Agroforestry in the Netherlands

The production potential and environmental advantages of a temperate food forest

Thesis research project

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Nico van Eeden

M.Sc. Industrial Ecology
Leiden University & Delft University of Technology

First supervisor: dr. M.J.J. Schrama
Second supervisor: dr. E.G.M. Kleijn

Preface

This thesis research project is an explorative study of the edible production potential and environmental advantages of a temperate food forest to conclude my M.Sc. Industrial Ecology at Leiden University and Delft University of Technology. To get to this aim, I use the case study of a plot from food forest *Schijndel* in the Netherlands to assess the future edible production potential and I will make an assessment of the nutrient- and water characteristics.

Additionally, the future production in kilograms will be differentiated among energy, carbohydrate, protein, fat, and fibre produce. The results will be compared with average recommended intakes to make an estimation on the nutritional carrying capacity of a food forest, in relation to conventional cultivation systems.

The aim of this work is to contribute to the scientific basis on quantifying the food production of a food forest in temperate climates, as it can help stakeholders with predicting the future production of such a forest. It will also provide a deeper insight into the nutrient management and water- characteristics of food forests placing it in the context of global environmental problems related to agriculture while also discussing the current literature body on these subjects.

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Abstract

Agriculture is a major driver of exceeding the planetary boundaries. Therefore, it is a principal sector that requires sustainable change. *Agroforestry*, described as the deliberate planting of trees on farm land or integrating farmers into forests, is one of the proposed solutions and has gained a lot of (renewed) attention in the Netherlands and elsewhere. A *food forest*, one of the subcategories, is defined as a human designed system with a variety of edible species grown in vertical layers based on the example of a natural forest. The aim of this research was to provide a more solid basis for the quantification of yields for temperate food forests together with describing advantages regarding nutrients (N, P) and water. To this end, a focal study plot of food forest *Schijndel* was analysed in which future yields and nutritional carrying capacities (NCCs) were modelled for 2020-2049 with an extrapolation to 2067. Results were compared with conventional fruit-, carbohydrate cropping-, nut- and meat systems. The results for this focal study plot showed a slow but steady yield increase towards a fresh weight yield of 7.1 t/ha in 2049 together with a balanced nutritional supply in terms of NCC for kcal (11.0 persons/ha), carbohydrates (13.1 persons/ha), proteins (11.6 persons/ha), fats (13.1 persons/ha) and fibres (23.0 persons/ha) in 2049. Nutritional results were in general significantly higher than few previous studies. The comparison between cultivation systems showed that the food forest plot had the highest overall NCC. Furthermore, the study plot scored high in the category of fats, modest for proteins and was not competitive with the best performing systems among carbohydrates, fibres and kcal. It is hypothesized that a food forest scores high in micronutrient provision as well, although this could not be substantiated in this study. Additionally, several environmental advantages such as reduced nutrient leaching, self-sufficiency and improved on-farm water cycling were indicated. Although, effects such as high annual nutrient removal and high N deposition on those parameters are yet insufficiently understood. In conclusion, a food forest is a more balanced system which takes more time to develop itself than most conventional systems, but offers continuous and (probably) durable yields. The main limitations in this research were the fact that applicable yield data was not readily available together with a premature literature body on effects such as shading on yields. Further research should be redirected towards measuring actual yields, nutrient- and water characteristics and compare those to systems with comparable soil and climate conditions such as adjacent fields together with a further economic assessment for which this study can provide a basis.

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Glossary

Adjusted yield model	Second yield model build for plot *H2* were the performance of species in a food forest was taken into account and that is used for further yield comparison and analysis.
Agronomy	The field of agronomy studies agriculture from an integrated, holistic perspective. Agronomists are specialists in crop and soil science, as well as ecology (American Society of Agronomy, 2020).
Arable land	Any land that is capable of being ploughed and used to grow crops.
Canopy	The canopy layer refers to the upper layer or habitat zone formed by mature tree crowns.
Catch crop	Crops grown for the purpose of taking up residual soil minerals, increasing annual dry matter production and reducing the risk of leaching and run-off.
ES	Ecosystem services (ES) are defined as the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing. Four types of ES are widely distinguished: provisioning (*e.g.* food), regulating (*e.g.* climate control), supporting (*e.g.* nutrient cycling) and cultural ES (*e.g.* recreation) (Costanza *et al.*, 2017).
Forest age	Age of the food forest in the model used to quantify the yield of plot *H2*. The planted species are assumed to be planted while 3 years of age. Hence, the species are three years older than the forest age.
KWIN	*Kwantitatieve Informatie Fruitteelt (NL)*. A report with extensive information on productivity and costs from the Dutch fruit sector published by *Wageningen University*. The edition used in this study is the KWIN 2009/2010 (Heijerman-peppelman & Roelofs, 2010).
LCA	Life Cycle Assessment (LCA). A method that is used in the field of Industrial Ecology and elsewhere to quantify environmental impacts relating to goods or services from a system perspective.
NCC	The nutritional carrying capacity (NCC) is a metric used to normalize and compare the outputs of a food system among different nutrient categories such as carbohydrates and proteins.
Non-specific model	This model is the initial yield model build for plot *H2* using data on fruit- and nut species and being non-specific for the yield of these species in a food forest.
NUE	The nitrogen use efficiency (NUE) indicating the outputs compared to the nitrogen inputs.
Plot *H2*	Plot *Hardekamp H2* of food forest *Schijndel*.
Temperate	Relating to or denoting a region or climate characterized by mild temperature.

1. Introduction

We are currently living in an era of major environmental challenges while sustaining a human population that is expected to rise with one or two billion people by 2050 (Foley, 2011). In fact, the current era starting from the Industrial revolution has been termed the *Anthropocene* where humans have a defining impact on the earth system and are driving environmental changes after a long period of relative ecological stability called the *Holocene* (Crutzen, 2002).

Recognizing the threat of environmental degradation accompanied by the development of humankind, Rockström *et al.* (2009) introduced the concept of *planetary boundaries* aiming to define a safe operating space for humanity on Earth. Five of the defined key global variables have already been exceeded or are at an increased to high risk of being exceeded: loss of biodiversity, disruption of the global nitrogen- and phosphorus cycle, land system change, global freshwater use and climate change (Campbell *et al.*, 2017). By clearing tropical forests, farming marginal lands and intensifying industrial farming among sensitive landscapes and watersheds, agriculture is a major driver behind four of those perturbances and considered a 'significant contributor' to the fifth: climate change while being a major or significant contributor to change for several other planetary boundary processes still in the safe zone (Campbell et al., 2017; Foley, 2011).

While change in all sectors is important, agriculture is certainly one of the principal sectors that requires sustainable change (Foley, 2011). Strategies such as reducing food waste, shifting diets away from meat, and halting the expansion of agriculture into tropical forests and savannas have been proposed (Foley, 2011). At the same time, it is argued that a renegotiation of the aims of agriculture is needed (Björklund, Eksvärd, & Schaffer, 2019). The narrow focus on production needs to be redirected to one that explicitly includes the values of other ecosystem services (ES) (Björklund *et al.*, 2019). Therefore, a paradigm shift is needed towards ecological intensification where food production can be sustained at a sufficient level for meeting the dietary needs of humankind while respecting and not putting ever increasing pressure on the biosphere (Rockström *et al.*, 2017).

To this, end many solutions have been proposed, ranging from conservation agriculture and precision farming to organic agriculture (Willett *et al.*, 2019). The method of agroforestry has become popular in recent years and has been acknowledged as one of those solutions (Pavlidis & Tsihrintzis, 2018). Agroforestry is defined as: *'A collective name for land-use systems in which woody perennials are deliberately grown on the same piece of land as agricultural crops and/or animals, either in some form of spatial arrangement or in sequence'* (Lundgren, 1982). In addition, as stated by Raintree (1986): *'There are two ways of arriving in agroforestry: either by integrating trees into farming systems, or by integrating farmers into forests.'* What makes agroforestry different from other practises is the fact that it leads to a different agricultural landscape offering an inherently higher biodiversity (Breidenbach, Dijkgraaf, Rooduijn, Nijpels-Cieremans, & Strijkstra, 2017), while being outside to what people tend to call 'true nature'.

The cultivation of trees and crops in close proximity with one another is an ancient practise that is used by farmers throughout the world (Nair, 1994). For example, in the Middle Ages in Europe it was common to clear degraded forests and grow crops for a varying period of time while planting trees beforehand, along with or afterwards on the same land (Nair, 1994). In temperate zones it was also common to use trees as a natural protection against the sun or as windbreaks (Nair, 1994; Pavlidis & Tsihrintzis, 2018). Further uses included hedgerows and so called '*streuobst*' which are the combination of fruit trees from different type on cropland, meadow or pasture (Herzog, 1998).

However, in the 20th century there was a decline in European agroforestry systems triggered by the Common Agricultural Policy (CAP) that led to a transition towards heavily specialized and intensified forms of agriculture (Torralba, Fagerholm, Burgess, Moreno, & Plieninger 2016). Monocultures became the norm (Pavlidis & Tsihrintzis, 2018).

Currently, the area which is covered by agroforestry in the European Union is still 15.4 million hectares (den Herder *et al.*, 2017). This is equivalent to 3.6 % of the territorial area and almost 9 % of the utilised agricultural area in Europe. From the studied approaches livestock agroforestry covers the largest area by far with 15.1 million hectares (den Herder *et al.*, 2017).

