MECHANISATION OF BERRY HARVESTING FOR FOOD FORESTS IN EUROPE

Master's thesis in Organic Agriculture

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Farming Systems Ecology
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Mechanisation of berry harvesting for food forests in Europe

Tags: food forest, berry harvesting, machinery, mechanisation, robotics, agroforestry, permaculture, artificial intelligence.

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Abstract

Being able to understand how food forests are set up and what processes take place it is required to understand what challenges they entail in the context of mechanisation. Looking at the different food forest systems from ecological and labour perspectives, a comprehensive analysis of the requirements and functions that need to be present in the mechanisation for such systems is needed. After assessing 2 food forest systems (in the Netherlands and Belgium) of 1,7 and 4.2 ha, it was concluded that the biggest share of labour in these systems is in berry harvesting, requiring 37-45% of total labour. Therefore, mechanisation of this activity could significantly reduce the farmer's labour demand.

In order to suggest machinery for such systems, a well-defined overview of the farming systems and farmers' objectives, needs and requirements was studied. Together with limitations of current pieces of machinery and suggestions for the suitable machinery, these aspects are addressed in this Master's thesis.

It was concluded that current agricultural machinery used for berry harvesting in monoculture orchards is not suitable for food forests. The solution that scored best on the farmer's requirements and carries functionalities needed to achieve farmer's objectives for berry harvesting was studied and described. It resembles a rather small versatile lightweight autonomous machine with artificial intelligence and a soft robotic gripper on board. It was concluded that such machinery would be useful for medium and large-scale food forests (>2 ha) and will require high investments for research and development. This can be achieved when there is a sufficient market for such mechanisation – existing food forests with high labour demand for harvest.

Contents

1 Introduction

1.1 Background

1.1.1. Current monoculture agriculture is unsustainable

Currently one of the most common agricultural practices is monoculture arable farming, which means growing one type of crop every year on the whole land (Riqueiro-Rodríguez et al., 2008).

In terms of sustainability performance of conventional arable farming, such farming is proven to have a variety of drawbacks, namely, soil degradation and soil compaction, underground water, air and ground pollution with chemicals sprayed (Riqueiro-Rodríguez et al., 2008). Reduction of soil biodiversity and soil organic matter caused by compaction and ploughing has negative impacts on crop growth. Because of intensive farming, soils get only poorer, less nutrients are available for plants (Riqueiro-Rodríguez et al., 2008), due to absence of cover crops, erosion takes place (Samson et al., 2019).

1.1.2. Effect of machinery on sustainability of monoculture agriculture

Over the years, big and heavy machinery has been developed aiming for high labour efficiency of monoculture fields (Bennett et al., 2019). With an increase of operating length and carrying capacity, machines became heavier over time (Bennett et al., 2019). Impact of conventional machinery on the soil structure got significantly higher (Samson et al., 2019). Because of that, subsoiling is often used by the farmers to break up the compation layer of the soil. This requires the use of even heavier machinery than the one that have initially caused compaction. Tillage not only have a negative effect on soil organic matter, by exposing soil to the open air, which speeds up oxidation of soil carbon, but also on soil life by mixing different soil layers (Samson et al., 2019).

1.1.3. Alternatives to current monoculture systems

Consequently, alternative practices started to develop (Samson et al., 2019), including, organic agriculture, intercropping, pixel farming, permaculture, syntropic agriculture, and agroforestry, one type of which is food forestry. In all these systems, farmers are aiming for improving the soil and other ecosystem services, no pollution of ground water, and generally for low-or-no impact on the environment, while getting sufficient harvests (Fig 1).

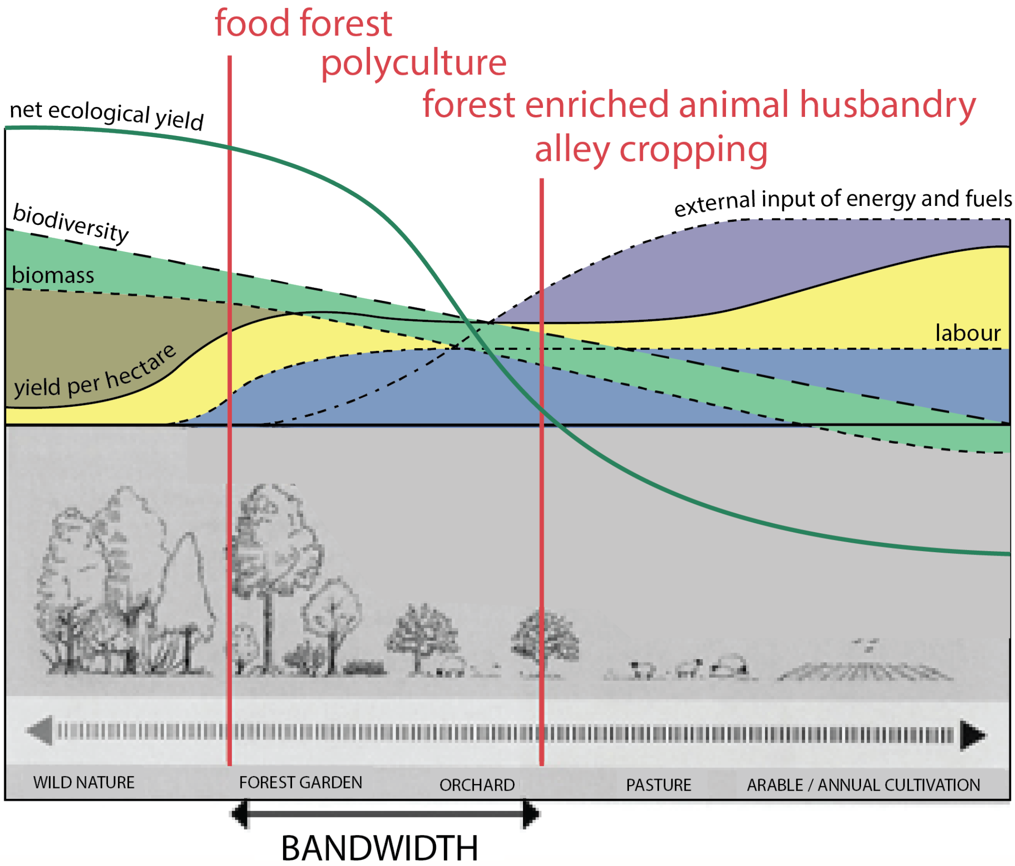

Figure 1 Performance indicators of various farming systems and wild nature, range of agroforestry systems marked in red. Increment is shown upwards from the horizontal axis. Adapted from Rotterdams Forest Garden Netwerk.

1.1.4. Agroforestry systems

Agroforestry counts several types of systems, each one with its own purpose (Fig 2). Alley cropping is a system where tree rows are placed on the sides of arable fields crops and are used to increase water retention capacity of the soil and provide additional fertilisation and/or wind protection for the crop grown in the strips between. Silvopasture entails the use of trees on pastures to protect cattle from the sun and provide additional source of fodder. Food forest orchards are a form of complex multi layer agroforestry system, where trees are planted in rows to allow for easier harvest. A food forest in its pure form has an irregular planting scheme aiming at highest biodiversity, space usage efficiency and biological interactions.

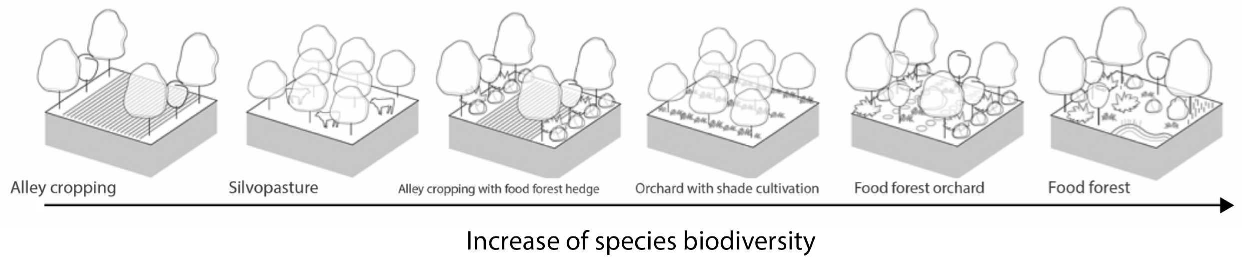

Figure 2 Various agroforestry systems. Adapted from Rotterdams Forest Garden Netwerk.

1.1.5. Food forests – the most complex form of agroforestry

Emerging as the most diverse agroforestry practice, a food forest or forest garden is designed to mimic a natural forest (Crawford, 2010). Green Deal 'Voedselbossen' (from Dutch: food forests) describes food forest as an ecosystem with:

- A canopy vegetation layer.
- Minimum 3 other vegetation levels, e.g. low trees, shrubs, herbs, creepers, tubers and climbers.
- A rich forest soil life.
- On the area of at least 0,5 ha

With adding more different crops to a system and creating a denser planting scheme than in conventional orchards, alley cropping and silvopastural systems, by including perennial crops, vines, shrubs and trees of different sizes and shapes which make up a multi layer system (Fig 1,2), it gets more complex to manage it. All the operations, apart from initial soil preparation in a food forest is currently done manually. In such an environment, since conventional machinery does not work, with less space to operate on, the only way to manage (prune, guide and harvest) such systems at the moment is by hand.

1.2. Problem statement

Substituting human labour in complex food forests requires a rethinking of machinery needed for performing operations. However, no overview of requirements and functionalities stated by food forest farmers is present. Therefore, it is also not clear which farmers' requirements are not met by the current agricultural machinery and which functions are absent in such machinery. Adding to that, what pieces of technology are missing and need to be developed in order to allow for the creation of suitable machinery.

1.3. Purpose of the study and research questions

Purposes of the study:

- Describe food forests in the Netherlands and Belgium from agroecological and labour perspectives.
- Analyse which operations need to be mechanised in food forests.
- Analyse the gap between current machinery and suitable machinery for food forests.

The main research question:

What are the needs for mechanisation in complex agroforestry systems?

Sub-questions (SRQ):

1. What are the challenges of food forests with regard to performing operations?
2. How much time is spent on operations in small scale food forests? When do they take place and how much time does each of them require on a yearly basis? How much time is spent per species?
3. What do food forests comprise of? How are they different from monoculture orchards?
4. What is the future vision of food forest farmer on the management of his systems? What objectives does the system need to meet in the TO BE situation?
5. What are the key actors involved in the research and development of suitable machinery?
6. What requirements are posed by the systems and farmers to the machinery?
7. What functions have to be present in machinery in order to perform desired operations, that are critical for meeting the systems objectives?
8. What solutions are possible and currently most suitable based on farmers' needs, requirements and required functions?
9. What is the gap between current machinery and suitable machinery? Why can current machinery not be used in food forests? What pieces of technology could be included in the suitable machinery to fulfil the functions?

1.4. Demarcation

The scope of the study is on all the operations, including harvest, pruning and guiding of woody perennial species bearing berries, nuts, fruits and other crops in different complex agroforestry systems within temperate climate, based on Dutch and Belgian food forests. Since food forests are the most complex agroforestry system counting up to 7-9 vegetation layers and often more than 50 species/ha, these systems were chosen to be included in this study. As every food forest is so different from the other, it is not possible to generalise food forests into one model that represents them all. Therefore, a number of food forest farmers in the Netherlands and Belgium were addressed. Since the aim of the research was to look at the needs for mechanisation, only farmers with such needs (either for their own farm or for complex agroforestry in general) were included. Due to availability, only one farmer had enough time to provide enough qualitative data for the labour analysis. Case study farms were reviewed from ecological and labour perspectives, while economics were left out of the scope.

2 Materials and methods

2.1 Selection of farms

In order to analyse complex agroforestry systems, case study farms were selected (Fig 3) from a long list of farming systems in the Netherlands and Belgium. A diversity of food forests was strived for, with different planting schemes, scale and at different stages of development in order to cater to a broad range of needs within the field. Both food forests are owned and managed by one farmer. Due to low response to the request for information, only one farmer, responsible for a total of 2 food forests, participated in provided quantitative data for labour analysis, while three other farmers contributed as experts.

Figure 3 Map of Benelux, case study farm locations. Adapted from Wikipedia.

2.1.1. Brief description of selected farms

- Eet Meerbosch

Eet Meerbosch is a 1.7 ha food forest located in industrial area in Nijmegen in the province of Noord-Brabant, The Netherlands and was started in 2018. Further description can be found in chapter 3.1.3.

- De Nieuwe Hof

De Nieuwe Hof is located on 4.2 ha, out of which 3.8 ha is a food forest and the rest is an arable permaculture garden, in Sint Truiden, Belgium, that was started in 2007 as a permaculture project under the name Samenland, where perennial woody species are grown next to a vegetable garden In 2019 the name of the farm changed and now it is being transformed into a food forest. Further description can be found in chapter 3.1.3.

2.2 Reflexive Interactive Design (RIO) methodology

RIO – Reflexive Interactive Design (Fig 4) – is a methodology that was developed to design of new farming systems, taking into account all the aspects from analyzing the system to external effects. It is a gradual and iterative process of several stages from identifying the addressed problem, all the way to prototyping and finally introducing the new system in practice. In this study, steps from A to H were performed.

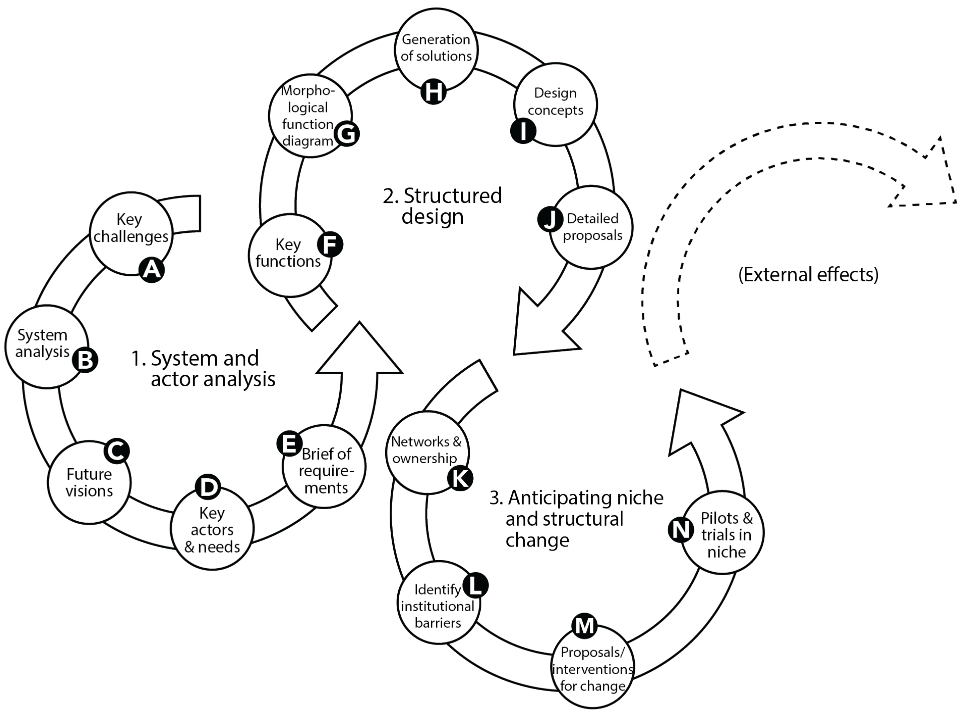

Figure 4 Three iteratively looped and linked cycles in RIO: system and actor analysis; structured design; and anticipating niche and structural change. Adapted from Bos et al., 2009.

- In step A, key challenges of the current system were identified. Quantitative data was collected from the farmer on labour hours spent per activity and its timeframe (Appendix C: questions 2A, 2F, 2I). Actual data on labour hours for 2019 was collected for food forest *De*

Nieuwe Hof and also estimated data was collected for *Eet Meerbosch* (approximately at 10 years of age). This data was then arranged in tables and graphs using Excel. Overall labour, being summed up and divided by the total area, was compared to Dutch monoculture orchards (Heijerman-Peppelman and Roelofs, 2010). Based on the comprehensive labour overview, the most labour intensive activity was identified. Activities per species group were overviewed as well to come to a more specific challenge. Focus was on making a design for performing this activity. Based on the farmer's answers during the interviews (Appendix C: questions 1J, 2H, 2J), challenges were formulated and arranged in the root cause analysis (RCA) diagram. The key challenge was formulated as an answer to the question "Why the given activity requires such a high workload?". The underlying challenges were identified having a cause and effect relation to the main challenge. Apart from the farmer, experts from food forestry were addressed as well. Their feedback on the challenges of the current food forest systems was considered during the formulation of the challenges.

- In step B, the current system was analysed, system elements and interactions between them are described. Mostly qualitative data was collected during interviews (Appendix C: Section 1, 2) with the farmer on farm description and activities performed. This data was then put in order and arranged in tables in a form of question-answer spreadsheet using Excel. In this step SRQ 3 is addressed.

- In step C, the future system is described based on farmer's objectives and vision. Qualitative data on what should be achieved in the TO BE system was collected from the farmer during interviews (Appendix C: question 3A). Data was then reformulated in forms of objectives, regarding the given operation and incorporated in the Excel spreadsheets, created in the previous step in the existing question-answer manner and figures. They were then used for further steps. In this step SRQ 4 is addressed.

