the selected case study farm.

4.2.1 Case study Het Middenbos

Het Middenbos, located in Tonden, the Netherlands, is a 22-hectare conventional dairy farm which is currently being converted into an agroecological estate. Over the last 100 years, this land has undergone a transition from forest to grassland, largely due to the introduction of cattle. However, the new direction of the farm reintroduces trees to the landscape by implementing various agroforestry systems, such as a food forest camping, a nut-focused complex agroforestry system, and tree meadows, in addition to partially restoring the natural forest. Cooperation of entrepreneurs in various business operations lies at the heart of this project (Stichting Regeneratie, n.d.-a). In Figure 6, an overview of the currently planned landscape elements can be found.

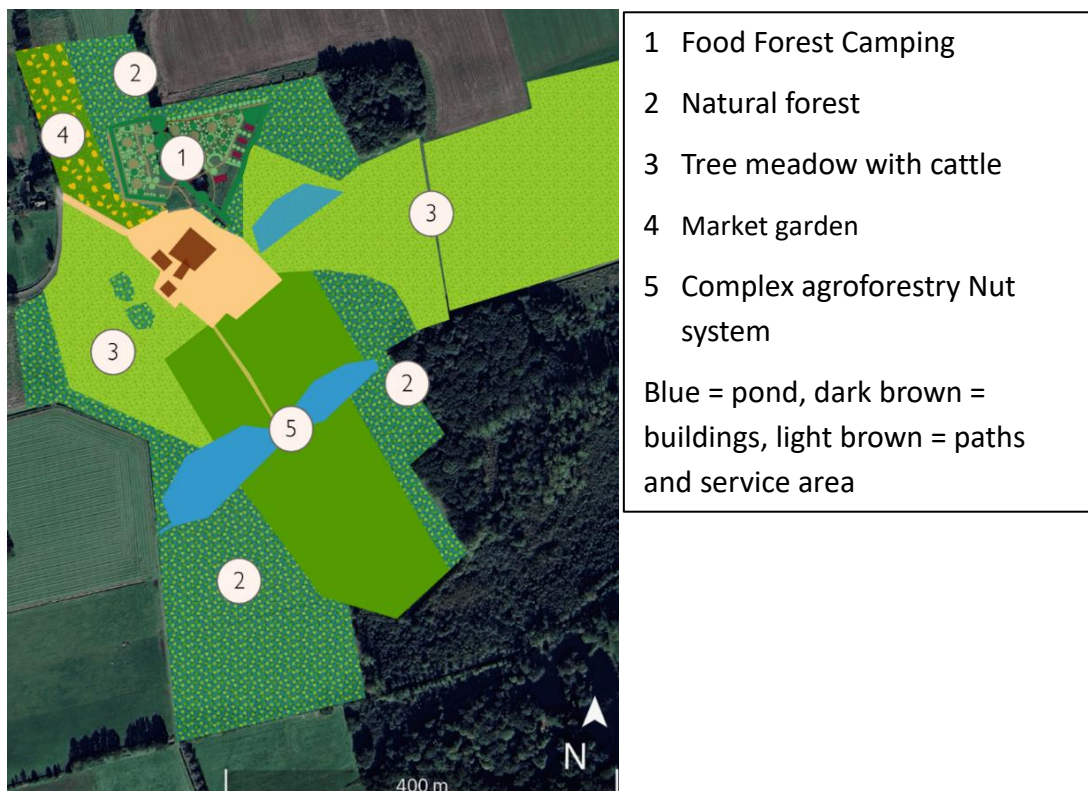


Figure 6: Map of landscape elements of Het Middenbos

This research focuses on the complex agroforestry nut system (5), which is about 4.5 ha. There will be temporary arable farming between the tree rows in the next six to ten years. In the long term, this will be replaced by no-dig market gardening with perennial herbs and vegetables. Stakeholders involved in the farm are described in chapter 4.4. The farm is characterised by loamy sandy soil, an organic matter content of 5 % and a pH of 5.3. The northern part of the complex agroforestry nut system is generally wetter than the southern part. Harvesting methods, in-field storage, and transport methods are considered in the design process, while sorting, off-field storage, and further processing are outside the scope of this research.



4.3 Future vision

While high harvesting efficiency is the primary focus of this thesis, the objectives of economic feasibility, high environmental sustainability, and high social wellbeing are equally important to consider in order to deliver design and harvesting scenarios that align with the overall vision of the case study farmer. All main objectives are described in more detail below. The developed objectives including their sub-objectives (objective tree) can be found in [Figure 7](#).

4.3.1 Economically feasible

To guarantee economically feasible harvesting operations, low investment and operating costs of machinery and tools are aspired. Additionally, the chosen harvest methods should be multifunctional, enabling harvest operations with minimal crop damage and allowing for harvesting at the optimal ripeness level, thereby facilitating diverse sales channels for both processed and fresh produce.

4.3.2 High harvesting efficiency

High harvesting efficiency is reached by minimising harvest and transport times, while simultaneously maximising harvested produce. To minimise labour hours, it is essential to guarantee easy access to plants, use machinery compatible with a dense planting scheme and multiple vegetation layers. Additionally, the system should be designed in a way that makes it easy for workers to understand and collaborate. Low transport times are achieved by minimising distances from harvest areas to collection points, from collection points to storage locations, and between plants that are harvestable at the same time. To maximise harvested produce, high yields and harvesting a high percentage of these yields are sought.

4.3.3 High environmental sustainability

Next to considering economics and efficiency, CAS inherently strives for high environmental sustainability. Therefore, the machinery used should be lightweight to avoid soil compaction and use minimal energy or gasoline, thereby minimising air pollution and other adverse environmental effects.

4.3.4 High social wellbeing

A high social well-being is another important objective for well-functioning CAS. Firstly, workers should experience low physical discomfort during harvesting, meaning they should be able to work in ergonomically supportive work positions, do not need to lift heavy and have a low risk of acquiring scratches and skin irritation. Since the case study farm also welcomes visitors on their camping a high visitor satisfaction is also essential, meaning that there should be open and navigable access for visitors in a diverse landscape.

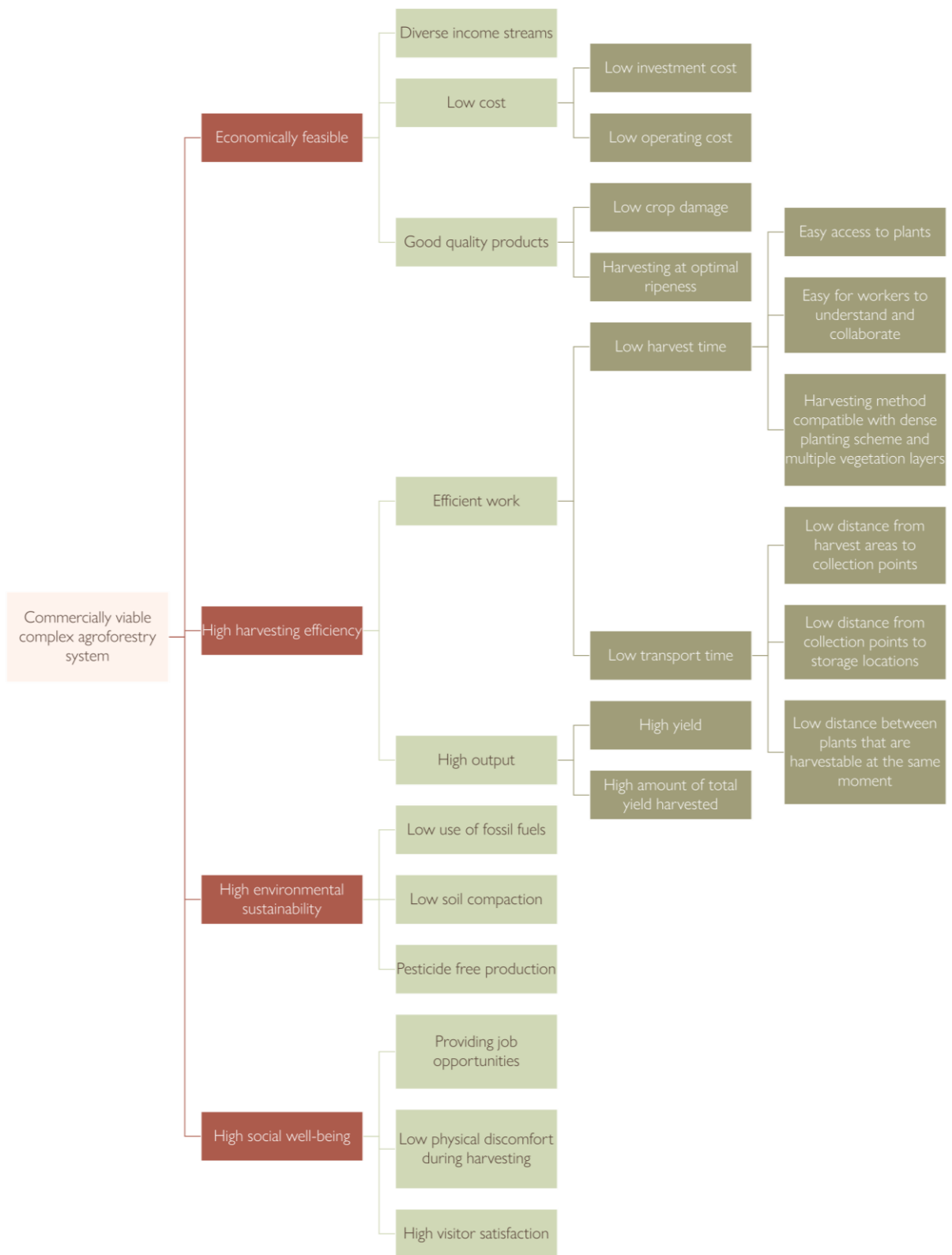


Figure 7: Objective tree for a commercially viable CAS



4.4 Key actors

Various actors are connected and/or involved with the case study farm. An overview of the most essential ones is given below.

The case study farm was previously a conventional dairy farm and is currently in transition to an agroecological estate. Currently, there is also a transition period between the new farmer, Sander, and the previous owner, Pieter. Pieter is not stepping down fully yet but will still perform arable farming till he retires in about six years. The dairy cows have left the farm; however, cows from neighbouring farmers will still graze on the tree meadows. Both farmers will carry out this part of the farming business. It is also essential to mention that the families of both farmers are also involved with the farm. A new young entrepreneur, Robin, will also join the business, taking care of a piece of the land, which may be expanded in the future.

Part of the property is being sold to the nature conservation organisation Natuurmonumenten. This organisation allows Sander to lease back this area and use it for natural forest, certain parts of the agroforestry plot and natural grassland. This lowers the financial burden for the farmer and increases economic viability.

Sander also initiated a project within the farm called Klimaatboerderij (Climate farm). The main focus of this project is water quality and quantity, biodiversity and yield (food, electricity), resulting in a maximised multifunctionality of agriculture. Partners of this project are the municipality of Brummen, the Waterschap (Water board), Stichting Regeneratie and Innovatie Cooperatie. It is part of the Regio deal, meaning that it receives subsidies from the national government. Next to these subsidies, the province of Gelderland also provides subsidies for the development of the agroforestry plots within the farm.

The camping guests are also important stakeholders of the farm. Their needs shape certain design decisions within the farm. The camping and surroundings should be aesthetically pleasing to be welcoming to visitors. Additionally, crops selected for the farm should be ready for harvest during the camping season.

Lastly, Neighbours also have an impact on the development of the farm since it is essential to the farmer to keep good relations with the surrounding neighbours. Discussion sessions are arranged so that all concerns are heard and a solution viable for everyone can be found.

On a wider context, various actors are involved in the research, design and development of complex agroforestry systems in the Dutch context. The main actors include research institutes, farmers, governmental institutions, agroforestry organisations, and agricultural machinery companies. An overview can be found in Appendix VII.



4.5 Brief of requirements

A brief of requirements for evaluating the design and harvest scenarios was developed. These requirements and a detailed description can be found in the table below.

Table 1: Brief of requirements, Index correlates with Table 3

Objective	Sub-objective	Index	Requirement	Description
High harvesting efficiency	Low harvest time, High yield	1	Harvesting efficiency is maximised in terms of output (kg) per labour input (hours).	Labour is restricted by the overall capacity of the people that will farm this piece of land. However, there are uncertainties on the exact capacity as it is unclear at this moment how many people will actually be involved (minimum of two) and how much labour will be available from the participation of camping guests. Furthermore, numerous activities must be executed (within the nut system but also in other parts of the farm), and the choice of system layout and harvesting methods for each activity leads to trade-offs in terms of labour. However, labour is definitely limiting, especially as this is only one part of the whole farming system; therefore, it is essential to increase harvesting efficiency to decrease the labour required. However, yields need to be considered as well. The aim is to not only decrease labour time but also maximise the yield harvested within that time.
	Harvesting method suitable for multiple vegetation layers	2	In the mature system, cultivation of herbs is possible without negatively affecting the harvesting efficiency of the nut cultivation.	As most efficient nut harvesting methods require an even surface and low vegetation, a trade-off arises with herb cultivation. Production and harvesting efficiency of nuts is the focus of this design. However, as it is a CAS, other vegetation layers and types are also essential. Therefore, the solutions proposed for the herb layer must align with the harvesting method of the nut system.
	Low transport time	3	Transport time (h/kg harvested product) is minimised.	The case study field is physically separated by a water body, resulting in two distinct fields: north and south. Therefore, transport distances can be minimised if all crops to be harvested in one harvest operation are either within the north or the south field. To decrease travel time even further, they should be grouped in adjoining tree



			rows. Cultivars of the same species can differ in their ripening times. Therefore, it is essential to consider cultivars' harvest periods and group plants accordingly.
Efficient work	4.1	Arable strips between tree rows are a multiple of 3m.	The width of the machinery used on the arable crops is 3m. To ensure efficient operations, the arable strips should be a multiple of this width, allowing the machine to fit within the row and avoid having to drive over the same place twice.
Efficient work	4.2	At least 6 meters of open space is maintained at the beginning and end of each arable strip, with the aim of minimising this area as much as possible.	According to the farmer, a minimum of 6 meters is required at the beginning and end of each arable strip for the machinery to turn. However, this creates a trade-off with the bulk production of nuts, with the aim of planting as many trees as possible and minimising unused space.
High yield	5.1	Nuts yield per nut species is at least 500kg, with a target of 1000kg.	The goal of the system is to produce nuts in bulk. The actual amount required depends on the specific requirements of the processing facility. The market for nuts produced in the Netherlands is currently quite low; therefore, there are not many processing facilities available. However, nut production in the Dutch context is generating momentum and the situation might differ once the nut trees are in full production. One processing facility, Veld 4, requests at least 700 kg for washing and drying of walnuts, and 1,500 kg for cracking (Veld 4, n.d.). However, with increasing nut production in the Netherlands, their requirements may also change. Additionally, the case study farmer also considers creating a processing facility on the farm. Due to these insecurities, it is hard to define exact yield levels. However, a realistic range for it to be considered bulk for this specific case study lies between 500 and 2000 kg per type of nut.
Efficient work, Good quality products	5.2	The spatial arrangement and choice of cultivars ensure uniformity in nut characteristics, enabling efficient and consistent post-harvest processing into high-quality products.	Processing nuts into high-quality products requires uniformity in nut characteristics, such as size, oil content, and taste. Specific cultivars are also more or less suitable for processing. Therefore, the design of spatial arrangement should minimise the mixing of different species and cultivars. Further, cultivars should be selected for their suitability in terms of processing.



Economically feasible	Efficient work	6	Vegetation planted within the three-meter-wide herb strips has minimal impact on arable farming.	Vegetation planted within the herb strips should not be overlapping into the arable strips so that arable machinery can pass without being disturbed (and vice versa the herbs are not disturbed by arable machinery). Further, shading can have negative impacts on the crops grown within the arable strips.
	Diverse income streams, good quality products	7	Food supply of fresh or processed produce for camping guests from April to October.	The food forest camping produces food for the camping guests. However, fruits attract wasps, which can be a safety concern for the guests. An additional food supply from the nut system can alleviate some pressure on the food forest camping. Guests stay from April to October. There is a trade-off between providing fresh produce throughout this period and maintaining harvesting efficiency. In terms of harvesting efficiency, harvesting larger amounts at once is beneficial.
	Diverse income streams	8	A diversity of revenue-generating business activities is possible.	By increasing the diversity of revenue-generating business activities, risks are spread. Therefore, the proposed solutions should encompass a diverse range of species, with options for fresh consumption and processing into various products. Furthermore, it should add additional value to the camping experience, thereby elevating the camping business.
	Low investment costs	9.1	Harvesting machines and tools can be used for at least two functions, with the target of performing as many as possible.	As there are many different crops to be harvested, investing in multiple harvesting methods is necessary. This, however, comes with increased investment costs. To keep investment costs as low as possible, harvesting methods should be able to fulfil multiple functions (key functions are listed in chapter 4.7), thereby reducing the number of harvesting methods required to complete all harvesting operations. This can mean, for example, that one harvesting method can harvest different types of crops. Another example is that one method could be used to reach, store and transport crops.
	Low investment costs	9.2	The investment costs for the nut harvesting method are below € 6000, with the target to minimise costs.	The case study farmer deals with trade-offs between investing in a harvesting method with the highest harvesting efficiency and the associated investment costs. Additionally, as mentioned above, as there are many different crops to be harvested, investing in multiple harvesting methods is necessary, creating a trade-off between investing in harvesting methods for each type of crop present in the system. 6000 Euros is an upper limit for investments in the nut harvesting method by the means



				of the case study farmer. However, there are uncertainties in regards to potential available subsidies that could cover part of the investment and increase the total investment capacity.
High environmental sustainability	Low soil compaction	10	Soil compaction in the top 40 cm is max 300 kPa/m ² , with the target to minimise it as much as possible.	Soil compaction has adverse effects on plant growth. To guarantee effective rooting by trees and shrubs, soil compaction in the top 40cm should be lower than 300 kPa/m ² .
	Pesticide-free production	11	No use of crop protection products.	In accordance with the farm's values, no pesticides are to be used to maintain production levels.
	Low use of fossil fuels	12	Machinery gasoline consumption should be as low as possible.	The farm's goal is to be climate positive. Therefore, the use of fossil fuels should be reduced as much as possible. However, to maintain harvesting efficiency levels and make labour possible, harvesting methods that use gasoline are not directly discarded.
	Providing Job opportunities	13	The system allows multiple entrepreneurs to be involved.	The system should enable multiple entrepreneurs with diverse backgrounds to participate in the farm. Therefore, the system needs to be designed in a way that enables communication and division of labour.
	High visitor satisfaction, high harvesting efficiency	14	Camping guests can self-harvest a variety of crops.	Crops intended for self-harvesting must be easily identifiable and accessible to camping guests to perform self-harvest. Depending on the plant knowledge of individuals and the diversity of species, this may require more or less guidance.
	High visitor satisfaction	15	The design should be visually appealing to enhance the camping experience for guests.	According to the case study farmer, the design should be aesthetically pleasing. As aesthetics are subjective, the case study farmer's opinion on what is aesthetic is used to evaluate this requirement.



4.6 State-of-the-art

This chapter describes state-of-the-art harvesting methods for nuts, fruits, and herbs commonly used on small-scale farms. A longlist of currently available tools and machinery developed by various companies and low-tech self-built options suitable for agroforestry systems, including pictures can be found in Appendix VIII.

4.6.1 Nut harvesting methods

When the harvest of nuts, like walnut, hazelnut, chestnut, is carried out, there are two options to detach the nuts from the tree for further collection. Either one waits for the nuts to fall naturally once they are fully ripe and the green husk bursts open, or shaking machines can be used to make nuts fall at the same time (Agroforestry Vlaanderen, 2022). When using shaking machines, knowledge of fruit ripening for the specific conditions of the farm is needed to carry out the right frequency and timing of shaking for an efficient harvest (M. Veld 4, personal communication, March 24, 2025).

There are two different options of shaking technology currently available on the market. When using a cable shaker, a steel cable is manually attached to a main branch or the trunk and then tightened, after which the shaking process can start (see Figure 8a). There are telescope poles available that make the attachment process more time-efficient (see Figure 8b). A shaking hook (see Figure 8c) can be attached to the telescope pole for manual shaking by hand. When using a cable shaker, the shaking process including transport to the next tree, positioning and attachment of a large high stem tree takes about 3-5 minutes, which leads to a shaking performance of about 20 trees per hour (Feucht-Obsttechnik, n.d.). Another technology is a trunk shaker (see Figure 8d), which is also attached to a tractor but automatically grabs the tree and then shakes it. There are different versions which come in various sizes, allowing a shaking performance from 55 to 300 trees per hour (AMB Rousset, n.d.-b).

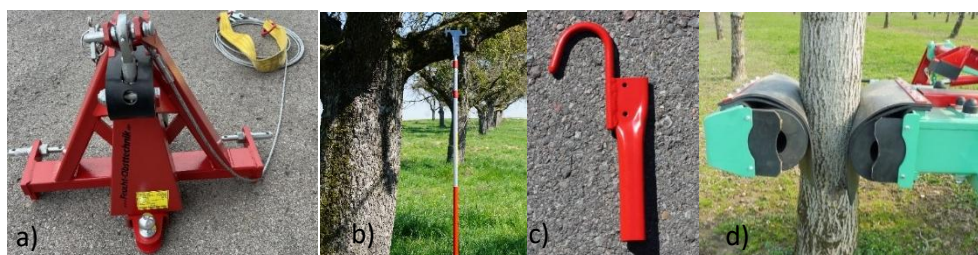


Figure 8: a) cable shaker (Feucht Obsttechnik, n.d.), b) telescope pole (Feucht Obsttechnik, n.d.), c) Shaking hook for manual shaking (Feucht Obsttechnik, n.d.), d) trunk shaker (AMB Rousset, n.d.)

After shaking or when the nuts naturally fall from the tree, nets can be used to catch the nuts and then subsequently collect them (Agroforestry Vlaanderen, 2022). Nets can either be placed on the ground or attached to the trees and hang in the air (H. Meißel, personal communication, April 4, 2025; M., Agroforestry Vlaanderen, 2022). An example of how this can look in practice can be found in Figure 9.



Figure 9: Examples of harvesting nets hanging between the tree rows, with a) harvesting nets off season at Meißelhof, Austria, b) harvesting nets during harvest season at Haselgut, Austria



If nets are not being used, there are different harvesting tools and machines available to collect nuts from the ground. The most decisive factor of whether a technology is suitable is the plantation size (Agroforestry Vlaanderen, 2022). Technologies available can be categorized into the following four groups:

- Manual (non powered) tools
- Powered hand-operated machines
- Self-propelled machines
- Powered machines pulled by external source

Manually handled tools can be used for smaller plots. A nut roller is a technology in which a round metal cage is attached to a stick in such a way that it can be rolled over the ground and thereby pick up the nuts (see Figure 11a). A special emptying bracket is available to easily empty the nuts into a bucket. Different options are available for different sizes of nuts. Another technology is based on a cylinder equipped with flexible fins rotating around its axis. By pushing or pulling (depending on the specific technology), the nuts are being picked up and transferred into a storage container. There are different options available for different sizes of nuts. Additionally, this technology can also be attached to a tractor or self-propelled mowing machine (Agroforestry Vlaanderen, 2022) (see Figure 11b).