In the Netherlands agroforestry has also emerged as a means of sustainable agriculture (Dooren, Oosterhof, Stobbelaar, & Dorp, 2018). As an illustration, multiple parties including the government and provinces signed the *Green Deal Voedselbossen*, a declaration of intent to promote the adoption of agroforestry in the Netherlands (Wiebes *et al.* , 2016). In this *Green Deal*, agroforestry has been divided into the following subcategories.

- Alley cropping
- Riparian zones
- Silvopasture
- Food forestry

A short description of these categories will be given below after which knowledge gaps with respect to the latter category will be described.

Alley cropping is a form of *silvo-arable agroforestry* and encompasses the integration of trees in rows with agricultural crops on farmland (Pardon, 2018). In general, enhancements in ES delivery have been indicated with, for example, a recent study showing increased levels in soil organic carbon (SOC) and nutrient concentrations in temperate alley cropping fields compared with monoculture control fields (Pardon *et al.*, 2017). However, competition between crops and tree rows has also been described to reduce crop yields in proximity to the latter in a temperate setting (Nelissen *et al.*, 2017). A meta-analysis by Torralba *et al.* (2016) indicated mixed results for productivity and generally a comparable productivity to for example pastures or monocultures while at the same time indicating a wide array of other eco-system benefits. For the (sub)tropics more studies have been conducted to assess the yields of alley cropping systems again showing positive and negative effects depending on the contextual interplay between location and positive and negative tree-crop interactions (Nair, P. R., Buresh, R. J., Mugendi, D. N., & Latt, 1999). Therefore, it remains difficult to give a single answer on productivity as some systems will perform better and some worse compared with non annual mono-cultivations. Currently, alley cropping is being investigated by *Wageningen University* to gain further knowledge on aspects such as productivity, soil fertility and pest control in the Netherlands (WUR, n.d.).

Riparian bufferzones are areas of permanent vegetation in semi-terrestrial areas between croplands and streams (Young, Ross, & Jaynes, 2019). *Riparian areas* receive water from groundwater discharge, overland and shallow subsurface flow and flow from adjacent surface water bodies. Therefore, they have high water tables and periodic flooding. Riparian zones are dynamic natural eco-systems which can filter nutrients, sediment and chemicals such as herbicides thereby preventing impairment of water quality (Anbumozhi, Radhakrishnan, & Yamaji, 2005; Hefting *et al.*, 2006). Therefore, riparian zones are considered best management practise for nutrient mitigation and scientific interest has risen considerably for these zones over the last decades (Prokovski, 2016, pp. 4–5; Young *et al.*, 2019).

However, riparian zones are also one of the most vulnerable eco-systems subject to climate change and human activity (Prokovski, 2016, p. 4). A riparian zone is not a production system in itself. However, the deliberate planting of riparian buffer strips has been described both complementary to regular croplands as agroforestry systems (Dix *et al.*, 1997).

Silvopasture is the integration of trees and shrubs with grazing animals on pasture land. However, with respect to livestock production, the following points should be addressed. Animal agriculture is responsible for a variety of environmental problems on a regional and global scale (Steinfeld *et al.*, 2006; Valk, Hollander, & Zijp, 2016; Westhoek *et al.*, 2011). For example, the FAO estimated with an LCA that animal agriculture alone contributes to 18 % of global anthropogenic GHG emissions, including 37 % of global methane and 65 % of nitrous oxide emissions (Steinfeld *et al.*, 2006). Animal agriculture is a leading cause of deforestation both directly through grazing as well as indirectly through feed crop production (Geist & Lambin, 2002; Veiga, Tourrand, & Piketty, 2002) and almost 30 % of human induced terrestrial biodiversity loss may be attributed to livestock production (Westhoek *et al.*, 2011). Other hazardous impacts are freshwater depletion and water pollution, soil acidification and air pollution which is also relevant in the present nitrogen crisis in the Netherlands (Marra, 2018; Steinfeld *et al.*, 2006). An essential aspect in the discussion is the low feed conversion rate of especially ruminants, illustrated by the fact that only 33 % of human protein consumption stems from livestock products (Havlík *et al.*, 2014) while in total 30 % of the land surface on earth is occupied by animal agriculture (Steinfeld *et al.*, 2006).

Thus, animal agriculture can be regarded as an inefficient and environmentally unfavourable practise when providing populations with protein. And while livestock can be used in (agro)silvopastural systems for a couple of eco-system benefits, it is fraught with difficulties. As an illustration of the climate change impact, one cow emits around 120 kg methane (GWP 100 equivalent to 2.5 tCO_2/y) (Grainger *et al.*, 2007). This is in stark contrast with annual land sequestration ranges of 'Low' (0-0.5 tCO_2/ha), 'Medium' (1-5 tCO_2/ha), 'High' (5-10 tCO_2/ha) to 'Extremely high' (>20 tCO_2 /ha). It means that only a minimum number of cows can be kept in order to be *'net climate positive'*. Therefore, the focus of this study will not be on livestock agroforestry but instead on food forests with multiple layers.

A *food forest* is defined as a land use system that adopts the structural and functional vegetation composition of a forest ecosystem and consists of a variety of edible plants grown in different vertical layers (Crawford, 2010). Food forests are also known as *home gardens*, *tropical forest gardens* or *edible gardens* and are among the oldest human land uses (Toensmeijer, 2016, p. 24). The majority of food forests is found in the (humid) tropics (Toensmeijer, 2016, p. 42). Following the *Green Deal* (Wiebes et al., 2016), an eco-system can be qualified as a food forest once the criteria below are met:

Number	Criterium
1	A human designed production eco-system based on the characteristics and design of a natural forest.
2	A high diversity of perennials or woody species, of which parts (*i.e.* fruits, leaves, seeds, nuts) can be consumed by humans.
3	The presence of a canopy layer and at least 3 other vegetation layers consisting of canopy trees, lower trees, shrubs, herbs or vegetables, ground-covering plants, underground plants grown for roots and tubers or vertical plants (vines and climbers).
4	A robust size; a minimum surface of 0.5 hectare in an ecologically rich area or a minimum of 20 hectare in an ecologically degraded area.

Table 1: Criteria of a food forest.

For an illustration of the multi-layered structure, see figure 1 (below) indicating the 7 commonly described layers of a food forest. In addition to those layers, Kitsteiner (2013) proposed to include two extra layers: a mycelial/fungal layer arguing the importance of the underground network and indicating the possibility of harvesting several mushrooms or fungi for medicinal use and an aquatic/wetland layer arguing that sometimes streams will flow through a food forest. Hence, aquatic species could be cultivated.

Figure 1: The 7 commonly described layers of a food forest. Illustration by Paul Kearsley, 2014.

Food forests are of rather recent origin in the Netherlands with the first food forest in *Swalmen* dating from 1995 (Dorp, 2020). Currently, around 48 ha of the Dutch agricultural area is covered with food forestry (Hoppenreijs *et al.*, 2019). Nonetheless, the covered area is expected to rise significantly in the 21st century, given the large interest, collaborative action and several projects with a minimum scale of 20 ha (Dorp, 2020; Hoppenreijs *et al.*, 2019; Wiebes *et al.*, 2016). Moreover, agroforestry practises, and food forests in particular, have been given envisioned a significant role in the Netherlands in 2120 as presented by Baptist *et al.* (2019).

With respect to literature on agroforestry, a lot of past research is done on tropical and subtropical regions but not so much on temperate agroforestry systems (Pardon, 2018). Despite this fact, there is a strong literature body on multiple ES regarding temperate agroforestry: *e.g.* carbon sequestration, water quality, erosion prevention, soil fertility and maintenance of biodiversity (Breidenbach *et al.*, 2017; Jose, 2012; Pavlidis & Tsihrintzis, 2018; Torralba *et al.*, 2016).

Specifically to food forests, there are three issues which need more scientific research before they can be sufficiently answered: production capacity, economic feasibility and nutrient management (Pepels, 2019). While this study does not go into depth on the economic aspects, the status of the literature with regards to productivity and nutrient management will be further highlighted below:

Edible production: Regarding the edible production of food forests in temperate climates, there is a lack of quantitative research (Björklund *et al.*, 2019; Skrøder & Henriksen, 2019). In Europe, very few studies were conducted towards the productivity of a temperate food forest (Boulestreau & Van Eck, 2016; Skrøder & Henriksen, 2019). The only previous attempt to quantify the production of a food forest in the Netherlands, was a M.Sc. thesis by Yann Boulestreau, which was co-authored by van Eck (2016). They assessed a 1 ha system based on a theoretically designed plot. Skrøder & Henriksen (2019) provided the only measured yield data from an actual food forest, the *Garden Cottage Forest* in Scotland, while mentioning also two other attempts at quantifying the calorific value of a temperate food forest (Hansen, 2015; Lavoll *et al.,* 2019).

Nutrient management: While the first explorations have been made (Pepels, 2019), more knowledge on this topic is needed, especially on soil specific effects, actual nutrient leaching rates, the ability of long term soil nutrient mining, and effects on water quality and water purity. All of these topics will be further outlined in chapter 4.5.