- In step D, stakeholders that are influencing the transition from a current to a future system were listed. Qualitative data on stakeholders was collected from the farmer (Appendix C: question 3E, 3F) as well as other farmers and experts in the relevant fields of study. The main actors were identified and described. Key elements (incl. stakeholders) were then listed in the Venn diagram. In this step SRQ 5 is addressed.

- In step E, requirements for the future systems were listed. Qualitative as well as quantitative data was collected from the farmer (Appendix C: question 3B) and other farmers both from food forestry and commercial orchard farming. Collected data was also incorporated in the existing Excel spreadsheets. Qualitative data was transformed into qualitative data after consulting relevant literature, was categorised into fixed and variable requirements and was arranged in a table – brief of requirements - using Excel. It was then used in further steps. In this step SRQ 6 is addressed.

- In step F, functions that need to be present in the future system to meet the system objectives in the TO BE situation were listed. Qualitative data was collected from the farmer (Appendix C: question 3C) and then put into an order and arranged in a key functions table in Excel by looking at the sub-functions that lie within key functions, consulting relevant literature, online engines e.g. Science Direct and Research Gate, using keywords e.g. obstacle avoidance, object recognition etc. It was then arranged in a table and was used in further steps. In this step SRQ 7 is addressed.

- In step G, relevant possible solutions were given per function listed in the previous step. Qualitative data was collected from experts in relevant fields as well as by consulting several articles in relevant field of study using sciencedirect.com and researchgate.com with keywords CNN, R-CNN, CNN ripeness, hybrid gripper, soft robotic gripper; online patent search engine Espacenet.com with keywords berry picking device, berry gripper, soft berry gripper, soft robotic gripper. The amount results of such search can be seen in Table 1. The data from several articles was then arranged in a morphologic chart in Excel. It was then used in further steps. In this step SRQ 8 is addressed.

Table 1. Search results for used keywords

Search keyword	Amount of results
Espacenet.com	
Berry picking device	1329
Berry gripper	239
Soft berry gripper	47
Soft robotic gripper	2297
Sciencedirect.com	
CNN	24212
R-CNN	18670
CNN ripeness	206
Hybrid gripper	8727

- In step H, by choosing the most suitable solution(s) per function based on farmer's vision, objectives and requirements, the overall solution was generated and described. The most suitable solutions per function were chosen and arranged in a table using Excel. The overall solution was compared to the two alternative ones, which represent current berry harvesting in food forests and monoculture orchards. These solutions were scored by me on a scale from 1 to 4, where 1 represents that the solution is not meeting the requirement and 4 represents that the solution fully meets the requirement. In this step SRQ 8 is addressed.

For SRQ 9, qualitative data was collected from the conclusions for the previous steps. It was then arranged in Word. Proposed solution (from step H) was compared with existing solutions (found using patent research engine Espacenet and searching for existing machinery using Google search engine).

2.3 Experts involvement

For steps A-C, E-F, H no experts were involved. For step D and G experts in food forestry, soft robotics, artificial intelligence (neural networks), agroforestry machinery, smart farming technology for food forests were involved. The full list of experts involved can be found in Appendix H.

3 Results

3.1. Key challenge of the food forests

3.1.1. Overall workload comparison between food forests and monoculture orchards

By comparing labour spent on harvest and maintenance of food forests and monoculture orchards (Fig 5), it became evident that there are significantly less labour hours required for maintenance activities in food forests than in monoculture orchards. In monoculture orchards 228-645 hours/ha/year is spent on maintenance activities such as plant protection (in form of spraying),

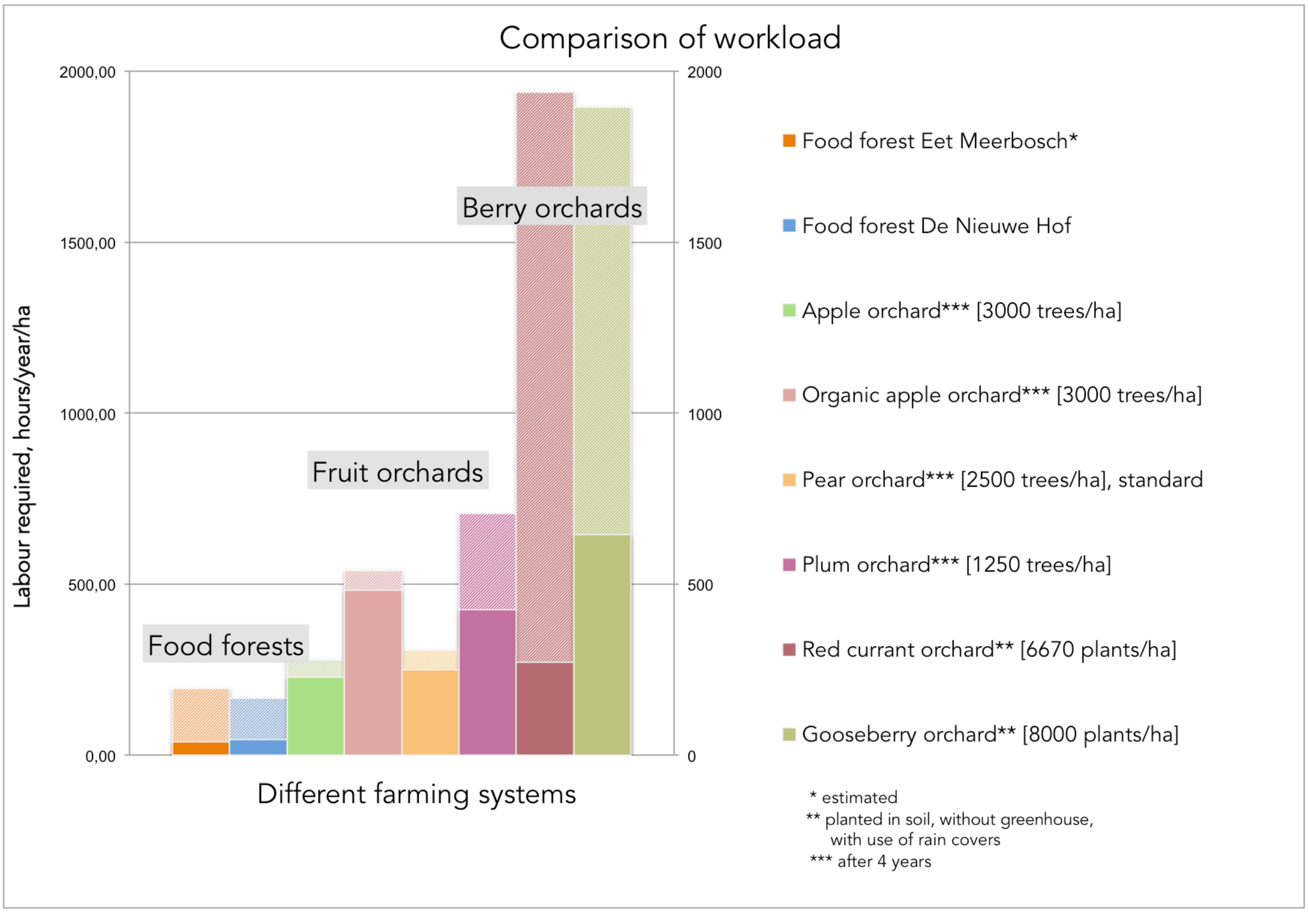

Figure 5 Comparison of labour required between food forests and monoculture fruit and berry orchards. Striped fill represents harvest, bold fill represents maintenance. Their sum represents the overall labour.

weed control (chemical and/or mechanical), frequent pruning (up to 2 times a year) and fertilisation (using manure or mineral fertilisers). These activities are not performed in the case study food forests. From maintenance point of view, food forests require only 38-45 hours/ha/year. Therefore, mechanising maintenance operations in food forests will not have a significant influence on the overall workload. While in monoculture fruit orchards biggest share of labour, 60-89%, is spent on maintenance activities, for red currant and gooseberry orchards it

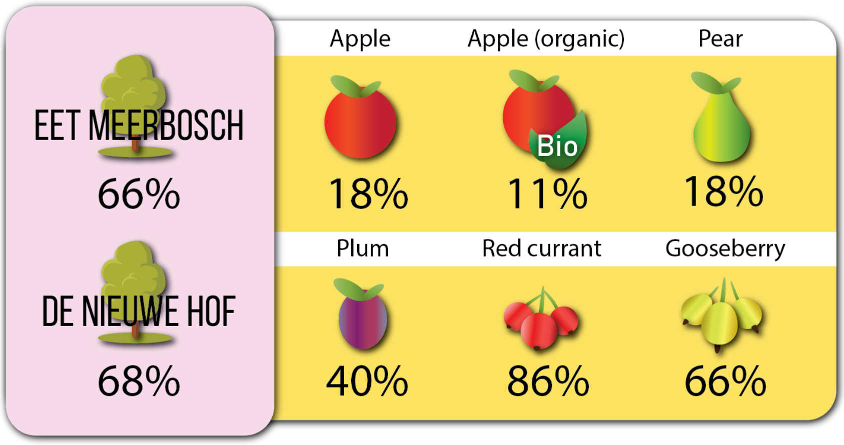

Figure 6 Share of harvest in the overall labour in terms of hours required per year for food forests and monoculture orchards.

is the opposite – only 14-34% is spent on maintenance . This is mainly due to a higher share of manual harvest in berry orchards. Apart from maintenance and harvest, education activities, e.g. tours, courses, work with students take place in the case study food forests. From harvest perspective, food forests are more labour intensive, requiring 66-68% of overall labour (with education activities included), than any other kind of monoculture orchards that were compared, apart from red currant orchard (Fig 6). When education activities are omitted for food forests, then harvest makes up 72-80% of the overall labour there.

3.1.2. Distribution of labour over the year in the two food forests

By analysing the distribution of labour in the two food forests, Figures 7-10 were created.

From a comprehensive labour overview of activities in the food forests, it became evident that:

- There is a smaller number of activities performed in the food forests than in monoculture orchards.
- Harvest is done from May until December.
- The months from June until October are the most labour intensive ones for both food forests. The biggest share of labour spent in these months is spent on harvesting (Fig 7, 8).

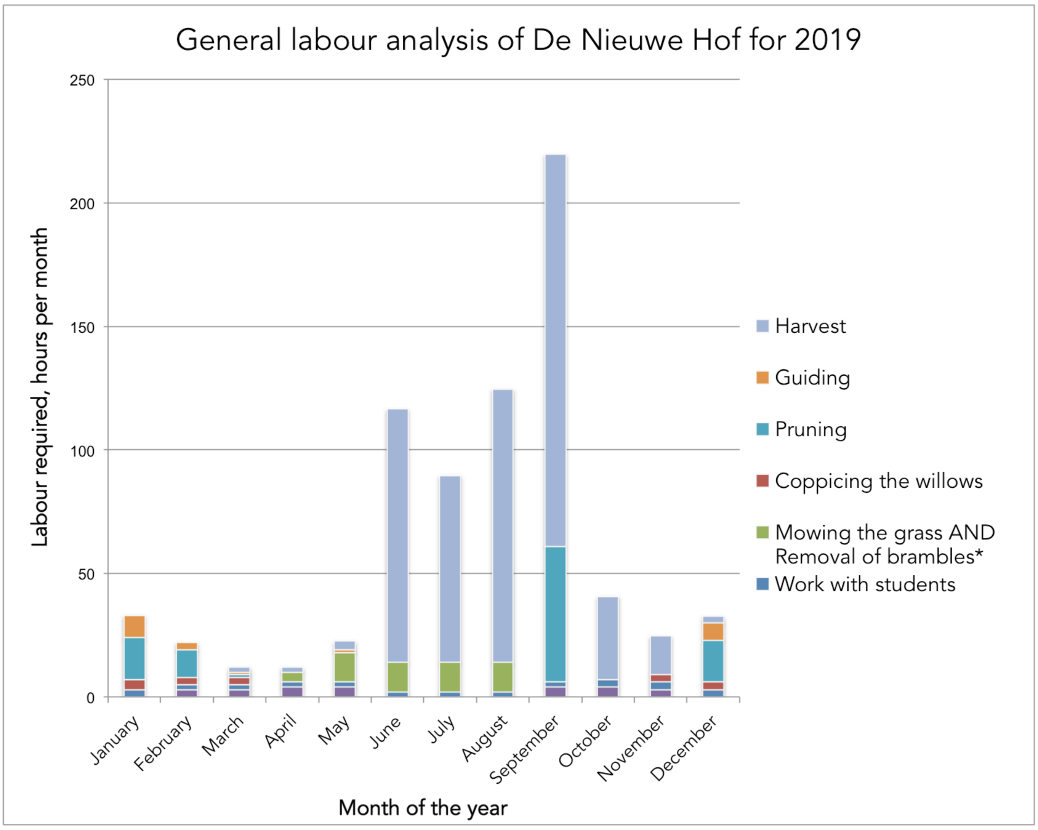

Figure 7 General labour analysis of De Nieuwe Hof for 2019

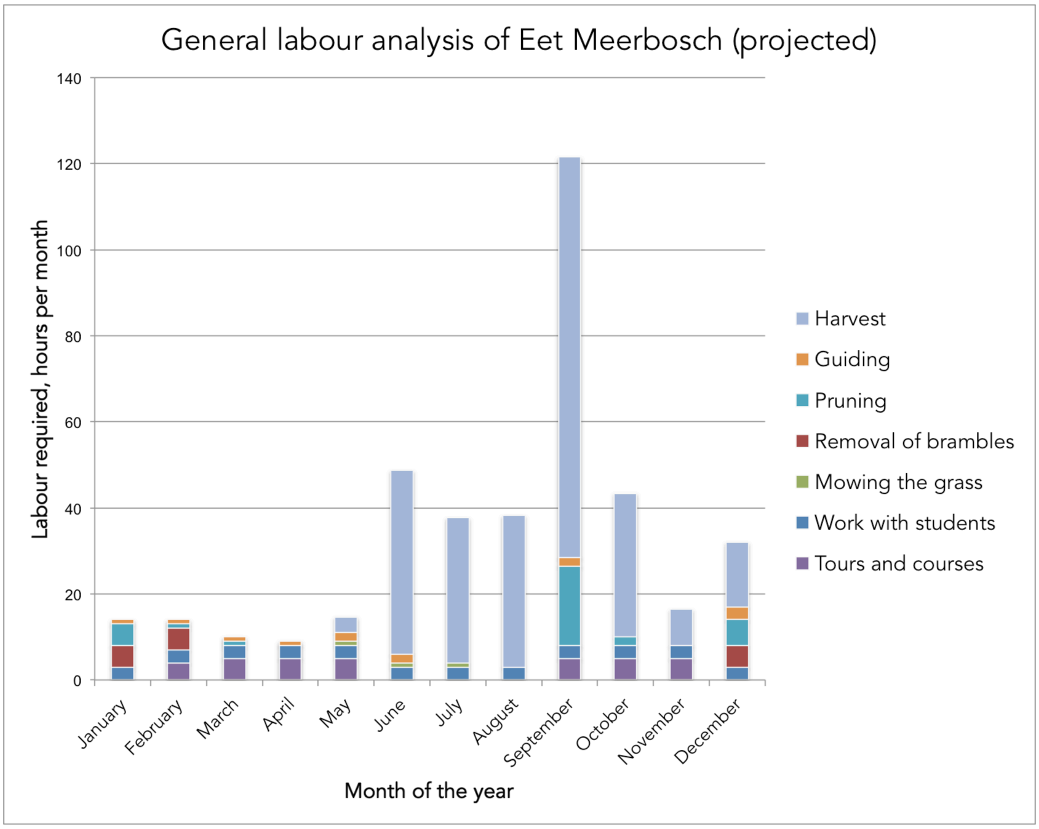

Figure 8 General labour analysis of Eet Meerbosch (projected)

From the labour analyses of harvest for various species groups (Fig 9, 10), it became evident that:

- Harvest of berries is the most labour intensive operation in food forests, occupying 37-45% of overall labour.
- Harvest of berries is done from May until September, with June-September having the peak labour workload.