Powered hand-operated machines are also making use of flexible fins which scoop up the nuts and transfer them into a storage container (see Figure 11c). Depending on the technology, the flexible fins are rotated either horizontally or vertically (see Figure 10) and can be powered with electricity or gasoline. The harvesting performance of these type of machines range from 1.5 – 4 tons per hour. The loading volume ranges from 40 to 200 liters (Feucht Obsttechnik, n.d.-b; Organic tools, n.d.-a).

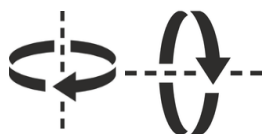


Figure 10: Vertical and horizontal axis rotation

Self-propelled machines use the same rotating fin technology, but are considerably larger in size. The conductor sits on the machine and steers it with some form of steering wheel (see Figure 11d). Instead of boxes at the back of the machine, hydraulic unloading systems are used, which increase the loading volume (ranging from 150 – 2100 litres). Harvesting performance ranges from 3-8 tons/h (for small and medium-sized machines). The largest machines are able to harvest one hectare of plantation in 45 minutes to 1 hour and 45 minutes (Agroforestry Vlaanderen, 2022; AMB Rousset, n.d.-a; Feucht Obsttechnik, n.d.-b).

Another option is placing the nuts in a row with either a broom or a sweeping machine which is pulled by an external source (R. & H. Tuenter, personal communication, March 20, 2025; Agroforestry Vlaanderen, 2022). Then the nuts can either be manually scooped up with a shovel or sucked up using a vacuum system (see Figure 11e). The long pipes of the vacuum system make it possible to harvest from a distance of 70-80 meters, which makes it especially useful in sloping terrain since the tractor does not need to drive the whole terrain. Manually scooping up the nuts results in fewer impurities being taken with the nuts. However, lots of manual labour is needed (R. & H., Tuenter, personal communication, March 20, 2025). Another option is to combine the suction system with the above-mentioned harvesting nets, thereby the nuts to be harvested are on a smaller surface area and are mixed with fewer impurities since they never touch the ground (E. Hörtenhuber, personal communication, May 29, 2025).

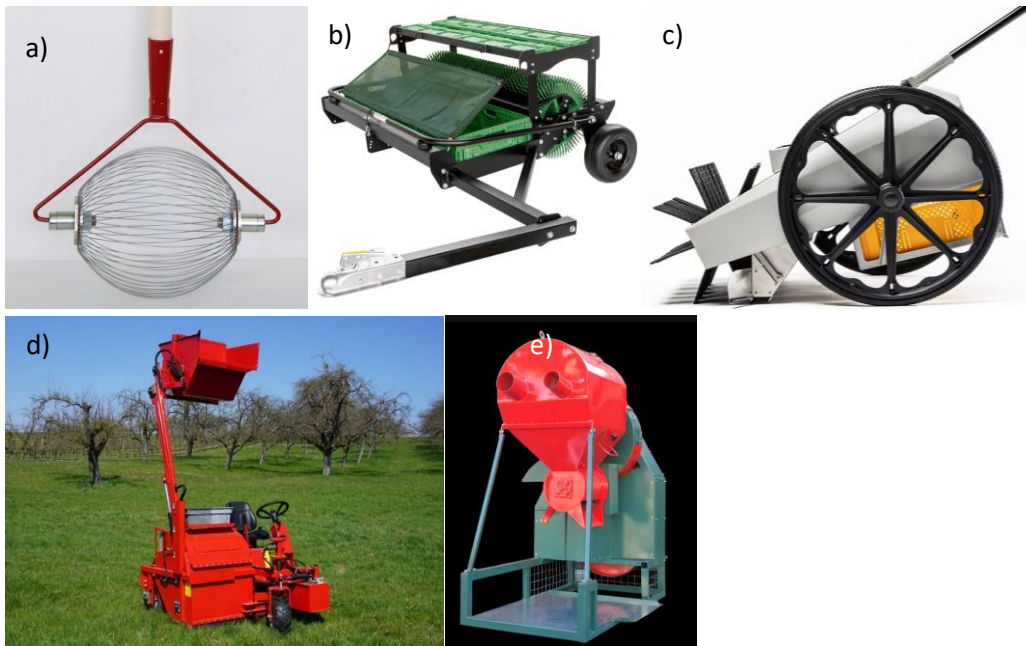


Figure 11: a) Manual tool (Veld 4, n.d.), b) manual tool pulled by external source (Bag-A-Nut, n.d.), c) Powered-hand operated (Organic tools, n.d.-b) d) Self-propelled harvester (Feucht Obsttechnik, n.d.-a) d) Suction system (Proizvodi Servis, n.d.)

4.6.2 Fruit harvesting methods

Manual fruit harvest ensures the precise determination of the crop's maturity level and minimises mechanical damage. Therefore, most fruits intended for fresh consumption are still harvested manually (Erkan & Dogan, 2019; Zhou et al., 2016). Various harvesting tools assisting manual harvest are available. For fruits that are cut from the branch, some form of harvesting shears or cutters is used. This ensures that the fruit stem is not torn from the fruit to prevent the entry of disease. The most commonly used tool is simple pruning shears, as shown in Figure 12 (AgriSETA, 2013).



Figure 12: Pruning shears (AgriSETA, 2013)

To store the fruit during harvest, several picking containers in various sizes, types and materials are used. Most commonly, so-called picking bags are used; they are available in various designs and materials, and some examples can be observed in Figure 13 (AgriSETA, 2013).



Figure 13: Picking containers (Terrateck, n.d.-a)



Fruits that can be damaged easily are often harvested into picking crates with low depth to avoid harvested produce from being compressed. These crates are often designed to be stacked upon each other. On the other hand, fruit that is able to withstand more pressure is often transported in bulk bins with a storage capacity of 350 kg (See Figure 14) (AgriSETA, 2013).



Figure 14: picking crate (left), bulk bin (right, (ELGIN AGRI-BIN, n.d.))

To reach fruit high in the tree, simple ladders that are either rested against the tree or stand by themselves are utilised (see Figure 15). Different types of ladders can be classified into movable, two-legged and three-legged ladders, made with materials such as metal and wood (AgriSETA, 2013; Erkan & Dogan, 2019). Another method frequently applied are harvest-assist platforms. These platforms range from simple trailers that are pulled with a tractor, as can be observed in Figure 16 (Guevara et al., 2021) to self-propelled vehicles with multilevel decks (Zhang & Stavros, 2023). However, even with the assistance of the previously mentioned methods, manual harvesting has high labour demands. The scarcity of available workers and rising wages make this method increasingly challenging (J. et al., 2024).



Figure 15: Different types of ladders, top left movable ladder (De Walnoothoeven)



Figure 16: Trailer and bulk bins transported with a tractor along the tree lines (Guevara et al., 2021)

Mechanical harvesting has the potential to increase the harvesting efficiency of fruits significantly (Li et al., 2011). However, for most fruits, mechanical harvest cannot maintain the quality necessary for fresh consumption. Therefore, it can only be utilised if the produce is further processed. There are different types of mechanical harvesting methods. Most commonly, a shaking mechanism is used to detach the fruits from the branches (Erkan & Dogan, 2019; Warrington, 2022). The same shaking mechanism presented in Chapter 4.6.1 can be applied here. Additionally, a handheld limb shaker is a possibility when harvesting fruits (see Figure 17). This type of shaker is often powered by a 2-stroke engine and transmits power through a boom and a C-shaped clamp (Arigela et al., n.d.). When a shaking mechanism is applied, fruits can either be harvested from the ground with sweeping-type machines, as discussed in the chapter above, or caught with some type of catching mechanism (see Figure 18). For small-scale farms, this catching mechanism can either be in the form of an upside-down umbrella, harvesting nets rolled out under the tree or a V-shaped catching frame (Warrington, 2022).



Figure 17: Handheld limb shaker(Arigela et al., n.d.)



Figure 18: Upside down umbrella catching mechanism (left, (HARVEST, n.d.)), Semimechanical harvester for blueberry (right, (Zhou et al., 2016))

4.6.3 Herb harvesting methods

In small-scale herb farming, herbs are often harvested manually, either by hand-picking or via cutting the herbs with scissors or a (hand) scythe. This enables high-quality and selective harvesting; however, labour requirements are high. Adaptations can be made to these tools to enhance harvesting efficiency. By attaching a plastic attachment funnel to scissors, herbs are held together when harvested and can be efficiently placed into a storage container, since the herbs will only fall out when the scissors



are opened. Another option is to fit a wire mesh onto a scythe. After each stroke, herbs are gathered in the mesh and can be placed on a nearby sheet (see Figure 19).



Figure 19: Left – Scissors with plastic funnel (Les Forestibles), right – Catching Scythe at Bronzewing farm (Small Scale Sustainable Herb Farming Lessons from France and Australia, 2020)

However, depending on the scale of the farm, human-scale mechanisation methods can be useful. The simplest mechanised harvesting method is a long-reach edge trimmer, where the crops are harvested by cutting the entire plant with a serrated blade. With this method, the crop needs to be manually collected from the ground. However, there are handheld tools and small-scale machines designed specifically for harvesting herbs that also use a serrated blade to harvest herbs, accompanied by a mechanism to transport the harvested herbs into a harvest bag. The different types of transport mechanisms are a macrame-braided string pick-up reel, a conveyor belt and airflow. Harvesting methods applying this transport mechanism are shown in Figure 20. Another method is a reaper-binder, this method cuts the herbs as the other methods mentioned before, however, instead of transporting them into a storage container, this machine collects the stems and binds them in bunches, leaving them on the ground.



Figure 20: a) long-reach edge trimmer (HYINDAI Power products, n.d.), b) handheld tool with macrame braided string pick-up reel (Terrateck, n.d.-c), c) hand pushed, powered harvesting method with conveyor belt transport mechanism (Terrateck, n.d.-b), d) Japanese tea harvesting machine with airflow transport mechanism, adapted with construction and tires to be used by one person (Zermanek Biohof), e) Reaper-binder (Comparetti et al., 2022)



4.7 Key functions & Morphological chart

A function analysis was carried out to identify key functions (see Table 2) essential to realising the system's objectives while meeting the requirements. Functions are defined as actions that are performed to convert inputs into outputs. Inputs and outputs can consist of flows of material, information and energy.

Table 2: Key functions

Function	Fresh produce	Processing	Description
Detach Nuts	Passive detachment		Nuts are being detached from the branch by gravity.
	Shake		Nuts are being detached from the branch by shaking the tree before the nuts fall naturally.
Collect Nuts			Nuts are being collected into storage containers.
Reach fruit			Reaching the fruit for subsequent detachment.
Grip fruit			Gripping the fruit by its body or stem for detachment.
Detach fruit			Detaching the fruit from its stem by using a pulling, twisting or cutting motion.
	Passive detachment		Fruits are being detached from the branch by gravity.
	Shake		Fruits are being detached from the branch by shaking the tree before the nuts fall naturally.
Collect fruit			Fruits are collected into storage containers.
Detach herbs			Harvesting herbs by detaching them from their stem.
Collect herbs			Herbs are collected into storage containers.
Store Harvest			Storing fruits, nuts, herbs and perennial vegetables during harvesting, to the central collection point and off the field.
Transport harvest			Transport fruits, nuts, herbs and perennial vegetables during harvesting, to the central collection point and off the field.

Based on the identified key functions, a morphological diagram was generated (see Figure 21). For each key function, four to ten working principles, also referred to as solutions, were identified. This morphological diagram was then used to generate creative scenario concepts.



Function	WP 1	WP 2	WP 3	WP 4	WP 5	WP 6	WP 7	WP 8	WP 9	WP 10
DETACH NUTS	Passive detachment		Shake							
	Natural drop	Hand	Cable shaker	Stem shaker						
COLLECT NUTS	Hand	Net	Wire basket	Shovel	Flexible fins horizontal	Flexible fins vertical	Suction (Vacuum)	Sweeper	Umbrella collector	
	Hand	Pole	Ladder	Platform						
REACH FRUIT	Hand	Pole	Ladder	Platform						
GRIP FRUIT	Hand	Soft gripper	Rigid gripper	Metal hook	Bag					
DETACH FRUIT (FRESH PRODUCE)	Pull or Twist				Cut					
	Hand	Soft gripper	Rigid gripper	Metal hook	Comb	Scissors	Knife			
DETACH FRUIT (PROCESSING)	Passive detachment		Shake							
	Natural drop	Hand	Hook shaker	Vibrating comb	Cable shaker	Stem shaker				
COLLECT FRUIT	Hand	Net	Wire basket	Pins	Flexible fins horizontal	Flexible fins vertical	Suction (Vacuum)	Sweeper	Umbrella collector	
	Hand	Net	Wire basket	Pins	Flexible fins horizontal	Flexible fins vertical	Suction (Vacuum)	Sweeper	Umbrella collector	
DETACH HERBS	Manual tools		Powered tools							
	Hand	Scissors	Scythe	Serrated blade	Scissors					
COLLECT HERBS	Hand	Blade channeler	Rake	Macramé braided string pick-up reel	Airflow	Conveyor belt				
	Hand	Blade channeler	Rake	Macramé braided string pick-up reel	Airflow	Conveyor belt				
STORE HARVEST	Bucket	Cup	cardboard tray	Bag	Crate	Storage container on wheels				
	Bucket	Cup	cardboard tray	Bag	Crate	Storage container on wheels				
TRANSPORT HARVEST	Manual handled transport					Mechanically assisted - pulled by external source				
	Picking harness	Runners	Single-wheeled cart	Two-wheeled trolley	Four-wheeled cart	Tow-behind trailer	Single-wheeled cart	Tricycle	4-wheeled vehicle	4(+) wheeled platform

Figure 21: Morphological diagram



4.8 Design and management scenarios

This paragraph first describes the spatial layout, choice of species and cultivars, harvesting and transport methods of the created design and management scenarios. Second, an insight in the evaluation of these scenarios is presented, which is followed by the final design and management scenario. Lastly, a summarizing paragraph describing factors to be considered when designing and selecting harvesting methods to enhance harvesting efficiency is presented.

4.8.1 Spatial layout

Row distances and orientation

Vegetation should be arranged in a pattern rather than randomly distributed across the field, to facilitate plant localization for observation and harvesting, as well as improve communication between workers. Making this arrangement in straight rows is most beneficial for observation and harvesting but also minimises distances to be travelled. Therefore, the spatial layout of the design was chosen to be tree rows following the landscape, which results in an almost North-South orientation. North-South orientation allows a more even light distribution on both sides of the tree and direct sunlight into the temporary annual crop rows. Distances between the tree rows vary from 9 to 15 meters (distances specified for each row can be observed in Figure 22). These distances were chosen based on tree crown width, to allow for sufficient space for the crown to properly establish while maintaining enough light in the system in the long term. Further, it is important that the tree row distances (TRD) are consistently a multiple of three (machine width) to ensure that machinery used for arable farming can operate efficiently.



Figure 22: Spatial layout case study Het Middenbos, tree row distances indicated in purple, tree row number indicated in black



The smallest TRD is 9 meters, meaning that a minimum of 6 meters of arable strip remains. Two sightlines with TRD of 15 meters were chosen to provide a view from the farm all the way to the end of the field and allow the possibility of no-dig market gardening in the long term. Lastly, a few TRD are 12 meters to allow for more space for arable farming in the first years and the possibility of adding additional rows in between in a later period. Around the tree lines, there are 3m wide strips that will never be used for arable farming in order to protect the trees from damage and to be able to introduce a herb layer. A visual example can be observed in Figure 23.

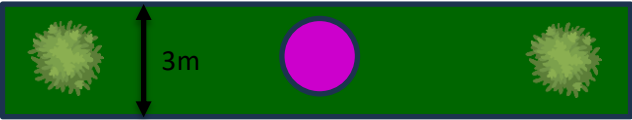


Figure 23: Width of herb layer strip below tree rows

The spacing between individual plants (within and between vegetation layers) was chosen to be wide enough at all growth stages to allow for easy observation and determination of the correct harvesting moment, as well as to prevent the harvesting process from being hindered by surrounding plants (planting distances and crown width per species can be found in Appendix IX).

4.8.2 Bulk scenario

Nut Species and cultivars

The bulk scenario focuses on the bulk production of chestnuts and hazelnuts. Hazelnuts are situated in the west of the plot, while chestnuts are to the east. This allows for a gradual increase in tree height from the open landscape in the NW of the plot towards the natural forest in the east. There is one species and cultivar per tree row to allow for ease of harvesting and processing into a uniform product. There are multiple cultivars from each nut species for cross-pollination.

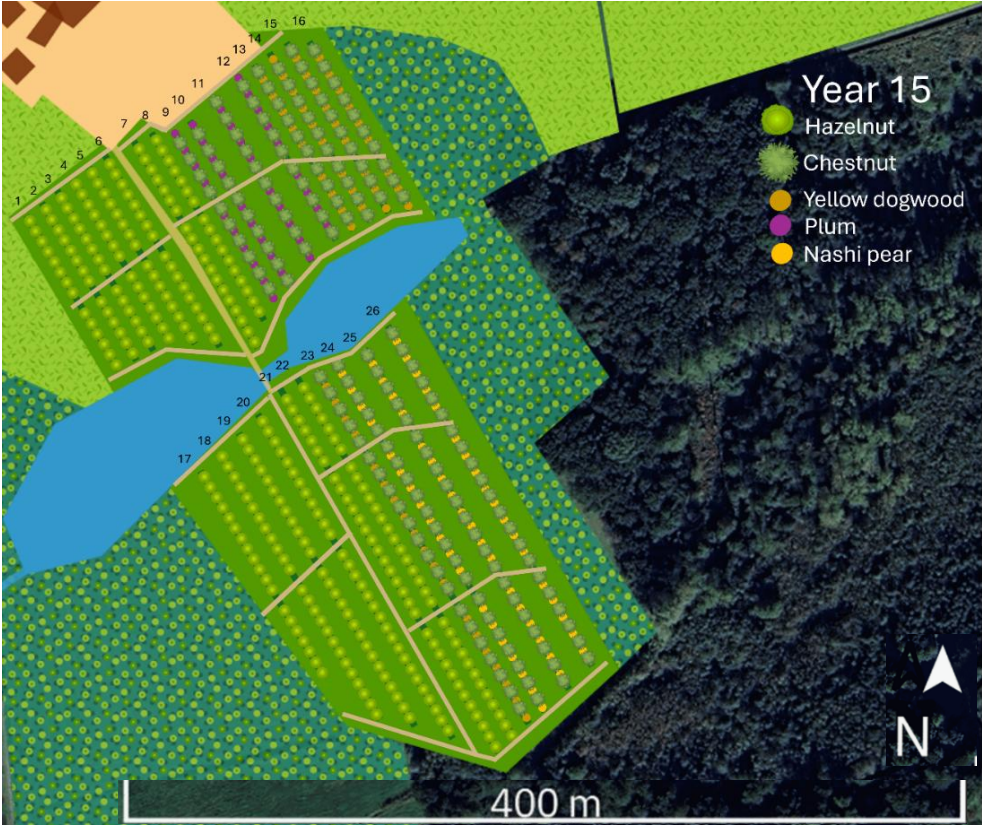


Figure 24: Bulk scenario spatial layout



The hazelnuts are planted in double density, resulting in a planting distance of three meters between trees (for a visual representation see Appendix IX, planting distances can be found in Appendix X). The cultivars chosen produce large nuts, easing harvesting and post-harvest operations. From a total of four cultivars, half are early and the other half are late cropping (see Table 8). The hazelnut cultivars grow in a tree shape, meaning there are fewer shoots close to the ground. This leads to efficient harvesting and the possibility of growing something underneath.

Chestnuts are interplanted with three different types of fruits, namely Nashi pear, Russian plum and Yellow dogwood. Chosen cultivars are hybrids between Japanese and European chestnuts that stay considerably smaller as compared to the common European chestnuts. This makes it possible to grow the chestnuts in a 9x9m grid. Hybrids were chosen as they generally have better resistance to diseases and pests and produce large nuts suitable for processing. Three different cultivars were selected, all being early-season cropping (see Appendix XI).

Nut harvesting method

The estimated harvesting time per harvesting method of the bulk scenario (without shaking, cable shaker and trunk shaker) plotted against the investment costs needed for this specific harvesting method can be observed in Figure 25.

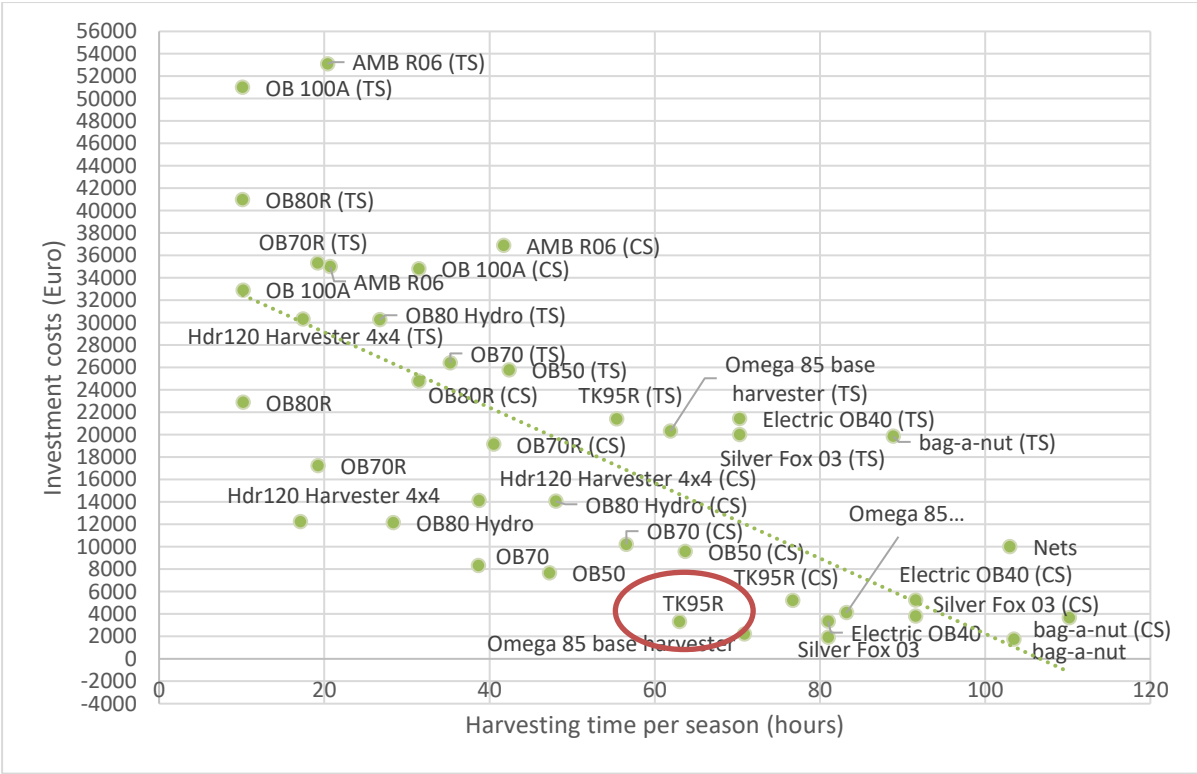


Figure 25: Total harvesting time of nuts versus investment costs (bulk scenario). TS = Trunk shaker, CS = Cable shaker

The trendline in Figure 25 clearly indicates a trade-off between investment costs and harvesting time. Based on the case study farmers' investment capacity, the most efficient harvesting method below an investment of 6000 Euros was selected. The TK95R harvester has an investment cost of about 3800 € and an estimated total harvesting time per season of around 60 hours. A visual representation of the harvester can be found below.