Given these knowledge gaps, questions begin to arise such as: what is the 'theoretical' productivity of an actual Dutch food forest and is it indeed more sustainable than conventional agricultural systems on aspects which are yet insufficiently explored? In addition, can the nutritional output of a food forest compete with conventional agricultural systems? If this is the case, it means that food forests may well be a viable alternative to conventional food production systems and this would give a strong argument for the further adoption of food forests in the Netherlands. With this in mind, the research question has been defined as follows:

How can the edible production of a temperate food forest contribute towards a sustainable Dutch food sector in 2050?

In addition, the following sub-questions were formulated:

- What is the theoretical edible production (kg) of a Dutch food forest over 2020-2050 and how does this compare to previously conducted studies?
- To what extent can such food forest fulfil the dietary requirements of people?
- How does the productivity (kg) and fulfilment of dietary requirements compare with conventional temperate agricultural systems?
- What are the environmental advantages of a temperate food forest with respect to nutrients and water quality and on-farm availability in comparison with conventional annual mono-cultivations?

In this thesis, the productivity of a 1 ha model system assumed to be representative for a food forest that maximizes edible production will be assessed between 2020 and 2050. A further extrapolation to 2067, when the species are 50 years old, will be made in order to assess the maximum theoretical productivity of a mature food forest. To avoid overly complex analyses, this research is predicated on climate and agricultural practices staying the same over the explored time frame (though it is noted that climate change will continue to have a significant impact on agriculture in the coming decennia). The model system is composed of a plot from food forest *Schijndel* in the Netherlands. Second, the nutritional values for the species will be obtained and combined with the yield results to make an estimation on the nutritional carrying capacity of a temperate food forest. Afterwards, the results will be compared with previously conducted studies on yield and nutritional produce of a food forest and several conventional food production systems in the categories *nuts*, *fruits*, *carbohydrate crops* and *meat*. In addition, the environmental characteristics regarding *nutrients* and *water quality* and *on-farm availability* of food forests will be addressed and compared with traditional annual mono-cultivations.

2. Theoretical framework

In this theoretical framework the subject of agricultural productivity will be briefly discussed, followed by a closer look at the topic of soil fertility since this is closely related to nutrient- and water characteristics and a basic understanding of soil fertility is necessary for making a comparison between a food forest and an intensively managed annual cropping system. The further environmental assessment will be treated in chapter 4.5.

2.1 Productivity

A common theory used in agronomy is the theory of limiting resources (Brooker *et al.*, 2015). In resource-poor systems there is often one limiting factor while in optimized systems this can be a combination of co-limiting resources. Common limiting factors are competition for light, water or nutrients (Brooker *et al.*, 2015).

Within an agroforestry system, there are several tree-crop interactions that have an effect on the productivity (Nelissen *et al.*, 2017). On the one hand, species compete mainly for light, water and nutrients as mentioned above (Nelissen *et al.*, 2017), while on the other hand several processes occur which have a positive effect on soil fertility and nutrient availability. Concerning soil fertility, Rao *et al.* (1998) summarizes the following improvements for agroforestry systems: On a physical level there is improved soil aggregation, porosity and pore connectivity, reduced soil bulk density and break up of hardpans/compacted soil layers. On a biological level there is build up of soil macrofauna and microbial populations, populations of vesicular arbuscular mycorrhizal fungi (VAM) and rhizobial populations and increased soil insects/reduced pests and pathogens. The next section treats basic mechanisms of soil fertility.

2.2 Basic mechanisms of soil fertility

Soil consists of particles which are either clay (<0,002mm), silt (0.002-0.05 mm) or sand (>0.05 mm) and is often a combination of those sediment types (Kettler, Doran, & Gilbert, 2001). Small clay particles hold large volumes of water. In combination with soil compaction (for example by heavy machines riding over the soil), this means that they drain slowly making these soils prone to flooding. Sandy soils with a high portion of sand particles are the opposite. They have a restricted nutrient holding capacity, high risk of nutrient leaching and lower water holding capacity. These soils are naturally prone to periods of drought (Pepels, 2019).

Plants take up nutrients via the soil solution which is the water that is hold by small soil particles. Plants can take up nutrients either by mass flow or diffusion. Plants need to take up both macro- and micro nutrients. Macronutrients like nitrogen (N), potassium (K) and phosphorus (P) are some of the most important ones needed in large quantities as they are building blocks for many proteins. Micronutrients like iron (Fe), zinc (Zn) and copper (Cu) are needed in much smaller quantities (Pepels, 2019).

Plants adopt several strategies to obtain nutrients when they are insufficiently available (Pepels, 2019):

- Root architecture change
- Rhizosphere acidification
- Mycorrhizal associations
- N-fixing bacteria associations

Root architectural changes such as lateral root growth and root hair elongation enable the plant to meet its nutrient requirements by increasing the absorptive surface area. In nutrient poor soils, root networks tend to be larger than plants grown in nutrient rich soils (Dotaniya & Meena, 2015).

Rhizosphere acidification is another mechanism to reach limiting nutrients. The rhizosphere is a vital region for the plant eco-system at <2mm from the root surface (Dotaniya & Meena, 2015). An example of this mechanism concerns Mangane (Mn) which is important for crop growth and the prevention of diseases (Dotaniya & Meena, 2015). Plants can release protons into the rhizosphere thereby lowering the pH. This increases the availability of Mn in the soil solution and thereby its availability for the plant (Dotaniya & Meena, 2015).

N-fixing bacteria associations means the association of certain plant species (especially from the *Leguminosae* family) with N-fixing bacteria (mainly from the genus *Rhizobia*) (Pepels, 2019). This is a well-known example of a symbiotic relationship between plant species and soil-borne microorganisms that feed on an abundance of the organic material mainly released by plant roots (Dotaniya & Meena, 2015; Toensmeijer, 2016, p. 25). In turn, the bacteria fixate N in the soil which is easily used by plants (Vance, 2001).

Mycorrhizal associations is another key strategy through which the plant can get access to required nutrients such as N, P, K, Cu and Zn and water (Dotaniya & Meena, 2015). The fungal hyphae are extensions of the root system that can increase the absorptive surface area and mobilize sparingly available nutrient sources by excreting chelating compounds and ectoenzymes (Marschner & Dell, 1994). Over 80% of terrestrial plants form a symbiotic relationship with mycorrhizal populations (van der Heijden, Martin, Selosse, & Sanders, 2015). There are several different mycorrhizae populations but most important are the vesicular arbuscular mycorrhizae (VAMF), ectomycorrhiza (ECM) and the ericoid mycorrhizae (EM). Studies show that in northern boreal forests up to 80% of the N is delivered by ECM (De Jong *et al.*, 2015). In nutrient poor eco-systems, up to 90% of P and N supply is provided by mycorrhizal fungi and N-fixing bacteria (van der Heijden, Bardgett, & van Straalen, 2008).

2.2.2 The soil food web

The process of capturing carbon by plants through photosynthesis and subsequent allocation of carbohydrates through the plant roots to the soil is called the *liquid carbon pathway* (Toensmeijer, 2016; 23). Plants allocate 10-20% of their carbohydrates to VAM and up to 50% to ECM and EM (van der Heijden *et al.*, 2015). Next to fungi, other micro-organisms as bacteria and protozoa thrive via the provided carbon. Faunal grazers such as nematodes will feed off the smaller organisms and are controlled by larger predators (De Jong *et al.*, 2015). Via excretions of these faunal grazers, nutrients can become available again for the plant (Pepels, 2019). When one component is out of balance, for example too much nutrients are trapped in an extensive bacterial population, this could alter the mineralisation-immobilization ratio and thus the nutrient-availability for plants potentially limiting plant growth and yield (Pepels, 2019). When considering a (food) forest, the gradual increase in the liquid carbon pathway which leads to the establishment of an extensive soil food web is accompanied by an increase in biomass production capacity during *succession* of the forest (Pepels, 2019). Hereby, it is often seen that bacteria dominant food webs are related to early stages of succession while the bacteria – fungi balance changes to fungi dominant systems towards later stages with different characteristics (De Jong et al., 2015). For example, fungal dominant systems are related with a slower nutrient cycling with fewer losses but also a lower nutrient availability although the effects of changes in these ratio are yet insufficiently understood (De Jong *et al.*, 2015).

3. Methodology

The methodology will be presented below within the categories of edible production (3.1), literature comparison of temperate food forest productivity (3.2), nutritional carrying capacity (3.3), comparison with temperate food systems (3.4) and environmental assessment (3.5).

3.1 Edible production

3.1.1 Case study

The Dutch food forest *Schijndel* in the province of *Brabant* will be analysed. The food forest is an initiative of *Stichting voedselbosbouw* in cooperation with *Groen Ontwikkelfonds Brabant*, *HAS University of Applied Sciences* and catering company *VITAM* (Blok & van Veluw, 2019). The goal of the project is to demonstrate that the professional development and exploitation of a large scale food forest can result in an economic revenue model for farmers while contributing to nature in the province of Brabant (Buiter & van Eck, 2018). The plantings started in 2019 and the forest has a total surface of 20.2 hectare distributed among 2 locations in *Schijndel*, *Boschweg* (8 plots: 4.2 ha) and *Hardekamp* (14 plots: 16 ha). In cooperation with *Stichting Voedselbosbouw*, plot *Hardekamp H2* has been chosen for this analysis since its representative plantings and surface of around 1 hectare (10850 m^2) which makes it feasible for recalculating the production into kilogram per hectare. Moreover, the species are selected on their predicted high performance within this (Dutch) food forest setting.