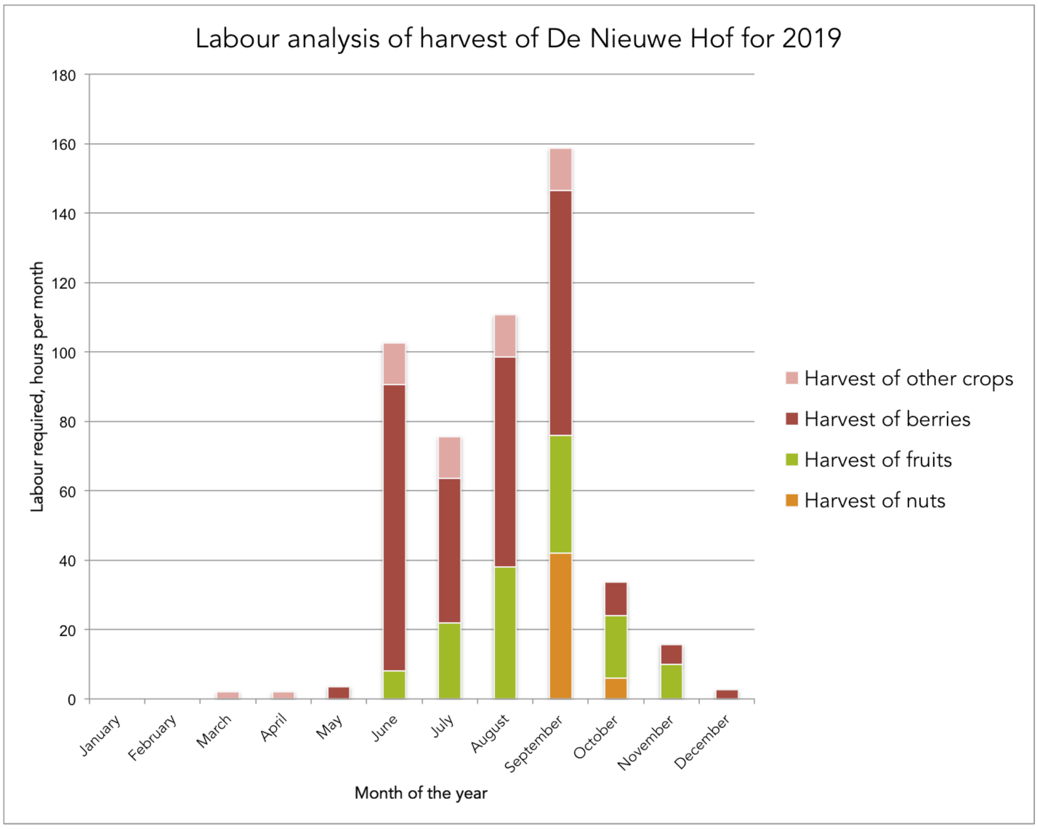

Figure 9 Labour analysis of harvest of De Nieuwe Hof for 2019

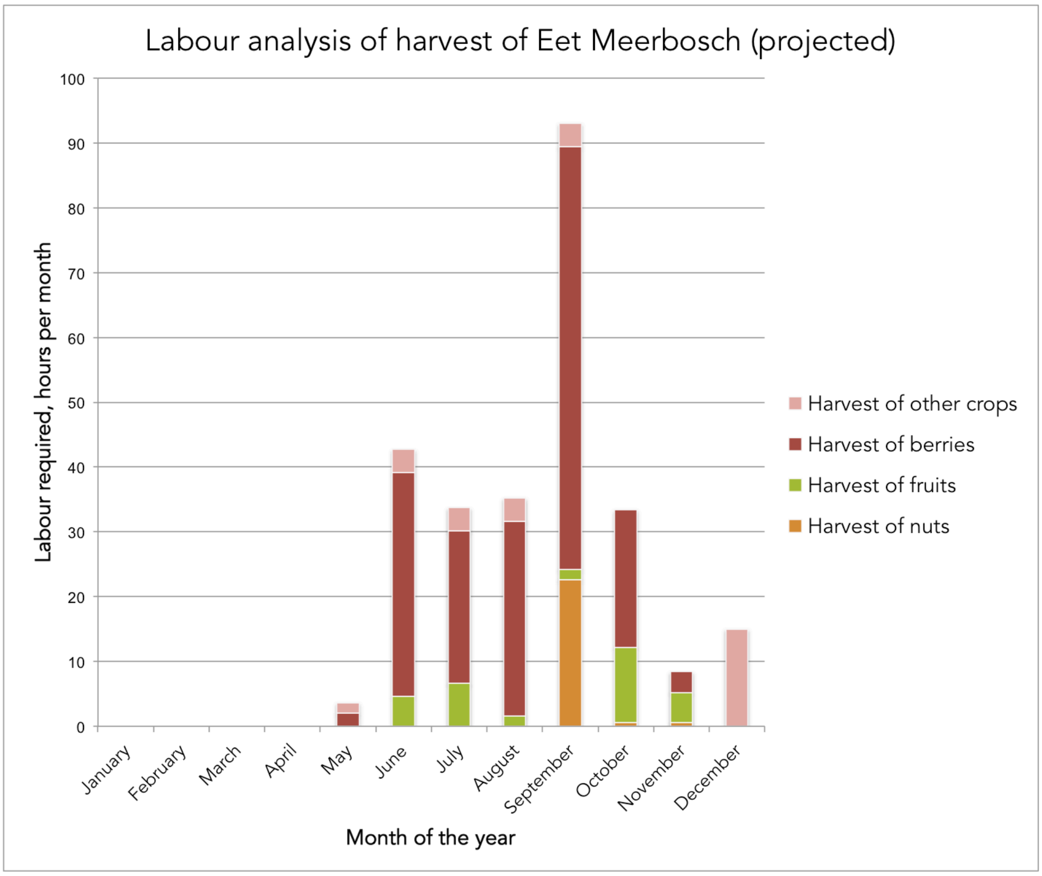

Figure 10 Labour analysis of harvest of Eet Meerbosch (estimated)

3.1.3. System analysis of the two systems and current technology

In this chapter, two case study farms are described.

- De Nieuwe Hof

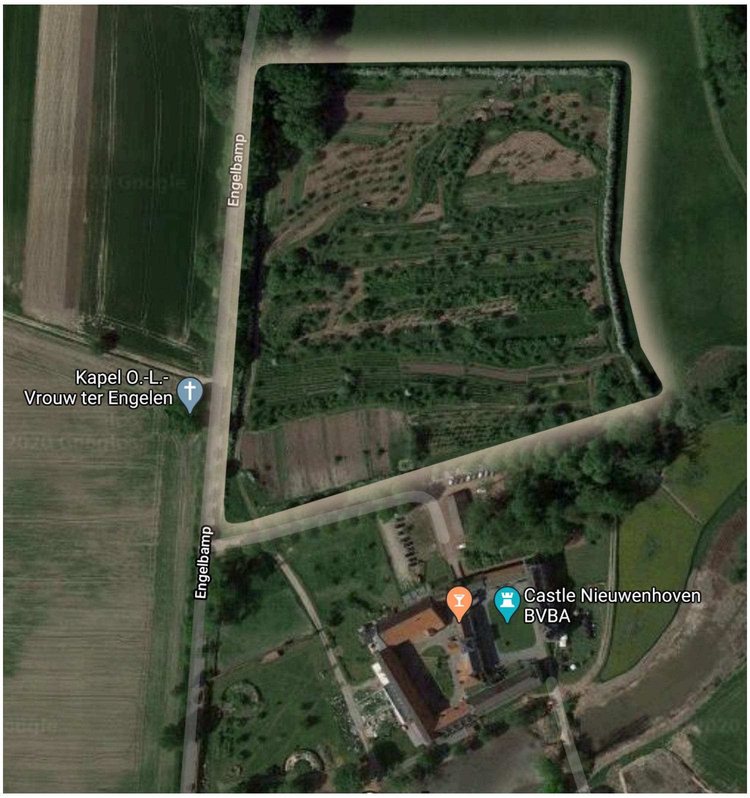

Figure 11 Map of De Nieuwe Hof. Adapted from Google Maps.

The food forest is located on the estate next to the Nieuwehoven castle on a slight slope, inclining outwards from the castle (Fig 11). In order to stop erosion, swales were created in 2007 and from 2009, most of the trees and shrubs were planted. Now it is a mature food forest with 39 edible woody perennial species. Among those are 19 berry species.

The farmer was interviewed in person and gave a tour of both farming systems. Based on the information provided, these farming systems were described from ecological (Appendix A) and labour perspectives (Appendix B).

In De Nieuwe Hof, a total of 2566 berry plants are grown. That is 675 berry plants/ha and 0.11 hours/berry plant is spent on harvest.

- Eet Meerbosch

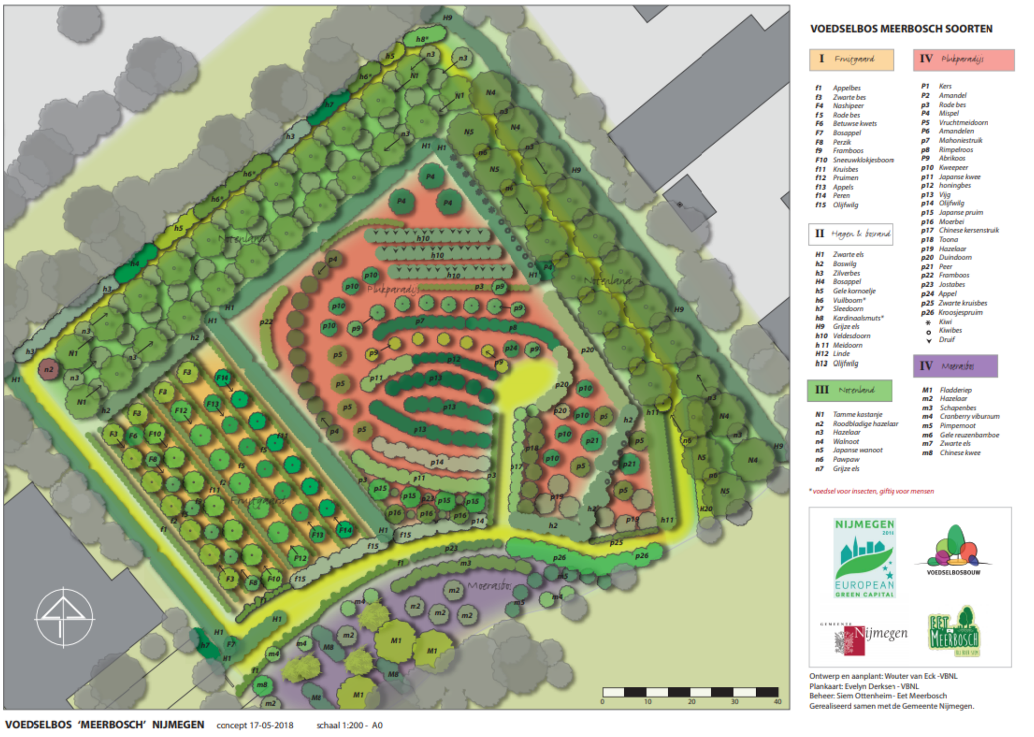

Figure 12 Plan of food forest Eet Meerbosch with separated zones ("Eet Meerbosch")

The land was previously used to produce hay for cows and was regularly fertilised with manure. There are now 47 edible woody perennial species planted together with fast-growing pioneer-, insect-attracting- and nitrogen-fixing species (Fig 12). Among the edible species, 20 are berry species. Food forest is not yet producing sufficient amount of crops to be sold commercially. Plants are planted in regular pattern to allow for easy harvesting. On SW side, a windbreak of alders is created to protect from prevalent winds coming from SW. Ditches are surrounding the food forest and the southern part of the land is constantly wet. The surface has almost no incline. Edible plant species grown originate from Europe, Northern America, and Asia. The food forest is located next to a CSA vegetable garden Moestuin Neerbosch, owned by the same farmer.

In Eet Meerbosch, a total of 874 berry plants are grown. That is 514 berry plants/ha and 0.21 hours/berry plant is spent on harvest.

Table 2. Berry species groups

Detachment method	Group #	Species
Pull/rotate	1	Kiwi berry, kiwi, pawpaw, white mulberry, black mulberry, sweet cherry, sour cherry, chokeberry, red currant, white currant, blackberry, raspberry, japanese wineberry.
Scrape	2	Autumn olive, arnoldiana hawthorn, black currant, cornelian cherry, gooseberry, honeyberry, jostaberry, sea buckthorn
Cut	3	Elderberry, grape.

From the species analysis, 23 unique berry species were identified in the two food forests. These species were then divided into groups, depending on the harvest method used (Table 2).

Currently, in a food forest no machinery is used for harvest. However, some machinery is still used. For a number of food forests, tractors have been used at the initial planting stage to prepare the soil, elevate the soil, create swales. The farmer uses soil cultivator to get rid of brambles and grass mower to trim the grass on paths. For harvest, food forest farmers rely either on their own labour or on volunteers. In both cases it is manual labour. However, outside of food forestry, various pieces of technology are being developed, that might be useful in food forests. Both hardware and software for artificial intelligence (YOLOv3, Keras, TensorFlow) is advancing with modern processors (CPU, GPU, TPU) being created by big high tech companies, like Intel, AMD, NVIDIA and Google, that allow for faster computations. Robotics companies, like Boston Dynamics are getting their products to the market with open source firmware to push the innovation in this field while others keep it private. Current robots seem to be able to substitute human labour in different fields, for example, construction sites, nuclear trash extraction etc. Within agriculture, the trend is in collecting data from sensors for management support, automation of movement and harvest in conventional monoculture fields and greenhouses. Some big agricultural machinery producers (John Deere, Fendt) are looking for alternatives to rather big conventional machines – swarms of small autonomous robots. In soft robotics, properties of different materials and structures are being researched and tested. Implementation of soft robotics in agriculture is also researched and companies like Octinion already implement them in their harvesting systems.

3.1.4. Root Cause Analysis

In order to recognise the challenges of the food forests, a Root Cause Analysis (RCA) diagram was created (Fig 13). The main challenge was identified as "Absence of suitable machinery for FFs".

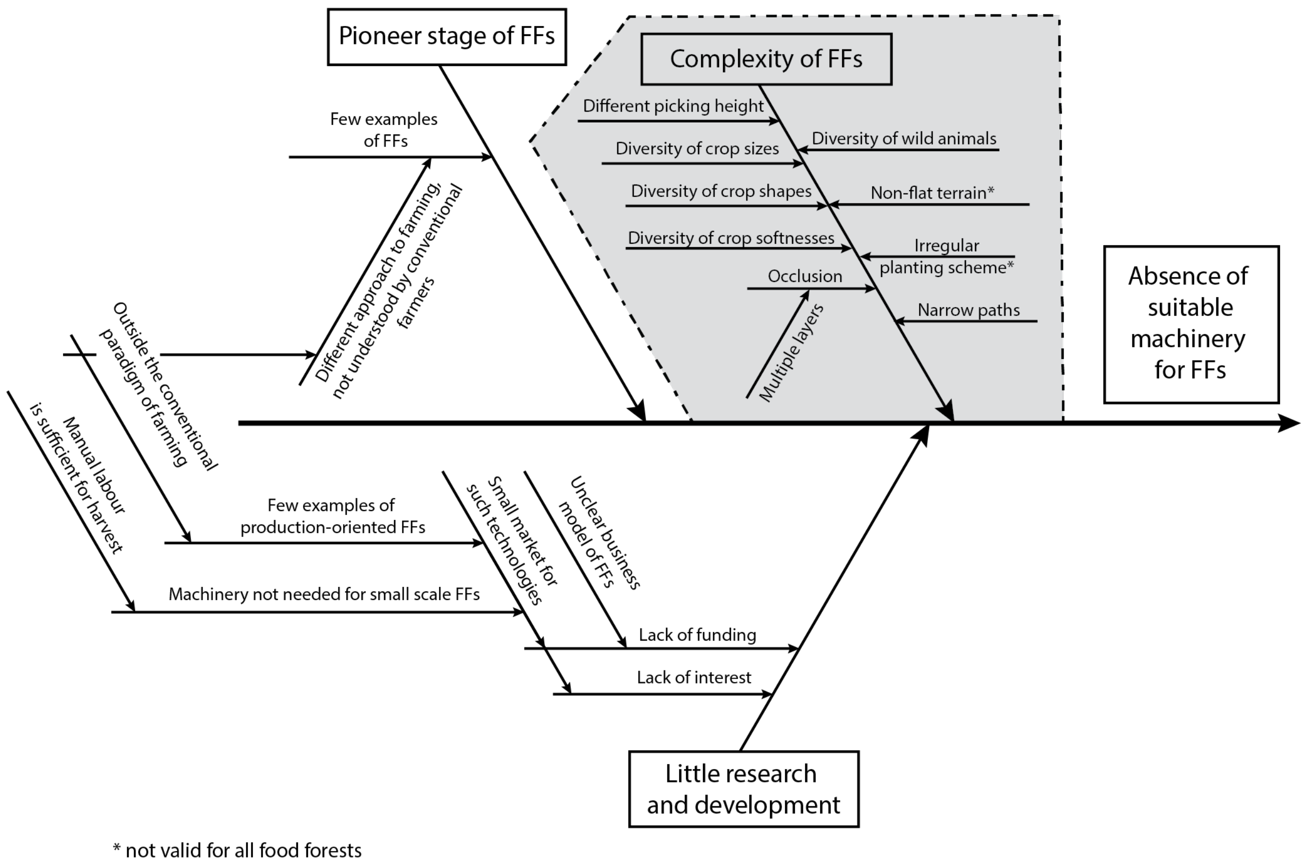

Figure 13 Root cause analysis for absence of suitable machinery for food forests (FFs). Challenges addressed by the design are marked grey.

After analysing the underlying causes of absence of suitable machinery for food forests to perform berry harvesting, three main ones were identified: Pioneer stage of FFs, Complexity of FFs and Little research and development. The underlying causes are pointing at the main causes with arrows. By taking a more detailed look together with the farmer and experts, it became evident that mainly complexity of food forest systems and small number of food forest systems comparing to other farming systems are the underlying causes. Within this design process, "Complexity of FFs" is the group of challenges to be solved as they directly influence the harvest of berries and are present in the food forests themselves. Other challenges are out of the scope, as they are on a higher level and don't have direct influence on the harvest of berries. Challenges in this group were formulated together with the farmer, after walking around the food forests and discussing what challenges they pose regarding the harvest of berries (Appendix C: question 1I).