Figure 26: TK95R harvester

It is a sweeper-type, powered, hand-operated harvesting machine. It is produced by the Italian company Tekna Agricultural Machinery. It has a loading volume of 40L and is equipped with an assisted box unloading mechanism. It is suitable for various nuts and fruits and has a fuel consumption of approximately 3 liters per hour. It requires an even surface with low vegetation for harvesting, which impacts the possibilities of the herb layer. In Appendix XIII the machine's characteristics, categorized into benefits and drawbacks can be found.

Fruit species and cultivars

The fruits Nashi pear, Russian plums and Yellow dogwood were chosen considering several factors, which can be observed below:

- They are early cropping so that income can already be generated before nuts reach their yield potential.
- Comparably high shade tolerance to still obtain a yield even when chestnuts are fully grown.
- Reliable yields in an extensive system
- Their harvest window is compatible with the harvest window of the nuts, meaning they can be harvested before the nuts are ready to be harvested.
- They are not so delicate, which makes harvesting easier and more efficient.
- High product quality with multiple sales options
- Compatible with harvesting mechanization

Cultivars are selected for their high yield and pollination compatibility. Nashi pear cultivars Chojuro and Niitaka have a high juice yield, making them suitable for processing. Dogwood cultivars Bolestraszycki and Swietlajczok stay on the bush and can therefore be harvested uniformly. Russian plums are bred for the Russian context, being able to crop in an extreme and short growing season, have good frost resistance and are very sturdy (cultivars chosen are Komeet and Gek). As yellow dogwood has the highest shade resistance, it was planted in rows with the darkest microclimate, while nashi pear and Russian plums are within rows that receive more sunlight.



Fruit harvesting method

Mechanical harvesting operations can increase the harvesting efficiency of fruits. However, fruit that is mechanically harvested is not suitable for fresh consumption. Therefore, the choice was made to process the larger portion of fruits into various products. The harvesting method selected reflects the scale of fruit production and consists of two parts, namely an umbrella collector and a handheld shaker (see Figure 27). The handheld shaker is used to detach the fruits, while the umbrella catches them and consequently collects them in a crate.



Figure 27: Umbrella collector (left), handheld shaker (right) (HARVEST, n.d.)

Herb design and harvesting methods

The herb layer in the bulk scenario primarily plays a supporting role since the ground cover must be compatible with the nut harvesting method. Clover is sown below the tree canopy, and flower strips for biodiversity are within the tree rows. Flower strips with “tea herbs” that can be used to make a Middenbos tea mix for sale to the camping guests are situated along the main path in the north field (species list see Appendix XIV, placement within layout see Figure 29). The tea herbs are harvested with scissors that have a plastic funnel attached (see Figure 28). This plastic attachment is helpful since when herbs are cut, they are held together and can then be efficiently placed into a storage container, since the herbs will only fall out when the scissors are opened.



Figure 28: Scissors with plastic funnel

The non-culinary herbs are mown before nuts are harvested to guarantee a smooth and even surface for harvesting. In the long term, herb cultivation can be introduced in the current arable strips. In the wide strips, large-scale chamomile, lucerne, marigold, or perennials can be grown for sale not only to camping guests but also off farm.

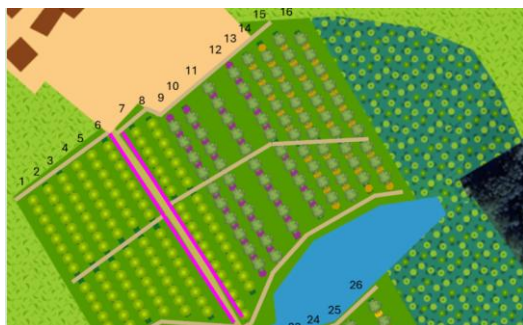


Figure 29: Middenbos tea mix cultivated in areas indicated in pink



4.8.3 Diversity scenario

In the diversity scenario, a higher diversity of nuts and fruits, as well as active herb cultivation, is introduced. Diversity refers to the number of species and cultivars, as well as the diversification of business activities and opportunities. A detailed description of the whole scenario can be found in the following paragraphs.

Nut Species and cultivars

In the diversity scenario, the focus lies on chestnuts, hazelnuts and walnuts. Hazelnuts are situated in the west of the plot, followed by walnuts in the centre, and then chestnuts to the east. This allows for a gradual increase in tree height from the open landscape in the NW of the plot towards the natural forest in the east. For better disease and pest resistance and cross-pollination, multiple cultivars are mixed within one row. To facilitate harvesting, there is one species per row, with cultivars grouped by harvest times.

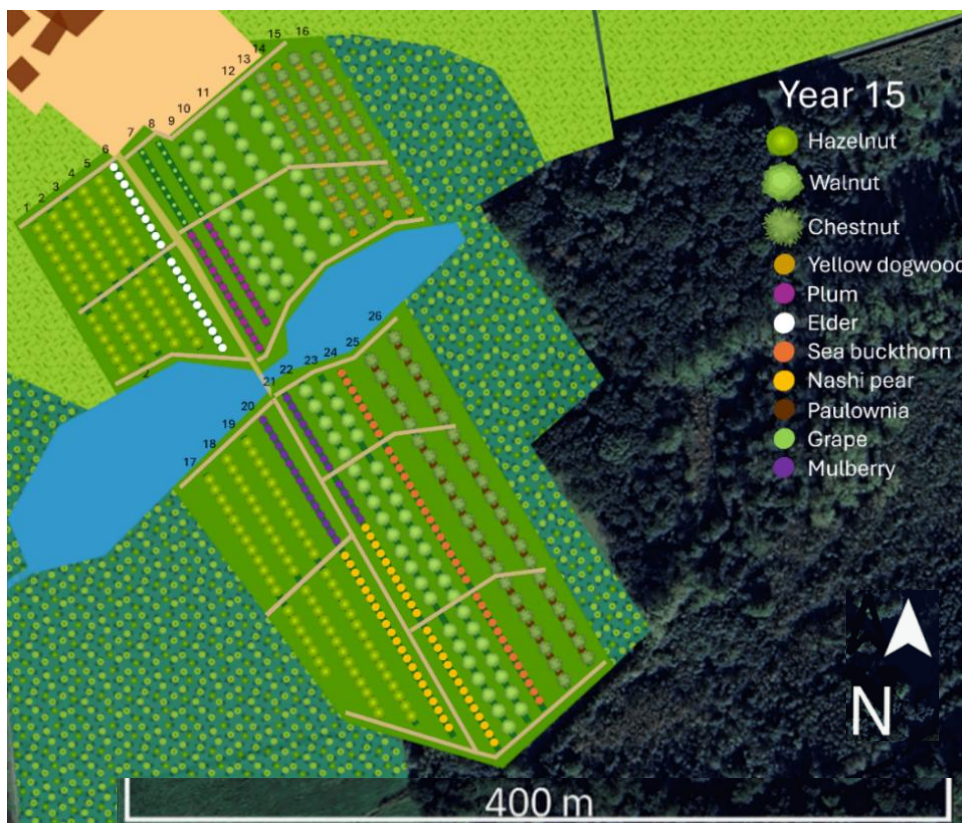


Figure 30: Diversity scenario spatial layout

The hazelnuts are planted in double density as compared to the final planting distance (for a visual representation, see Appendix IX; planting distances can be found in Appendix X). The cultivars chosen produce large nuts, easing harvesting and post-harvest operations. From a total of four cultivars, half are early and the other half are late cropping (see Appendix XI). The hazelnut cultivars grow in a tree shape, meaning there are fewer shoots close to the ground. This leads to efficient harvesting and the possibility of growing something underneath.

Walnuts are also planted in double density (4.5m planting distance between trees; for a visual representation, see Appendix IX, for planting distances see Appendix X). Cultivars are mid to late ripening. By choosing cultivars that are more tolerant of low temperatures and frost, as well as cultivars that sprout late, frost damage risks are lowered.



Additionally, several other factors were taken into account when selecting cultivars, which are presented below:

- High, stable yield
- High quality and uniformity of processing
- Compatible for pollination
- For various climate extremes

Chestnuts are intercropped with yellow dogwood in the northern field, and with Pauwlonia in the southern field. In addition to the three selected cultivars in the bulk scenario, three relatively late-season cropping cultivars are added, thereby spreading the harvest over a longer period and reducing the risk of pests and diseases. Pauwlonia is for wood production and will be cut down before its shading can impact the nut trees.

Nut harvesting methods

As for the bulk scenario, calculations were performed to compare different harvesting methods and select the most suitable one for the context of the case study farm and the respective scenario. The harvesting time per harvesting method plotted against the investment costs (without shaking, cable shaker and trunk shaker) can be observed in Figure 31.

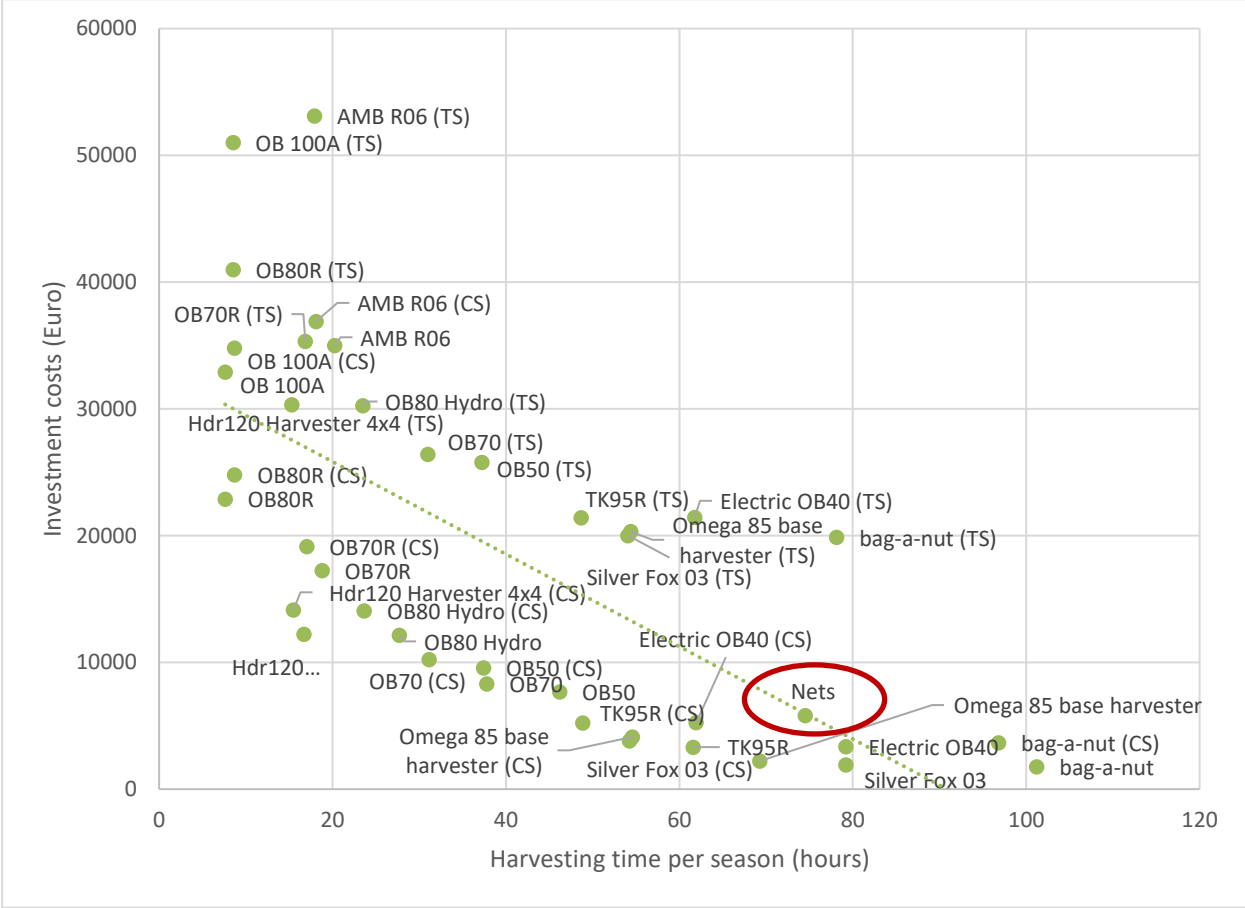


Figure 31: Total harvesting time of nuts versus investment costs (diversity scenario). TS = trunk shaker, CS = cable shaker

In this scenario, the trendline also clearly represents a trade-off between investment costs and harvesting time. As an active herb layer is desired for this scenario, a harvesting method that aligns with this design choice was selected. Harvesting nets mounted between the tree rows are a viable option. As can be seen in Figure 31, this method results in an estimated harvesting time per season of 75 hours and an investment cost of around 5800 Euros for the whole area when bought new. A



Chestnut farmer in Austria reported that his harvesting efficiency, compared to harvesting by hand, had increased from 10-20 kg/hour to 200 kg/hour. A visual representation of the harvesting nets can be seen in Figure 32.



Figure 32: Harvesting nets at Haselgut, Austria

As mentioned above, harvesting nets are mounted between the tree rows. They consequently catch the falling nuts, which gather in the centre of the net. This means the nuts to be harvested are in a much smaller area. The herb layer beneath the trees remains unaffected and can be harvested before or after the nut harvest occurs. Once trees are high enough, the net can be mounted at a height which enables a person to walk below, elevating the net and pushing the nuts to one side of the net, where it can be efficiently gathered into a large crate.

This harvesting method has the possibility to involve multiple people in the harvesting process. Furthermore, if available, hail nets used to protect fruits can be repurposed, significantly lowering the investment costs. As mentioned before, this harvesting method also leaves more possibilities for an active herb layer, as it does not interfere with the plants that grow below. Furthermore, it is a low-tech harvesting method that does not require any gasoline. Additionally, as the nuts never touch the ground, they are exposed to less moisture and dirt, reducing the risk of quality loss. However, the nets are very visible and may not be perceived as aesthetically pleasing. It also requires post-harvest sorting. In Appendix XIII the harvesting methods characteristics, categorized into benefits and drawbacks can be found.

Fruit species and cultivars

As in the bulk scenario, yellow dogwood is interplanted within the chestnut trees. However, in the diversity scenario, additional pure fruit rows are added. This was done to allow for more possibilities for fruit cultivation. Further, they separate the different types of nuts, reducing the risk of mixing. As in the bulk scenario, Russian plums and Nashi pears are selected. In addition, mulberry, elder, grapes and sea buckthorn are introduced. This results in more diversity for small-volume processing and sales, such as to camping guests or companies like Wilderland or the Roze Bunker. Fruit species were chosen in consideration of the same factors as the bulk scenario. In addition to this, attention was paid to whether they could be harvested in bundles by cutting whole branches or by mechanical harvesting. An overview of cultivars of all fruit species can be found in Appendix X.

Fruit harvesting method

As in the bulk scenario, an umbrella collector combined with a handheld shaker is chosen to harvest yellow dogwood, russian plum and nashi pear in addition to mulberry. Sea buckthorn is harvested by cutting the branches with the berries on them, which are then frozen and the berries are subsequently separated from the branches by rubbing them off with thick leather gloves. Elder is pruned to stay low, which makes it easy to reach and cut the (big) flowers from the branches, which are then collected into crates (for cutting pruning shears are used, see Figure 33). Grapes are also cut with scissors and directly harvested into crates. For the fruits harvested from shrubs or trees that are low enough to be



harvested when a worker stands on the ground, a harvesting belt which is able to support a crate is being used, that way both hands are free for picking the fruits (see Figure 33).



Figure 33: From left to right :Harvesting belt, Pruning shears, Wheelbarrow ladder

Once the trees become too high to reach the fruits from the ground, a ladder wheelbarrow can be used (see Figure 33). A ladder wheelbarrow is essentially a ladder on wheels which can be moved just like a traditional wheelbarrow. It has a space to place a crate on top and is available in various sizes. This method is multifunctional as it enables the worker to reach the fruits, makes it easy to move the ladder from tree to tree, the fruits do not need to be carried on the body during harvest and it can also be used to transport the harvest to the central collection point.

Active herb cultivation and harvesting

In the diversity scenario, an active herb cultivation is chosen. Left and right of the tree rows, 90cm wide herb strips are grown. There are two categories of produce. Firstly, perennial shoot vegetables for restaurants, which are mulched with leaves to reduce weed pressure. Secondly, herbs produced for buyers such as the Roze bunker and Wilderland. An overview of the species and their placement can be found in Figure 34.

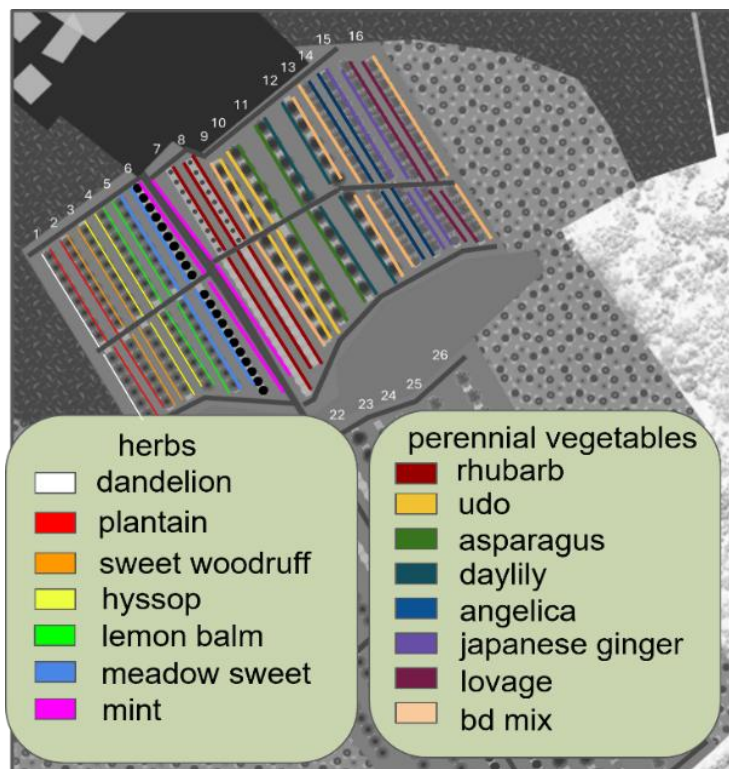


Figure 34: herb layer species diversity scenario



In the long-term species such as sweet violet, hosta, fern and wild garlic, which grow in especially shaded areas, can be introduced. Perennial vegetables are harvested by hand. The selected harvesting method for the herbs is a powered, hand operated baby leaf harvester, which is powered by a cordless drill and uses a conveyor belt which transports the herbs into a large bag (see Figure 35).



Figure 35: Powered, hand operated baby leaf harvester (left), cordless drill power source (right) (Terrateck)

4.8.4 Central collection paths

For efficient transport operations both from harvest areas to collection points and from collection points to storage locations, a network of central collection paths was created. During the harvest one follows the tree rows and stores harvest in the corresponding storage unit (see Appendix XVI) which is transported in a wheelbarrow to the next central collection point. An example of the harvest path is indicated in Figure 36.

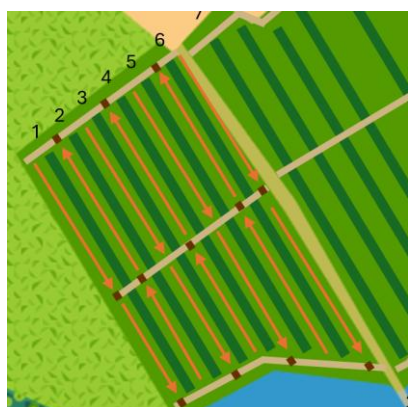


Figure 36: Harvesting path example row 1 to 6, orange arrows indicate the path the harvester takes, brown boxes are central collection points

A micro tractor with corresponding trailer then picks the harvest from this central collection points. Since the tractor uses only the central collection paths, he needs to cover shorter distances and does not compact the soil within the tree rows.

4.8.5 Evaluation

The generated scenarios were evaluated by the case study farmer based on sub-objectives drawn from the requirements. A four-point scale was applied, with one being the lowest and four the highest score. The diversity scenario scored slightly higher than the bulk scenario, as can be observed in Table 3. In addition, verbal feedback from the case study farmer also highlighted the preference towards the diversity scenario. The sub-objectives evaluated by the case study farmer were derived from the previously defined requirements and therefore stand in relation to one another. This chapter examines the connections between the sub-objective evaluation, case study farmers' comments, expert feedback and the requirements to provide a more detailed evaluation and formulate a final recommendation.



Table 3: Evaluation form scenarios & goals, evaluated by case study farmer; B= Bulk scenario, D= Diversity scenario;* indicates that the sub-objective was explained in more detail; sub-objectives

Objective	Sub objective	B	D	Index	Requirement	
High harvesting efficiency	High harvesting efficiency	4	2	1	Harvesting efficiency is maximised in terms of output (kg) per labour input (hours).	
	Harvesting methods suitable for dense planting scheme and multiple vegetation layers	3	3	2	In the mature system, cultivation of herbs is possible without negatively affecting the harvesting efficiency of the nut cultivation.	
	High transport efficiency of harvest*	4	3	3	Transport time (h/kg harvested product) is minimised.	
	Sufficient workspace for machines*	4.1			4.1	Arable strips between tree rows are a multiple of 3m.
		4.2	3	3	4.2	At least 6 meters of open space is maintained at the beginning and end of each arable strip, with the aim of minimising this area as much as possible.
	Bulk production of nuts	5.1			5.1	Nuts yield per nut species is at least 500kg, with a target of 1000kg.
		5.2	4	3	5.2	The spatial arrangement and choice of cultivars ensure uniformity in nut characteristics, enabling efficient and consistent post-harvest processing into high-quality product.
Temporary arable farming the first six to ten years	3	3	6	6	Vegetation planted within the three-meter-wide herb strips has minimal impact on arable farming.	
Economically feasible	Food supply for camping guests from April to October	2	4	7	Food supply of fresh or processed produce for camping guests from April to October.	
	Diversity of revenue-generating business activities	3	4	8	A diversity of revenue-generating business activities is possible.	
	Low investment costs	9.1			9.1	Harvesting machines and tools can be used for at least two functions, with the target of performing as many as possible.
9.2		4	2	9.2	The investment costs for the nut harvesting method are below € 6000, with the target to minimise costs.	