3.1.2 Estimating the edible production

The future edible production of the case study will be estimated for the time span of 2020-2050 with a further extrapolation to 2067 corresponding with forest year 47 when the species are 50 years old. This is the same time horizon as used in the project plan by Buiter & van Eck (2018) although the forest species are already excepted to mature in 2049Planting data on species distribution, species specific data and expert knowledge on performance of these species in a food forest system will be obtained, and two models will be created in Microsoft Excel. First, a non-specific yield model will be built in which data, non-specific to a food forest, on fruit and nut- species are used. This is done for the reason that food-forest specific yield data may be even more difficult to find than general data on the yields of those species. The adjusted yield model will be based on data related to the performance of species in a food forest by taking into account several dynamics of a food forest. This will be done in order to approach the yield development of a food forest more accurately while also showing the contrast with the non-specific model for the same species. Below is a representation of the stepwise methodology.

Step	Description
1	Determine the planting scheme for plot *H2*
2	Non-specific yield model
3	Determine what could influence non-specific yield
4	Adjusted yield model

Table 2: Approach for estimating the future yields of plot H2.

Step 1 - Planting scheme

The planting scheme consists of 3 nut species (*Castanea sativa, Juglans cinerea* and *Corylus avellana*) and 9 fruit species (*Prunus salicina x Prunus armeniaca, Pyrus pyrifolia, Cydonia oblonga, Elaeagnus umbellata, Ficus carica, Hippophae rhamnoides, Chaenomeles speciosa/japonica, Ribes x nidigrolaria* and *Ribes rubrum*). All species are assumed to be planted on January 1, 2020 and planting age of all species is 3 years old. The total number of plants on plot *H2* is 1064 (963 per ha). As can be seen in table 3, the food forest has 4 vegetation layers. In reality, there will be a variety of annuals, like onions, grown in the early years but this will not be included in the model since the annuals will not take a large part in the yields of this plot and no data on count and variety was available. See appendix A.1 for the design of plot *H2*. An overview of the species distribution is represented below:

Scientific name	English name	Layer	Intra-row spacing (m)	Planting age (y)	Number
Castanea sativa	European Chestnut	Canopy layer	8	3	25
Juglans cinerea	White walnut	Canopy layer	10	3	20
Prunus salicina x Prunus armeniaca	Pluot/aprium	Sub-canopy layer	4	3	50
Pyrus pyrifolia	Asian pear	Sub-canopy layer	4.5	3	40
Cydonia oblonga	Quince	Sub-canopy layer	4	3	5
Corylus avellana	Hazelnut	Shrub layer	3	3	100
Elaeagnus umbellate	Autumn olive	Shrub layer	2.5	3	80
Ficus carica	Fig	Shrub layer	3	3	67
Hippophae rhamnoides	Sea buckthorn	Shrub layer	3	3	67
Chaenomeles speciosa/japonica	Japanese quince	Low-shrub layer	1	3	200
Ribes x nidigrolaria	Jostaberry	Low-shrub layer	2	3	100
Ribes rubrum	Red berry	Low-shrub layer	1	3	300

Table 3: Planting characteristics for plot H2 (numbers are not scaled to 1 ha). Take notice that, for the Hippophae rhammnoides, 1/7 is a male plant and will not bear any fruits. Therefore, effectively 53 plants will be incorporated in the yield calculations regarding this species.

Step 2 – Non-specific yield model

Non-specific yield of the species means without taking into account the dynamics of a food forest and using data of the regular monocrop cultivation methods for the fruit species. With respect to the integration of the plantings in the yield calculations, the following choices were made:

- Depending on data availability, production is either following a yield pattern taken from the KWIN report (Heijerman-peppelman & Roelofs, 2010), following a yield pattern from other literature sources or following a linear yield pattern towards the maximum yield of the species.
- For the nut species *Corylus avellana,* 50 % shell weight has been assumed following Boulestreau & Van Eck (2016). This part has been omitted in the yield calculations. For the

other nut species, data represented dry edible weight and therefore no estimation had to be made on shell portion. The inedible portion of the fruit species has been considered negligible.

- Planting age has been assumed 3 years for all species.
- After the economic lifetime, production is predicted to be 75 % of the maximum production.
- When more than one source was found, the mean of the literature range was chosen.
- For several species it was not possible to find the required data such as maximum output (kg). For this species data from a related species has been used (*e.g.* data from the *Juglans regia* instead of the actual planted *Juglans cinerea*). For a further overview, refer to appendix B.1.
- Finally, the number of species in the model has been multiplied with a correction factor (*0.92*) to allow for a yield comparison per hectare instead of the actual 10.850m^2 of the plot.

An overview of the used variables is presented in table 4 below:

Scientific name	Productive from age (y)	Max economic age (y)	Starting output (kg)	Mature productivity from age (y)	Maximum output (kg)	Yield pattern
Castanea sativa	3	500	2	14	20	Linear
Juglans cinerea	4	300	1	30	18	Literature/Linear
Cydonia oblonga	1	25	2	7	16	KWIN
Prunus salicina x armeniaca	2	18	3.125	8	23	KWIN
Pyrus pyrifolia	1	25	2	7	16	KWIN
Corylus avellana	3	40	0.2	10	9	Linear
Elaeagnus umbellata	2	30	0.5	8	7.5	Linear
Ficus carica	3	30	1	7	14.3	Linear
Hippophae rhamnoides	3	30	1	7	11.5	Linear
Chaenomeles speciosa/japonica	1	25	2.6	7	11	KWIN
Ribes x nidigrolaria	1	10	0.35	5	1.1	KWIN
Ribes rubrum	1	8	1.2	4	2.7	KWIN

Table 4: Modelling details for the non-specific yield model for plot H2. See H2_yield_non-specific .xlsx for a full overview of literature sources used and for the yield evolution (overall and per species). It should be noted that for the Juglans cinerea, data from the Juglans regia is used, for the Prunus salicinia x armeniaca data from the Prunus domestica and for the Pyrus pyrifolia yield data from the Cydonia oblonga.

Step 3 Determination of factors influencing yield

After the non-specific yields have been calculated in the model, a consultation with agroforestry expert Wouter van Eck (2020) led to several adaptations of these productivity numbers. More specifically, the following general points have been considered:

- *Economic lifetime:* The concept of economic lifetime has been abandoned since the lifetime of plants and trees in a food forest is estimated to be much longer than in a conventional cultivation system such as a red berry system with an average lifetime of 8 years (Heijerman-peppelman & Roelofs, 2010). Therefore, the species will now maintain their mature productivity beyond the time scope of 30 years (plus the extrapolation when species are 50 years old) unless a factor limits their yield (van Eck, 2020).
- *Canopy species:* Additionally, the canopy and sub canopy species are assumed to have a continuous yield increase until their expected maximum growth potential in this plot has been

reached (van Eck, 2020). The year of this expected maximum growth potential has been assumed in forest year 47 for all species except for the chestnut tree. Here, the higher numbers of the literature range have been chosen regarding *Juglans regia* (37.5 kg/tree - dry weight). For the *Cydonia oblonga,* only one literature value could be found for high stem species (47.5 kg/tree) and has been applied to both *Cydonia oblonga* as *Pyrus pyrifolia.*

- *Fertility during succession:* As been explained in the previous chapter, the build up of soil organic matter (SOM) together with the establishment of an adequate soil food web will expand over time. It is hypothesized that biomass production capacity will be increasing accompanied by an increasing nutrient availability during *succession* until the system has matured and an equilibrium between SOM addition and decomposition will be achieved. Based on estimations but also as a result of this succession, the species are thought to have a slower yield increase than a normal system and this has been applied into the yield development of the species (as opposed to the non-specific yield model). Refer to appendix B.2 for further documentation.
- *Light:* The main limiting factor for species growth in northern temperate agroforestry systems is usually light (Pardon, 2018; Smith, Pearce, & Wolfe, 2013). Light was also the most important limiting factor in the model design by Boulestreau & Van Eck (2016) given adequate nutrient availability. Therefore, a yield reduction by shading is included in this model with an assumed reduction rate for the *Corylus avellana* (2022-2049: *-1 %/y*), *Ribes x nidigloria*: (2022-2049: *-3 %/y*) and *Ribus rubrum* (2022-2049: *-1 %/y)*. See also appendix B.2.
- *Pollination:* For bearing adequate yields, several species are dependent on pollinators and up to 75 % of the total species on Earth benefit at least to a certain degree from animal pollination in terms of fruits and seed set and yield (Bartomeus *et al.*, 2014). Since pollinator populations nest in cavities of trees (Taki, Yamaura, Okabe, & Maeto, 2011), the inhabiting pollinator populations are expected to increase with the succession of the food forest. However, the scale of the effect of forest succession on pollination services delivered by those populations is unclear together with specific effect it has on the yield. Hence, this model does not account for the effect of increased pollinator populations on yield given insufficient literature/empirical studies to draw information from.
- *Bird consumption:* the inhabiting bird population increases with the succession of a food forest and will consume a percentage of the yield (van Eck, 2020). This is in contrast with conventional cultivation systems where measures are in place to prevent those losses. Although, for cherry systems the KWIN does report total losses (through rain damage and bird consumption) of 10-25 %. For this project, no further efforts have been undertaken to model losses through bird consumption although they have to be kept in mind evaluating the net yield potential of different food systems.