3.2. Future vision

Based on the vision of interviewed food forest farmers, *GreanDeal Voedselbossen* and *Louis Bolk's Masterplan Agroforestry* (organisation and project supporting food forests in the Netherlands) attention to the food forests is rising in the Netherlands with new projects appearing every year. With two big projects from *Voedselbosbouw Nederland*, Schijndel (20 ha) and Eemvallei Zuid (30 ha), bigger companies, like *VITAM* are starting to get involved. For such big food forests future mechanisation is considered from the design stage. Such food forests are basically food forest orchards, where trees are planted in rows with wider spacing, to allow for easier navigation. For case study farms specifically, the farmer also envisions mechanisation in the future. However, when identifying objectives, it is important to not only look at a food forest from production perspective. Objectives for two case study farms, regarding harvest of berries were formulated in Figure 14.

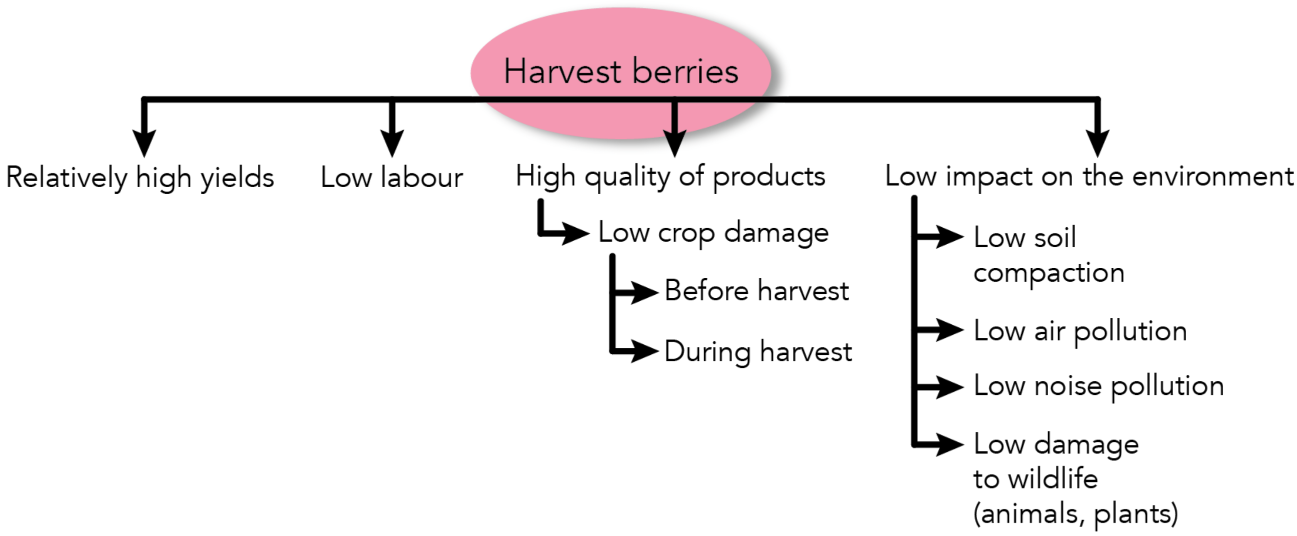

Figure 14 Objective tree for food forest systems, regarding berry harvesting

After analysing the objectives of the farmer, it became evident that he is not aiming at high yields, but rather wants to leave a certain share of edible crops for the wildlife. However, the farmer expressed his interest in having low labour. He sees berry harvesting not only as the most labour intensive activity, but also as the most intricate one, requiring high precision and tender approach in order to ensure high quality of products. Having a high quality of harvested products is also among his objectives. This entails, that there will be low damage to berry crops both before harvest and during harvest. However, he stated his concern about the effect of mechanisation on the environment where it operates. He wants to have a low impact on the environment i.e. low soil compaction; low air and noise pollution and low damage to wildlife (Fig 14).

3.2.1. Key actors

Looking at agriculture machinery actors, companies that create machinery for harvesting berries make them to be used in conventional orchards, with regular rows of densely planted trees or shrubs. Among the companies that develop implements for berry harvesting are Weremczuk (Poland) and Jagoda (Poland). Implements that are now sold for berry farmers can harvest: currants, aronia berry, gooseberry, juneberry (suskatoon), raspberry, blueberry, sour cherry.

Among robotic companies that offer harvesting solutions for berry harvesting are Agrobot and Octinion – both only suitable for harvesting strawberries.

Among the Dutch research institutes, who are doing research on robotics are Wageningen University and Research, Technical University Eindhoven, Technical University Delft, Technical University Twente. Among institutes that are doing research on food forests are Wageningen University and Research, Van Hall Larenstein, Louis Bolk Instituut, NIOO, HAS hogeschool.

Among the governmental institutes who financially support food forests are various municipalities and provinces (of which Province Brabant is actively realising various projects connected with transition to a food forest).

Among the nature conservation institutes that are offering financial support for ecosystem services at food forests are Staatsbosbeheer, Waterschap, Brabantse Milieufederatie, Vogelbescherming.

Among NGOs supporting food forests are Voedselbosbouw Nederland, Groen Ontwikkelfonds Brabant and numerous food forest farmers who create pioneer projects, offer their help for design, support and supervision of food forests.

3.3. Requirements for machinery

Based on the farmer's input, requirements for suitable machinery were listed (Table 3). A full description of the list of requirements with references for the assigned values can be found in Appendix E.

Table 3. Brief of requirements for machinery

Index	Rank	Aspect	Requirement		Motivation	Relavant objective	Source
Variable requirements							
1	1	Harvest efficiency	≤2% of the crops are damaged during harvest, with target value of 0%.		≤ than human performance. Value given by the expert.	Low berry damage	Wil Sturkeboom*
2	1	Harvest efficiency	≤ 0.11 hours/berry plant/year spent on harvesting**.		≤ than in the current systems. Value used was calculated by dividing amount of labour (hours/ha/year) spent on berry harvesting by plant density of berry plants (plants/ha).	Low labour	Siem Ottenheim
3	1	Harvest efficiency	Out of the desired amount of ripe berries, 100% are harvested.		Desired portion of overall berries needs to be harvested completely to allow for sufficient income.	Relatively high yields	-
4.1	1	Recognition efficiency	Target berry species are recognised with..	100% precision	Critical, if not met can make it impossible to meet req. 6,7.	Relatively high yields & Low berry damage	-
4.2	2	Recognition efficiency	Target berry species are recognised with..	100% recall	Less critical, if not met cannot lead to high crop damage, but can lead to certain crop loss.	Relatively high yields & Low berry damage	-
5.1	1	Recognition efficiency	Target harvestable plant parts (berries) are recognised with..	100% precision	Critical, if not met can lead to high damage of plants and crops growing on them.	Relatively high yields & Low berry damage	-
5.2	2	Recognition efficiency	Target harvestable plant parts (berries) are recognised with..	100% recall	Less critical, if not met cannot lead to high crop damage, but can lead to a certain crop loss.	Relatively high yields & Low berry damage	-
6.1	1	Recognition efficiency	Ripeness is recognised with..	100% precision	Critical, if not met can lead to harvest of unripe berries, which can lead to crop damage and decrease of income.	Relatively high yields & Low berry damage	-
6.2	2	Recognition efficiency	Ripeness is recognised with..	100% recall	Less critical, if not met cannot lead to high crop damage, but can lead to a certain crop loss.	Relatively high yields & Low berry damage	-
7	1	Environmental impact	Exerted ground pressure ≤ 55 kPa, with target value of 0 kPa.		≤ than of a human.	Low soil compaction	Siem Ottenheim, Wouter van Eck*
8	1	Environmental impact	Sound pressure level, produced by each individual machine is ≤45 dB(A), with target value of 0dB.		≤ than sound pressure level in a natural forest.	Low noise pollution	Siem Ottenheim, Wouter van Eck*
9	1	Environmental impact	≤ 1.043 kg CO2/hour is produced, with target value of 0 CO2/hour.		≤ than by human breathing. Converted from 2.3 pounds to kg using converter.	Low air pollution	Siem Ottenheim, Wouter van Eck*
Fixed requirements							
10	1	Flexibility of application	Crops in size range 0,5-15 cm (for individual berries) and 5-20 cm (for bunches) are harvested.		Range of berry sizes in the systems.	Relatively high yields	Siem Ottenheim
11	1	Flexibility of application	Pressure on berries during harvest is within the appropriate range.***		Based on the calculated maximum acceptable pressure per berry species. Critical for softer berries, where gripping is involved.	Low berry damage	Siem Ottenheim
12	1	Physical characteristics	Vertical reach of machinery is from ground level to 8 m.**		Range where berries can be found in the systems.	Relatively high yields	Siem Ottenheim
13	1	Physical characteristics	Width of each individual machine is ≤1 m.		Width of paths in the food forests.	Low damage to wildlife	Siem Ottenheim
14	2	Environmental impact	No damage is dealt to vegetation and wildlife during operations, unless approved by a farmer (e.g. making paths through nettles).		Damage is only accepted if trampling is required to access target plants (berry species).	Low damage to wildlife	Siem Ottenheim, Wouter van Eck*
15	2	Environmental impact	No trespassing on nature areas.		Shelter areas designated for wild animals must not be attended.	Low damage to wildlife	Wouter van Eck*

* expert
** strictest value among 2 systems used
*** no previous research was found

Mainly, the farmer requires machinery to harvest berries from different height - from ground level (for shrubs) up to 8 m high (for trees) of the given ripeness level and without damaging both crops and the surrounding environment. The farmer also requires machines to have a weight of an average person, be quiet and avoid disturbing nature areas and wildlife that thrives in food forests. The crops that are harvested should be intact and have a desired ripeness level. Therefore, be ready to be sold directly to the customers for fresh consumption. A list of species-specific parameters can be found in Appendix E.

3.4. Key functions

Table 4. Key functions of machinery

	Key function		Short explanation of key function
1.1	Sense species		Data collection stage. Used for plant species identification.
1.2	Sense ripeness		Data collection stage. Used for plant ripeness analysis.
2	Sense objects		Data collection stage. Used for obstacle avoidance, planning paths.
3	Determine objects		Data processing stage. Identify plants, plant parts, paths, animals, humans. Used for plant species identification, obstacles avoidance, plant part identification.
4	Locate plants		Data processing stage. Create reference points (with coordinates) per plant, used for planning paths.
5	Plan paths		Data processing stage. Plan paths for movement.
6	Move harvester		Move through a food forest.
7	Analyse and determine ripeness		Using input data, sense colour values. Compare them to the existing examples of berries in different ripeness stage, give a ripeness score on a selected scale.
8.1	Grip crop	Grip by body	Grip berry by its body.
8.2		Grip by peduncle	Grip berry by peduncle.
9.1	Separate crop from branch	Pull	For species that require pulling.
9.2		Rotate	For species that require rotating.
9.3		Scrape	For species that require scraping.
9.4		Split	For species that require split of peduncle.

Key functions are listed in Table 4 and are fully described in Appendix F. Based on relevant literature and experts' opinions, functions that are most critical for performing harvest of berries and meeting farmer's objectives were listed.

3.5. Morphologic chart

After finding possible solutions per function, morphologic chart was created (Figure 15). The solutions given both represent the current situation (manual work) as well as high-tech future

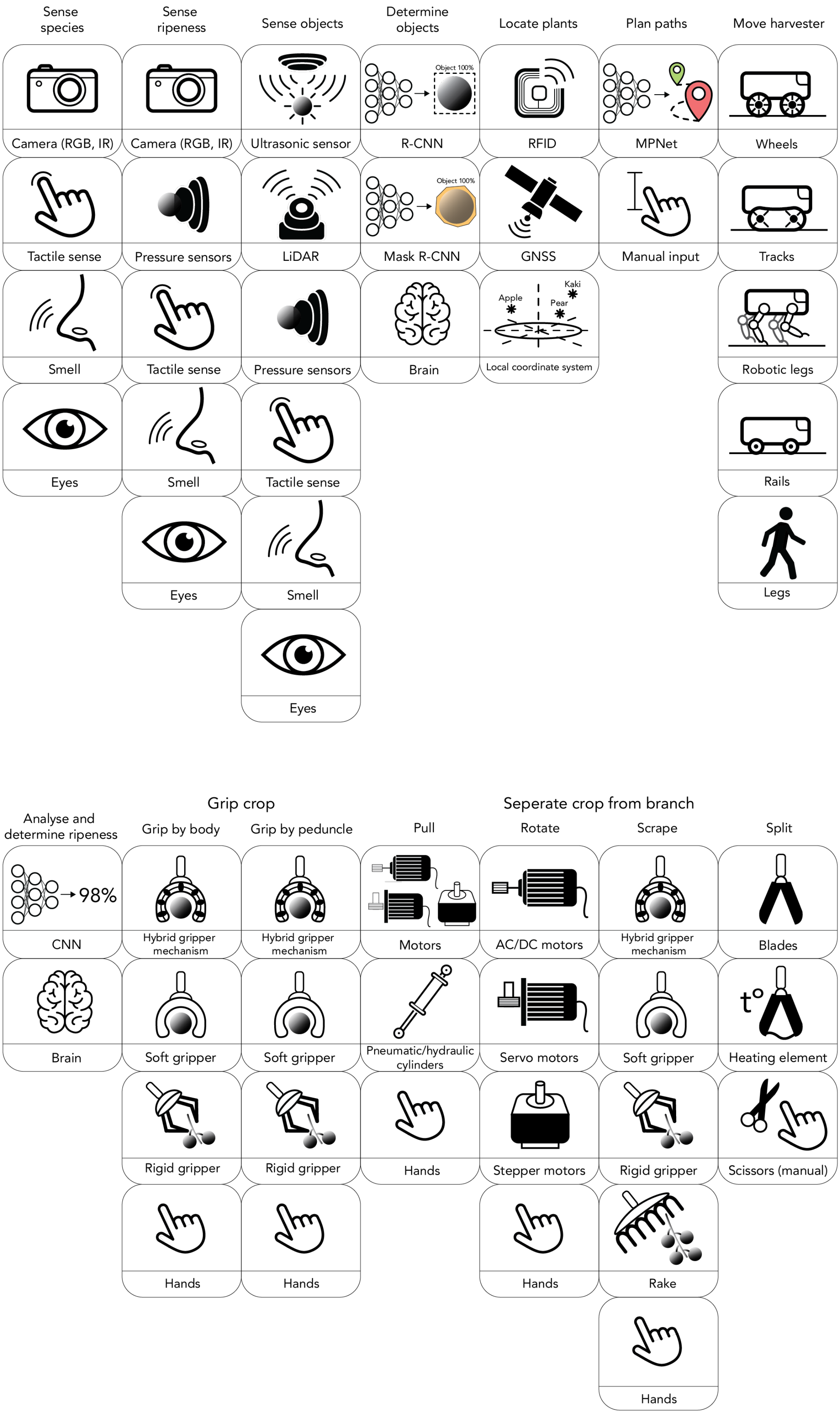

Figure 15 Morphologic chart

(robotic legs, deep learning). This is a diverging step that involves a broad view on all the possible solutions that are able to perform the listed functions, looking both at the ones that are currently present on the market, as well as those that are still to be developed or adapted to the given functions. The full description of morphologic chart can be found in Appendix F.

In possible solutions to some of these functions, different types of Artificial Neural Networks (ANN) are listed (Karmarkar, 2018; Ren et al., 2016; Gandhi, 2018; Qureshi et al., 2019), – these are very promising pieces of modern artificial intelligence that will make it possible to teach a machine to work in a complex multi-species environment with many variables. Apart from ANNs, soft robotics is another piece of modern technology. Soft robotics is a sector of robotics that relies on compliant mechanisms that do not have sturdy joints. Such mechanisms are currently used (Park et al., 2019) to grab objects without damaging their surface and compromising their integrity. Moreover, by adjusting the rigidity and pressure applied, such mechanisms can be soft as well as hard. Their passive adaptivity allows for work with objects of different softness, sizes and shapes. However, compliant mechanisms can only operate in two states – actuated and non-actuated and therefore can only grab an object and apply constant pressure to it. However, in order to detach a crop from a branch, rotating and pulling is required as well. Therefore a hybrid gripper mechanism that combines soft and rigid parts could be a possible solution.

3.6. State of the art – specific technological solutions for the key functions (incl. patents)

In this chapter, technological solutions (patents) are described.

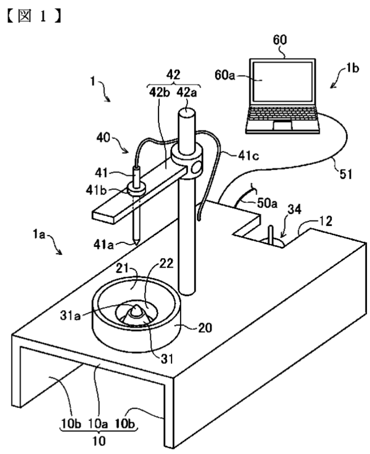

Figure 16 Hardness measuring device of fruit

For sensing ripeness, a pressure-based sensor can be used (Fig 16). An example of such is described in patent JP2015028445A. By monitoring the applied pressure on the surface of a secured fruit, the point (applied pressure) of surface destruction can be observed. This solution is currently not implemented for berry harvesting.