High environmental sustainability	Lightweight machines to reduce soil compaction	3	4	10	Soil compaction in the top 40 cm is max 300 kP/m ² , with the target to minimise it as much as possible.
	No use of crop protection products	4	4	11	No use of crop protection products.
	Limiting the use of fossil fuels	2	3	12	Machinery gasoline consumption should be as low as possible.
High social wellbeing	Well-being and job satisfaction	3	4	13	The system allows multiple entrepreneurs to be involved.
	Combination of individual and guided self-harvesting	3	4	14	Camping guests can self-harvest a variety of crops.
	Aesthetics	3	4	15	The design should be visually appealing to enhance the camping experience for guests.
Sum		48	51		

A detailed description of the requirement evaluation can be found in Appendix XVII. An overall overview of how the two scenarios scored on the four main objectives is presented in Figure 37. It can be observed that the bulk scenario scores highest for harvesting efficiency and economic feasibility, while the diversity scenario scores highest for environmental sustainability and social wellbeing. However, overall, the diversity scenario scored slightly higher than the bulk scenario, as can be observed in Figure 37. In addition, verbal feedback from the case study farmer also highlighted the preference towards the diversity scenario. To come to a final advice, the diversity scenario will be taken as a starting point and further improved by integrating positive aspects of the bulk scenario and advice from the expert feedback. This results in a final scenario which is presented in the chapter below.

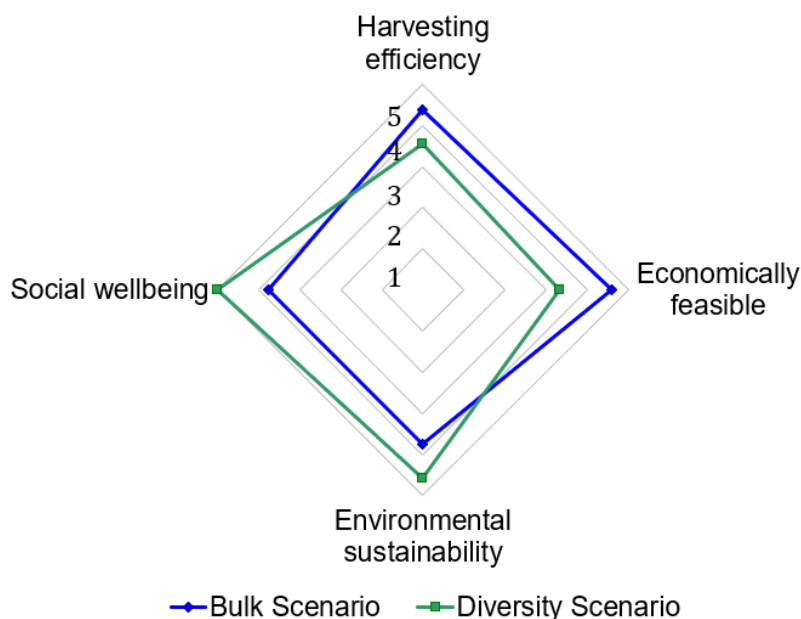


Figure 37: Evaluation of objectives



4.8.6 Final scenario

The evaluation revealed that, overall, the diversity scenario aligned most closely with the farmer's objectives. However, certain elements of the bulk scenario performed better in comparison. Additionally, several areas for improvement were identified. Taking all aspects into account, a final scenario was developed—building on the diversity scenario and incorporating targeted improvements. The following chapter outlines the modifications made to arrive at this final design.

Spatial layout

During the evaluation, the case study farmer mentioned that he also wants to use a 9m wide machine; therefore, certain rows as planned in the diversity scenario are not wide enough for this machine to pass. Therefore, tree row distances (TRD) were adapted in the final scenario. All TRD in the south field are a minimum of 12 meters, meaning that a 9m arable strip remains, making it possible for the biggest arable machine to pass and the possibility of adding additional rows in between in a later period. The south field was made more wide as compared to the diversity scenario to be able to make multiple rows where the arable machine with a width of 9m can pass. However, a few rows have a TRD of 9 meters, meaning that a 6m arable strip remains. These areas will not be used for arable farming, but instead for no-dig market gardening. This choice was made to balance arable farming space with total tree density. One sightline with a TRD of 15 meters was chosen to provide a view from the farm all the way to the end of the field and allowing the possibility to also introduce no-dig market gardening in the long term. Lastly, a 15m wide opening from east to west in the north field is added. This is due to the farmer's request to have a space where the cows from the adjoining tree meadows can pass..

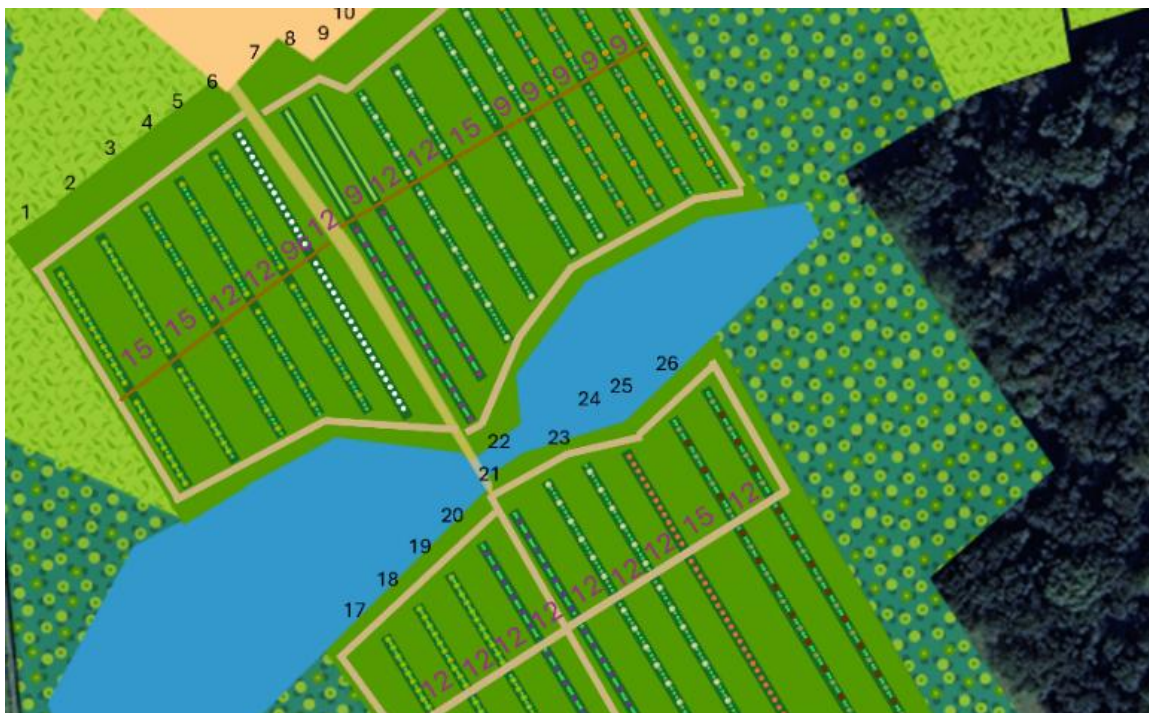


Figure 38: Spatial layout final scenario; tree row distances indicated in purple, tree row numbers indicated in black

Nut Species and cultivars

There is one species and cultivar per tree row to allow for ease of harvesting and processing into a uniform product. There are multiple cultivars from each nut species for cross-pollination. Nut trees in the northern field are late-ripening cultivars, while those in the southern field are early-ripening ones.



The hazelnuts are planted in double density (a visual representation can be found in Appendix 0. Half the trees will be taken out once they take up too much space and interplanted by adding additional rows between the existing ones. Replanted trees will face a yield reduction for re-establishment for some years, and a certain tree mortality can be expected. From a total of four cultivars, half are early and the other half are late cropping (see Appendix XI). Walnuts are also planted in double density (6m distance between trees), for a visual representation, see Appendix IX.



Figure 39: Final scenario spatial layout

Nut harvesting methods

Since the farmer wants to slowly introduce an active herb layer but is uncertain whether harvesting nets are suitable in terms of both aesthetics and functionality, the option of using either remains open. These harvesting methods are intended for use when nuts are fully mature, allowing some years to pass before a final decision must be made. The farmer can experiment with herbs in some areas, determining in more depth if there are herb species that can be mowed to create an even and low surface (without increasing mortality rates), for a sweeping machine to harvest efficiently. Additionally, harvesting nets for one row can be purchased to experiment with this method as well. It is important to note, that with both the harvesting nets and the harvesting machine, harvesting efficiency can be significantly increased as compared to manual harvest (see Figure 40). However, investment costs for harvesting nets are higher (see Table 4).

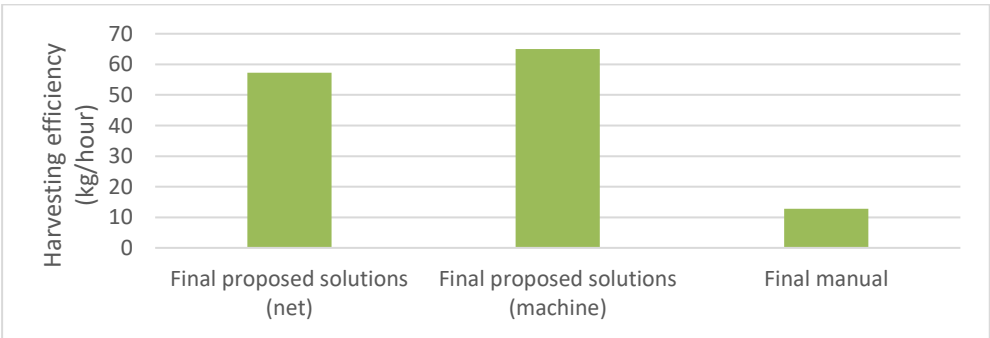


Figure 40: Harvesting efficiency final scenario



Table 4: Investment costs and harvesting time per season for nut harvesting method options in diversity scenario

Harvesting method	Investment costs (€)	Harvesting time per season (h)
Nets	6250	71
TK95R	3800	56

Fruits

The fruit species remain the same as in the bulk scenario. However, planting distances in the bulk scenario were overestimated. In the final scenario, trees and shrubs are planted more closely together than in the diversity scenario, resulting in a higher total yield.

Herbs

As mentioned above, the farmer wants to slowly introduce the herb layer. This is due to two reasons. Firstly, the investment costs are spread over a longer period. Secondly, to be able to experiment with the herbs and the nut harvesting method to reach a final decision. Therefore, only a few strips are being implemented in the first phase, as shown in Figure 41. Strips west of row seven are placed next to the 3m-wide herb layer that is beneath the tree rows and extends to the main path. One larger strip, approximately 3m wide, is placed to the north of the field. All other strips are 90cm wide and placed within the three meter herb strip below the tree rows.

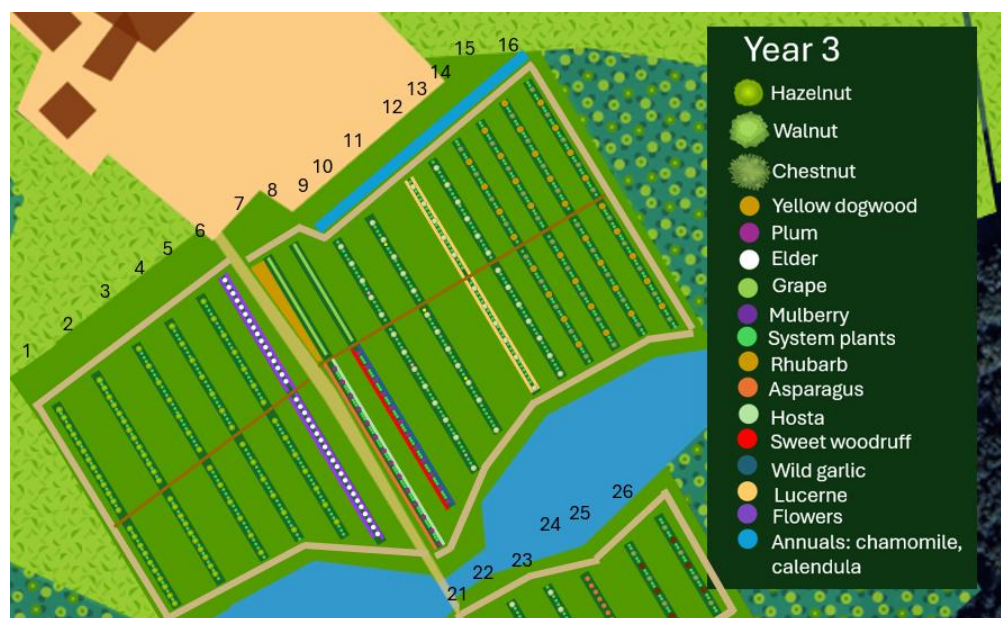


Figure 41: Herb layer final scenario

There are three categories of produce. Firstly, perennial shoot vegetables (Rhubarb, Asparagus, Hosta) for restaurants, which are mulched with leaves to reduce weed pressure. Secondly, herbs produced for buyers such as the Roze bunker and Wilderland (Sweet woodruff, wild garlic, lucerne). Lastly, annual and perennial flowers, which are an experiment for the farmer.

Perennial shoot vegetables are harvested by hand, either by twisting the plant or using a simple knife. The flowers are harvested with pruning shears. The herbs are harvested with a handheld, electric harvester for baby leaves (see Figure 42). This harvester is powered by an electric drill, cuts the herbs with a serrated blade and then pulls the herbs with a macrame braided string pick-up reel into a harvest bag.



Figure 42: Electric handheld harvester for baby leaves

System plants

As the field borders a forest inhabited by deer, temporary system plants will be added between the tree rows to deter them and reduce the risk of damage to the valuable nut and fruit trees (for a visual representation see Appendix IX). Additionally, these system plants contribute biomass and support the system's establishment phase. System plants will be removed/pruned as needed to guarantee sufficient space between plants to be harvested in order to guarantee efficient observation and harvesting of the main species.

Central collection paths

In order to make the path of the micro tractor and trailer, which picks up the harvested produce and transports it off field more efficient, harvesting paths around the field were added. Additionally, in order for the tractor to always end up on the main path, an even number of paths within the field were chosen. The path the micro tractor has to take can be observed in Figure 43. The path harvesters take within the tree rows stays the same as compared to the diversity scenario, as can be observed in Figure 36.

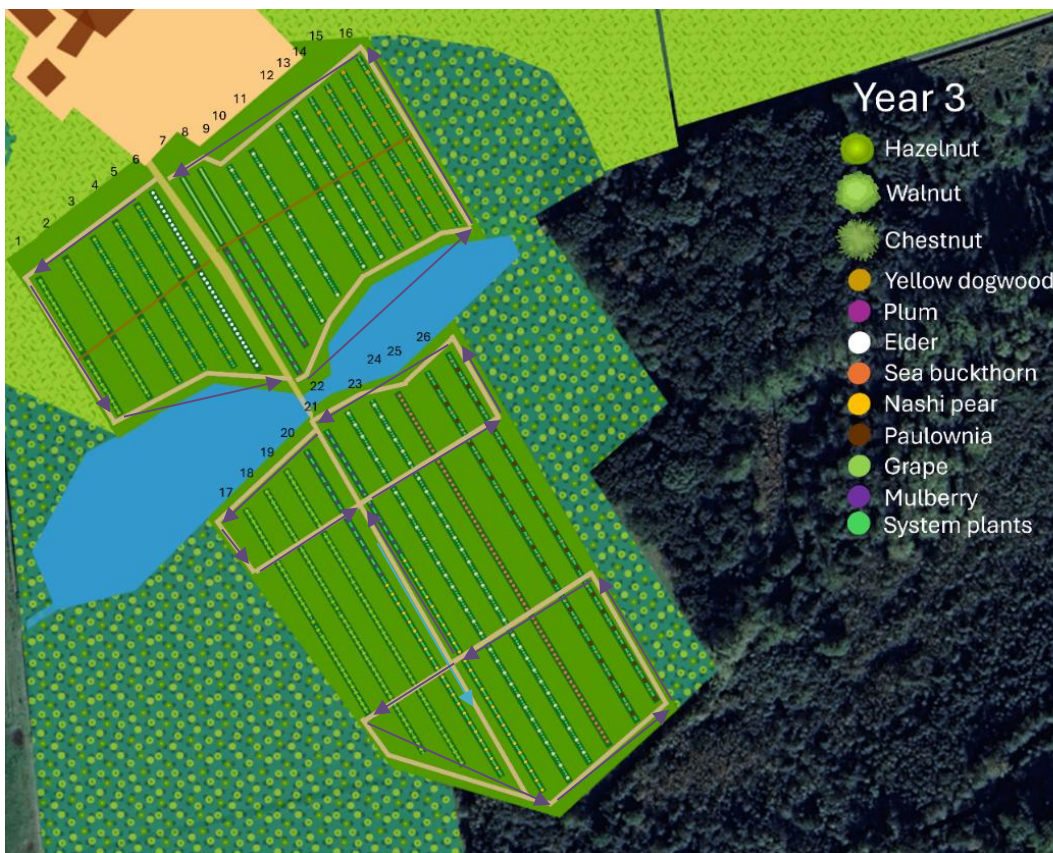


Figure 43: Central collection paths, purple arrows indicate micro tractor path



5 Discussion

The results of this study provide insights into the development of design and low-tech management solutions aimed at increasing harvesting efficiency and meeting farmers' objectives. In the following sections of this chapter, interpretations, implications and limitations of these findings will be discussed.

5.1 Data Sources and implementation

This research is based on two main sources of input: a literature review and interviews with farmers. Literature provides generalizable knowledge, while interviews can give a context-specific understanding. By drawing on both academic and practical knowledge, complementary insights are gained, thereby increasing the validity of the research. However, it is essential to note that interviews were conducted with a select group of people active in the field. Their perspective may not fully represent the diversity of views and practices. Interviewees were identified through online research, which led to a selection bias in favour of farmers with an online presence.

Additionally, farmers with limited time might not have had the capacity for an interview, as conducted during this research, leading to the exclusion of their perspectives, which could have provided valuable insights. Additionally, findings generated through interviews may reflect individual preferences and context-specific constraints. This may influence the findings, making them less generalizable to other contexts.

This research is part of the engineering doctorate of Jordy van Eijk, who is conducting research on five pilot projects. Due to time constraints, only one of these projects was selected as a case study farm. Ideally, two or three case studies would have been selected to allow for comparison between different systems and objectives, thereby generating findings applicable to a broader scale. However, the case study chosen for this research was selected because its scale is large enough to consider investing in harvesting technology, making labour efficiency especially important. Additionally, the spatial layout had not yet been defined, allowing it to be informed by the requirements of suitable harvesting methods. This allowed the insights gained on harvesting efficiency and suitable harvesting methods to influence spatial layout and species and cultivar selection, resulting in potentially more unconventional solutions.

5.2 Reflexive interactive design process

As mentioned above, the case study farm is still in development, which offers certain benefits, however, also leads to many uncertainties. An important step in the reflexive interactive design process is to define requirements that need to be met to achieve the systems objectives. Due to the above-mentioned uncertainties, multiple requirements, e.g. fossil fuel use and labour capacity, could not be quantitatively defined. The absence of clearly defined labour constraints limited the ability to accurately evaluate the labour demands of the different scenarios. Additionally, post-harvest sorting methods were not considered in the scenario generation. Differences in labour requirements of post-harvest sorting could potentially impact the overall harvesting efficiency of the generated scenarios. Further, the temporal distribution of labour was not taken into account, meaning that it is not determined whether labour peaks can be adequately covered.

Further, there is a clear trade-off between investment costs and harvesting efficiency, making investment capacity an essential factor to consider when selecting suitable harvesting methodology. Investment capacity is dependent on the farmer's own capital and potential available subsidies. Due to a lack of information regarding available subsidies, they were not considered in the scenario



generation. As a result, the assumed investment capacity may be lower than what is actually available, potentially leading to the selection of harvesting methods with lower harvesting efficiency than might be feasible.

The system's focus is bulk production of nuts, with the aim of generating a reliable income. However, there is significant uncertainty in estimating what is a feasible income from this system. This is since even though the scale of this project is relatively large in the context of CAS, nut production remains small compared to what is available on the market (considering import). In the Netherlands, few farmers currently grow nuts, which presents a market opportunity but also limits access to local processing infrastructure. Additionally, multiple types of nuts are being produced, each with different processing and marketing needs, further fragmenting volumes per species and complicating logistics. Lastly, estimating the opportunities available is increasingly difficult since the nuts will only be in full production in a couple of years. As a result, evaluation of bulk production in terms of yield and income remains uncertain.

5.3 Nut harvesting method selection tool

As the case study focused on bulk nut production, a selection tool was created to enable more informed choices when selecting a nut harvesting method in a specific context. The tool was based on the “Mimosa” interactive tool for selection of nut harvesting machinery in an agroforestry context, developed by the Flanders Research Institute for Agriculture, Fisheries and Food. However, this tool requires the user to input data on the number of harvests per season, which can be challenging to estimate for CAS. This is because CAS involve multiple nut species and cultivars, with differing ripening times, ripening period length and needs in terms of how quickly they need to be picked up to avoid quality loss. Further, in the Mimosa tool, the harvesting operations are averaged over the surface area of the plot, which works for a simple agroforestry system, with equal tree spacing. However, in CAS, tree spacing and placement can vary over the total area. To address these issues and make a tool applicable to CAS, this research developed a calculation mechanism to estimate the amount of harvesting operations and yield per harvesting operation, taking into account species and cultivars' ripening period, as well as the harvesting frequency needed to avoid quality loss. This enabled the estimation of labour requirements for the developed scenarios. These results, in addition to the investment costs of the harvesting methods, formed the basis for selecting a suitable harvesting method.

Assumptions made in the calculations might influence these results. Firstly, there are high uncertainties in applied yield levels. Yield corrections for soil type and environmental factors were applied; however, more data on nut cultivation in the Dutch context are needed to produce more accurate results. Secondly, the assumption was made that cultivars in the same cropping period can be harvested at the same time. However, different nut species and cultivars may react differently to environmental factors, and as a result, cropping periods may shift.

Aspects that could potentially affect the selection of suitable harvesting methods, which were not considered in the selection tool, will be discussed here. Firstly, the return on investment (ROI), which evaluates the investment gains compared to its costs, meaning that, depending on the profit that can be generated, a harvesting method with higher investment costs might be feasible and in turn increase harvesting efficiency. Secondly, different harvesting methods have varying needs regarding in field transport and sorting, which can affect total labour requirements. Third, more advanced harvest technology is correlated with increased harvesting efficiency and investment costs. Additionally,



repairs can be more challenging, leading to higher overall maintenance costs and dependence on external experts.