Step 4 Adjusted yield model

The described factors have led to several adaptations for these species. Table 5 below shows the new modelling details with regards to the adjusted yield model. For an explanation of the exact adaptations, see appendix B.2.

Scientific name	Years to productivity	Starting output (kg)	Mature productivity from age (y)	Maximum output (kg)	Yield pattern
Castanea sativa	7	2.5	30	25	Linear
Juglans cinerea	5	2	50	37.5	Literature/Linear
Cydonia oblonga	3	2	50	48.5	KWIN
Prunus salicina x Prunus armeniaca	3	6	8	23	KWIN
Pyrus pyrifolia	4	2	50	48.5	KWIN
Corylus avellana	5	0.2	10	9	Linear
Elaeagnus umbellate	2	0.5	8	10	Linear
Ficus carica	4	1	12	14.3	Linear
Hippophae rhamnoides	4	1	7	11.5	Linear
Chaenomeles speciosa/japonica	3	2.6	9	6	KWIN
Ribes x nidigrolaria	1	0.35	5	1.1	KWIN
Ribes rubrum	1	1.2	4	2.7	KWIN

Table 5: Modelling details for the adjusted yield model for plot H2. See attached document H2_yield_adjusted.xlsxfor a full overview of literature sources used and for the yield evolution (overall and per species). It should be noted that for the Juglans cinerea, data from the Juglans regia is used, for the Prunus salicinia x armeniaca data from the Prunus domestica and for the Pyrus pyrifolia yield data from the Cydonia oblonga. In addition, take notice that the max economic age has been abandoned since all species have been assumed to stay maximum productive beyond the time scope of this yield estimation (when species are 50 years old) unless another factor (in this case shading) limits their yield.

3.2 Nutritional carrying capacity

After an estimation of the edible production has been made, it is useful to look at the nutritional carrying capacity (NCC). Boulestreau & Van Eck (2016) calculated the NCC per nutrient following: *Nutrient produce [kg/ha/y] / required nutrient intake per person [kg/y]* . In addition, the overall NCC was calculated using the lowest NCC per nutrient. For example, if nutrient produce of carbohydrates, proteins and fibres was enough to meet the required intakes for 3 persons but the system produced fats for 1 person, the overall NCC was defined as 1 for that year.

In this study, the nutritional carrying capacity is also defined as the number of persons whose annual recommended intakes can be met with the edible production of a system. In more detail, the development of energy-, carbohydrate-, fat-, protein- and fibre production will be quantified and divided by the annual recommended intake of an average Dutch adult. The methodology and data collection will be explained in more detail below.

3.2.1 Macronutrients and energy

For the purpose of calculating the nutritional carrying capacity, dietary requirements for energy, carbohydrates, proteins and fats were obtained from recommendations of the Health Council of the Netherlands (NL: *Gezondheidsraad*) together with nutritional contents, see appendix C. They represent the estimated average requirement of an adult (characteristics: mean of M/F, age group 31-50 years with the low average level of physical activity in the Netherlands) (Hautvast, 2001). For the category fats, the upper limit of the range (40 % of daily energy requirement) has been taken. To obtain the amount of recommended fats in grams, this amount has been divided by the energy content of fat: 9 kcal/g. For the category carbohydrates the recommended daily intake (40 % of energy requirement) was divided by 4 kcal/g to obtain the recommended amount in grams. For the category fibres the mean value of the recommendations for men and woman (35g) was taken from *Voedingscentrum* (*'Vezels | Voedingscentrum,' n.d.*). In accordance with the recommended dietary allowances of the Health Council of the Netherlands on protein, the lacto-ovo vegetarian pattern and vegan dietary pattern requirements are respectively 1.2 and 1.3 times higher than the values derived in the recommendations (Hautvast, 2001). Therefore, a correction factor of 1.3 has been applied to the recommended protein intake since the analysed food forest is a plant based system. The obtained intakes will be multiplied by an average year (365.25 days) to obtain annual recommended intakes.

Nutrient	Recommended daily intake	Unit	Source
Energy	2617	kcal	Hautvast, 2001
Carbohydrate	217	g	Hautvast, 2001
Protein	55 / 71.5 (vegan dietary pattern)	g	Hautvast, 2001
Fat	116	g	Hautvast, 2001
Fibre	35	g	*Voedingscentrum.nl, n.d.*

3.2.2 Micronutrients

After the macronutrients it is also useful to look at micronutrients such as iron and vitamins. For a limited number of micronutrients (iron, vitamin C, vitamin A) data will be gathered to see if a complete calculation is possible. For this purpose, the mean of the required micronutrient intake for adult men and women has been retrieved (Health Council of the Netherlands, 2018).

3. Literature comparison of productivity in different temperate food forests

The obtained productivity numbers will be compared with previously conducted studies that quantified the fresh weight production, dry weight production or nutritional value produce to see if the numbers are in proportion and for what reasons.

3.3.1 Fresh weight comparison

The edible production of plot *H2* resulting from the adjusted yield model will be compared with different aforementioned studies that have quantified the productivity of temperate food forests. The productivity will be compared based on the fresh edible weight. For plot *H2*, this means that the weight of the dried nuts, excluding shells, will be taken and for the fruits, the total weight including skins, pits and water content. If a study has used a different methodology, for example including the shell of the nuts or excluding inedible parts this will be mentioned.

3.3.2. Dry weight comparison

In addition, a dry weight comparison has been incorporated. For plot *H2*, this means the same value for nuts, used in the fresh weight comparison. For the fruits, the water portion will be discarded.

3.3.2. Nutritional value comparison

The nutritional values, calculated in section 4.2, will be compared with the two previous studies on this topic: the study by Boulestreau & van Eck (2016) and Skrøder & Henriksen (2019). For this comparison, the nutritional values from the studies will be divided by the average annual recommend intake for energy and macronutrients used for plot *H2* to increase the comparability. Also two studies, as mentioned by Skrøder & Henriksen, will be included that estimated the caloric yield output of a (temperate) food forest, *i.e.* a B.Sc. thesis by Hansen (2015) and a study by Lavol et al. (2019) which was noted as *'in preparation'* and does not seem to be published yet.

3.4 Comparison with temperate agricultural systems

The estimated edible production of plot *H2* over 2020-2050 will be compared with conventional agricultural food systems among four categories: fruits, nuts, carbohydrate crops and meat. For this comparison, the dry weights will be compared as well as the nutritional values described in the previous chapter. Temperate systems are included with a preference for Dutch cultivation systems if data is available. The data collection of the four categories is further discussed below.

Fruits

For the category of fruits, yield numbers from the KWIN (Heijerman-peppelman & Roelofs, 2010) are taken for *Pyrus communis 'Conference'*, *Pyrus communis 'Conference superspil'*, *Malus domestica 'Elstar'* with artificial irrigation, *Malus domestica 'Elstar'* without artificial irrigation on a drought sensitive area, *Ribes rubrum* and *Ribes uva-crispa* systems. After the end of the economic lifetime, the species are thought to be grown again on the same hectare. Thus, the production pattern from the KWIN gets iterated. For an overview of the system details, see appendix D.1.

Carbohydrate crops

For the category of carbohydrate crops, yield numbers from the KWIN *'Akkerbouw en vollegrondsteelt'* (Hendriks-goossens, 2009) were taken for potatoes (*S. tuberosum*). Furthermore, the mean value of the definitive harvest numbers from CBS over 2017, 2018 & 2019 was used for wheat cultivation in the Netherlands (*'StatLine - Akkerbouwgewassen,'* 2020). For the system details, see appendix D.2.

Nuts

For the category of nuts, yield numbers for sweet chestnuts (*Castanea sativa*) ('Tamme kastanje (Castanea sativa) in agroforestry - Agroforestry Vlaanderen,' n.d.) and cultivation numbers on hazelnut (*Corylus avellana*) in the Dutch province of *Zeeland* were used (Verdonckt *et al.*, 2016). For the system details, see appendix D.3.

Meat

For meat, average land use numbers (m^2/kg) were retrieved for beef cattle (feedlot systems) (17,5 m^2/kg) and poultry (6,5 m^2/kg) from Westhoek *et al.* (2011) and calculated into kg per ha. These numbers represent from cradle to retail. In reality, further losses from retail towards consumed meat of 20 % are assumed by Westhoek *et al.* (2011). Furthermore, a wide range existed of land use intensities of different meat systems with numbers up to 420 m^2/kg for organic beef meat from Brasil (Blonk, Kool, & Luske, 2008). For the comparison of proteins, the recommended protein intake has been used without the correction factor, see 3.2.1. For the system details, refer to appendix D.4.

3.5 Environmental assessment

Besides looking at the sheer production that comes out of a food forest, there are multiple other ES that are affected, in different ways than in traditional farming practises. Although there are many aspects which are potentially affected differently, given time limitations, the focus will be put on two major categories: nutrient management (regarding nitrogen and phosphorus) and water characteristics. The main research question which this part aims to answer is: *What are the environmental advantages of a temperate food forest with respect to nutrient management and water quality and on farm-availability in comparison with conventional annual mono-cultivations?*

In order to the answer this sub-question, a desk research will be carried out with the following structure: First, there will be an overview of the global problems given. Then, the situation in a food forest will be described and compared with conventional annual monocultures. Conventional, in this sense, means that the system is intensively managed including fertiliser treatment and possibly including tillage activities such as yearly ploughing. Lastly, evidence from literature is sought for the main identified potential advantages after which a conclusion will be given on the potential benefits of a food forest in these domains and which subjects should be redirected by future research. The structure is illustrated below:

Section	Description
Nutrients (N & P)	
1	Overview of global environmental problems.
2	Finding environmental benefits for a food forest in this domains over conventional (annual) mono-cultivations.
3	Discussing the self-sufficiency of a food forest system
Water	
4	Overview of global environmental problems.
5	Finding benefits for a food forest in this domain over conventional (annual) mono-cultivations.
General	
6	General conclusion on environmental advantages of a food forest in these domains.