For sensing objects, a capacitive pressure sensor with nested matrix electrodes can be used (Fig 17). And example of such is described in patent US2017010707A1. Such sensor by measuring the difference in resistance can evaluate location and force from an external object. This solution is currently not implemented for berry harvesting.

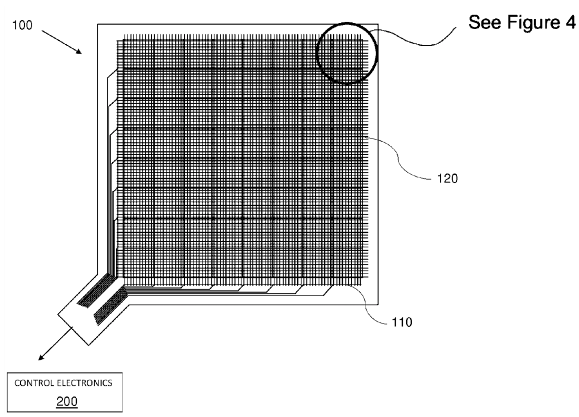

Figure 17 Capacitive tactile sensor

LiDAR and ultrasonic sensors are already widely used in various commercial products, for among others, automotive industry and robotics.

For moving, robotic legs are the newest solution. An example of it can be found in robots of Boston Dynamics, e.g. Spot (Fig 19). It is not implemented for berry harvesting

Among patents available on grippers, soft robotic gripper (Fig 18) that is used for strawberries is described in patent BE1024167B1.

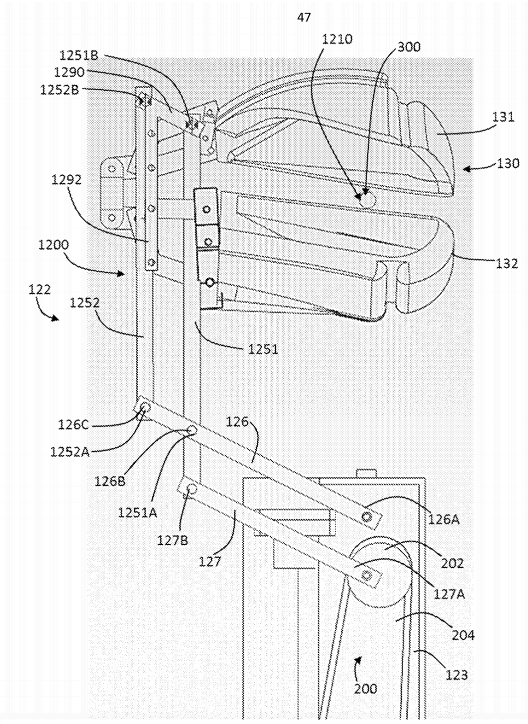

Figure 18 Implement for fruit picking for a robotic arm

Figure 19 Robot Spot, Boston Dynamics

While an example of rigid robotic gripper (Fig 20), used picking strawberries by peduncle that embodies various functions listed in Figure 15 is described in patent US10292414B1. It uses ultrasonic sensors, imaging and blades for detaching strawberry from branch.

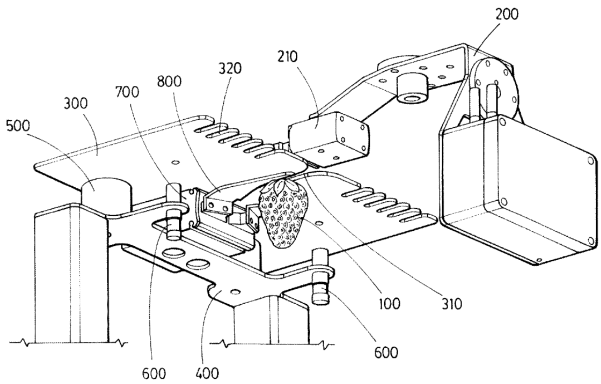

FIG.1

Figure 20 Apparatus for fruit decapping

Other solutions listed in Figure 15 are commonly used and sold commercially. Therefore no patents on them are described here.

Among technologies that are not currently used in food forests, but in monoculture berry orchards, are implements that can be attached to a tractor. Usually, a place for people to stand on is included in the implement, so that they can exchange full crates with the empty once and sort the berries. Companies like Weremczuk and Jagoda offer a range of such implements.

Considering the physical properties, such implements are minimum 1,5 meters, but usually 3 meters wide, while the requirement from the farmer is maximum 1 meter. The smallest tractor (60 hp) that is required to carry such implements is on average 1,8 meters wide and weights 2,1-2,5 tons. Therefore, such combination of tractor and implement doesn't meet the requirements on maximum width and usually run on diesel, so don't meet the requirement on CO2 produced during operation either. Because of that it cannot be implemented in a food forest. Current berry harvesting machines can harvest 10 out of 23 berry species listed by the farmer mechanically, however they currently work only within a monoculture environment with plants in rows of one plant wide. So not only a multi-layer environment makes it impossible to use such machinery in a food forest, as it requires space above the rows, due to its construction, but also some of the species cannot be harvested with existing machinery. 1 species – grape can be harvested mechanically, compromising its integrity, and therefore not allowing it to be sold for direct fresh consumption. 12 of the berry species that are cultivated in the two food forests cannot be harvested mechanically at all.

3.7. Generation of solution

An overall solution (solution 1) was composed and evaluated on the requirements on the scale from 1 to 4 (Table 5), where 1 shows that the solution doesn't meet the requirement and 4 shows that the solution meet the requirement perfectly. Solution 1 corresponds best to the farmer's objectives

Table 5. Evaluation of solutions on the requirements

#	Requirement	Solutions		
		1 (high tech)	2 (manual)	3 (low tech with manual harvest)
1	≤2% of the crops are damaged during harvest, with target value of 0%.	3	4	3
2	≤ 0.11 hours/berry plant/year spent on harvesting.	4	3	3
3	Out of the desired amount of ripe berries, 100% are harvested.	3	3	3
4.1	Target berry species are recognised with 100% precision.	3	3	3
4.2	Target berry species are recognised with 100% recall.	3	3	3
5.1	Target harvestable plant parts (berries) are recognised with 100% precision.	3	3	3
5.2	Target harvestable plant parts (berries) are recognised with 100% recall.	3	3	3
6.1	Ripeness is recognised with 100% precision.	3	3	3
6.2	Ripeness is recognised with 100% ripeness.	3	3	3
7	Exerted ground pressure ≤ 55 kPa, with target value of 0 kPa.	4	4	3
8	Sound pressure level, produced by each individual machine is ≤45 dB(A), with target value of 0dB.	4	3	2
9	≤ 1.043 kg CO_2/hour is produced, with target value of 0 CO_2/hour.	4	4	1
10	Crops in size range 0,5-15 cm (for individual berries) and 5-20 cm (for bunches) are harvested.	3	3	3
11	Pressure on berries during harvest is within the appropriate range.	3	3	3
12	Vertical reach of machinery is from ground level to 8 m.	4	3	1
13	Width of each individual machine is ≤1 m.	4	4	1
14	No damage is dealt to vegetation and wildlife during operations, unless approved by a farmer (e.g. making paths through nettles).	3	3	1
15	No trespassing on nature areas.	3	3	3
	Score:	60	58	45

and requirements for performing the key functions mentioned before, and is described here (Fig 21). This solution is compared to solution 2 (current solution for the food forests) and solution 3 (current solution for monoculture berry orchards). Solutions 2 and 3 can be found in Appendix G.

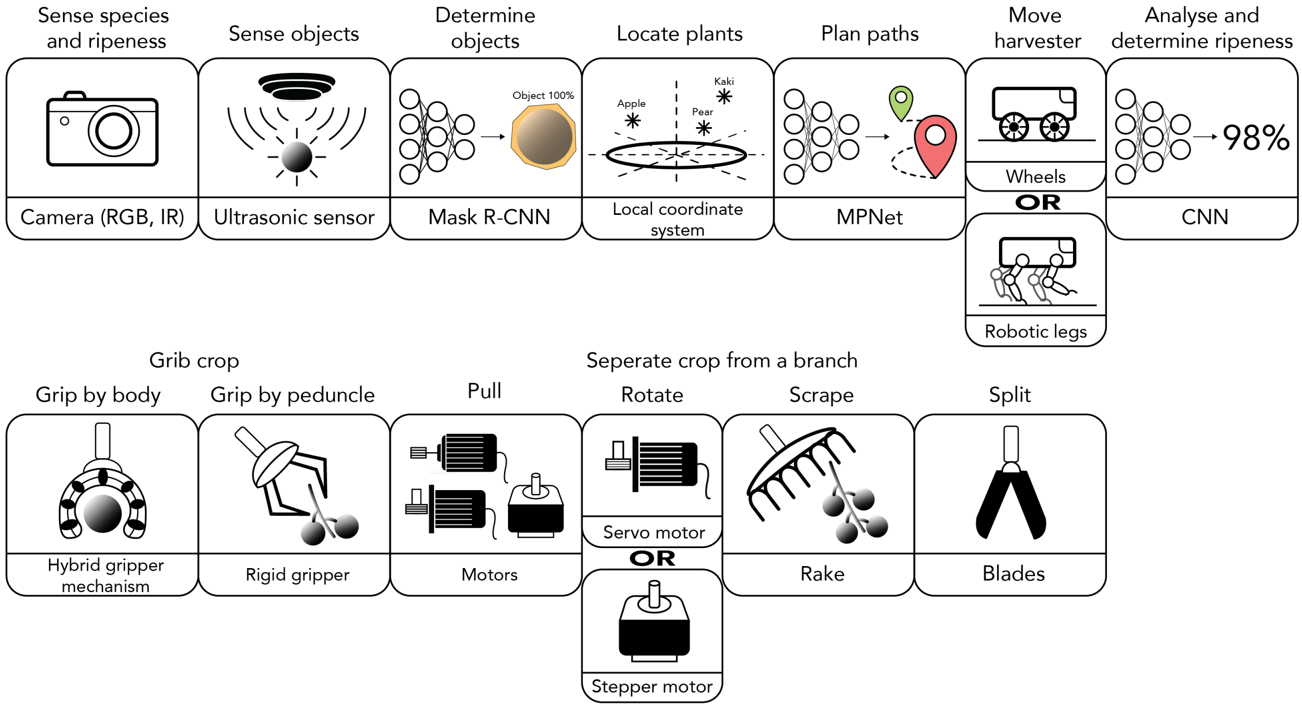

Figure 21 Generated solution – high tech solution

This solution scores highest on farmers' requirements, it represents an autonomous machine with artificial intelligence that has reduced weight compared to a manned machine. For every operation where the choice was between a human input and automatic solution, the latter was chosen, based on the farmer's will to maximise automation in the solution. For data collection and processing as well as navigation, the machine will rely on artificial intelligence i.e. various neural networks – each one good at performing a given task.

Both ultrasonic and LiDAR sensors are used in modern devices, machinery and robotics. Ultrasonic sensor was chosen instead of LiDAR for sensing the environment because LiDAR sensors available on the market are more expensive and heavier on average than ultrasonic ones. Currently, ultrasonic sensors are mainly used for the same task in modern autonomous vehicles.

For determining objects, Mask R-CNN (Ren et al., 2016; Gandhi, 2018) was used, as it outputs a mask – an image overlaying the identified object pixel by pixel, rather than with a frame, like with regular R-CNN (Karmarkar, 2018). Such an output gives a more precise representation of a crop and gives information not only about the boundary dimensions of a crop, but its precise shape. This could lead to more precise picking operation and reduce crop damage.

Considering locating plants, a local coordinate system was chosen instead of GNSS (Global Navigation Satellite Systems) as the latter have generally bigger error, of a couple meters, which in a food forest, could lead to severe crop damage. Local coordinate system allows for precise locating of plants, however requires a more storage capacity. Therefore, creating a local coordinate system based on identified plants was chosen as a non-intrusive and precise solution.

For path creation – MPNet (Motion Planning Network) (Qureshi et al., 2019) was used. It is a neural network that by constantly evaluating proximity to various surfaces, (located and analysed by ultrasonic sensor in this case), creates suitable paths, avoiding collision, from point A to point B. It can be used not only for planning movement of the whole machine, but also of individual picking component – gripper for instance.

When discussing with the farmer, what mechanism do they see appropriate for moving, wheels (if they are small) and robotic legs were more appreciated, as they are more lightweight and therefore cause less soil compaction.
For gripping crop by body, hybrid gripper mechanism (Park et al., 2019) was selected. For crops like pawpaw, which are bigger than most berries (10-15 cm), are soft and need to be harvested individually, hybrid gripper mechanism works the best as it is able to avoid damaging the crop while gripping and adapt to its dimensions.
For gripping crops by peduncle, rigid gripper was chosen, as it is sufficient for the task. Insignificant damage to peduncle doesn't effect the quality of the product itself.
For separating crop from branch by pulling, motors were chosen as the lighter alternative to pneumatic/hydraulic cylinders. By transforming rotating motion of motors into forward motion, they can be used for pulling berries from branches.
For separating crop from branch by rotating, among the possible motors, either one of servo and stepper motor can be used. Both of them allow for setting speeds (servo) and rotation angles (stepper), which allows for precise motion and should not cause crop damage.
For separating crop from branch by scraping, rake was chosen as the simplest solution that should be sufficient for the task. Soft robotic mechanisms are also possible, but they will be costly in development.
For separating crop from branch by splitting, blades were chosen, as they can provide clean cuts, without causing much damage to crops. Burning element could close wound immediate however can lead to fires, especially during dry summers. Blades in term get dull with time, however, alloys that are used in construction tool manufacturing as well as cutlery can preserve the cutting edge for a long time.

3.8. Gap between current and suitable machinery

Current agriculture machinery (tractors and implements) is not designed to work in a food forest environment. Specifically, dimensions and weight do not suit the system. Therefore, these should be reduced to operate in food forests. This could be achieved by reducing the weight of the chassis, removing a driver and going towards an autonomous machine. However, the pulling force could get reduced and make it impossible to pull implements, therefore functionalities of such implements have to be transferred to the main machine. The environmental impact of a combustion engine is also not acceptable by the food forest farmers, therefore, more eco-friendly alternatives have to be introduced.

The social aspect is of high importance in the case of adapting current berry harvesting machinery to be used in a denser, multi-crop environment. The current paradigm of efficient farming is what keeps machinery at the level of conventional monoculture systems. Innovation will probably come from a new company that will be able to answer to the public demand for sustainable food forest farming.

Current agriculture robotics in most cases are designed to work with one crop, identify and harvest it. Versatility is what is missing in such systems. Therefore, training such robotics to work with a variety of crops will make it work in a food forest. However, with new research and development of software and hardware, come high investment costs. Due to the small market for such machinery, which is due to a small number of existing mature food forests in the world, investments and unclear business plan on their return is one of the limiting factors for such companies to develop their products further towards a higher versatility in application.

Current soft robotics are also not yet adapted to be used for harvesting a variety of crops. Current artificial intelligence advancements in both hardware and software have advanced enough to be used in automotive industry and therefore, could be sufficient, after adaptation to a different environment, for berry harvesting in a food forest.

4 Discussion

In this study, only ecological and labour side of food forests were assessed, however, economics are also important to consider in order to holistically analyse these systems. All the conclusions of this study were made without considering the economics.

It is assumed that the proportion of labour hours spent on harvest in similar systems, assuming that these systems are also situated in the temperate climate zone of Europe and are around 10 years old, will be not significantly different from 68-75% of the total labour hours and harvest of berries will take up to 40% of the total labour. Also, the distribution of labour hours throughout a year would be similar in any other food forest. However, it is worth noticing that the numbers that were used in the labour analyses were given only for the year 2019, which had the hottest summer in the last decades in the Netherlands together with 2018, and based on the words of food forest farmers, harvest was actually higher than expected due to the heat in the summer, while their neighbouring conventional arable farmers suffered from droughts and losses of harvest. Also, the numbers provided were not recorded by the farmers directly during the harvest, but rather approximated based on their memory. However, it was observed that by increasing and decreasing the calculated amount of total labour hours for harvest by 50%, to count for a possible error in the numbers, this was still the most labour-intensive operation, taking 58-76% share of the total labour in these farming systems.

Another aspect to keep in mind is that all the data acquired during the study was only for the year of 2019, and labour hours per activity per species will differ in time. In general, during the first 5 years there is almost nothing to harvest. From year 5-10, berries, nut shrubs and some fruit trees gain their maturity and produce sufficient amounts of crops. Starting from year 10 onwards, some plants will have to be removed from the system to allow for the further growth of others. At this stage most of the plants have already gained their full maturity, apart from climax trees. From year 30 nut trees will start to close canopies and even more plants will be removed. At that time, the nut production will be at its peak, while production of berries and fruits will go down. At various time frames, different species will be present in the system and will have different production rates. All this requires a long research process to get a more comprehensive overview of a food forest growth and its labour dynamics throughout its lifetime. It is worth to collect such data for every consequent year of a food forest to better understand how it develops. However, it is required to also describe each system that is observed individually, both quantitatively and qualitatively, as farmer's principles and planting scheme have drastic effect on the representativeness of such data.