5.4 Contextualisation within Literature

The spatial layout design and species selection in this research were conducted with the aim of enhancing the efficiency of harvesting operations. This reflects the shift from a design approach purely focused on ecological perspectives (Crawford, 2010; Jacke & Toensmeier, 2005) towards the integration of productivity and economic viability in the most recent research on CAS (Bracke, n.d.; Nationaal Monitoringsprogramma Voedselbossen (NMVB), 2023; J. Van Eijk & Van Der Stok, 2022)

A study applying the same methodology, the reflexive interactive design process, explicitly focused on berry harvesting within CAS ((Burhomistrenko, 2020) This allowed a more in-depth analysis of quantifying requirements and solutions in berry harvesting, potentially increasing the validity of the research. However, the systems perspective adopted in this research, with a focus on the whole system and how it interacts, rather than its individual parts, enabled the analysis of trade-offs between different aspects of the system. It revealed a trade-off between labour efficiency and complexity, aligning with findings from Steinfeld (2024). However, it also highlighted the potential of smart harvest solutions to partially mitigate this trade-off. To further enhance this method, a decision science modelling approach, as applied by van t'Ooster et al. (2015), can be used to optimise the storage and transportation system in relation to yields.

The spatial layout of the design and low-tech management scenarios is characterised by tree rows following the landscape. This choice was made to facilitate arable farming and, more importantly, to enhance harvesting efficiency. This approach aligns with the findings of Boulestreau et al. (2016) and Bracke et al. (2024), who also implemented tree-line systems in production-oriented CAS to enable an easy and efficient harvesting process. However, there is no consensus whether rows in temperate climates should follow a North-South or East-West orientation. While this research selected for a north-south orientation to promote more even light distribution on both sides of the tree rows and to direct sunlight into the temporary annual crop strips, Boulestreau et al. (2016) implemented west-east oriented tree lines. The debate over the most beneficial orientation is also present within the Dutch food forest movement. For example, the large-scale production food forest in Schijndel includes plots with identical species arranged in both orientations to monitor and compare the effects of row orientation on system performance (Voedselbos Schijndel, n.d.; Poortman, A, personal communication, 16.07.2025).

While harvesting technology is an essential aspect to consider for improving harvesting efficiency in CAS, social factors must also be taken into account. CAS are a small-scale, human-inclusive form of agriculture (Netwerk Voedselbosbouw, n.d.-b). Many initiatives aim to increase social cohesion and connect with nature (Albrecht & Wiek, 2019). Volunteers who participate in the harvesting process are seeking a connection with nature and the community (M. Lokin, personal communication, March 28, 2025). This can essentially be seen as a strength and should be considered when selecting harvesting methods. For example, harvesting nets have the potential to increase harvesting efficiency compared to manual harvesting and make it possible to include multiple people in the harvesting operations. Community can also be harbored as a strength by connecting with other CAS to share tools and machinery, thereby increasing investment power.



6 Conclusion

There is a need to increase harvesting efficiency in complex agroforestry systems to improve their economic viability. Therefore, the aim of this research was to develop and evaluate different design and low-tech management scenarios for complex agroforestry systems (CAS) that enhance harvesting efficiency and align with farmers' objectives. Key challenges for achieving harvesting efficiency in complex agroforestry systems related to four main topics: high system complexity, physically challenging and time-intensive work, the use of alternative crops, and inaccessibility of paths. To overcome these challenges, smart harvest solutions and design strategies were applied.

The most suitable harvesting method for a farmer depends on various factors. The selected harvesting method for a particular species must align with all vegetation layers and be able to operate without damaging surrounding plants. If nuts or fruits are harvested from the ground with a machine that requires an even and low surface vegetation, the herb layer needs to reflect this. Additionally, the load volume, working width, working speed efficiency and whether a shaking method is applied are factors that influence the harvesting efficiency of such harvesting methods. While increasing these factors leads to increased harvesting efficiency, investment costs also generally rise. On the other hand, if harvesting nets are chosen, there are more possibilities for cultivating culinary herbs. However, the canopy height of shrubs and trees interplanted among the nut trees must be above or below the height of the net. Furthermore, a low-tech harvesting method that does not require any gasoline, scores positively on the objective of environmental sustainability. Next, mechanical harvesting of fruits can be significantly increased by implementing a shake-and-catch mechanism. However, these fruits do not meet the quality standards of fruit for the fresh market and fossil fuels are also required for this method. If the farm is not only focused on food production but also incorporates a social aspect, considerations of whether harvesting can be performed with multiple people need to be considered when choosing a suitable method. Lastly, since CAS are complex systems with multiple species to be harvested, utilising multifunctional harvesting methods that can harvest multiple types of crops or fulfil multiple functions can be beneficial in increasing economic feasibility.

When designing for harvesting efficiency, vegetation should be arranged in a pattern rather than randomly distributed across the field, in order to facilitate plant localisation for observation and harvesting, as well as improve communication between workers. Making this arrangement in straight rows is most beneficial for observation and harvesting, but also minimises distances to be travelled. For ease of post-harvest processing, grouping one species and cultivar per tree row and vegetation layer is beneficial. Additionally, grouping cultivars with the same harvest window in adjacent tree rows helps minimise the distance that must be covered during each harvest operation. Next, the spacing between individual plants (within and between vegetation layers) should be wide enough to allow easy observation and determination of the correct harvesting moment and prevent the harvesting process from being hindered by surrounding plants at all growth stages. When selecting species and cultivars, making smart combinations to reach overlapping harvesting windows allows for more produce to be harvested in a single operation, thereby reducing the total number of harvest operations and increasing harvesting efficiency. Additionally, species choice should take factors such as fruit size, whether they can be harvested in bundles or by cutting whole branches, ease of picking, reliable yields in an extensive system into account. For efficient transport operations, it is recommended to establish central collection points that are connected by central collection paths. This means that the transport unit gathering the harvested produce to transport it to its storage location only has to follow the central collection paths, resulting in a minimised travelling distance and soil compaction. These paths



should be designed in a way that no turning at the end of the path is needed, but rather, a continuous path that passes by all central collection points.

Taking these factors into account, two distinct scenarios with scenario-specific targets were developed for a pilot case: a bulk and diversity scenario. Both scenarios share a common planting pattern: tree rows aligned with the landscape contour, spaced between 9 and 15 meters apart. However, they differ in the following aspects: The diversity scenario is characterised by a higher complexity as compared to the bulk scenario. Specifically, the bulk scenario prioritises the bulk production of chestnuts and hazelnuts, whereas the diversity scenario includes chestnuts, hazelnuts and walnuts. Additionally, the bulk scenario features three types of fruits, whereas the diversity scenario incorporates seven. Lastly, the herb layer in the diversity scenario consists of a wide variety of culinary herbs and perennial vegetables, whereas in the bulk scenario, it primarily serves a supporting function. These scenario-specific characteristics influenced the selection of appropriate harvesting methods. In the bulk scenario, nut harvesting is performed using a powered, hand-operated sweeper-type machine. Fruit is harvested mechanically with a handheld shaker and collection umbrella, and culinary herbs are harvested manually with scissors. The remaining herb layer is maintained through conventional mowing. The diversity scenario, on the other hand, features harvesting nets for nut harvest, the same mechanical fruit harvesting methods as in the bulk scenario, in addition to handpicking, which is supported by a wheelbarrow ladder or harvest belt. Culinary herbs are harvested with a hand-operated, electric-powered baby leaf harvester.

Overall, both scenarios scored high in relation to farmers' objectives, with the bulk scenario achieving 48 points and the diversity scenario 51 out of a possible 60. However, their performance varied across objectives. While both scenarios demonstrated a significant improvement in harvesting efficiency compared to manual harvesting, the bulk scenario outperformed the diversity scenario, achieving 1.7 times greater efficiency. Additionally, the bulk scenario was rated higher in terms of economic feasibility. In contrast, the diversity scenario excelled in environmental sustainability and social well-being. The results demonstrate that the trade-off between system complexity and labour requirements could be reasonably overcome, highlighting that, even within complex systems, there is considerable potential to improve harvesting efficiency.



7 Recommendations

To further enhance this approach, future studies should analyse the temporal distribution of labour requirements. While it is essential to identify total labour needs for all harvesting operations, it is also crucial to account for labour peaks to determine if they can be adequately covered. Furthermore, operations research and logistics planning are needed to better align plant yields with the capacity of storage and transport units, thereby optimising the design and number of central collection paths. Furthermore, to improve yields and harvesting efficiency of alternative crops, which can contribute to a broader range of locally produced food, more data on the needs and care of these plants is required. Similarly, further investigation into herb species that can be mown low without increasing mortality rates, while maintaining a sufficiently even surface to enable compatibility with sweeper-type nut harvesting machines, could offer valuable insights for farmers planning to use this type of harvesting method. Additionally, further development of the nut harvesting selection tool could enhance the identification of the most appropriate harvesting methods. Exploring additional harvesting techniques and collecting the necessary data to integrate them into the tool would expand the range of available options for users. Moreover, transport and post-harvest sorting labour requirements should be examined and, if significant, incorporated into the overall labour assessment to support more informed decision-making.



8 Literature

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Appendix

I. Background information

a. Agroforestry

i. Definition

Agroforestry is an ancient form of agriculture, which has largely disappeared due to intensification of agricultural production. In recent years, it is coming back into focus because of its environmental and economic benefits (Marie-Laure, 2020). There are various definitions of agroforestry, but one thing they all have in common is the "intentional" or "deliberate" integration of woody perennials with agricultural crops and/or animals (Agroforestry in Europe Current Status and Future Prospects, n.d.; Luske et al., 2020; Marie-Laure, n.d.). Agroforestry aims at integrating woody perennials into the agricultural system to create environmental and economic value (Luske et al., 2020). Therefore, this report defines agroforestry as the following:

Agroforestry is a land use system that intentionally integrates woody perennials (trees and shrubs) with agricultural crops and/or animals on the same land management unit in order to diversify production for increased environmental and economic benefits (Luske et al., 2020; Marie-Laure, 2020; Nair, 2008; Prins et al., 2023).

ii. Classification

The classification of agroforestry systems revolves around the configuration of the core components (trees, crops and animals) in space and time (see Figure 44). Several studies have attempted to establish clear classifications, which has shown to be difficult due to many combinations of woody perennials, crops, and animals. In the Netherlands, several types of agroforestry are present (Luske et al., 2020; Rebisz, 2019):

- Silvopastoral systems, where productive grasslands and livestock are combined with trees or shrubs.
- Silvoarable systems, where arable farming or field vegetable cultivation is combined with fruit trees or shrubs.
- Boundary planting, where grassland or arable farming is combined with hedges to create a windbreak or fence of an area for livestock.
- Complex agroforestry systems are a cultivation system consisting of multiple vegetation layers for the production of a wide range of fruits, nuts, seeds, vegetables and herbs.

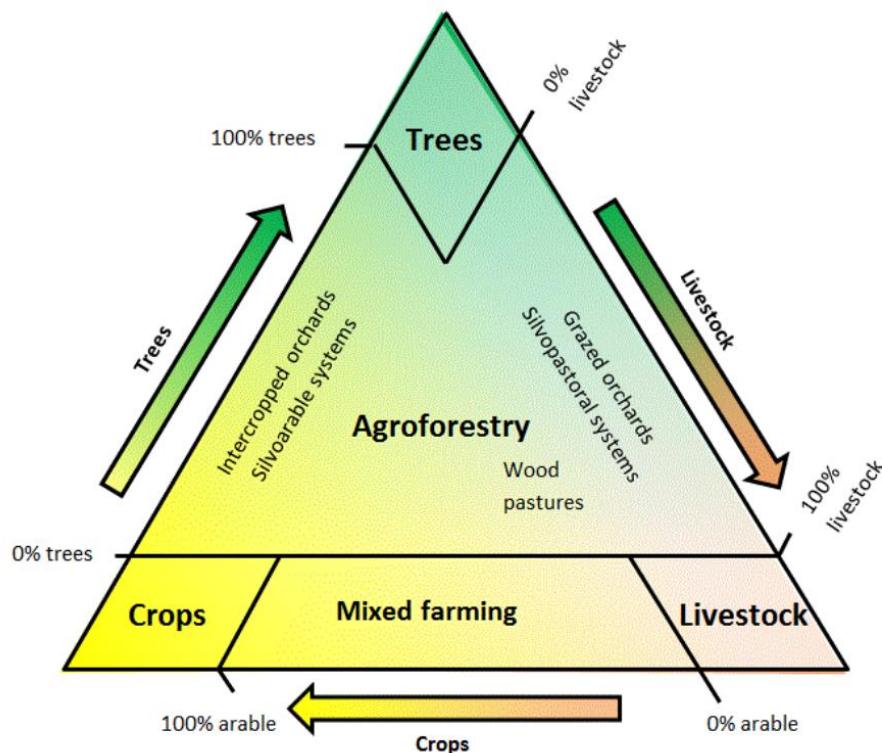


Figure 44: Agroforestry triangle, adapted from Burgess et al., 2015

iii. Policy

Agroforestry is recognised as an agricultural system on EU level. Farmers can receive subsidies from the Common Agricultural Policy (CAP) in the form of direct payments per hectare of land and for establishment or maintenance under the rural development strand of the CAP (Marie-Laure, 2020). In the Netherlands, agroforestry practitioners face issues related to the agriculture and nature policy and the fact that agroforestry is currently not recognised as an agricultural system.

In 2020 the Ministry of Agriculture, Nature and Food Quality commissioned an advice for the development and scaling up of agroforestry in the Netherlands. The output of this commission was formulated as a Masterplan that addresses opportunities, obstacles and solutions of agroforestry systems which can potentially tackle social challenges such as climate mitigation, climate adaptation, landscape restoration, soil and water quality and biodiversity restoration. Part of this Masterplan is to connect initiatives and organizations related to agroforestry and to create advice for policy and legislative changes (Agroforestry Nederland, n.d.).

An important recent change in the agroforestry landscape is the creation of the Dutch National Forest Strategy, in which the government set highly ambitious goals for forests but also specifically for agroforestry in the Netherlands. The aim of this strategy is to establish 25,000 hectares of agroforestry and 1000 hectares of CAS by 2030 (Kruit, n.d.; Ministerie van Landbouw, n.d.).

Till recently, landowners that want to start an agroforestry project ran into financial issues since there was the possibility that their land will be devalued if trees were planted on agricultural land (EURAF, 2023). From 2023 onwards, 100 trees per hectare may be planted on arable and grassland (previously 50) and landscape elements count towards the basic premium. Further, if one plants more than 100 productive trees on 1 hectare, the plot can be registered with the crop code of the trees, which means the whole area counts as agricultural land for the basic premium. This also



counts for non-productive trees like fodder hedgerows. Additional premiums can also be obtained for eco-activities such as woody elements – which, for example, hedgerows count towards (Groen, 2024; Rijksdienst voor Ondernemend Nederland, 2023). Planting subsidies that could be received via the CAP are still not accessible since the Netherlands does not indicate that they want to make use of this in their strategic plan (EURAF, 2023). Nonetheless, in some provinces, planting subsidies from the local Government (e.g. Municipality of Utrecht) are available (Agroforestry netwerk Nederland, 2025).

iv. Size of sector

Worldwide, agroforestry is practised by 1.2 billion people on around 1 billion hectares of land (FAO, 2020). In the EU-27, agroforestry systems have a total area of about 15.4 million hectares, which is almost 9% of the total agricultural area (these numbers exclude reindeer husbandry) (Marie-Laure, 2020). In the Netherlands, half of the total surface area is agricultural land, which is about 2.2 million hectares (Centraal Bureau voor de Statistiek, 2020). Out of this, only around 2000 hectares are agroforestry (Nationale Bossenmakelaar, 2024). Despite this fact, the above-mentioned agroforestry Masterplan of the Louis Bolk Institute projects considerable growth in the sector through the implementation of this plan (see Figure 45) (Luske et al., 2020). The recent changes regarding the Forest Strategy and subsidies can further enhance this growth.

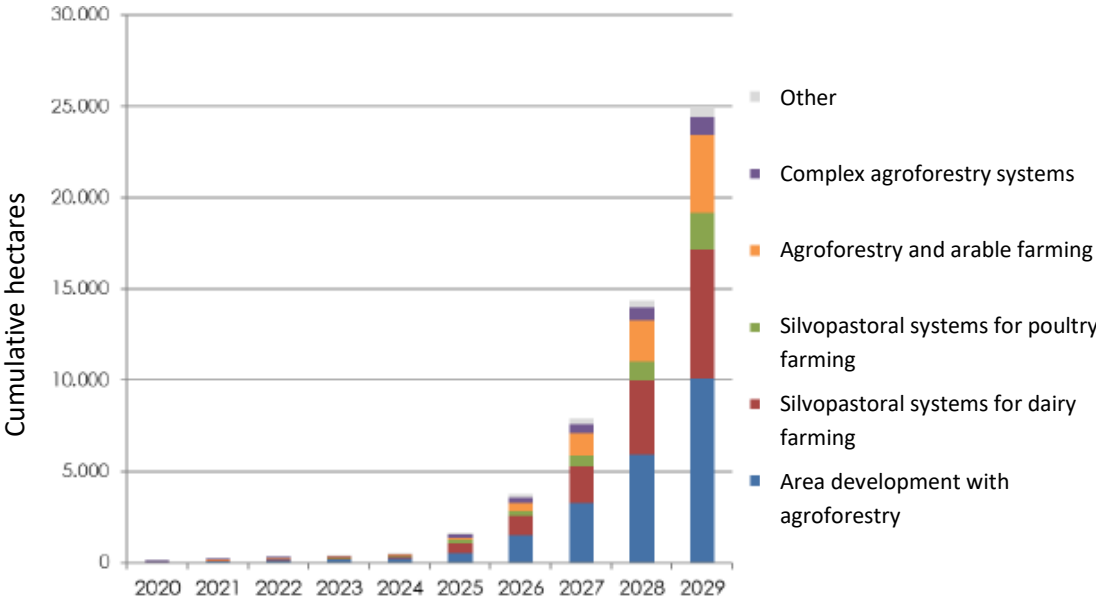


Figure 45: Estimated scaling up of the number of hectares of agroforestry over the years. Adapted from Luske et al., 2020

b. Complex agroforestry systems

i. Policy

Next to the current policy advancements, as well as issues faced by agroforestry practitioners, CAS has made significant progress concerning policy. The Green Deal Food forest led to the addition of its own crop code and food forests being recognised as an agricultural method (Green Deal Voedselbossen, 2020b; Netwerk Voedselbosbouw, n.d.-a). This means that a food forest can now be properly registered, allowing the area to be recognized as agricultural land and gaining the benefits that come with it (such as agricultural subsidies) (Netwerk Voedselbosbouw, n.d.-a; Rijksdienst voor Ondernemend Nederland, 2023). The crop code eliminates the need to create a separate plot for all the different species that grow in a CAS. Further, the Green Deal recognises the potential of CAS to



mitigate problems sustained by industrial agriculture. However, it was signed with the condition that additional research would be carried out to create more evidence of the above mentioned potential (Roodhof, 2024).

The Dutch government has set an ambitious goal to establish at least 1000 hectares of food forests on agricultural land by 2030 (Rijksdienst voor Ondernemend Nederland, 2023). This target is significant, considering that the total area of agroforestry systems in the Netherlands currently amounts to 2000 hectares (Nationale bossenmakelaar, 2024). Nonetheless, in practice, this support still needs to be integrated into laws, regulations, and available subsidies. Only in some municipalities, subsidies are now available and zoning laws are more inclusive for CAS (Roodhof, 2024).

ii. Size of sector

Complex agroforestry systems are gaining momentum within the Netherlands (Ziegler, 2024). Hundreds of initiatives are popping up throughout the country (Kruit, n.d.) The exact number of initiatives is unclear due to the large number of private CAS (Schuurmans, 2024). Roodhof (2024), identified 231 CAS throughout the Netherlands, but mentions that this is not an exhaustive list. Further research that builds on Roodhofs's (2024) database found an additional 156 initiatives, totaling to about 400. Out of the 342 municipalities in the Netherlands, at least 211 have one CAS (Schuurmans, 2024). A map with the number of CAS per province in 2023 can be found below (see Figure 46). At the moment, little is known regarding the size in hectares of CAS. However, following the government's ambitious goal of establishing 1000 hectares of food forests by 2030, the foundation Voedselbosbouw also sets this as a target value (Buiter & de Waard, 2020).



Figure 46: Number of food forests per province in 2023 (Schuurmans, 2024)



II. Terms related to complex agroforestry systems encountered during this study



Figure 47: Terms related to CAS encountered during this study



III. Interview guide

Interview guide CAS farmers

0 Introduction

- Thanking for their time and participation
- Introducing myself and thesis topic
- The interview will take around X minutes

1 Consent questions:

- 1.1 Consent to take notes and record the interview
- 1.2 Consent to use information gathered during interview in my MSc thesis report anonymously

2 Description of the farm

- 2.1 Can you introduce your farm?

Checklist of topics: farm size, marketed products, main business model (education, research, nature, social, production) + other activities, main source of income, start date,

- 2.2 How many people work on your farm and what are their tasks/responsibilities?
- Do you track labour on the farm?

3 Current harvesting methods – problems they experience

- 3.1 How do you harvest your crops? Which machines and tools do you currently use?
- 3.2 How do you monitor fruit ripeness?
- 3.3 Why did you choose to do your harvesting operations the way you currently do? Have you considered other ways of harvesting?
- 3.4 What are advantages and disadvantages with the current ways of harvesting?
- 3.5 What parts of harvesting are the most time consuming?
- 3.6 What parts of harvesting feel the most “challenging/frustrating”?
- 3.7 What restrictions does your system pose onto machinery? (e.g. width, height)
- 3.8 What restrictions does your machinery pose to the system (e.g. path width, undergrowth)
- 3.9 What do you think are weak points of currently available machinery?
- 3.10 Explain proposed solutions from other farmers → Why do you think this would or would not work in your system?

4 Future vision – potential solutions that are currently missing on the market

- 4.1 What alternative harvest solutions do you envision for the future? What functionalities should these new solutions have?
- 4.2 Why are these alternatives interesting for you?
- 4.3 What are your requirements for the new machinery?

5 What needs to happen to reach vision

- 5.1 Which stakeholders (companies or people) are in your opinion important to involve in the development and introduction of new machinery?
- 5.2 What is the first step that would need to be taken in order to develop these new solutions?

6 Reken tool: Explain reken tool calculates like this and that

- 6.1 What do you think about the way harvest efficiency is calculated? Do you think essential aspects are missing and should be included?



- 6.2 What assumptions used in the tool are different for a Food Forest Context and how do they differ?
- 6.3 What information is needed in order to better calculate the harvesting efficiency with the rekentool in future?
- 7 Looking further
 - 7.1 What other farmers/experts would you recommend I contact? (people in your network you think will have interesting / insightful answers to my topic)
 - 7.2 Can I approach you again in case I have additional questions or later in the evaluation phase of the design scenarios?
- 8 Ending
 - We have reached the end of this interview.
 - I have no further questions at this point – do you have anything to add?
 - I would like to thank you greatly for your participation. I have enjoyed conducting the interview with you and I hope that this is mutual.
 - Say that the recording will be stopped
 - How I will feedback the information to them – would they like the final report?
 - Social talk

Interview guide farmers cultivating herbs, fruits and nuts

0 Introduction

- Thanking for their time and participation
- Introducing myself and thesis topic
- The interview will take around X minutes

1 Consent questions:

- 1.1 Consent to take notes and record the interview
- 1.2 Consent to use your name and information gathered during interview in my MSc thesis report

2 Description of the farm

- 2.1 How would you describe your farm?
 - o Checklist of topics: farm size, marketed products, main orientation (education, research, nature, social, production) + other activities, main source of income, start date
- 2.2 How many people work on your farm and what are their tasks/responsibilities?
- Do you track labour spend on the farm?