Table 6: Structure of environmental assessment.

4. Results

The results will be presented below among edible production (4.1), nutritional carrying capacity (4.2), literature comparison of temperate food forest productivity (4.3), comparison with temperate food systems (4.4) and environmental assessment (4.5).

4.1 Edible Production

The results of the edible production calculations will be detailed among the non-specific yield model and the final adjusted yield model. The latter one is adopted for the further nutritional value calculations and comparisons with both previous studies as temperate conventional cultivation systems.

4.1.1 Non-specific yield model

The estimation of the non-specific yield model can be seen as an intermediate result before the final adjusted yield model. The model has the exact same species as plot *H2* but does not include the dynamics of a food forest and is based upon *e.g.* normal production patterns of fruit cultivations mainly taken from the KWIN report (Heijerman-peppelman & Roelofs, 2010). The projected edible fresh weight production increases from 1.9 t/ha in 2020 towards its maximum of 6.5 t/ha in 2034 before it gradually drops to 5.5 t/ha in 2049. The dry weight production develops from 0.37 t/ha in 2020 to 1.9 t/ha in 2049 with a maximum of 2 t/ha in 2046. Take notice of the multiple declines in production which corresponds with the end of economic age of several species after which their production decreases with an assumed 25 % in this model. As stated before, this economic age is based on the economic lifetime of the species in conventional cultivation systems after which the production of these species is expected to drop. Overall, the maximum production of the system is achieved rather early but the system does not have a prolonged high fresh weight production. In contrast, the dry weight production stays on approximately the same level after 2030 since the nut trees do show an increasing development up to a point after which they sustain their productivity in this model.

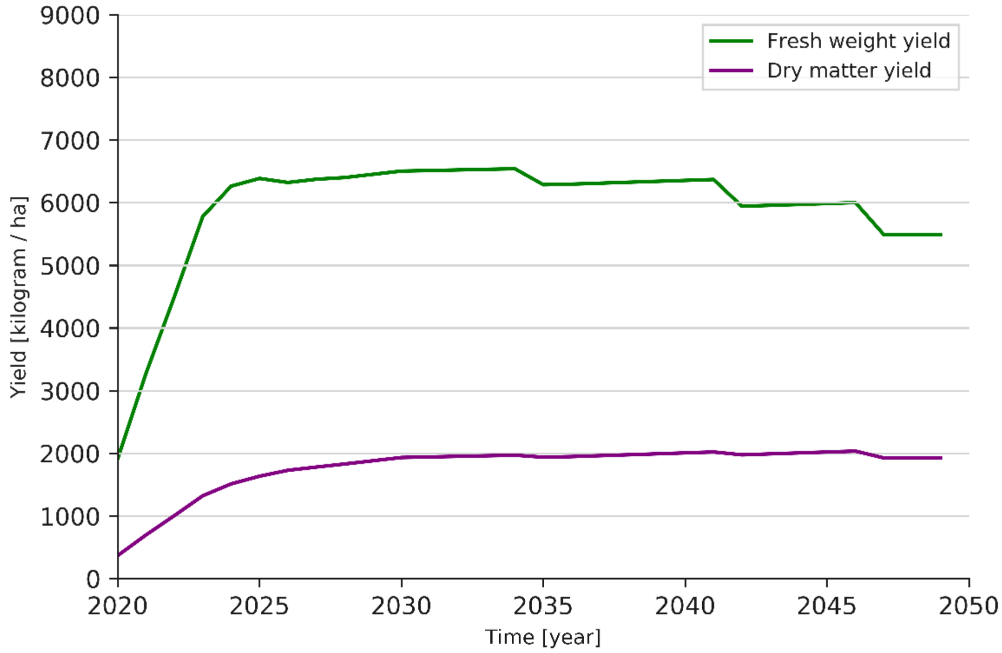

Figure 2: Non-specific yield model – Edible production on plot H2 between 2020 and 2050. Fresh edible yield is defined as the total weight of the fruits and the weight of the dried unshelled nuts.

4.1.2 Adjusted yield model

The results of the adjusted yield model show that the edible fresh weight production on plot *H2* develops from 1.6 t/ha in year 1 until 7.1 t/ha in 2049. The productivity increases at a slower pace compared to the non-specific yield model but has a 30 % higher fresh weight productivity and 19 % higher dry weight productivity in 2049.

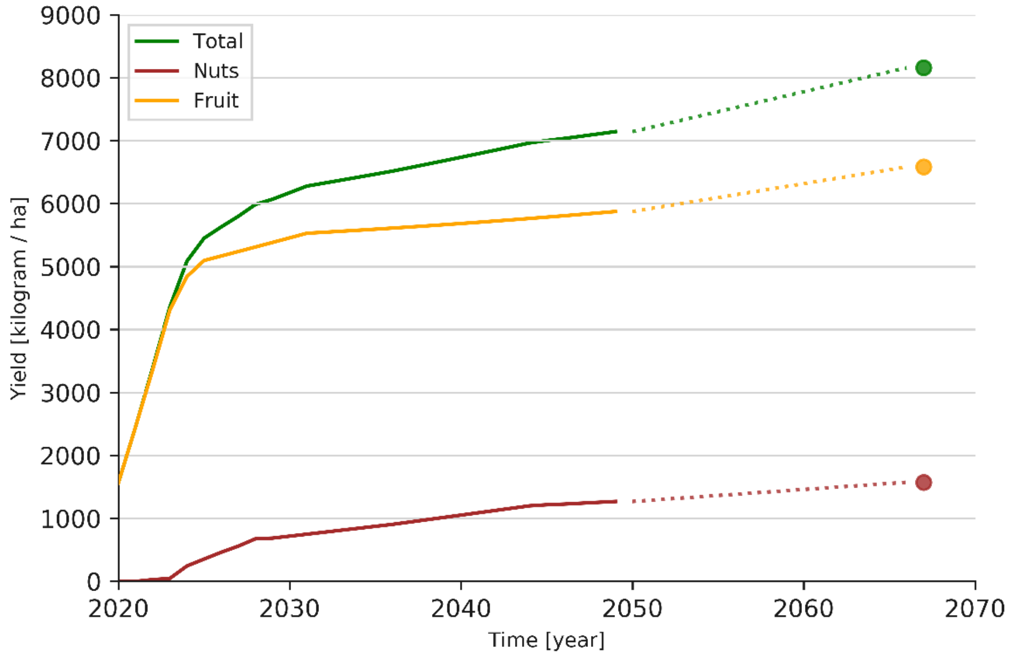

Figure 3: Adjusted yield model - Fresh edible weight production of plot H2 over 2020-2050 including an extrapolation for forest year 47 (2067) when species are 50 years old. Fresh edible yield is defined as the total weight of the fruits and the

weight of the dried unshelled nuts. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

As can be noted from figure 3, the fresh weight share of the nuts increases from 0 % in 2020 up to 17.8 % in 2049 versus 82.2 % in 2049 for fruits. The relatively minor share of nuts in the fresh weight comparison can attributed to the fact that the nuts are dried and the fruits contain a lot of water, around 85 % of their weight.

The result of the predicted dry weight production can be seen in figure 4. The dry weight production will increase from 0.25 t/ha in 2020 to 2.3 t/ha in 2049. As opposed to the fresh weight production, the share of nuts in the yield now becomes dominant from forest year 16 onwards. Take under consideration that the fresh edible weight estimation already entailed the dried nuts without shell. Therefore, the development of the nut production is the same in both graphs.