Due to the fact that food forest is the most species-diverse farming system and other agroforestry systems like fruit/berry or nut orchards, alley-cropping and silvopasture are usually much less diverse, the solutions created for food forests might be able to fulfil the farmers' requirements for such agroforestry systems as well. With the growing number of food forests in the Netherlands, especially of large scale ones, the demand for machinery is expected to rise as well. However, it takes a food forest to grow for at least for 5 years to have sufficient amounts of crops available for harvest. And this entails that the need for such machinery will only come at that time.

After consulting with the experts in relevant fields of technology, it was concluded that it will require significant amount of resources to develop a piece of technology, both hardware and software to be able to work with every species in a food forest.

The trend of on-going research on alternative small autonomous machinery for agriculture in big companies like John Deere, shows that attention to such is rising and that more small autonomous solutions for agriculture will appear in future.

The overall generated solution was created based on the input of one farmer and was limited to the listed solutions per function. With researching more possible solutions, another overall solution may appear and may score even higher on the farmer's requirements.

5 Conclusions

There is a need for mechanisation for mature medium to large scale food forests (>2 ha), specifically for berry harvesting. For smaller food forests, manual harvest is sufficient. Machinery that is demanded by food forest farmers has to be small, versatile, quiet, lightweight, eco-friendly and non-nature-invasive. The farmers stated their concern on the safety of machinery for the environment it will operate in, specifically for plants and animals. Labour analysis concluded that harvest of berries requires most time and mechanising it will have the biggest impact on the farmer's labour balance. Following RIO methodology from step A to step H, it became evident that current agriculture machinery is not suitable for food forests and that alternative machinery needs to be developed. Together with that, it was concluded that individual pieces of technology that would fulfil farmers' requirements for mechanisation are already present on the market and are used for performing similar tasks, however they require some adaptations to be used in the food forest environment. In future, mechanisation of berry harvest could reduce the workload not only in food forests, but also in permaculture farms, as well as less complex agroforestry systems, like monoculture orchards. Food forests can act as training grounds for such machinery. Increase of the number of food forests around the world could lead to creation of suitable machinery. The data that was collected in this study, namely labour analysis and machinery analysis could be used for labour estimation in other small scale as well as large scale food forests, research and development of suitable machinery. In order to develop such machinery, various stakeholders need to be involved, especially research institutes and private sector initiatives – those who are going to research and develop such mechanisation. Policy makers and agroforestry (incl. food forest) farmers, will help to create a bigger market for such mechanisation by making food forestry more popular within agriculture.

5.1. Recommendations

As more food forests get mature, and bigger food forests are being created, it is essential to review more of them from mechanisation point of view to create a more comprehensive list of edible species that need to be harvested mechanically, describe parameters for those species and also to get more of other farmers' requirements for such machinery. Also, as every food forest is unique, it is valuable to collect more farmers' opinions on what limitations their land poses for mechanisation.

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Appendices

Appendix A Description of the farming systems

Food forest De Nieuwe Hof

Connection with customers

The farmer is looking forward to using the castle as a gathering place for people who come to visit the food forest, also people leaving in the castle will be the future customers. Besides that, the farmer is planning to sell the products from De Nieuwe Hof in Nijmegen. Local customers that used to come and handpick fruits and berries at Samenland will become the customers of De Nieuwe Hof.

Way of farming

Started as a productive permaculture project, there are many places with only one layer of vegetation and big open space. The farmer is planning to plant more trees and introduce more layers to the system. The farmer is planning to continue pruning certain species, guiding and harvesting in the biodynamic way.

Food forest Eet Meerbosch

Connection with customers

People who come to get their vegetables, flowers, herbs, eggs and (occasionally) pork meat at Moestuin Neerbosch are not yet familiar with the products that will be available from Eet Meerbosch, so in order to get them acquainted with what a food forest can offer, the farmer is planning to sell the products of his other food forest in Belgium, De Nieuwe Hof (which is described later) here in Nijmegen. And then when Eet Meerbosch starts to produce sufficient amount of crops, they will be available for purchase on subscription basis, so that customers can get weekly baskets.

Way of farming

At Eet Meerbosch the farmer is willing to experiment with different practices, for example, he wants to see how well the food forest performs if he doesn't prune certain trees. Grafting is also what the farmer sees himself doing in future, once the food forest is completely established. The farmer is not planning to prune trees to see what the effect of that will be on the harvest. He will also guide and harvest. The food forest will be managed in an organic way.

Appendix B Labour analysis of the farming systems

Food forest De Nieuwe Hof

Considering the fact that the farmer has just recently taken over De Nieuwe Hof, all the data on labour was provided by the previous owner. As the previous owner was managing the plants in a way to maintain high production, this ended up in a rather high workload. However, these numbers may change significantly as the current farmer starts to manage it in other way. The total labour required is 214 hours/ha/year.

Harvest

Harvest has been done by hand and as with the previous farming systems, requires the most labour, about 70% of the total labour spent on an annual basis. Harvest of berries takes up 45% of total labour.

Guiding

At De Nieuwe Hof, only berry bushes and creepers are guided using ropes to allow for easier access to the berries and support of the branches. This takes 3% of total labour.

Pruning

Pruning has a noticeable role in the management of the system and takes up 13% of total labour. All pruning is done by hand. Pruning is done to manage of blossom on the trees, that is said to have a positive effect on harvest.

Mowing the grass and removal of brambles

Grass is mowed together with brambles removal. Brambles appear in various locations throughout the area, mainly at the borders of food forest with surrounding fields and hedges. They are removed both mechanically and manually, depending on the accessibility. That takes up 7% of total labour.

Work with students and Tours and courses

These activities are as important for the farmer as harvest, guiding or pruning, and take up 7% of total labour.

Food forest Eet Meerbosch

Labour hours for Eet Meerbosch were estimated by the farmer, based on the actual data collected of De Nieuwe Hof. The activities performed were listed and the total labour required per year (when all the plants are mature and producing crops in sufficient quantities) is projected to be 235 hours/ha/year. Harvest is taking up 66% of total labour, harvest of berries only – 45% of total labour.

Appendix C Interviews with farmers

Table C.1. Interview with Siem Ottenheim (food forest De Nieuwe Hof)

Section	Corresponding stage of RIO	#	Question	Answer
1. Overview of the farming system	B	1A	How do you typify your farming system?	Food forest with a permaculture approach, aimed at high production of common fruits and berries.
		1B	When did you start the farm?	2007 - started by Siem's mother and David made first three swales to stop landslides, planted first pears and sour cherries. In 2009 Taco came to live in the community there, wanted to do things connected with his Permaculture course, and that was the start of Samenland. In November 2019 it was aquired by Siem. (12 years old).
		1C	What is the size of your farm?	4.2 ha.
		1D	How would you divide the development of your farm in stages (time-steps)?	2007 - first three swales were made and first pears and sour cherries planted by Siem's mother and David (friend). 2009 - Taco Blom started to create a permaculture plot, called Samenland. November 2019 - Siem took over the land.
		1E	What crops did you grow in each of them: 1) 2) 3)	-
		1F	What crops did you sell/ expect to sell during each stage? 1) 2) 3) n)	
		1G	How / to whom do you sell your products?	Self harvest (incl. vegetables), restaurant (incl. vegetables), pickup boxes, collaboration with 'Boer en Buur' - platform for selling farm products to direct customers.
		1H	How many people work in the system?	One person will take care of the land at a time, either Siem or his colleague. Siem also says that 3 people on full time can manage the harvest of the whole farm.
		1I	What are the restrictions posed by your system to the machinery?	The land was designed based on the size of a small tractor - the paths are 1 m wide, land has a slight incline and also swales and ditches across the whole farm. Tall grass can make it difficult to collect fruits and nuts from the ground, but the grass can be mowed before the harvest. On Sunday mornings land mowing is prohibited and leaves blowers that work on fuel, are forbidden as well.
		1J	What do you feel could be the weak points of the new machinery?	The maintenance could be expensive, and the farmers will not have the knowledge to do it themselves. It is fine if someone will come and repair it from the company, but it could be too expensive for a small scale farmer. Generally, machinery is not that interesting for the small scale farmers.
2. Operations in the system	F,G	2A	What are the operations performed at the farm at the INITIAL PLANTING STAGE and AT THE MOMENT?	Initially, water management was done by creating swales to prevent landsliding, as when it rains, the water used to flow towards the castle, together with clay soil. Also lucerne was sown as the pioneer species.
		2B	How are they done at the moment:	-
		2C	a) What processes are performed manually?	Harvest, pruning.
		2D	b) What processes are performed mechanically?	Tilling (klepelmaaier), cultivating (only veggies), chainsaw pruning (mostly for willows), mowing of grass.
	B	2E	c) What machinery do you currently use?	Klepelmaaier, cultivator (subsoiler), chainsaw, mower.
	F	2F	How much time do you spend on each operation?	see labour analysis.
		2G	When is every operation performed?	see labour analysis.
		2H	For what operations is there insufficient workforce available?	There is enough people, young people cshool), mainly volunteer work.
		2J	What other operations will need to be done in future if there are any?	Grafting, cut off the pioneer species.
		2K	What are advantages and disadvantages with the current ways of working?	The system is designed so that it can be managed completely by three people working on full-time basis. No disadvantages really, however Siem wants to transform the permaculture project into a more "natural" food forest by planting more trees. This could require more labour.
3. Future vision on management of the system	A,C	3A	Per operation: What alternative solution from how you currently do it do you envision for the future for executing them? Why are these interesting alternatives to you?	Mechanical harvest, because it is faster, especially of berries, as they take a lot of time, if you want to harvest all from them.
	E	3B	What are your requirements for the new machinery?	Light, electric motor or better (more environmentally sustainable), quiet, fit within 1 m wide paths.
	F,G	3C	What functions that need to be present in the new machinery?	Harvest berries, fruits,nuts, analysis of the plot - more valuable for monoculture than for a self-sust food forest.
	C	3D	Do you think that machine should follow the ecology of the farm or dictate the planting patterns?	Combination, some trees and plants are good fitting together ecologically, so they should not be separated for the sake of easier mechanical harvest. Machine is not leading, but it is important to make work easier and quicker.
	D	3E	Which stakeholders are important for the development and introduction of new machinery?	Engineers and researchers, farmers with experience in complex agroforestry systems, investors.
		3F	Who else do you think should be involved in this research?	Martijn, cow farmer (alley cropping on a big scale), milieu defensie in brabant*, Taco Blom, engineers.
4. Additional	C	4A	If you had an opportunity to buy a new piece of machinery, what would be an acceptable investment for you to make and when would you expect it to pay back?	It is hard to evaluate, because the visitors like more to come, harvest by themselves, and pay right away for the amount of crops they harvested, rather than pay a yearly subscription for that. It makes it hard for Siem to evaluate what the annual revenue will be, and therefore allocate a budget for investments.

Table C.2. Interview with Siem Ottenheim (food forest Eet Meerbosch)

Section	Corresponding RIO stage	#	Question	Notes
1. Overview of the farming system	B	1A	How do you typify your farming system?	Food forest
		1B	When did you start the farm?	January, 2018
		1C	What is the size of your farm?	1.7 ha, excl. existing edge with old deciduous trees, surrounding the area.
		1D	How would you divide the development of your farm in stages (time-steps)?	Planting 6 days in Jan 2018 with 15 volunteers, coordination by Wouter. In 8 years from now, lowest veg. will be planted example rhubarb, strawberry, daslook.
		1E	What crops did you grow in each of them: 1) 2) 3)	-
		1F	What crops did you sell/ expect to sell during each stage? 1) 2) 3) n)	
		1G	How / to whom do you sell your products?	Every Saturday, sell products from belgium, then add the products from this food forest. Get people familiar with the products of the food, later - abonnement with weekly fruit boxes. 250 clients at the garden.
		1H	How many people work in the system?	Siem, two paid people, 1 internship.
		1I	What are the restrictions posed by your system to the machinery?	Not really, the landscape is more flat than in Belgium. Crops are in rows, so should be easy to harvest.
		1J	What do you feel could be the weak points of the new machinery?	The maintenance could be expensive, and the farmers will not have the knowledge to do it themselves. It is fine if someone will come and repair it from the company, but it could be too expensive for a small scale farmer. Generally, machinery is not that interesting for the small scale farmers.
2. Operations in the system	F,G	2A	What are the operations performed at the farm at the INITIAL PLANTING STAGE and AT THE MOMENT?	Only planting in a bare grass field, now - cut branches from big trees (not planted as a food forest) and brambles, prune the branches below the graft point.
		2B	How are they done at the moment:	-
		2C	a) What processes are performed manually?	Harvest, pruning.
		2D	b) What processes are performed mechanically?	Tilling (klepelmaaier) for the brambles, cultivating (only veggies), chainsaw pruning (mostly for willows), no mowing of grass, only one strip for the people to walk from the entrance to the center (3 times in a year)
	B	2E	c) What machinery do you currently use?	Klepelmaaier, cultivator (subsoiler), chainsaw, mower.
	F	2F	How much time do you spend on each operation?	see labour analysis.
		2G	When is every operation performed?	see labour analysis.
		2H	For what operations is there insufficient workforce available?	There is enough people, young people cshool), mainly volunteer work.
		2J	What other operations will need to be done in future if there are any?	Grafting, cut off the pioneer species, e.g. zilverpopulier in the moerasbos area.
		2K	What are advantages and disadvantages with the current ways of working?	Easier to harvest more efficiently due to the flatter terrain. A lot of work without machines. A lot of berries.
3. Future vision on management of agroforestry system	A,C	3A	Per operation: What alternative solution from how you currently do it do you envision for the future for executing them? Why are these interesting alternatives to you?	Mechanical harvest, because it is faster, especially of berries, as they take a lot of time, if you want to harvest all from them.
	E	3B	What are your requirements for the new machinery?	Light, electric motor or better (more environmentally sustainable), quiet, fit within 1.5 m wide paths. Low machine, size of the shrub to not hit the aboive growing fruit trees.
	F,G	3C	What functions that need to be present in the new machinery?	Harvest berries, fuirts, nuts, (analysis of the plot - more valuable for monoculture than for a self- sust food forest). Planting - is a lot of work.
	C	3D	Do you think that machine should follow the ecology of the farm or dictate the planting patterns?	Combination, some trees and plants are good fitting together ecologically, so they should not be separated for the sake of easier mechanical harvest. Machine is not leading, but it is important to make work easier and quicker.
	D	3E	Which stakeholders are important for the development and introduction of new machinery?	Engineers and researchers, farmers with experience in complex agroforestry systems, investors.
	D	3F	Who else do you think should be involved in this research?	Martijn, cow farmer (alley cropping on a big scale), milieu defensie in brabant*, Taco Blom, engineers.
4. Additional	C	4A	If you had an opportunity to buy a new piece of machinery, what would be an acceptable investment for you to make and when would you expect it to pay back?	Same as for De Nieuwe Hof, but, in general, is not needed for such a small food forest.