3 Harvest methods

- 3.1 How do you harvest your crops? Which machinery do you currently use?
- 3.2 How do you monitor fruit ripeness?
- 3.3 What are advantages and disadvantages with the current ways of harvesting?
- 3.4 Why did you choose to do your harvesting operations the way you currently do?
- 3.5 Have you considered other ways of harvesting? And why did you deem them unsuitable?
- 3.6 What is the most challenging when harvesting?
- 3.7 What restrictions does your system pose onto machinery? (e.g. width, height)
- 3.8 What restrictions does your machinery pose to the system (e.g. path width, undergrowth)

4 Transferability of methods to food forest environment

- 4.1 Have you heard of Food Forests and what do you think about them?
- 4.2 What challenges could you imagine when applying harvesting method x in a food forest context?
- 4.3 How to deal with those?



4.4 Which stakeholders (companies or people) are in your opinion relevant to involve in the development and introduction of new machinery for harvesting in food forests?

5 Looking further

5.1 What other farmers/experts would you recommend I contact? (people in your network you think will have interesting / insightful answers to my topic)

5.2 Can I approach you again in case I have additional questions or later in the evaluation phase of the design scenarios?

4 Ending

- We have reached the end of this interview.
- I have no further questions – do you have anything to add?
- I would like to thank you greatly for your participation. I have enjoyed conducting the interview with you and I hope that this is mutual.
- Say that the recording will be stopped
- Social talk



IV. Nut harvesting method selection tool

The Excel sheet containing the calculations for the final scenario can be accessed by following this [link](#). Calculations in this Excel sheet are number-coded, as referred to in the description below.

- 1) First, a planting list was established indicating the species, cultivar, and number of trees per row.
- 2) Second, the yield to be harvested of a specific cultivar during a single harvest operation was calculated. This was done by first calculating the total yield (kg) for each cultivar using the number of trees from the planting list and yield (kg/tree), which was obtained from the Rekentool. Next, this total yield was divided by the number of times harvesting is necessary for both harvesting with and without shaking (see Table 5).

Table 5: Nr. Of harvest operations with and without shaking for chestnuts, walnuts and hazelnuts and their respective harvesting period; Since Hazelnuts only need to be harvested two times, shaking was not considered.

	Chestnuts	Walnuts	Hazelnuts
Nr. of harvest operations with shaking	3 (M. Veld 4, personal communication, March 24, 2025)	3 (M. Veld 4, personal communication, March 24, 2025)	-
Nr. of harvest operations without shaking	3-4 (H., Meißel, personal communication, April 4, 2025)	5 (Wertheim, 1981)	2 (R. & H., Tuenter, personal communication, March 20, 2025)
harvesting period (days)	10-14 (H., Meißel, personal communication, April 4, 2025)	10-14 (Wertheim, 1981)	21-28 (R. & H., Tuenter, personal communication, March 20, 2025)

- 3) Third, a harvesting calendar was created that groups nut cultivars by their respective harvesting periods. Data on harvesting periods was obtained from the book “How to grow your own nuts: Choosing, cultivating and harvesting nuts in your garden (Crawford, 2017).
- 4) Next, harvest operations needed to perform the total nut harvest were determined (see appendix XII). This was done based on the harvesting calendar and data in Table 5. The assumption was made that cultivars in the same category can be harvested at the same time.
- 5) Then, the total yield to be harvested per harvest operation was calculated by summing up the yield of the cultivars (as calculated in step 2) harvested during this harvest operation.
- 6) Following, the area to be harvested per harvesting operation was determined based on the spatial layout of the scenario.

$$Area = Row\ length\ (m) * width\ to\ be\ harvested(m)$$

- 7) By summing up the area of each cultivar that is to be harvested during a specific harvesting operation, the total area to be harvested during this operation was determined.
- 8) This enabled the calculation of the yield in kg/ha for each harvesting operation.

$$Yield\ \left(\frac{kg}{ha}\right) = Total\ yield\ \frac{kg}{Area}\ (ha)$$



- 9) Following this step, the Mimosa calculation method was applied. First, a harvesting delay factor was calculated for each suitable harvesting method (Input data obtained from the Mimosa selection tool). This delay factor varied depending on the loading volume of the harvesting method.
- 10) The real harvester driving speed (hours/ha) was then calculated with the working width and working speed, corrected by the delay factor. The harvester driving speed in kg/h was then calculated using the formula in Table 6. An exception of this calculation are harvesting nets. Since for this harvesting method, harvesting speed can not be calculated in the same way as a machine, data on harvesting speed for this method was estimated based on data received during an interview with a farmer using this method (H., Meißel, personal communication, April 4, 2025).
- 11) Finally, the harvesting time per harvesting operation was calculated by taking the total yield and dividing it by the harvesting speed (see Table 6). The harvesting time per harvesting operation was then summed up resulting in the labor needed to perform all harvesting operations by a specific harvesting method.

Table 6: Overview calculations nut harvesting selection tool

Harvesting speed (kg/h)	Harvesting time (h)
= Yield (kg/ha)/ Harvester driving speed (h/ha)	=Total yield (kg)/Harvesting speed (kg/h)

- 12) Additionally, for harvesting with a shaker, two different types of shakers were considered. A cable and a trunk shaker. A cable shaker is cheaper but also less efficient. The time it takes to carry out the shaking operation was calculated based on the amount of trees that needed shaking and the shaking capacity (trees/hour). Data was obtained from companies producing this type of shaker (AMB Rousset, n.d.; Feucht Obsttechnik, n.d.). This was then added to the total harvesting time.
- 13) Next to the labour needed, the investment costs also play a crucial role in deciding which harvest method is suitable. Therefore, the harvesting time per harvesting method (without shaking, cable shaker and trunk shaker) was plotted against the investment costs needed for this specific harvesting method. This output was then used to select a suitable nut harvesting method for the design and low-tech management scenarios.



V. Feedback form expert evaluation

The feedback form used during the expert evaluation can be accessed via this [link](#).



VI. Calc. Harvesting efficiency

Based on Data from the ReKentool, the total yield of nuts and fruits for each scenario was calculated. Data on the manual harvest speed of each fruit species was also obtained from the ReKentool. The labour necessary to harvest each fruit species was calculated as indicated in the equation below.

$$\text{labour fruit harvest manual} = \frac{\text{Total yield fruit (kg)}}{\text{harvest speed } \left(\frac{\text{kg}}{\text{hour}}\right)}$$

The labour required to harvest each fruit species was then summed up to determine the total labour requirements for manual fruit harvest. Next, the harvest speed (trees/hour) of fruits mechanically harvested was obtained from the company that produces the respective harvesting method. The labour necessary to harvest each fruit species was then calculated as indicated in the equation below.

$$\text{labour fruit harvest mechanical} = \frac{\text{Number of trees}}{\text{harvest speed } \left(\frac{\text{trees}}{\text{hour}}\right)}$$

To calculate the total labour required to harvest all fruits as proposed in the scenarios, a sum was made of the labour for the species that are mechanically harvested, plus the species that are manually harvested. The labour necessary to harvest nuts was obtained from the calculations as represented in Appendix IV. The harvesting efficiency for each scenario and type of produce (fruits, nuts) was then calculated based on the formula below.

$$\text{Harvesting efficiency } \left(\frac{\text{kg}}{\text{hour}}\right) = \frac{\text{Yield (kg)}}{\text{labour (hour)}}$$



VII. Key actors involved in the research, design and development of complex agroforestry systems in the Dutch context

Dutch research institutes that are doing research on agroforestry systems are Wageningen University & Research, HAS Green Academy, Van Hall Larenstein University of Applied Sciences, the Louis Bolk Institute and the Netherlands Institute of Ecology. Further, crossing borders to Belgium, the Flanders Research Institute for Agriculture, Fisheries and Food also contributes to agroforestry research in the temperate context.

There are various pioneering farmers in the Netherlands and abroad who, through their practice of (complex) agroforestry methods, are creating knowledge in this field. Furthermore, small-scale producers of fruits, nuts, and herbs, who aim to produce environmentally friendly food, are also influencing the available knowledge, which can be partly transferred to CAS. There can also be lessons learned from farmers in similar climates who grow crops with potential for Dutch agroforestry systems.

Governmental institutes are especially of importance due to the subsidies they provide to CAS. CAS practitioners can receive subsidies from the CAP, the agricultural policy of the European Commission in the form of direct payments per hectare of land and for establishment or maintenance (Marie-Laure, 2020). However, the Dutch government does not indicate in their strategic plan that they want to provide planting subsidies (EURAF, 2023). Local governments of provinces and municipalities partly do provide planting subsidies. Further, the Dutch National Forest Strategy is favouring agroforestry in the Netherlands, potentially providing additional subsidies.

There are various agroforestry organisations and networks focusing on (complex) agroforestry systems. They contribute to advancing the agroforestry movement by generating and sharing knowledge, creating pioneering projects and providing support for the design of (complex) agroforestry systems. Among Dutch organisations, Stichting Voedselbosbouw, Voedsel uit het bos, Agroforestry network Netherlands, Stichting Agroforestry Netherlands and Stichting Regeneratie are important actors to be mentioned.



VIII. Longlist harvesting methods

Reach

- <https://www.terrateck.com/de/90-schubkarre-wagen-und-leiter>
- <https://www.henchman.fr/echelles/platform-tripod-ladders/>
- <https://www.triangle-outillage.fr/119-echelle-et-marche-pied>
- <https://www.magellan-bio.fr/accessoires/5754-mini-echafaudage.html>
- https://www.groworganic.com/products/ahs-telescopic-fruit-harvester-10-ft?_pos=2&_sid=892483118&_ss=r
- https://www.groworganic.com/products/pole-fruit-picker?_pos=3&_sid=892483118&_ss=r
- <https://www.triangle-outillage.fr/outils-wolf/4265-cueille-fruits-wolf-multi-star.html>
- <https://frucotec.com/de/products/berglady?srsId=AfmBOorSYQ0GUihSHHfrWYK9HAy-LZzb1mDfMESBsMVHlyIEI-Cr-h5d>
- Tractor with front stacker
- Self-built step ladder with wheels:



Figure 48: Self built step ladder with wheels for fruit harvest (De walnoothoeven)

Detach (fresh produce)

Fruit

- https://www.groworganic.com/products/ahs-telescopic-fruit-harvester-10-ft?_pos=2&_sid=892483118&_ss=r
- <https://www.triangle-outillage.fr/ramasseurs-de-fruits/1701-cueille-fruit.html>
- <https://www.groworganic.com/products/clip-n-pick-pruner-head-only>
- <https://www.triangle-outillage.fr/outils-wolf/4265-cueille-fruits-wolf-multi-star.html>
- https://www.groworganic.com/products/pole-fruit-picker?_pos=3&_sid=892483118&_ss=r
- <https://www.magellan-bio.fr/recolter/7905-ramasse-baies.html>
- <https://www.gardena.com/int/products/soil-ground/combisystem/combisystem-berry-picker/970638101.html>

Herbs

- <https://www.terrateck.com/de/erntemaschine-fur-junge-triebe-und-aromatische-pflanzen/154-erntemaschine-fur-babyleaf.html>
- <https://www.terrateck.com/de/weitere-ernteausrustung/394-erntemaschine-fur-babyleaf-und-schnittsalate.html>
- <http://www.supercut.net.au/>



Figure 49: Easycut 2000 – remodeled Japanese tea harvester (Kräuterhof Zermanek)

- <https://www.terrateck.com/de/148-erntewerkzeuge>
- <https://www.terrateck.com/de/148-erntewerkzeuge>
- https://www.leroymerlin.fr/produits/taille-haies-thermique-sur-perche-52-cm3-3-cv-longueur-3-30-metres-85605980.html?Megaboost&at_medium=Sea-Paid&at_campaign=BREC-09-JARDIN-PMAX-SHP-PLA-Tier1-3P&at_source=google&at_market=M2&at_section=R9&at_campaign_id=20490785932&at_campaign_type=PMAX&at_campaign_sub_type=PLA&at_account=FIL-ROUGE-SHOPPING&at_account_id=921-620-5076&gad_source=5&gad_campaignid=20481276900&gclid=EAlaIqobChMIIJ-dhtDLjgMVVToGAB2xtifOEAQYBCABEgJDCPD_BwE&gclsrc=aw.ds
- <https://barebonesliving.com/products/herb-harvest-strip-tool?srltid=AfmBOooiBUcuTNGbVQGFByB9RUopotxqlcXbicVVLn2LrCjkbDqpgwM>
- Scissors with plastic attachment (les Forestibles, France):



Figure 50: Scissors with plastic funnel (Les Forestibles)

- Catching Scythe (Bronzewing farm, (Small Scale Sustainable Herb Farming Lessons from France and Australia, 2020)):



Figure 51: Catching Scythe (Bronzewing farm, (Small Scale Sustainable Herb Farming Lessons from France and Australia, 2020)

Detach (processing)

Hard fruits or nuts

- <https://shop.feucht-obsttechnik.de/Schuettler-OS-Seil-Schuettler-OS/81825>
 - o Teleskopstange; <https://shop.feucht-obsttechnik.de/Teleskopstange-TS-fuer-Schuettler-OS/697>
- <https://www.triangle-outillage.fr/ramasseurs-de-fruits/5236-secoueur-d-arbres.html>
- <https://www.amb-rousset.com/en/shakers/cable-shaker/>
- <https://obstsammler.com/geraete/card-obstschuettler/>
- <https://www.harvesting.rs/tresac-h1-professional.php>
- <https://feucht-obsttechnik.de/de/obsterntetechnik/schuettelgeraete/stammschuettler-mechanisch/#>
- <https://www.amb-rousset.com/en/shakers/economical-hydraulic-shakers-range/>

Soft fruit

- <https://www.agrieuro.fr/peigne-vibreux-electrique-volpi-giulivo-4you-706-peigne-vibreux-pour-recolte-dolives-rallonge-p-880.html>
 - o <https://www.agrieuro.fr/peignes-vibreux-et-secoueurs-olives-c-1927.html>
- https://www.youtube.com/watch?v=DEBUeaQ32zU&list=PLfK4D0f627XsehdsUii-1s4Hlrk3_uX
 - o <https://spacesonicltd.eu/shop/olive-harvesters/atrax-1600/>
- <https://www.campagnolasrl.de/elektrischer-schu%CC%88ttelhaken/blaubeerernte/>
- <https://www.triangle-outillage.fr/ramasseurs-de-fruits/3174-peigne-a-myrtilles.html>

Collect

Hard fruit/Nuts



- <https://www.organic-tools.com/obstauflesemaschine-obstraupe>
- <https://feucht-obsttechnik.de/de/obsterntetechnik/obstauflesemaschinen/>
- <https://obstsammler.com/geraete/card-obstigel-type-800/>
- <https://veld4.nl/product/roll-blitz-walnootraper-met-houten-steel/>
- <https://www.agroforestryvlaanderen.be/nl/nieuws/oogst-van-noten-welke-methodes-en-machines>
- <https://www.triangle-outillage.fr/accessoires/3506-filet-recoltec-vert-noir-.html>
- <https://www.magellan-bio.fr/recolter/7910-filet-de-recolte.html>
- <https://agrifournitures.fr/filets-recolte/207-filet-de-recolte-lonodis-pro-double-trame-50grm-rouleau-de-100-metres.html>
- <https://www.agrieuro.fr/filets-pour-la-recolte-des-olives-c-1933.html>
- <https://fruitcollector.net/tuote/fruit-collector/?lang=de>
- <https://feucht-obsttechnik.de/en/nut-processing/hazelnut/harvesting-hazelnuts/>
- <https://www.terrateck.com/de/schubkarre-wagen-und-leiter/1480-erntewagen-fur-oliven-fur-kiste-60x40h30cm---farbe-grau.html>
- <https://proizvodi.servisioncar.hr/de/>
- https://www.harvesting.rs/sakupljac-3_3m.php
- Harvesting nets examples farmers (Meißelhof Austria (top), Haselgut Austria (bottom)):



Figure 52: Harvesting nets (Meißelhof Austria)



Figure 53: Harvesting nets (Haselgut Austria)



Soft fruit

- <https://www.triangle-outillage.fr/ramasseurs-de-fruits/3174-peigne-a-myrtilles.html>
- <https://www.freshplaza.com/north-america/article/9499691/harvesting-gloves-represent-an-evolution-in-the-collection-of-berries-and-other-small-fruits/>
- <https://www.campagnolasrl.de/zubehoerteile-professional-line/wagen-fur-die-heidelbeerernte-24/>

Store

Fruit/Nuts/Vegetables

- https://www.fruugo.at/wasserdichte-ernte-afel-picking-bag-beutel-obst-lagerung-schurze-fur-outdoor-farm-obstgarten/p-205071766-435906435?language=de&ac=KelkooCSS&asc=pmax&gad_source=5&gclid=EAlaIQobChMIuMOsqfH6igMVnxiiAx1Z4yBfEAQYBCABEgJOE_D_BwE#
- <https://www.terrateck.com/de/90-schubkarre-wagen-und-leiter>
- <https://www.terrateck.com/de/bac-eimer-und-erntekorb/373-ventraler-erntesack.html>
- <https://www.terrateck.com/de/bac-eimer-und-erntekorb/1104-seitliche-erntekorbe.html>
- <https://www.terrateck.com/de/bac-eimer-und-erntekorb/896-haltegurt-fur-kistenhalterung-auf-bauchhohe.html>
- <https://www.terrateck.com/de/bac-eimer-und-erntekorb/818-flexibler-erntekorb-38-l.html>
- <https://www.terrateck.com/de/bac-eimer-und-erntekorb/1268-stabile-erntekiste-auf-bauchhohe-mit-halterung-gurten.html>
- <https://www.triangle-outillage.fr/harnais-paniers/5832-tablier-de-recolte.html>
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- Car trailer
- Harvesting sleigh (De Ring, Netherlands)



Figure 54: Harvesting sleigh used for berry harvest. Crates are placed on top and the sleigh is being pulled per hand during harvest operation.

- Electric cargo bike



IX. Spatial layout year three

Bulk scenario



Figure 55: Spatial layout year three bulk scenario



Diversity Scenario

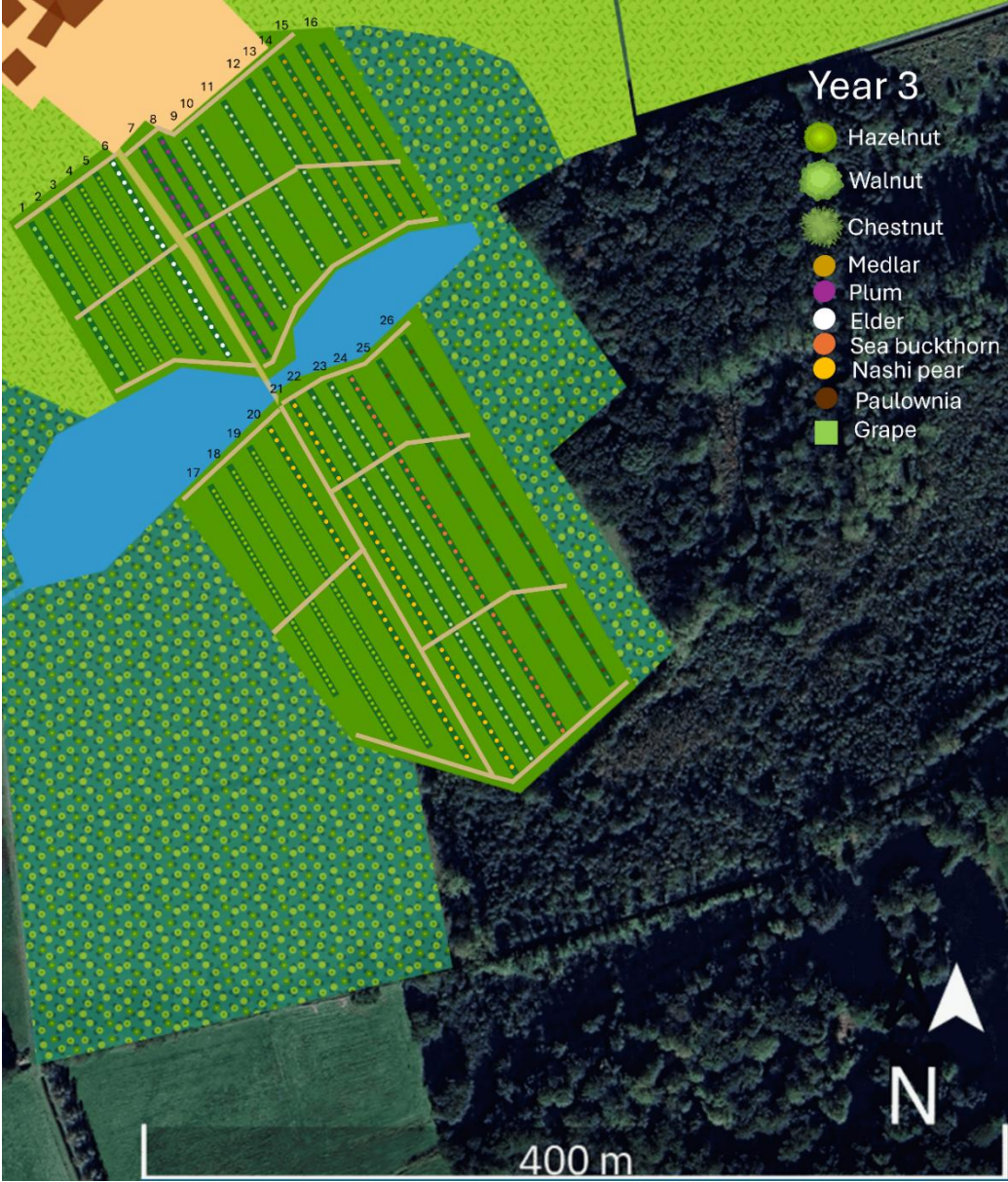


Figure 56: Spatial layout year three diversity scenario



Final scenario

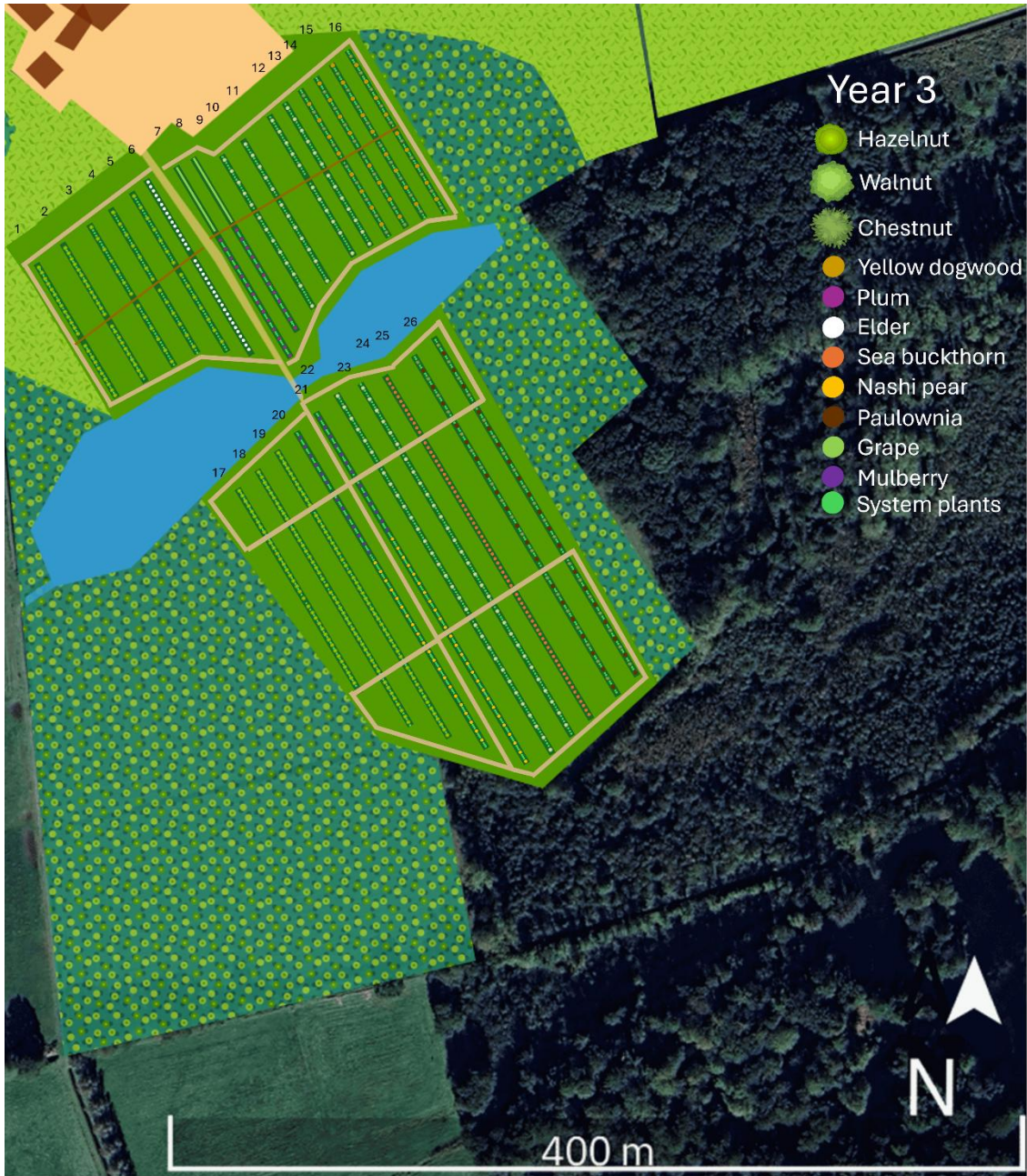


Figure 57: Spatial layout year three final scenario



X. Planting list

Table 7: Planting list per scenario including Planting distance before and after thinning, number of trees, crown width

Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Bulk scenario	1		Corylus avellana	Gustav Zeller	3	6	29	14	6
Bulk scenario	2		Corylus avellana	Gustav Zeller	3	6	30	14	6
Bulk scenario	3		Corylus avellana	Lang Tidling	3	6	30	14	6
Bulk scenario	4		Corylus avellana	Zeller	3	6	31	15	6
Bulk scenario	5		Corylus avellana	Lang Tidling	3	6	33	16	6
Bulk scenario	6		Corylus avellana	Zeller	3	6	36	17	6
Bulk scenario	7		Corylus avellana	Gustav Zeller	3	6	39	19	6
Bulk scenario	8		Corylus avellana	Lang Tidling	3	6	36	17	6
Bulk scenario	9		Castanea crenata x sativa	Zeller	3	6	10	10	6
Bulk scenario	9		Prunus cerasifera x	Marigoule	9	9	9	9	8
Bulk scenario	10		Prunus salicina	Komeet	9	9	9	9	4
Bulk scenario	10		Castanea crenata x sativa	Marigoule	9	9	10	10	8
Bulk scenario	10		Prunus cerasifera x	Gek	9	9	9	9	4
Bulk scenario	11		Castanea crenata x sativa	Marigoule	9	9	10	10	8
Bulk scenario	11		Prunus cerasifera x	Precouce migoule	9	9	9	9	8
Bulk scenario	11		Prunus salicina	Komeet	9	9	9	9	4
Bulk scenario	12		Castanea crenata x sativa	Precouce migoule	9	9	10	10	8
Bulk scenario	12		Prunus cerasifera x	Gek	9	9	9	9	4
Bulk scenario	12		Prunus salicina	Gek	9	9	9	9	4
Bulk scenario	13		Castanea crenata x sativa	Precouce migoule	9	9	10	10	8
Bulk scenario	13		Castanea crenata x sativa	Bouche de Betizac	9	9	10	10	8
Bulk scenario	13		Cornus mas	Bolestraszycki	9	9	9	9	4



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Bulk scenario	14		Castanea sativa	crenata x Bouche de Betizac	9	9	10	10	8
Bulk scenario	14		Cornus mas	Bolestraszycki	9	9	9	9	4
Bulk scenario	15		Castanea sativa	crenata x Marigoule	9	9	10	10	8
Bulk scenario	15		Cornus mas	Swietljaczok	9	9	9	9	4
Bulk scenario	16		Castanea sativa	crenata x Marigoule	9	9	10	10	8
Bulk scenario	16		Cornus mas	Swietljaczok	9	9	9	9	4
Bulk scenario	17		Corylus avellana	Halls Giant	3	6	40	19	6
Bulk scenario	18		Corylus avellana	Halls Giant	3	6	52	25	6
Bulk scenario	19		Corylus avellana	Corabel	3	6	56	27	6
Bulk scenario	20		Corylus avellana	Corabel	3	6	62	30	6
Bulk scenario	21		Corylus avellana	Halls Giant	3	6	70	33	6
Bulk scenario	22		Corylus avellana	Halls Giant	3	6	71	33	6
Bulk scenario	23		Castanea sativa	crenata x Marigoule	9	9	21	21	8
Bulk scenario	23		Cornus mas	Elegantny	9	9	20	20	4
Bulk scenario	24		Castanea sativa	crenata x Precouce migoule	9	9	21	21	8
Bulk scenario	24		Pyrus pyrifolia	chojuro	9	9	19	19	4
Bulk scenario	25		Castanea sativa	crenata x Bouche de Betizac	9	9	21	21	8
Bulk scenario	25		Pyrus pyrifolia	hakko	9	9	18	18	4
Bulk scenario	26		Castanea sativa	crenata x Bouche de Betizac	9	9	21	21	8
Bulk scenario	26		Pyrus pyrifolia	niitaka	9	9	18	18	4
Diversity scenario	1		Corylus avellana	Lang Zeller, Zeller	3	6	30	14	6



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)	
Diversity scenario	2		Corylus avellana	Lang Zeller, Zeller	Tidling Gustav		30	14		
Diversity scenario	3			Lang Zeller, Zeller	Tidling Gustav	3	6	31	14	6
Diversity scenario	4		Corylus avellana	Lang Zeller, Zeller	Tidling Gustav		31	15		
Diversity scenario	5			Lang Zeller, Zeller	Tidling Gustav	3	6	32	16	6
Diversity scenario	6		Sambucus nigra			5	5	21	4	
Diversity scenario	7	south	Prunus cerasifera x salicina	Komeet		5	5	14	4	
Diversity scenario	7	north	Vitis vinifera	Himrod		5	5	9		
Diversity scenario	8	south	Prunus cerasifera x salicina	Gek		5	5	12	4	
Diversity scenario	8	north	Vitis vinifera	Venus		5	5	9		
Diversity scenario	9		Juglans regia	Broadview, Mars	Lara,	4.5	9	21	10	8
Diversity scenario	10		Juglans regia	Broadview, Mars	Lara,	4.5	9	20	9	8
Diversity scenario	11		Juglans regia	Broadview, Mars	Lara,	4.5	9	20	10	8
Diversity scenario	12		Juglans regia	Broadview, Mars	Lara,	4.5	9	19	10	8



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Diversity scenario	13		Castanea sativa	crenata x Bouche de Betizac, Precouce migoule	9	9	10	10	8
Diversity scenario	13		Cornus mas	Bolestraszycki	9	9	9	9	4
Diversity scenario	14		Castanea sativa	crenata x Bouche de Betizac, Precouce migoule	9	9	10	10	8
Diversity scenario	14		Cornus mas	Bolestraszycki	9	9	9	9	4
Diversity scenario	15		Castanea sativa	crenata x Marigoule, Bournette	9	9	10	10	8
Diversity scenario	15		Cornus mas	Swietljaczok	9	9	9	9	4
Diversity scenario	16		Castanea sativa	crenata x Marigoule, Bournette	9	9	10	10	8
Diversity scenario	16		Cornus mas	Swietljaczok	9	9	9	9	4
Diversity scenario	17		Corylus avellana	Halls Giant, Corabel	3	6	39	19	6
Diversity scenario	18		Corylus avellana	Halls Giant, Corabel	3	6	51	25	6
Diversity scenario	19		Corylus avellana	Halls Giant, Corabel	3	6	56	27	6
Diversity scenario	20	north	Morus alba x rubra	Illinois Everbearing	5	5	15	15	4
Diversity scenario	20	south	Pyrus pyrifolia	Chojuro	5	5	21	21	4
Diversity scenario	21	north	Morus alba x rubra	Illinois Everbearing	5	5	14	14	4
Diversity scenario	21	south	Pyrus pyrifolia	Hakko	5	5	25	25	4



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Diversity scenario	22		Juglans regia	Fernor, Franquette, Fernette	4.5	9	44	20	8
Diversity scenario	23			Fernor, Franquette, Fernette			43	20	
Diversity scenario	24		Hippophae rhamnoides	Sirola	5	5	31	31	4
Diversity scenario	25		Castanea crenata x sativa	Mareval, Precouce migoule	9	9	21	21	8
Diversity scenario	25		Paulownia tomentosa		9	9	18	18	4
Diversity scenario	26		Castanea crenata x sativa	Mareval, Precouce migoule	9	9	21	21	8
Diversity scenario	26		Paulownia tomentosa		9	9	18	18	4
Diversity scenario			Hippophae rhamnoides	Polmix	5	5	6	6	4
Final scenario	1		Corylus avellana	Halls Giant	3	6	23	12	6
Final scenario	1		System plant		3		21		
Final scenario	2		Corylus avellana	Halls Giant	3	6	23	12	6
Final scenario	2		System plant		3		22		
Final scenario	3		Corylus avellana	Halls Giant	6	6	13	13	6
Final scenario	3		System plant		1.5		34		
Final scenario	4		Corylus avellana	Corabel	6	6	13	13	6
Final scenario	4		System plant		1.5		35		
Final scenario	5		Corylus avellana	Corabel	6	6	14	14	6
Final scenario	5		System plant		1.5		39		
Final scenario	6		Sambucus nigra		2.5		37	37	4
Final scenario	7		Prunus cerasifera x salicina	Komeet	5		14	14	4
Final scenario	7		System plant		1.25		39		



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Final scenario	7		Vitis vinifera	Himrod	2		17	17	
Final scenario	8		Prunus cerasifera x salicina	Gek	5		12	12	4
Final scenario	8		System plant		1.25		33		
Final scenario	8		Vitis vinifera	Venus	2		17	17	
Final scenario	9		Juglans regia	Fernor	6	12	13	7	8
Final scenario	9		System plant		1.5		39		
Final scenario	10		Juglans regia	Fernor	6	12	12	7	8
Final scenario	10		System plant		1.5		35		
Final scenario	11		Juglans regia	Franquette	6	12	11	7	8
Final scenario	11		System plant		1.5		35		
Final scenario	12		Juglans regia	Franquette	6	12	13	7	8
Final scenario	12		System plant		1.5		35		
Final scenario	13		Castanea crenata x sativa	Mareval	9		9	9	8
Final scenario	13		Cornus mas	Bolestraszycki	9		8	8	4
Final scenario	13		System plant		1		35		
Final scenario	14		Castanea crenata x sativa	Mareval	9		9	9	8
Final scenario	14		Cornus mas	Swietljaczok	9		8	8	4
Final scenario	14		System plant		1		35		
Final scenario	15		Castanea crenata x sativa	Belle epine	9		9	9	8
Final scenario	15		Cornus mas	Bolestraszycki	9		9	9	4
Final scenario	15		System plant		1		36		
Final scenario	16		Castanea crenata x sativa	Belle epine	9		10	10	8
Final scenario	16		Cornus mas	Swietljaczok	9		9	9	4
Final scenario	16		System plant		1		39		
Final scenario	17		Corylus avellana	Lang Tidling Zeller	3		36	19	6
Final scenario	17		System plant		3		37		
Final scenario	18		Corylus avellana	Gustav Zeller	3		46	24	6



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Final scenario	18		System plant		3		47		
Final scenario	19		Corylus avellana	Lang Zeller	3	Tidling	52	27	6
Final scenario	19		System plant		3		52		
Final scenario	20	north	Morus alba x rubra	Illinois Everbearing	5		13	13	4
Final scenario	20	south	Pyrus pyrifolia	Chojuro	5		21	21	4
Final scenario	20		System plant		1.25		105		
Final scenario	21		Morus alba x rubra	Illinois Everbearing	5		13	13	4
Final scenario	21		Pyrus pyrifolia	Hakko	5		26	26	4
Final scenario	21		System plant		1.25		112		
Final scenario	22		Juglans regia	Broadview	12		31	16	8
Final scenario	22		System plant		1.5		90		
Final scenario	23	north	Juglans regia	Lara	12		15	8	8
Final scenario	23	south	Juglans regia	Mars	12		15	7	8
Final scenario	23		System plant		1.5		89		
Final scenario	24		Hippophae rhamnoides	Polmix	2		11	11	4
Final scenario	24		Hippophae rhamnoides	Sirola	2		63	63	4
Final scenario	25	north	Castanea crenata x sativa	Bouche de Betizac	9		9	9	8
Final scenario	25	south	Castanea crenata x sativa	Marigoule	9		10	10	8
Final scenario	25		Paulownia tomentosa		9		19		
Final scenario	25		System plant		1		77		
Final scenario	26	south	Castanea crenata x sativa	Bournette	9		10	10	8
Final scenario	26	north	Castanea crenata x sativa	Precouce migoule	9		9	9	8
Final scenario	26		Paulownia tomentosa		9		19		
Final scenario	26		System plant		1		78		
Final scenario	17a		Corylus avellana	Lang Zeller		Tidling		20	6



Scenario	Row	Placement in row	Species	Cultivar	Planting distance start	Planting distance after thinning	Amount (at start)	Amount (after thinning)	crown width (m)
Final scenario	18a		Corylus avellana	Gustav Zeller Lang Tidling		6		22	6
Final scenario	19a		Corylus avellana	Zeller		6		22	6
Final scenario	1a		Corylus avellana	Halls Giant		6		11	6
Final scenario	2a		Corylus avellana	Halls Giant		6		11	6



XI. Harvesting calendar

Table 8: Chestnut and Hazelnut cultivars of the bulk scenario and their cropping period. Starting in early autumn with E= early, EM = early medium, M = medium, ML = medium late

Species	Cultivar	E	EM	M	ML
Chestnut	Marigoule				
	Bouche de Betizac				
	Precouce migoule				
Hazelnut	Gunslebert				
	Corabel				
	Lang Tidling Zeller				
	Gustav				

Table 9: Chestnut, Hazelnut and Walnut cultivars of the diversity scenario and their cropping period. Starting in early autumn with E= early, EM= early medium, M= medium, ML = medium late, L = late

Species	Cultivar	E	EM	M	ML	L
Chestnut	Marigoule					
	Bouche de Betizac					
	Précoce Migoule					
	Mareval					
	Belle Epine					
	Bournette					
Hazelnut	Halls Giant					
	Corabel					
	Lang Tidling Zeller					
	Gustav Zeller					
Walnut	Fernor					
	Franquette					
	Fernette					
	Broadview					
	Lara					
	Mars					



Table 10: Chestnut, Hazelnut and Walnut cultivars of the final scenario and their cropping period. Starting in early autumn with E= early, EM= early medium, M= medium, ML = medium late, L = late

Species	Cultivar	E	EM	M	ML	L
Chestnut	Marigoule					
	Bouche de Betizac					
	Precouce migoule					
	Mareval					
	Belle epine					
	Bournette					
Hazelnut	Halls Giant					
	Corabel					
	Lang Tidling Zeller					
	Gustav Zeller					
Walnut	Fernor					
	Franquette					
	Broadview					
	Lara					
	Mars					



XII. Harvesting operations

Based on the harvesting calendar, harvesting period and the number of harvest operations (with or without shaking), species and cultivars were grouped to be harvested during a specific harvest operation. The result can be observed in the tables below.

Table 11: Harvesting operations Bulk scenario without shaking

<u>Harvest operation 1</u>	<u>Harvest operation 2</u>	<u>Harvest operation 3</u>	<u>Harvest operation 4</u>	<u>Harvest operation 5</u>
Chestnut (1/4 of total yield) - Bouche de betizac - Precouce migoule Hazelnut (1/2 of total yield) - Lang Tidling Zeller - Gustav	Chestnut (1/4 of total yield) - Bouche de betizac - Precouce migoule	Chestnut (1/4 of total yield) - Bouche de betizac - Precouce migoule - Marigoule	Chestnut (1/4 of total yield) - Bouche de betizac - Precouce migoule - Marigoule	Chestnut (1/4 of total yield) - Marigoule
<u>Harvest operation 6</u>	<u>Harvest operation 7</u>	<u>Harvest operation 8</u>	<u>Harvest operation 9</u>	
Chestnut (1/4 of total yield) - Marigoule	Hazelnut (1/2 of total yield) - Lang Tidling Zeller - Gustav	Hazelnut (1/2 of total yield) - Gunslebert - Corabel	Hazelnut (1/2 of total yield) - Gunslebert - Corabel	



Table 12: Harvesting operations Bulk scenario with shaking

<u>Harvest operation 1</u>	<u>Harvest operation 2</u>	<u>Harvest operation 3</u>	<u>Harvest operation 4</u>	<u>Harvest operation 5</u>
Chestnut (1/3 of total yield) - Bouche de betizac - Precouce migoule - Marigoule Hazelnut (1/2 of total yield) - Lang Tidling Zeller - Gustav	Chestnut (1/3 of total yield) - Bouche de betizac - Precouce migoule - Marigoule	Chestnut (1/3 of total yield) - Bouche de betizac - Precouce migoule - Marigoule	Hazelnut (1/2 of total yield) - Lang Tidling Zeller - Gustav - Gunslebert - Corabel	Hazelnut (1/2 of total yield) - Gunslebert - Corabel



Table 13: Harvesting operations Diversity scenario without shaking

<p>Harvest operation 1</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav 	<p>Harvest operation 2</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule 	<p>Harvest operation 3</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule - Marigoule - Bournette 	<p>Harvest operation 4</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule - Marigoule - Bournette 	<p>Harvest operation 5</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Marigoule - Bournette <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara -Mars
<p>Harvest operation 6</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Marigoule - Bournette <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara -Mars 	<p>Harvest operation 7</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara -Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Giant - Corabel 	<p>Harvest operation 8</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara -Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine 	<p>Harvest operation 9</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara -Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette 	<p>Harvest operation 10</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette
<p>Harvest operation 11</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette 	<p>Harvest operation 12</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Giant - Corabel 	<p>Harvest operation 13</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette 		



Table 14: Harvesting operations Diversity scenario with shaking

<p>Harvest operation 1</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Bouche de Betizac - Precouce migoule <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav 	<p>Harvest operation 2</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Bouche de Betizac - Precouce migoule 	<p>Harvest operation 3</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Bouche de Betizac - Precouce migoule - Marigoule - Bournette 	<p>Harvest operation 4</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Marigoule - Bournette 	<p>Harvest operation 5</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Marigoule - Bournette <p>Walnut 1/3 :</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars
<p>Harvest operation 6</p> <p>Walnut 1/3 :</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars 	<p>Harvest operation 7</p> <p>Walnut 1/3 :</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav 	<p>Harvest operation 8</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Hans Giant - Corabel 	<p>Harvest operation 9</p> <p>Chestnut 1/3:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Walnut 1/3:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette 	<p>Harvest operation 10</p> <p>Walnut 1/3:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette
<p>Harvest operation 11</p> <p>Walnut 1/3:</p> <ul style="list-style-type: none"> - Fernor - Franquette - Fernette <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Hans Giant - Corabel 				



Table 15: Harvesting operations Final scenario without shaking

<p>Harvest operation 1</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav 	<p>Harvest operation 2</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule 	<p>Harvest operation 3</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule - Marigoule - Bournette 	<p>Harvest operation 4</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Bouche de Betizac 66 - Precouce Migoule - Marigoule - Bournette 	<p>Harvest operation 5</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Marigoule - Bournette <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars
<p>Harvest operation 6</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Marigoule - Bournette <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Lang Tidling Zeller - Gustav <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars 	<p>Harvest operation 7</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Giant - Corabel 	<p>Harvest operation 8</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine 	<p>Harvest operation 9</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Broadview - Lara - Mars <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - 	<p>Harvest operation 10</p> <p>Chestnut ¼:</p> <ul style="list-style-type: none"> - Maraval - Belle epine <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette -
<p>Harvest operation 11</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette 	<p>Harvest operation 12</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - <p>Hazelnut ½:</p> <ul style="list-style-type: none"> - Giant - Corabel 	<p>Harvest operation 13</p> <p>Walnut 1/5:</p> <ul style="list-style-type: none"> - Fernor - Franquette - 		



Table 16: Harvesting operations Final scenario with shaking

<p>Harvest operation 1 Chestnut 1/3: - Bouche de Betizac - Precouce migoule Hazelnut ½: - Lang Tidling Zeller - Gustav</p>	<p>Harvest operation 2 Chestnut 1/3: - Bouche de Betizac - Precouce migoule</p>	<p>Harvest operation 3 Chestnut 1/3: - Bouche de Betizac - Precouce migoule - Marigoule - Bournette</p>	<p>Harvest operation 4 Chestnut 1/3: - Marigoule - Bournette</p>	<p>Harvest operation 5 Chestnut 1/3: - Marigoule - Bournette Walnut 1/3 : - Broadview - Lara - Mars</p>
<p>Harvest operation 6 Walnut 1/3 : - Broadview - Lara - Mars</p>	<p>Harvest operation 7 Walnut 1/3 : - Broadview - Lara - Mars Chestnut 1/3: - Maraval - Belle epine Hazelnut ½: - Lang Tidling Zeller - Gustav</p>	<p>Harvest operation 8 Chestnut 1/3: - Maraval - Belle epine Hazelnut ½: - Hans Giant Corabel</p>	<p>Harvest operation 9 Chestnut 1/3: - Maraval - Belle epine Walnut 1/3: - Fernor - Franquette</p>	<p>Harvest operation 10 Walnut 1/3: - Fernor - Franquette</p>
<p>Harvest operation 11 Walnut 1/3: - Fernor - Franquette Hazelnut ½: - Hans Giant Corabel</p>				