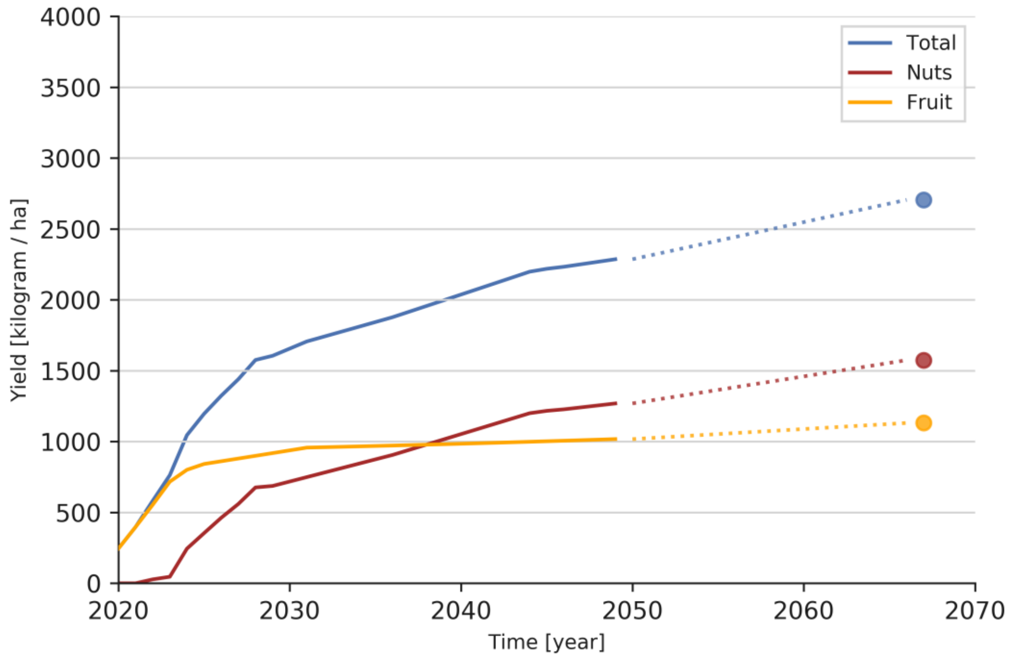

Figure 4: Food forest – Plot H2: Dry edible weight production over 2020-2050 including an extrapolation for forest year 47 (2067). Dry edible weight was defined as without the water content (and excluding shell of the nuts). Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

Both graphs include an extrapolation to year 2067 when the species in the food forest are 50 years old. This extrapolation has to be analysed carefully as it is based on the assumptions of a linear yield increase for walnut trees after forest year 30 until the mean of highest yield values from literature (Boulestreau & Van Eck, 2016; Wertheim, 1981) and an extrapolation towards the maximum yield value for the high stem pear species from literature (Radović, Nikolić, Milatović, Rakonjac, & Bakić, 2016). The extrapolated production in 2067 is included in the comparison with conventional cultivation methods as the ‘theoretical’ maximum production potential for this food forest.

4.2 Nutritional carrying capacity

4.2.2 Overall nutritional carrying capacity

The overall nutritional carrying capacity increases from 0.2 persons per ha in 2020 up to 11 persons per ha in 2049 for macronutrients and energy intake (see figure 5). Considering that the total Dutch agricultural area among grassland (910.000 ha), arable land (516.000 ha) and horticulture (9.400 ha), equals 1.425.400 ha (*Rijksoverheid, n.d.*), this means that the annual intake of 15.7 million persons could potentially be met in 2049 with regards to the macronutrients and energy intake when this areal would be converted into a food forest such as plot *H2*. This means that the limiting nutrient produce is still enough to feed this number of persons. The calculated overall nutritional carrying capacity in 2067 is 13.5 persons per ha.

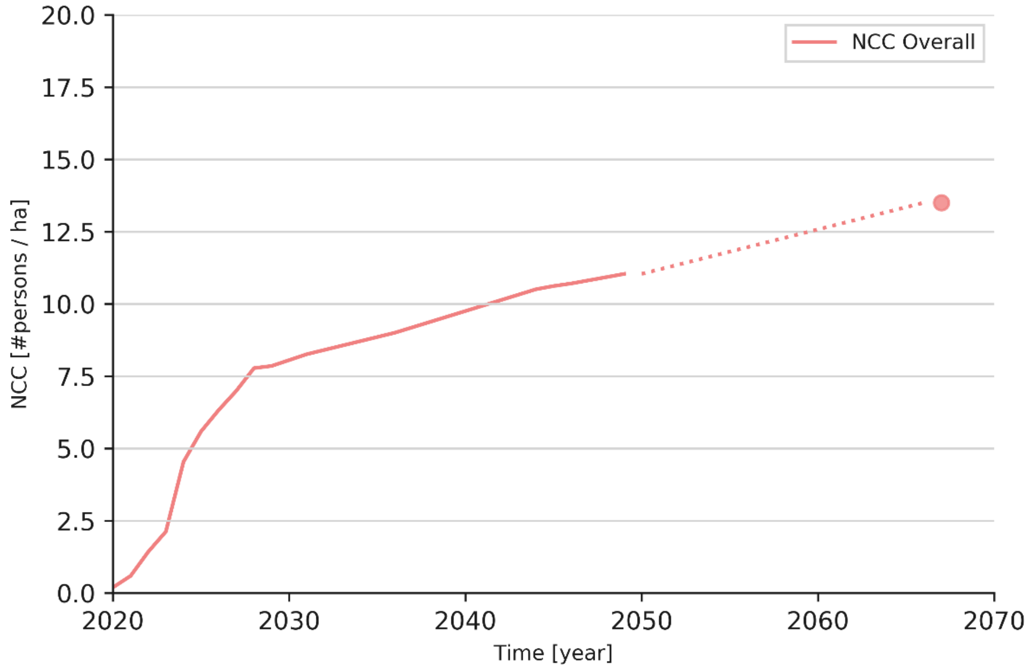

Figure 5: Overall nutritional carrying capacity on plot H2 with regards to macronutrients (carbohydrates, proteins, fats, fibres and energy intake) over 2020-2050 including an extrapolation to forest year 47 (2067).

4.2.3 Differentiation into energy and macronutrients

A closer look at the nutritional carrying capacity, illustrated in figure 6 (below), reveals that in particular the fibre production is high compared to the recommended intake (23 persons per ha in 2049). It can also be observed that the carrying capacity for fats starts slow (0 persons per ha in 2020) but does accelerate in year 4, when the *Corylus avellana* start bearing hazelnuts, and reaches 13.1 persons per ha in 2049, similarly to carbohydrates. The protein and energy supply is a bit lower: 11.6 and 11 persons per ha respectively in 2049 which makes the calorific value supply the weakest nutritional factor of the food plot although not by a great length. This can for example be explained by the fact that no real carbohydrate crops are grown in this system such as wheat or potato.

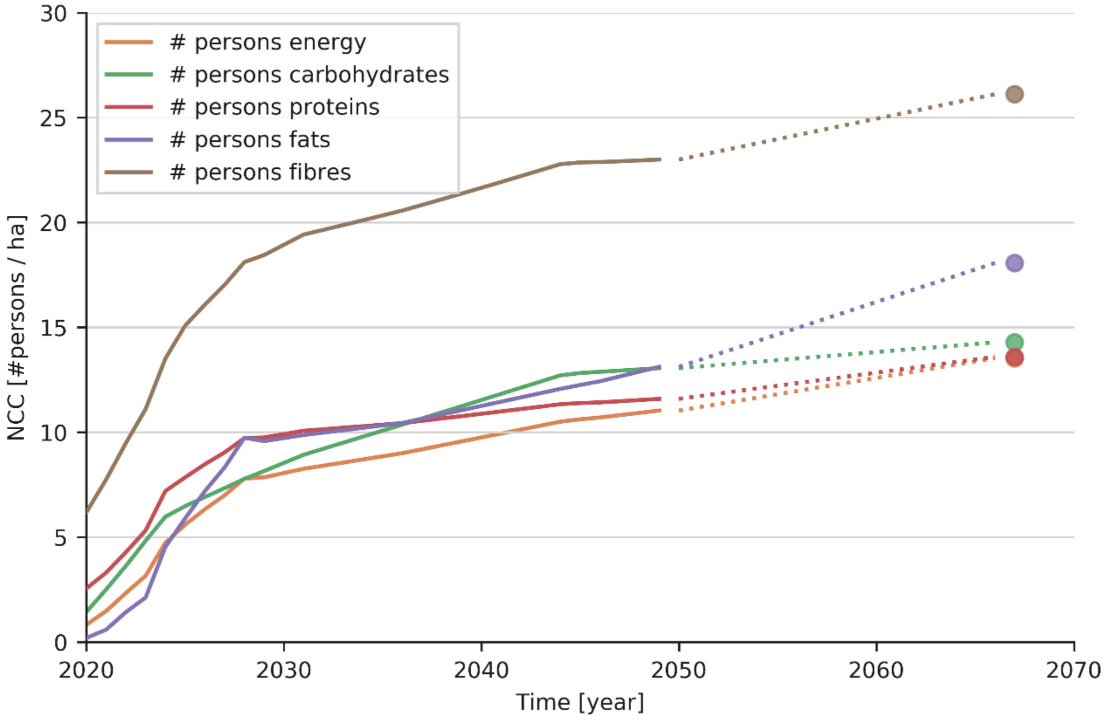

Figure 6: Plot H2 - Nutritional carrying capacity for macronutrients and energy intake from plot H2 over 2020-2050 including an extrapolation for forest year 47 (2067). See appendices E1-E6 for a further differentiation into fruits/nuts and sugars (for carbohydrates).

In 2067, the fibre- (26.1 persons per ha) and fat produce (18 persons per ha) have further increased, mainly as the quince canopy species (high in fibre) and walnut yield (high in fat) keep increasing until 2067. These NCCs are followed by carbohydrates, protein and kcal: 14.3, 13.6 and 13.5 persons per ha respectively. When again considering the Dutch arable land this means that the edible production of a food forest would now potentially be able to meet the macronutrient and energy requirements of 19.285.662 people. However, this entails the nutritional value of a single plot for a model system which may be an overestimation. This will be outlined in sections 4.3.3 (comparison with previous studies) and 5.1.5 (discussion). Moreover, losses occur, for example through consumption of a portion of the harvest by inhabiting bird populations and conservation losses similar to conventional cultivation systems (*e.g.* Heijerman-peppelman & Roelofs, 2010). The actual value of these results for the contribution to the Dutch agricultural sector will be further addressed in the discussion as well.