Appendix D Species lists

Table D.1. Species list (perennial woody species) for food forest De Nieuwe Hof, including labour analysis per species

#	Species	Common name	Level in the system	Species group	Current age, years	Harvest		Pruning		Guiding		Number of plants	Working height
						Period	Labour required, hours per year	Period	Labour required, hours per year	Period	Labour required, hours per year		
1	Actinidia arguta	Kiwi berry	Climber	Berries	6	Sep-Nov	6	—	—	spring-summer	1	15	up to 2m
2	Vitis vinifera	Grape			8	Sep	6	winter-spring	4	winter-spring	4	48	up to 2m
3	Cornus mas	Cornelian cherry	High tree		8	Aug	8	—	—	—	—	60	up to 2m
4	Morus alba	White mulberry			8	Aug-Sep	4	—	—	—	—	1	up to 2,5m
5	Morus nigra	Black mulberry			12	Aug-Sep	16	—	—	—	—	3	up to 8m
6	Prunus avium	Sweet cherry			12	Jun	16	—	—	—	—	10	up to 8m
7	Prunus cerasus	Sour cherry			12	Jun	16	winter	2	—	—	75	up to 2,5m
8	Sambucus nigra	Elderberry		Other (flowers)	10	May-Jun Sep	7 10	— —	— —	— —	— —	25	up to 2,5m
9	Aronia prunifolia	Chokeberry	Low tree	Berries	8	Oct-Dec	8	—	—	—	—	45	up to 2m
10	Hippophae rhamnoides	Sea buckthorn	High shrub		8	Aug	8	—	—	—	—	12	up to 2,5m
11	Zanthoxylum simulans	Sechuan pepper			8	Aug-Nov	4	—	—	—	—	2	up to 2,5m
12	Ribes nigrum	Black currant			5	Jun-Sep	36	winter	8	—	—	360	up to 1,5m
13	Ribes rubrum	Red currant			5	Jun-Sep	48	winter	12	winter	4	787	up to 1,5m
14	Ribes rubrum	White currant			5	Jun-Sep	8	winter	3	winter	1	125	up to 1,5m
15	Rubus idaeus	Raspberry (summer and autumn varieties)			3	Jun Sep	12 12	winter winter	2 2	winter winter	2 2	374	up to 1,5m
16	Rubus fructosia	Blackberry			4	Aug-Oct	12	winter	2	winter	2	120	up to 1,5m
17	Ribes uva-crispa	Gooseberry	Low shrub		10	Jun-Jul	24	winter	10	winter	4	387	up to 1,5m
18	Ribes x nidigrolaria (R. nigrum x uva-crispa)	Jostaberry			10	Jul-Aug	8	—	—	—	—	41	up to 1,5m
19	Rubus phoenicolasius	Japanese wineberry			3	Jul-Sep	8	winter	1	winter	1	76	up to 1,5m
20	Cydonia oblonga	Quince	High tree	Fruits	12	Oct	8	—	—	—	—	6	up to 2,5m
21	Halesia carolina	Carolina silverbell			8	Jun	2	—	—	—	—	5	up to 1-3m
22	Malus domestica	Apple (strong rootstock)			12	Jun-Nov	36	—	—	—	—	70	up to 3m
23	Mespilus germanica	Medlar			10	Oct-Nov	8	—	—	—	—	22	up to 2,5m
24	Prunus armeniaca	Apricot			12	Jul	8	—	—	—	—	7	up to 2,5m
25	Prunus domestica	Plum			12	Jul-Sep	12	Sep	16	—	—	80	up to 2,5m
26	Prunus persica	Peach			10	Aug-Sep	48	—	—	—	—	10	from 1.5 to 4 m
27	Prunus salicina	Japanese plum			8	Jul-Aug	8	—	—	—	—	10	up to 2,5m
28	Pyrus communis	Pear			12	Jul-Nov	8	winter	16	—	—	66	up to 5m
29	Pyrus pyrifolia	Sand (nashi) pear			8	Sep	36	—	—	—	—	8	up t 3 m
30	Malus domestica	Apple (weak rootstock)	Low tree		5	Jul-Nov	8	—	—	—	—	23	up to 2m
31	Poncirus trifoliata	Trifoliate orange			8	Nov	1	—	—	—	—	3	up to 1,5m
32	Chaenomeles japonica	Japanese quince	Low shrub		7	Oct-Nov	2	—	—	—	—	4	up to 1m
33	Castanea sativa	Sweet chestnut	Canopy	Nuts	8	Oct	6	—	—	—	—	9	ground level
34	Corylus avellana	Hazelnut			10	Sep	24	—	—	—	—	90	ground level
35	Juglans regia	Walnut			8	Sep	6	—	—	—	—	10	ground level
36	Prunus dulcis	Almond			8	Sep	6	—	—	—	—	8	ground level
37	Carya illinoinensis	Peacan			8	Sep	6	—	—	—	—	9	ground level
38	Betula sp.	Birch	High tree	Other (sap)	8	Mar-Apr	4	—	—	—	—	7	up to 2m
39	Rosa rugosa	Ramanas rose	High shrub	Other (rosehips)	8	Jun-Sep	48	—	—	—	—	185	up to 1,5m

Table D.2. Species list (perennial woody species) for food forest Eet Meerbosch, including labour analysis per species (projected)

#	Species	Common name	Level in the system	Species group	Current age, years	Harvest: Period, month	Harvest: Labour required, hours	Pruning: Period, month	Pruning: Labour required, hours	Guiding: Period, month	Guiding: Labour required, hours	Number of plants	Working height
1	Actinidia arguta	Kiwi berry			0	Sep-Nov	5	—	—	Mar-Aug	5	7	up to 2m
2	Actinidia kolomikta	Kiwi	Creeper		0	Sep	3	—	—	Mar-Aug	5	7	up to 2m
3	Vitis vinifera	Grape			0	Sep	10	Dec-Feb	5	Dec-Feb	5	30	up to 2m
4	Asimina triloba	Pawpaw	High tree	Berries	2	Oct	10	—	—	—	—	10	up to 2 m
5	Cornus mas	Cornelian cherry			2	Aug	2	—	—	—	—	10	up to 2m
6	Crataegus arnoldiana	Arnoldiana hawthorn			3	Sep-Oct	6	—	—	—	—	23	up to 2,5m
7	Morus nigra	Black mulberry	High tree		4	Aug-Sep	8	—	—	—	—	3	up to 8m
8	Prunus avium	Sweet cherry			3	Jun	8	—	—	—	—	4	up to 8m
9	Sambucus nigra	Elderberry		Other (flowers)	3	May-Jun Sep	4 6	— —	— —	— —	— —	6	up to 2,5m
10	Aronia x prunifolia	Chokeberry			3	Aug-Sep	10	—	—	—	—	100	up to 1,5m
11	Elaeagnus umbellata	Autumn olive			3	Sep-Oct	10	—	—	—	—	26	up to 2m
12	Hippophae rhamnoides	Sea buckthorn			3	Aug-Sep	8	—	—	—	—	11	up to 2,5m
13	Lonicera caerulea	Honeyberry			3	Jul	6	—	—	—	—	17	up to 2,5m
14	Ribes nigrum	Black currant	High shrub		3	Jun-Sep	20	Dec-Feb	4	—	—	140	up to 1,5m
15	Ribes rubrum	Red currant		Berries	3	Jun-Sep	20	—	—	—	—	118	up to 1,5m
16	Ribes rubrum	White currant			3	Jun-Sep	8	—	—	—	—	32	up to 1,5m
17	Rubus idaeus	Raspberry			3	Jun Sep	10 10	— —	— —	— —	— —	160	up to 1,5m
18	Viburnum lentago	Sheepberry			3	Sep-Nov	5	—	—	—	—	4	up to 1,5m
19	Ribes uva-crispa	Gooseberry	Low shrub		3	Jun, Jul	5	Dec-Feb	4	Dec-Feb	1	116	up to 1,5m
20	Ribes x nidigrolaria (R. nigrum x uva-crispa)	Jostaberry			3	Jun, Aug	6	—	—	—	—	50	up to 1,5m
21	Cydonia oblonga	Quince			3	Oct	6	—	—	—	—	5	up to 2,5m
22	Ficus carica "brown turkey"	Fig			3	Aug-Sep	6	—	—	—	—	8	up to 2,5m
23	Halesia carolina	Carolina silverbell			1	Jun	3	—	—	—	—	7	up to 1-3m
24	Malus domestica	Apple			3	Jun-Nov	10	—	—	—	—	7	up to 3m
25	Mespilus germanica	Medlar			3	Oct-Nov	5	—	—	—	—	12	up to 2,5m
26	Prunus armeniaca	Apricot	High tree		3	Jul	5	—	—	—	—	7	up to 2,5m
27	Prunus domestica	Plum			3	Jul-Oct	10	Sep	2	Sep	2	7	up to 2,5m
28	Prunus persica	Peach		Fruits	3	Aug-Sep	4	—	—	—	—	7	from 1,5 to 4m
29	Prunus salicina	Japanese plum			3	Jul-Aug	3	—	—	—	—	4	up to 2,5m
30	Prunus tomentosa	Chinese cherry			3	Aug	3	—	—	—	—	6	up to 1,5m
31	Pyrus communis	Pear			3	Jul-Nov	10	Dec-Feb	3	—	—	7	up to 5m
32	Pyrus pyrifolia	Sand (nashi) pear			3	Sep	12	—	—	—	—	10	up to 3 m
33	Poncirus trifoliata	Trifoliate orange	Low tree		3	Nov	1	—	—	—	—	3	up to 1,5m
34	Chaenomeles japonica	Japanese quince	Low shrub		3	Oct-Nov	2	—	—	—	—	3	up to 1m
35	Castanea sativa	Sweet chestnut			2	Oct	8	—	—	—	—	23	ground level
36	Corylus avellana	Hazelnut			2	Sep	10	—	—	—	—	62	ground level
37	Juglans ailantifolia	Japanese walnut			0	Sep	3	—	—	—	—	6	ground level
38	Juglans ailantifolia x cinerea	Buartnut	Canopy	Nuts	0	Sep	3	—	—	—	—	3	ground level
39	Juglans nigra	Black walnut			2	Sep	1	—	—	—	—	1	ground level
40	Juglans regia	Walnut			2	Sep	10	—	—	—	—	11	ground level
41	Prunus dulcis	Almond			3	Sep	8	—	—	—	—	8	ground level
42	Staphylea pinnata	Bladder nut			2	Sep-Nov	2	—	—	—	—	2	ground level
43	Tilia cordata	Small leaved lime, linden	Canopy	Other (leaves, flowers)	3	May-Sep	2	Oct	1	—	—	21	up to 2m
44	Toona sinensis	Chinese cedar		Other (leaves)	3	May-Sep	2	Oct	1	—	—	7	up to 2m
45	Phyllostachys aureosulcata	Yellow groove bamboo		Other (shoots)	3	May-Sep	2	—	—	—	—	2	ground level
46	Phyllostachys vivax 'Aureocaulis'	Big gold bamboo	High shrub	Other (shoots)	3	May-Sep	2	—	—	—	—	1	ground level
47	Rosa rugosa	Ramanas rose		Other (rosehips)	3	Jun-Sep	8	—	—	—	—	31	up to 1,5m

Appendix E Machinery requirements

Brief of general requirements

The requirements for machinery (Table E.1) can be split up into variable and fixed requirements, based on the values that are assigned. For variable requirements, a value is set up as well as the target value, the aim is to get as close to the target value as possible. For fixed requirements, a value or region of values is assigned, but no target value is given – all values within the given region equally satisfy the requirement. All the requirements are then divided into various aspects i.e. groups of requirements. Each requirement and motivation for including it in the brief of requirements is described below.

1. ≤2% of the crops (berries) is damaged during harvest, with target value of 0%.
During the harvest, no more than 2% of crops are damaged. This includes target and non-target crops[1] *among the species that need to be harvested (See Appendix D).*

2. ≤ 0.11 hours/berry plant/year spent on harvesting berries.
Solutions for harvest of berries should be as efficient or more efficient than humans. The value was calculated from the labour analysis of the two farming systems and the strictest value was chosen.

3. Out of the desired amount of berries, 100% are harvested.
For each system the farmer defines a portion of total ripe berries that he wants to harvest. For example, for Eet Meerbosch it is essential to leave a portion of ripe berries for wildlife, while previously in De Nieuwe Hof maximum amount of ripe berries was picked. Requirement is to harvest all the ripe berries that are desired to be harvested by the farmer, allowing for both sufficient income and ecological sustainability. 100% is a target value, while there is also a minimal accepted value, that was not assigned for the farmer, as economics were out of the scope.

4.1. Target berry (plant) species are recognised with 100% precision[2]**.**
Maximum amount of recognised berry species are correctly identified. This requirement is fundamental and critical, as without being able to identify maximum amount of berry species correctly requirements 5 and 6 cannot be met.

4.2. **Target berry (plant species) are recognised with 100% recall**[3]**.**
Maximum amount of berry species present in the food forest is correctly recognised. Reaching the maximum for this requirement is less critical, as if not met it can lead to certain crop loss, however, it cannot lead to significant crop damage.

5.1. Target harvestable plant parts (berries) are recognised with 100% precision.
Maximum amount of identified berries are correctly recognised. Reaching the maximum for this requirement is critical, as if not met, this could lead to damage of plant parts other than berries e.g. leaves, branches. This can have an indirect effect on plant health and further harvests crop damage and loss of harvest.

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[1] Crops that are either assigned to be harvested or not, based on the parameters set up by a farmer e.g. ripeness threshold, selected crop species etc.

[2] Portion of correctly identified items among the selected ones.

[3] Portion of the relevant items which are selected.

5.2. Target harvestable plant parts (berries) are recognised with 100% recall.
Maximum amount of berries present in the food forest is correctly recognised. Reaching the maximum for this requirement is less critical, as if not met it can lead to certain crop loss, however, it cannot lead to significant crop damage.

6.1. Ripeness is recognised with 100% precision.
For maximum amount of berries, ripeness is correctly recognised. Reaching the maximum for this requirement is critical, as if not met, this could lead to harvest of unripe berries, which have lower value and can significantly decrease the income.

6.2. Ripeness is recognised with 100% recall.
Maximum amount of ripe berries in the food forest is correctly recognised. Reaching the maximum for this requirement is less critical, as if not met it can lead to certain crop loss, however, this can be acceptable for a farmer.

7. Exerted ground pressure ≤ 55 kPa.
The harvesting solution that is operating in a food forest, should exert ground pressure equal to or lower than of an average human ("Ground pressure"), with the aim to minimise its weight, to reduce soil compaction. This aspect is important for food forest farmers as high soil compaction is one of the reasons why conventional machinery is not accepted by them.

8. Sound pressure level, produced by each individual machine is ≤45 dB(A), with target value of 0dB.
Based on the farmers objective to reduce the noise pollution that has impact on wild birds and animals, sound pressure level must be not higher than 45 dB. This value is the highest observed value in a natural forest (Kyon et al., 2014; "Sound pressure", 2004) and therefore is safe for the wildlife living in a food forest. This requirement is of high importance for food forest farmers, as one of the ecosystem services that are provided by food forests is natural habitat.

9. ≤ 1,043 kg CO_2/hour is produced.
CO_2 production rate of a harvesting solution must be equal or smaller than from human breathing, as this has negative impact not only on a food forest, but also on the environment and the planet. This is an aspect that is crucial for food forest farmers and is one of the reasons why conventional machinery is not used by them (Palmer, 2009). The value was taken from the source ("How much does breathing contribute to climate change?") and converted using online converter ("Carbon Dioxide - Weight and Volume Equivalents").

10. Crops in size range 0,5-15 cm (for individual berries) and 5-20 cm (for bunches) are harvested.
Berries from all the berry species listed for two systems, are harvested.

11. Pressure on berries during harvest is within the appropriate range.
Maximum accepted pressure on berries varies among the species. This is especially critical for soft berry species, where gripping of berries themselves is involved for harvest. No range of values is assigned here, but this needs to be calculated and applied for harvest procedure to allow for safe intact harvest.

12. Vertical reach of machinery is from ground level to 8 m.

Berries should be harvested within a given range. The range represents a vertical region where berries can be found for the species listed for two systems.

13. Width of each individual machine is ≤1 m.
Width of the paths in the food forests is 1 m and the harvesting solution should be able to pass them.

14. No damage is dealt to vegetation and wildlife during operations, unless approved by a farmer (e.g. making paths through nettles).
While farmers don't want any damage being caused during harvest in a food forest, it is arguable whether this requirement is indeed aimed at absolutely 0% damage to vegetation, as in some cases, paths will be needed to be made by the machinery to reach certain plants. Therefore, there should be an interaction between a farmer and harvester to decide whether damage on certain vegetation in a certain moment in a certain place of a food forest is acceptable by a farmer.

15. No trespassing on nature areas[4].
In other food forests, like Ketelbroek and Schijndel, certain areas are often created to act as shelters for wildlife. These areas must not be trespassed.

Among the listed requirements, the high scores for accuracy (precision and recall) of recognition and safe harvest are most challenging to meet for high technological solutions. When these requirements are met, it will be possible to conclude that mechanical harvest is able to substitute human labour for food forests and have similar or better performance.

Brief of species-specific parameters

Apart from general requirements, it's worth mentioning that the diversity of species entails a variation of different properties of edible crops growing on them. Therefore, when developing technologies to

Table E.2. Species-specific parameters for harvest.

#	Species	Common name	Group	Parameters for harvest						Parameters for recognition	Machinery for safe harvest of ripe products is already available (**Y**), or with (**C**)ompromising integrity, or (**N**)ot at all
				(**I**)ndividual, (**D**)ouble, or (**B**)unch (>3)	(**E**)asy or (**H**)ard to detach, (**C**)utting is required, or picking from (**G**)round	(**+**) Soft when ripe, (**++**) extra soft, or (**-**) hard	Stem (**A**)ttached after harvest, or (**N**)ot	Size of a single fruit, or for a whole bunch (^), cm	(O)rientation on a branch, (**H**)anging loosely, (**C**)losely attached	(**C**)olor changes when ripe, or (almost) (**N**)ot	
1	Actinidia arguta	Kiwi berry		I	E	++	A	3..4	H	N	N
2	Actinidia kolomikta	Kiwi		I	E	++	A	3..4	H	N	N
3	Vitis vinifera	Grape		B	C	+/-	A	10..20^	H	C	C
4	Asimina triloba	Pawpaw		I,D	E	++	A	10..15	H	C	N
5	Cornus mas	Cornelian cherry		I	E	-	N	1..2	H	C	N
6	Crataegus arnoldiana	Arnoldiana hawthorn		I(B)	H	-	A	0.5..1	H	C	N
7	Morus alba	White mulberry		I	E	++	A	2..3	H	C	N
8	Morus nigra	Black mulberry		I	E	++	A	2..3	H	C	N
9	Prunus avium	Sweet cherry		I,D	E	-	A*	3..4	H	C	Y
10	Prunus cerasus	Sour cherry		I,D	E	+	A*	2..3	H	C	Y
11	Sambucus nigra	Elderberry		B	C	+	A	10..20^	H	C	N
12	Aronia x prunifolia	Chokeberry	Berries	I(B)	E	-	N	0.5	H	C	Y
13	Elaeagnus umbellata	Autumn olive		I	E	+	N	0.5..1	C	C	N
14	Hippophae rhamnoides	Sea buckthorn		I	H	-	A	0.5..1	C	C	Y
15	Lonicera caerulea	Honeyberry		I	E	-	N	1..2	C	C	N
16	Ribes nigrum	Black currant		I	E	+	N	1..1,5	C	C	Y
17	Ribes rubrum	Red currant		B	E	++	A	5..12^	H	C	Y
18	Ribes rubrum	White currant		B	E	++	A	5..12^	H	C	Y
19	Rubus fructosia	Blackberry		I	E	++	N	3..4	H	C	Y
20	Rubus idaeus	Raspberry		I	E	++	N	2..3	H	C	Y
21	Rubus phoenicolasius	Japanese wineberry		I	E	++	N	1,5..2	H	C	N
22	Ribes uva-crispa	Gooseberry		I	E	-	A	1..2	H	C	Y
23	Ribes x nidigrolaria (R. nigrum x uva-crispa)	Jostaberry		I	E	-	N	1..2	H	C	N

Notes:
+/- parameter differs per variety and/or depends on the time when harvested
n/a parameter not applicable to the part harvested
I(B) crop grows in bunches, but is to be picked by individual fruit
* depends on the desired shelf life

[4] Areas defined by a farmer that must be left undisturbed.

perform harvest, it is important to assess each individual species based on parameters, that will determine the way of mechanical harvest and pose specific requirements in order to allow for safe harvest without damaging the target crops as well as the surrounding vegetation. The most relevant and critical parameters were determined, and their values per species are listed in Table E.2.