XIII. Benefits and drawbacks of nut harvesting methods in Bulk and Diversity Scenario

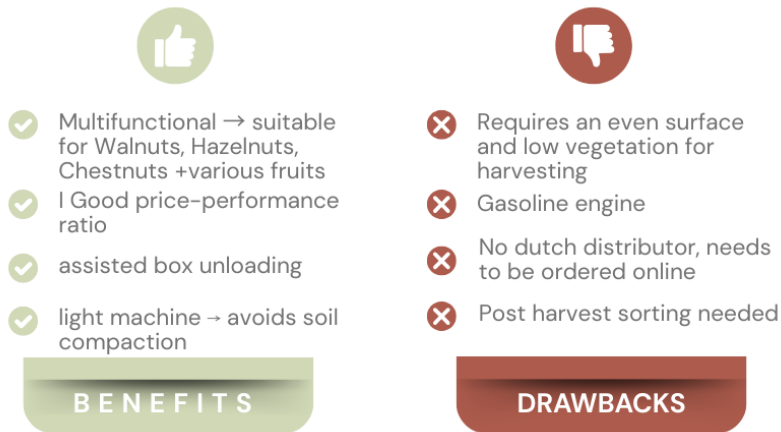


Figure 58: Benefits and drawbacks of nut harvesting method bulk scenario

Diversity scenario

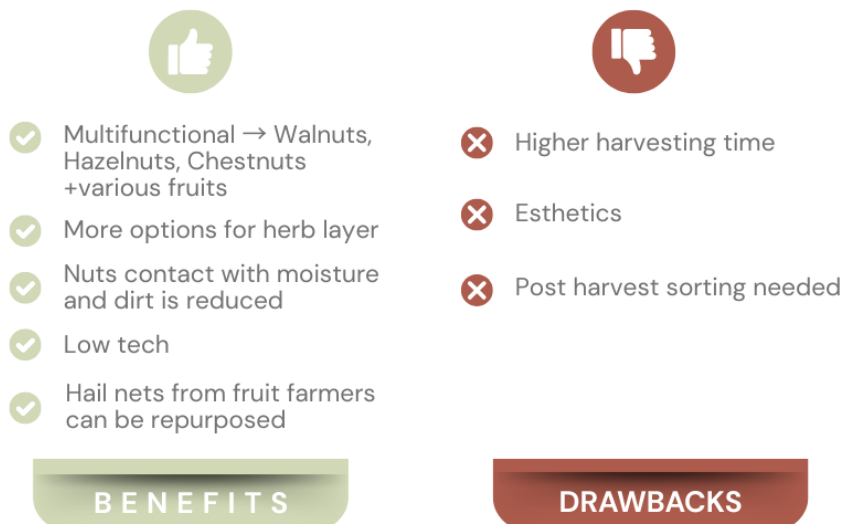


Figure 59: Benefits and drawbacks of nut harvesting method diversity scenario



XIV. Species list Middenbos tea mix

Yarrow, marsh mallow, marigold, cornflower, rosebay willowherb, wild carrot, meadowsweet, wild strawberry, common daisy, musk mallow, true chamomile, sweet yellow clover, cicely, oregano, narrowleaf plantain, salad burnet, meadow sage, dandelion, red clover, sweet violet



XV. Concept generation in morphological diagram

★ = diversity scenario, ★ = bulk scenario

Table 17: Concept generation of bulk and diversity scenario

Function	WP 1	WP 2	WP 3	WP 4	WP 5	WP 6	WP 7	WP 8	WP 9	WP 10
DETACH NUTS	Passive detachment		Shake							
	Natural drop	Hand	Cable shaker	Stem shaker						
COLLECT NUTS	Hand	Net	Wire basket	Shovel	Flexible fins horizontal	Flexible fins vertical	Suction (Vacuum)	Sweeper	Umbrella collector	
REACH FRUIT	Hand	Pole	Ladder	Platform						
GRIP FRUIT	Hand	Soft gripper	Rigid gripper	Metal fingers	Bag					
DETACH FRUIT (FRESH PRODUCE)	Pull or Twist					Cut				
	Hand	Soft gripper	Rigid gripper	Metal fingers	Comb	Scissors	Knife			
DETACH FRUIT (PROCESSING)	Passive detachment		Shake							
	Natural drop	Hand	Hook shaker	Vibrating comb	Cable shaker	Stem shaker				
COLLECT FRUIT	Hand	Net	Wire basket	Pins	Flexible fins horizontal	Flexible fins vertical	Suction (Vacuum)	Sweeper	Umbrella collector	
DETACH HERBS	Manual tools		Powered tools							
	Hand	Scissors	Scythe	Serrated blade	Scissors					
COLLECT HERBS	Hand	Blade channeler	Rake	Micrame braided string pick-up reel	Airflow	Conveyor belt				
STORE HARVEST	Bucket	Cup	cardboard tray	Bag	Crate	Storage container on wheels				
TRANSPORT HARVEST	Manual handled transport					Mechanically assisted - pulled by external source				
	Picking harness	Runners	Single-wheeled cart	Two-wheeled trolley	Four-wheeled cart	Tow-behind trailer	Single-wheeled cart	Tricycle	4-wheeled vehicle	4(+) wheeled platform



XVI. Storage unit per crop type

Table 18: Storage unit per crop type for bulk and diversity scenario

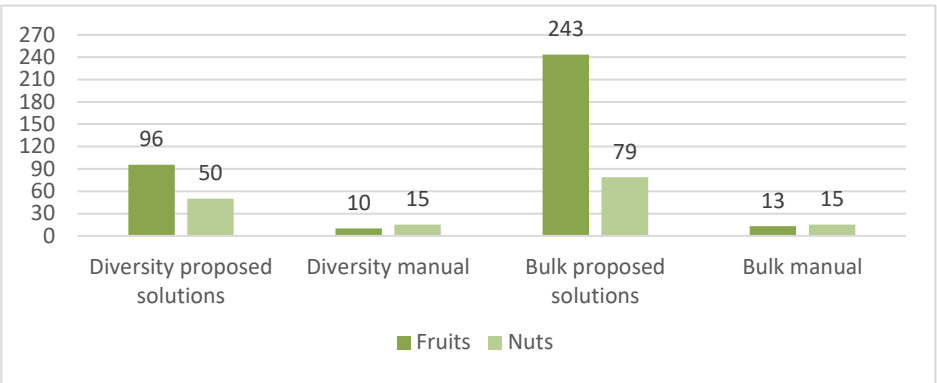
Type of crop	Bulk scenario	Diversity scenario
Nuts	Storage space of harvesting machine	crate
Yellow dogwood, nashi pear, Russian plum, mulberry	crate	crate
elder	-	bucket
Sea buckthorn	-	crate
grape	-	crate



XVII. Requirement evaluation

A detailed underpinning of the self-conducted evaluation on the requirements can be found in the table below. Numbers correlate to the Index as mentioned in Table 3.

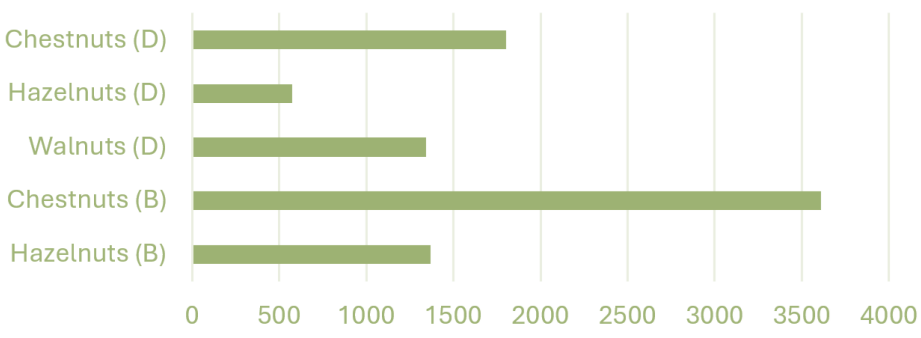
Table 19: Requirement evaluation

Index	Description
1	<p>The harvesting efficiency for fruits and nuts was calculated to compare and evaluate the scenarios. As shown in Figure x, the bulk scenario achieves 2.5 times higher efficiency for fruits and 1.5 times higher for nuts compared to the diversity scenario. However, both scenarios significantly improve harvesting efficiency relative to manual harvest. In the diversity scenario, nut harvesting efficiency is three times higher, and fruit harvesting efficiency nearly ten times higher. In the bulk scenario, nut harvesting efficiency is five times higher, and fruit harvesting efficiency increases by a factor of 18.</p>  <p>Figure 60: Harvesting efficiency in kg/hour for diversity and bulk scenario</p> <p>The harvesting efficiency of the herb layer was not quantitatively defined, as there was insufficient data available on harvest speeds for the diverse range of herbs and perennial vegetables present. However, in the diversity scenario, herbs are harvested using a method with a capacity of 300 kg/hour, whereas in the bulk scenario, they are harvested manually with scissors, indicating lower harvesting speeds. Furthermore, all areas below the nut trees must be mowed well before nut harvesting begins. However, the herb layer in the diversity scenario is on a much larger scale, indicating that more yield needs to be harvested. Additionally, the diversity scenario includes perennial vegetables, which are harvested by hand. In total, the herb layer of the diversity scenario requires more labour. Harvesting efficiency is, however, increased by utilising an efficient harvesting machine for cutting herbs. Overall, these results align with the farmer’s evaluation, who rated the bulk scenario a four and the diversity scenario a two.</p>
2	<p>The harvesting nets in the diversity scenario do not require an even surface or low vegetation, thereby not impacting species choice in the herb layer. However, during the nets are in use (end August till October), the nets interfere with harvest, observation and weeding of the herb layer. This implicates that harvesting of the herbs needs to be timed in accordance with the nut harvest.</p> <p>The sweeping machine in the bulk scenario requires an even surface of the herb layer, with vegetation lower than 15cm below the tree canopy for efficient harvest. Clover that is planted below the tree canopy acts as a support plant during its growth and is able to be mowed to the above-mentioned standards. However, no herbs for consumption can be grown. This reasoning aligns with the case study farmer’s evaluation, as both scenarios enable efficient herb harvesting but also present certain drawbacks.</p>
3	Bulk Scenario



	<p>In the bulk scenario, hazelnuts in the north field are early ripening cultivars, with two rows of the same cultivar being next to each other. Hazelnuts in the south field are late ripening, also with two rows of the same cultivar. This can be characterised as efficient grouping which decreases transport distances during hazelnut harvest.</p> <p>Chestnut varieties are all early ripening. Since chestnuts are in both the north and south field, during chestnut harvest, both fields need to be harvested. Nashi pear and plum are situated in one location of the field. Yellow dogwood is mainly in the north field, while there is one row that needs to be harvested in the south field.</p> <p>Diversity scenario</p> <p>In the diversity scenario, hazelnuts in the north field are early ripening cultivars. Hazelnuts in the south field are late ripening. Two cultivars with the same ripening period are mixed within each row. The same combination of cultivars is repeated over multiple rows (five in the north field, three in the south field). Therefore, this can also be characterised as efficient grouping which decreases transport distances during hazelnut harvest. Chestnut varieties in the north field are early ripening, in the south field they are medium to late ripening. Two cultivars with the same ripening period are mixed within each row. In the north field, the same combination of cultivars is repeated in two consecutive rows. Walnut varieties in the north field are medium ripening, while in the south field they are late ripening. Two cultivars with the same ripening period are mixed within the row. The same combination of cultivars is repeated in at least two consecutive rows. Fruits of the same species are grouped in the same row or in adjoining rows.</p> <p>Summary</p> <p>Overall fewer species and cultivars and uniform rows with only one cultivar, resulted in a larger areas of trees that are the same species and cultivar, increasing transport efficiency. However, groupings for both scenario are done with harvesting period, which in theory should be able to be harvested at the same time period. Thereby lowering transport times. Additionally, it needs to be taken into account that different species and cultivars may react differently to environmental factors, potentially shifting harvesting periods for one species more than another. Since there are more species in the diversity scenario, this would create a bigger impact for this scenario.</p> <p>Path layout</p> <p>Expert feedback indicated that it would be more efficient to also add paths around the fields so that the micro tractor would not need to do a 180 degree turn at the end of the path.</p>
4.1	<p>The arable harvesting machines discussed prior to the evaluation have sufficient workspace since arable strips are a minimum of 6m, which is a multiple of three meters. However, during the evaluation, the case study farmer mentioned that he also wants to use a 9m wide machine; therefore, certain rows are not wide enough for the machine to pass. This will be addressed in the final scenario. An open space of exactly 6m is maintained at the beginning and end of each arable strip.</p> <p>The sweeping machine for the nut harvest in the bulk scenario has sufficient workspace, as the herb layer below the tree canopy is clover, which is mowed before harvest. Trees interplanted within the chestnut rows also do not impact the harvest since the stem of the tree is outside of the canopy of the nut trees.</p> <p>Harvesting nets for the nut harvest in the diversity scenario can be attached on a height that is below both the nut tree and fruit tree canopy, giving sufficient space for the nets to be put without having gaps in between.</p> <p>Mechanical fruit harvest and the wheelbarrow ladder for manual picking require a 1m wide access path around the fruit trees and the possibility to walk around the tree. This is possible in both scenarios.</p> <p>The herb harvesting machine in the diversity scenario has a total width (including tires) of 1.4m, providing sufficient space in the 1.5m herb strip on each side of the trees.</p>



4.2	<p>Exactly six meters of open space are maintained at the end and the beginning of each arable strip.</p> <p>Overall, both scenarios give sufficient space for the harvesting machines. The only aspect that needs improvement is the width of the arable strips.</p>																		
5.1	<p>It can be observed in Figure x that nut yields after 15 years are above 500kg for all nut species in both scenarios. In the Bulk scenario, both hazelnuts and chestnuts are even above the target of 1000 kg. In the diversity scenario, walnuts and chestnuts are also above the 1000kg target. Hazelnuts however are in the lower end of the range.</p>  <table border="1" data-bbox="319 448 1244 784"> <caption>Data for Figure 61: Nut yields after 15 years</caption> <thead> <tr> <th>Scenario</th> <th>Nut Species</th> <th>Yield (kg)</th> </tr> </thead> <tbody> <tr> <td>Diversity (D)</td> <td>Chestnuts</td> <td>~1800</td> </tr> <tr> <td>Diversity (D)</td> <td>Hazelnuts</td> <td>~600</td> </tr> <tr> <td>Diversity (D)</td> <td>Walnuts</td> <td>~1400</td> </tr> <tr> <td>Bulk (B)</td> <td>Chestnuts</td> <td>~3600</td> </tr> <tr> <td>Bulk (B)</td> <td>Hazelnuts</td> <td>~1400</td> </tr> </tbody> </table> <p>Figure 61: Nut yields after 15 years for Bulk scenario (B) and Diversity scenario (D)</p> <p>The farmers score of 4 and 3 points for the bulk and the diversity scenario correlates with this data.</p>	Scenario	Nut Species	Yield (kg)	Diversity (D)	Chestnuts	~1800	Diversity (D)	Hazelnuts	~600	Diversity (D)	Walnuts	~1400	Bulk (B)	Chestnuts	~3600	Bulk (B)	Hazelnuts	~1400
Scenario	Nut Species	Yield (kg)																	
Diversity (D)	Chestnuts	~1800																	
Diversity (D)	Hazelnuts	~600																	
Diversity (D)	Walnuts	~1400																	
Bulk (B)	Chestnuts	~3600																	
Bulk (B)	Hazelnuts	~1400																	
5.2	<p>In the bulk scenario, there is one cultivar per row, while in the diversity scenario multiple cultivars are mixed within one row. According to expert feedback, mixing cultivars within the row makes processing afterwards complex since different cultivars mean different sizes, oil content, taste, etc. Therefore, mixing cultivars within the row as is done in the diversity scenario is sub-optimal for further processing.</p>																		
6	<p>Trees planted within the rows are not estimated to be growing larger than 3m in diameter, thereby not overlapping into the arable strips. Additionally, shading is also estimated to have minimal impact on the arable crops in the first six years (J. van Eijk, personal communication, June 12, 2025).</p>																		
7	<p>The harvest season, where fresh produce can be supplied to the camping guests in the bulk scenario is three months (from July to September). For the diversity scenario, it is five months (May to October). This is due to the elderflowers that advance the harvest season to May and late chestnut and walnut varieties that extend the season into October. However, in both scenarios, fresh produce is combined with processed produce that can be stored longer and provide food supply for the camping guests over the whole season. Examples of this are nut oil and flour, juices, syrup, jams, etc.</p>																		
8	<p>While the bulk scenario produces two type of nuts and three type of fruits, the diversity scenario produces three types of nuts and seven types of fruits. Additionally, the herb layer in the diversity scenario produces various herbs and perennial vegetables, while in the bulk scenario the herb layer plays mainly a supporting role. Therefore, the diversity scenario has more diverse processing and marketing options, resulting in the potential of creating a higher diversity of revenue-generating business activities.</p>																		
9.1	<p>The nut harvesting method for the bulk scenario can be used for two functions: the hazelnut and chestnut harvest. The harvesting method of the diversity scenario can be used for three functions: harvest of chestnuts, walnuts and hazelnuts.</p> <p>The harvesting method for mechanical fruit harvests three types of fruits in the bulk scenario and four types of fruits in the diversity scenario. Furthermore, the wheelbarrow ladder for fruit picking is multifunctional, not only because it can be used for all types of fruits, but also because it enables the reaching of fruit, storage of the harvest, and can also</p>																		



	<p>be utilised as a transport unit. Additionally, the harvesting belt utilised in the diversity scenario can be utilised for all types of fruits.</p> <p>The herb harvesting method in both the diversity and bulk scenario can fulfil the harvesting operation of all herbs cultivated.</p> <p>This indicates a multifunctional use of all harvesting methods. In the diversity scenario, multiple methods fulfil more functions compared to the bulk scenario due to the higher species diversity and the adaptability of the tools/machines to multiple fruits, nuts, and herbs. However, since there is a higher species diversity, also more harvesting methods are necessary. This results in an overall higher investment cost for all harvesting methods combined; for a full overview, see XVI. However, it is essential to consider that the largest price difference results from the harvesting method of the herb layer. Since there is a higher yield in terms of culinary herbs in the diversity scenario, these costs will potentially be offset in the long term since more income can be expected.</p>
9.2	When examining the nut harvesting methods investment costs, it can be observed that both are below the maximum target of € 6,000. However, the diversity scenario is situated at the higher end (€ 5,800), while the bulk scenario requires only € 3,800.
10	Considering the type of harvesting methods for the fruit, nut and herb layer, the load of the harvest is the main impact on the soil. Therefore, soil compaction is not estimated to become an issue.
11	The high species diversity increases pest and disease resistance, thereby decreasing the need to use crop protection products.
12	In the bulk scenario, the nut harvesting method and the handheld shaker utilise a gasoline motor, which requires fossil fuels. However, as this is machinery intended for a comparably small scale, consumption is rather low. The nut harvester requires 3 liter/hour. For the handheld shaker no information regarding gasoline use is available. However, the tank volume of 1.2 litres suggests very low gasoline use. In the diversity scenario, only the handheld shaker requires gasoline.
13	The row-based system design facilitates clearer communication between entrepreneurs. Labour can be divided by assigning responsibility for the cultivation of individual vegetation layers to different entrepreneurs. Additionally, produce processing offers another opportunity for labour division. Given the active herb cultivation and greater diversity of fruits and nuts in the diversity scenario, it has the potential to involve more entrepreneurs compared to the bulk scenario.
14	The higher species diversity in the diversity scenario makes self-harvesting for camping guests more interesting as compared to the bulk scenario, as they can harvest a larger variety of fruits, nuts, and herbs to prepare well-balanced meals. However, this also correlates with the need for more intensive supervision, as a higher system complexity is more difficult to understand.
15	Species diversity in the diversity scenario enhances the landscape's appeal. However, according to the case study farmer, the harvesting nets have an industrial look. Since they only need to be unrolled during the harvest period, which lasts four weeks for hazelnuts and two weeks for walnuts and chestnuts, this does not have a significant impact on the overall experience.



XVIII. Investment costs

Below an overview of the Investment costs for the selected harvesting methods of the bulk and diversity scenario can be found.

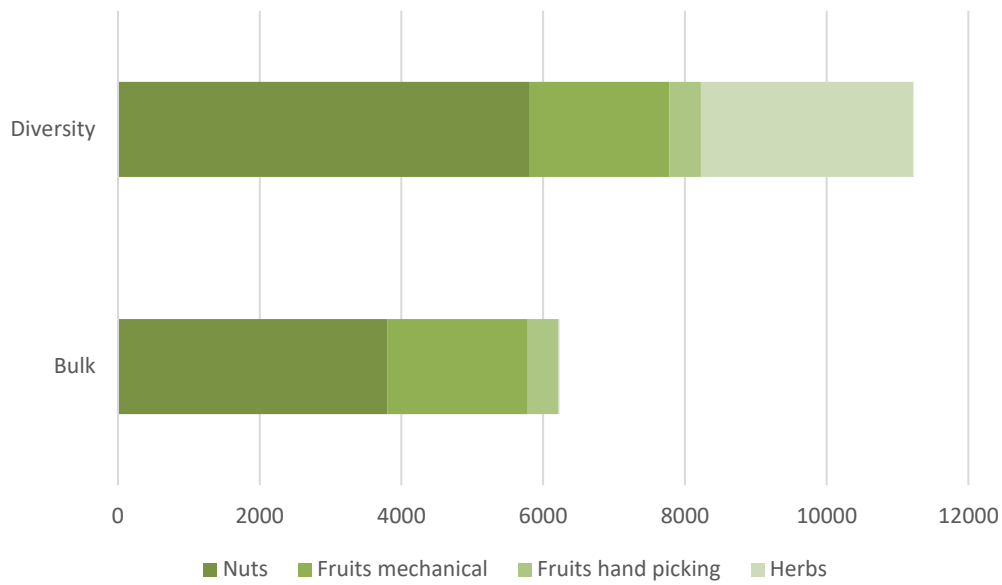


Figure 62: Investment costs of harvesting methods in bulk and diversity scenario



XIX. AI

Grammarly was used during this thesis to rephrase text in an academic writing style and ensure proper spelling. Additionally, ChatGPT which is included as an add-on in WhatsApp was used for brainstorming and to find synonyms. Grammarly was applied to all sections of the text, while ChatGPT was mainly used for brainstorming key functions and morphological chart descriptions.