Appendix F Key functions of machinery

1. Sense species, ripeness.

Collect data for species and ripeness identification.

2. Sense objects.

Collect data for object identification.

3. Determine objects.

Determine objects in the input data e.g. path, tree, human, ditch etc. for path planning; identify every berry species listed in Table E.2; identify harvestable plant part – berries.

4. Locate plants.

Create data points that will be used to make paths in a food forest.

5. Plan paths.

Plan paths (trajectories) from point A to point B, choosing the shortest routes, avoiding obstacles in a food forest.

6. Move harvester.

Move through a food forest to perform harvest.

7. Analyse and determine ripeness.

Using acquired images, after processing them (giving color value for each image), compare them to a database of images. Using a selected scale, give a ripeness score for berries on the images. Two functions were combined into one, as they represent one processing stage that can be performed with the same solutions.

8.1. Grip crop by body.

Maintaining constant pressure, secure the crop e.g. pawpaw, kiwi by its body.

8.2. Grip crop by peduncle.

Maintaining constant pressure, secure the crop (e.g. grape, elderberry, red currant, chokeberry) by its body.

15.1. Separate crop from branch by pulling.

Pull a berry (peduncle) outwards from branch to detach it (e.g. pawpaw, kiwi) from branch. Applicable for species group 1 (Table 1).

15.2. Separate crop from branch by rotating.

Rotate a berry (peduncle) around its axis to detach it (e.g. pawpaw, kiwi) from branch. Applicable for species group 1 (Table 1).

15.3. Separate crop from branch by scraping.

Scrape berries (without gripping them beforehand) to detach them (e.g. arnoldiana hawthorn, sea buckthorn etc.) from branch. Applicable for species group 2 (Table 1).

15.4. Separate crop from branch by splitting

Split the peduncle perpendicular to its axis to detach crops (e.g. elderberry, grape) from branch. Applicable for species group 3 (Table 1).

Morphologic chart

1. **Sense species, ripeness.**

For sensing the plants, camera that works within RGB and IR is a solution that is already used for imaging in horticulture, for example by Phenospex in their 3D scanner PlantEye. Eyes resemble human vision.

2. **Sense objects.**

For sensing the environment, different sensors can be used, they are different in type of waves that are used, Ultrasonic sensor relies on ultrasonic sound waves and LiDAR on electromagnet waves. Both technologies are used in the context of obstacle avoidance and path making. Apart from those pressure sensors can be used (US2017010707A1).

3. **Determine objects.**

In order to determine objects in the input data i.e. images and sensor data, R-CNN (Karmarkar, 2018) and Mask R-CNN are used (Ren et al., 2016). Apart from the high-tech solutions, human tactile sense, smell and eyes can be used.

4. **Locate plants.**

In order to create these data points, RFID tags, GNSSs can be used as well as local coordinate system build based on the objects previously identified. Examples of such systems are Galileo (EU), GPS, NAVSTAR (US), GLONASS (Russia), BeiDou (China).

5. **Plan paths.**

In order to make paths (trajectories) from point A to point B, and avoid obstacles, MPNet is already being used in robotics (Qureshi et al., 2019) Such technology is also used to calculate the rotation of motors of a robotic arm for example to approach an object. Manual input requires a human to assign a path that a machine should follow.

6. Move harvester.

In order to move through a food forest wheels, tracks, robotic legs and rails can be used, as well as human legs when no mechanisation is considered. Currently, small wheels can be found in agricultural robots like Oz from Naïo Technologies and robotic legs in small robots like Spot from Boston Dynamics [refnum]. Tracks are used in certain conventional machinery, while rails are used in greenhouse horticulture machinery.

7. **Analyse and determine ripeness.**

In order to analyse and determine ripeness score for target crops, CNNs are used. By processing and comparing given images to a database, CNN can give a ripeness score in percentage as an output. This is currently used in single-crop applications, for example for banana ripeness analysis (Mazen and Nashat, 2018). Currently, brain is used for this function.

8.1. Grip crop by body

To secure a crop, both soft grippers and rigid grippers can be used, as well as a combination of the two – hybrid gripper mechanism (Park et al., 2019). Hands are currently used for harvesting most berry species, especially the soft ones. Soft robotic grippers can be currently found on robotics arms for harvesting strawberries (Preter et al., 2018; BE1024167 (B1)). An example of rigid gripping mechanism can be found in a robotic strawberry harvester by Agrobot.

8.2. Grip crop by peduncle.

To secure the peduncle all the solutions above can be used as well. For this function rigid robotic mechanism is sufficient, as insignificant damage of peduncle itself doesn't have high influence on quality of the final product. In some cases, gripping crops by peduncle is used for tender berries, for example for strawberry harvesting by Agrobot (US10292414 (B1)).

9.1. Separate crop from branch by pulling.

Pulling motion for detaching crops can be achieved by using motors and transforming rotation motion into forward motion. For this purpose, AC/DC, Servo and Stepper motors can be used. Another solution could be the use of pneumatic/hydraulic cylinders, which are currently used for lifting and turning applications in numerous kinds of machinery. These cylinders allow for forward motion, however, are often heavier than the motors listed above.

9.2. Separate crop from branch by rotating.

To rotate a crop, different kind of motors can be used. Regular AC/DC motors, servo motors and stepper motors are currently used in robotics ("Experts outreach for motors"). Hands are also used, when no mechanisation is considered. Regular AC/DC (depending on application – AC for industrial robots, DC for portable robots) motors run constantly, when power is applied ("Experts outreach for motors"). Speed is controlled only by input voltage from the power source. Servo motors are enhanced with a controller that allows for input of velocity settings, which are sent to a driver amplifier, that feeds the servo motor ("Experts outreach for motors"). Stepper motors can operate with or without feedback. It is controlled by pulsed command signals and can stop at any given point. Rotation of such motors is broken up into small angular steps. Stepper motors are often used for rotation oriented applications, where precise rotation angles are required ("Experts outreach for motors").

9.3. Separate crop from branch by scraping

For berries that are currently harvested by scraping them from branches with fingers, no gripping of individual berries is required. For such application, soft robotic and rigid robotic grippers can be adapted to perform sequential actuation of different "fingers". Among the handheld tools that are currently used to maximise harvest efficiency, rake is used ("Wild huckleberry picking rake").

9.3. Separate crop from branch by splitting

To split the peduncle, blades, heating element or regular man-held scissors (or garden shears) can be used. Blades are already being used in Agrobot strawberry harvester (US10292414 (B1)) and in Sweeper bell pepper harvester (Arad et al., 2020). Heating element is an alternative, that could possible instantly *heal the cutting point by burning it. However, this could lead to fires, when done during dry summers in a dense food forest environment. Different kinds of scissors and shear are currently used to split the peduncles of berries. They allow for precise cut, minimising damage dealt to a plant.*

Appendix G Alternative solutions

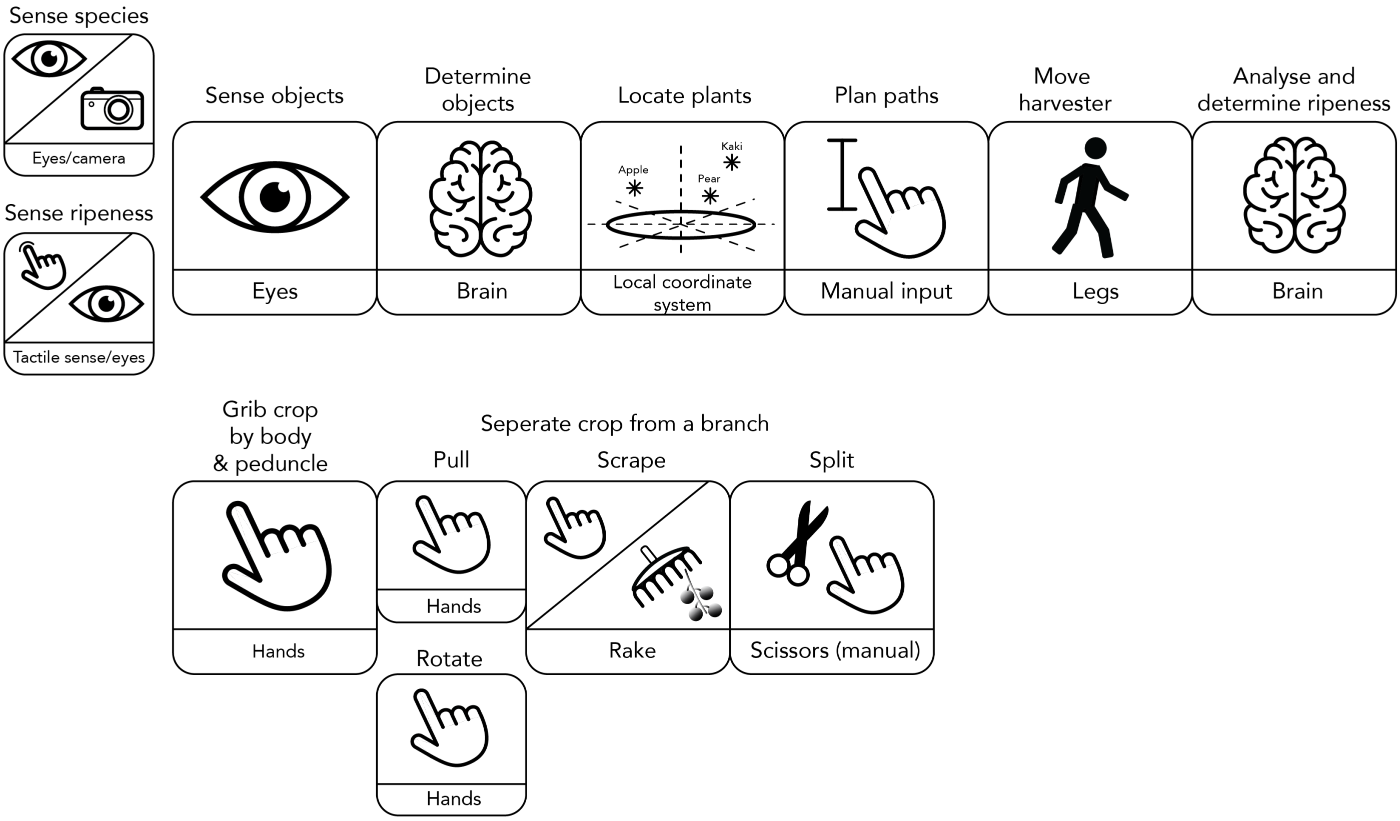

Figure G.1 Solution 2 – manual

Solution 2 (Fig G.1) represents the current solution for berry harvesting in food forests, being people. Data collection and processing, are done using human eyes and brain, movement is performed by walking and harvest is done manually, or using certain tools, like rake.

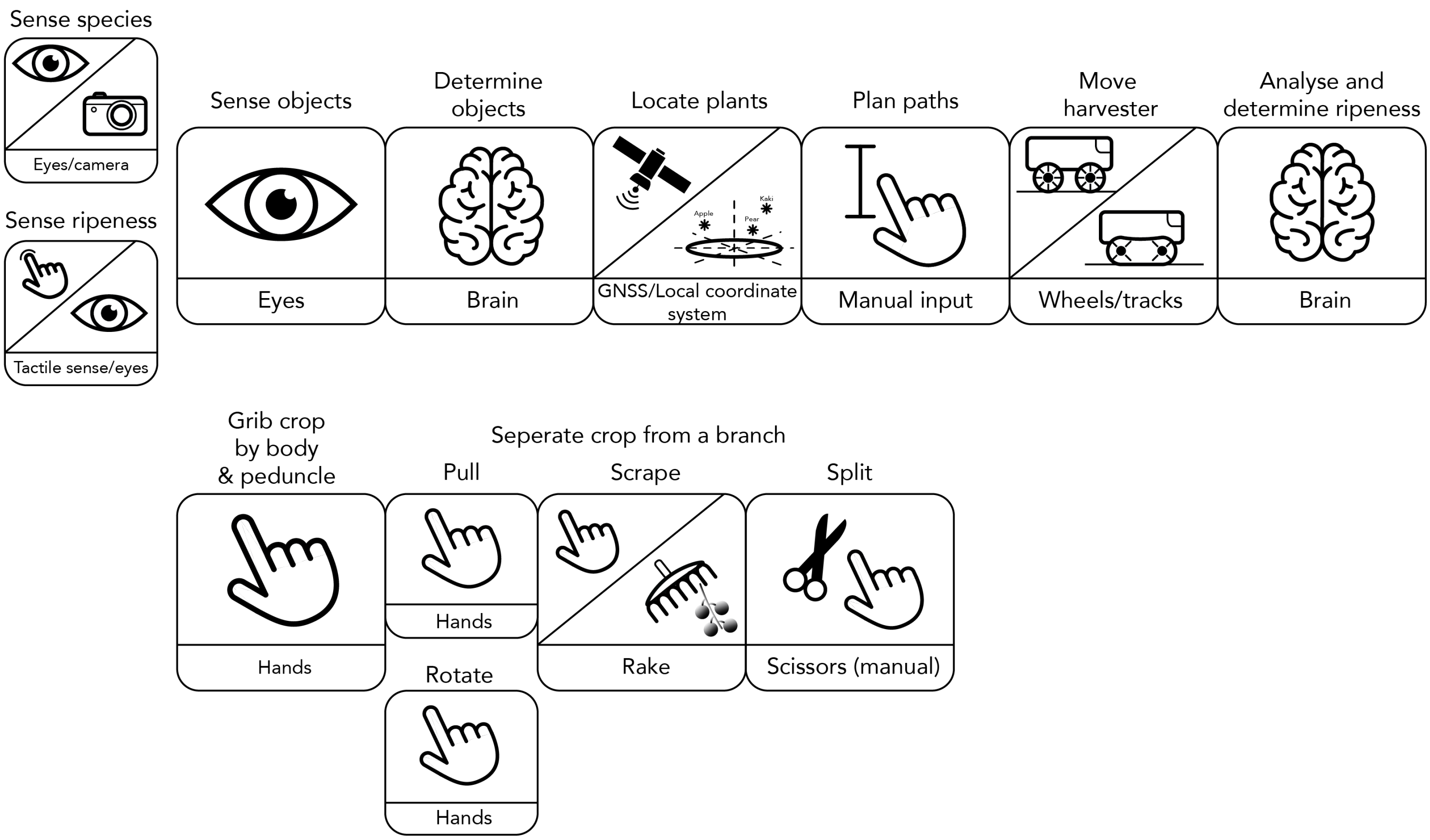

Figure G.2 Solution 3 – low tech with manual harvest

Solution 3 (Fig G.2) represents low tech machinery that guides manual harvest. This solution is widely used in commercial soft berry orchards, where people are responsible for harvesting, while machine either drives people while they are harvesting or carries boxes to collect the harvested berries.

Appendix H Interviewees and experts involved

Farmers:

- Siem Ottenheim. De Nieuwe Hof, Eet Meerbosch, CSA Tuinderij moestuin Neerbosch, Veehouderij Neerbosch. https://eetmeerbosch.nl/
- Wouter van Eck. Foodforest Ketelbroek, Grean Deal Voedselbossen. https://greendealvoedselbossen.nl/koplopers/ketelbroek/
- Wil Sturkeboom. Fruittuin van West. http://fruittuinvanwest.nl/
- Bastiaan Rooduijn. Food forest De Overtuin, Coöperatie Ondergrond, Rotterdams Forest Garden Netwerk. http://www.rfgn.nl/2017/09/voedselbos-de-overtuin/

Experts:

- Haris Khan. Wageningen University and Research
- Andrew Dawson. Wageningen University and Research
- Ali Leylavi Shoushtari. Wageningen University and Research
- Marius Monen and Nico Schoutsen. Cooperative Smart Sustainable Farming