4.2.3 Differentiation into micronutrients

Regarding micronutrients, it was not possible to make a complete calculation since data was not readily available for *e.g.* iron (*Hippophae rhammnoides*) and vitamin A content (*Hippophae rhammnoides, Elaeagnus umbellata, Chaenomeles speciosa*) and due to time limitations. For vitamin C it was not possible to deduce which amount of vitamins gets lost during cooking of the Chaenomeles speciosa.

4.3 Literature comparison of productivity in different temperate food forests

4.3.1 Fresh weight estimations

A limited number of previous studies have measured or modelled the yield of a food forest, as mentioned in the introduction. When first comparing our results to the study by Boulestreau & van Eck (2016), it can be noted that the production pattern is largely identical with for example a 3 % lower fresh yield productivity of plot *H2* in year 14 and 5 % lower fresh yield of plot *H2* in year 21, see also figure 7 (below). This could be attributed to the fact of overlapping species, 50 % of the species on plot *H2* are present in Boulestreau's design, and that yield data on several species was obtained from Boulestreau. Likewise, in both studies the nut : fruit ratio is rather similar: 3:12 (plot *H2*) versus 3:13 (Boulestreau). However, take notice that the total number of nut species is fairly different between the studies: plot *H2* has 23 chestnut trees, 11 walnut trees and 92 hazelnut plants compared with 11, 10 and 57 respectively for Boulestreau. Therefore, the dry yield would probably be lower than on plot *H2*. Take into consideration that species age is already 3 years at the start of plot *H2* while Boulestreau's design starts with sprouts. As a consequence, the yield of plot *H2* is 3 years ahead.

The main methodological differences between the studies are replanting of species after the end of the economic lifetime (Boulestreau) and no continuous yield increase of the canopy species after year 30 (Boulestreau) compared with further growth of the walnut species and (this study). Furthermore, skins and pits are included in the fresh weight calculations of Boulestreau in contrast with the methodology of this research where fresh weight was defined as fresh edible weight and thus the shells of the nuts have been excluded. As a result, the yield estimates of Boulestreau are 7 % lower (for year 50) when corrected for this difference. It is also important to note that Boulestreau calculated a limited number of years (1, 2, 5, 10, 14, 21, 40, 50) corresponding with the first and last model year plus moments in between when certain species were replanted. This explains the drop in production in year 40 and subsequent increase towards year 50 when the newly planted species have a recurrent yield development towards their maximum.

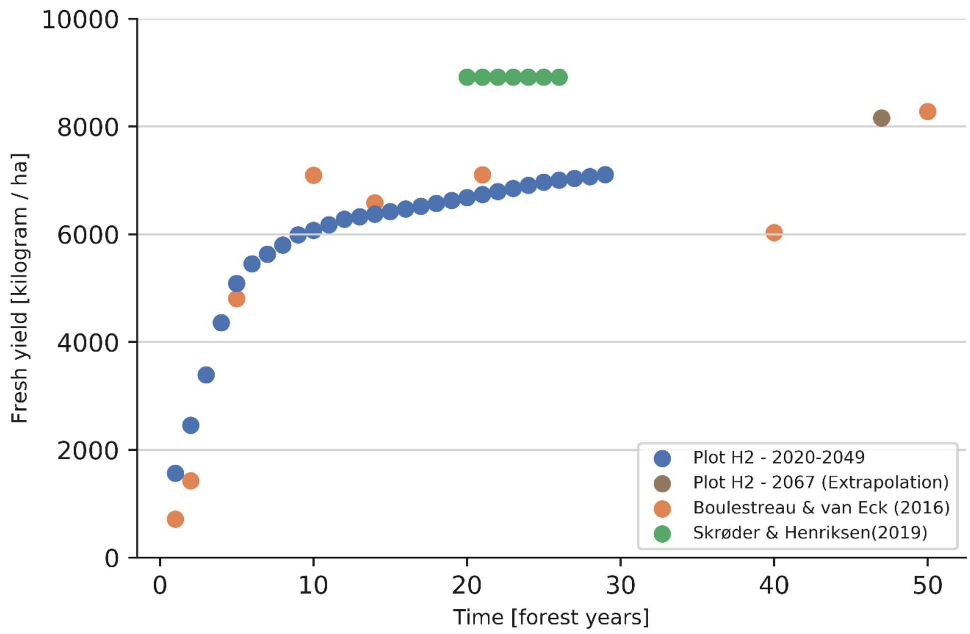

Figure 7: Fresh weight comparison - literature. Fresh weight means wet weight for Skrøder and Henriksen (2019), including shelled weight of nuts (Boulestreau & van Eck, 2016) and dried unshelled weight for nuts (plot *H2*).

Skrøder & Henriksen (2019) measured actual harvest yields over the years 2011 until 2017 corresponding with forest years 20 to 26 of the *Garden Cottage Forest* in Scotland. As can be seen, these actual yield numbers are quite promising and are the highest in the comparison. However, the fact the distribution towards a high occurrence of fruits and vegetables species may account for this while the actual nutritional supply, as shown later, will give different results. Differences include the fact the investigated food forest is a peri-urban food forest and the numbers are heavily scaled up from 0.08 ha towards 1 ha. With respect to the species this food forest is characterized by a high fresh yield share in yield of fruits (*67 %)* and vegetables (26.5 %) and a low share of nuts (*1.3 %*) compared with plot *H2* which has a larger share of nuts in 2049 (17.8 %) and subsequent 82.2 % share of fruits.

4.3.2 Dry weight estimations

Based on the available material it appears that only one previous dry weight estimation has been conducted. Ir. Wijnand Sukkel, senior agricultural researcher at *Wageningen University*, estimated a dry matter yield of 3.35 t DM/ha. His calculation was based on a 50/50 fruit/nut distribution and the average yield of a mature system. Production numbers for the fruits were taken from the KWIN. For fruits, the mean yield of apples/pears/prunes was taken and for nuts the mean of hazelnut- and walnut production. The resulting productivity is 40 % higher than the result of our case study (2.3 t DM/ha) in year 30 and 20 % higher than the extrapolated 2.7 t DM/ha in 2067 when plot *H2* is expected to mature. However, this is not a real scientific report but a rough estimation. Furthermore, since the numbers are taken from the KWIN this means that they could represent an overestimation as the values in the KWIN represent values for fertilised species. The comparison is depicted below.

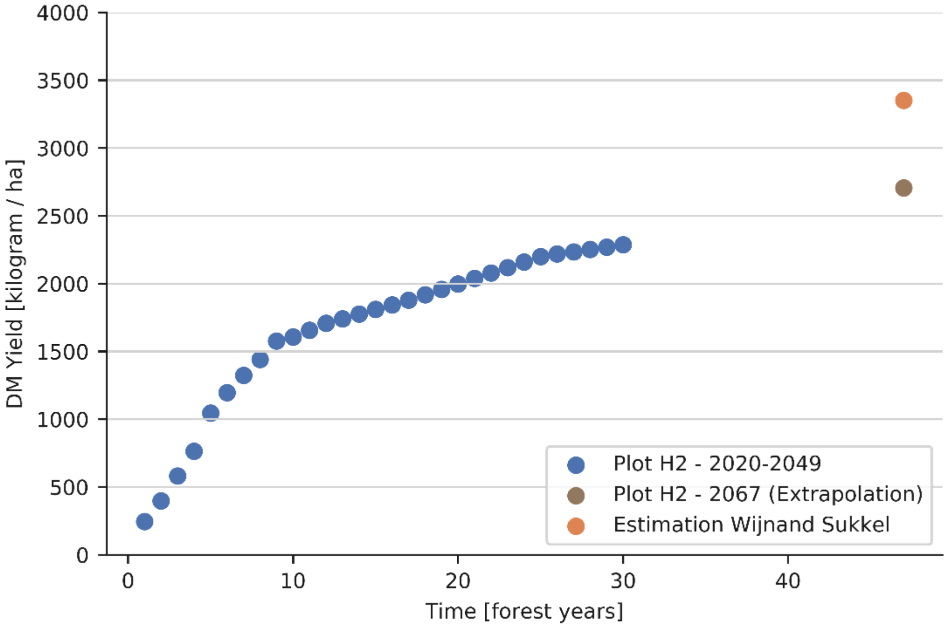

Figure 8: Dry weight estimations. Comparison of plot H2 with other estimation.

4.3.3 Nutritional carrying capacities in previous studies

Both Skrøder & Henriksen (2019) and Boulestreau & van Eck (2016) included a calculation for the nutritional carrying capacities for the respective categories shown in table 7 (below). The nutritional value produce of all studies is divided by the recommend intakes used in this study (see section 3.2.1), to increase the comparability. The year 2040 has been taken for plot *H2* as it, given species age of 3 years while planted, is theoretically most comparable with the outputs of the *Garden Cottage Forest* of Skrøder & Henriksen (2019) which is the mean of the years 20-26. Based on the same reasoning, the year 2067 is taken for the comparison with Boulestreau for year 50 in his calculations.

Category	Plot *H2* (in 2040)	Skrøder & Henriksen (years 20-26)	Plot *H2* (in 2067)	Boulestreau & van Eck (in year 50)
Energy (kcal) / NCC	9.324.554 / 9.8	5.188.432 / 5.4	12.934.106/ 13.5	6.816.653 / 7.1
Carbohydrates (g) / NCC	910.395/ 11.5	1.070.336 / 13.6	1.127.346 / 14.3	769.823 / 9.8
Proteins (g) / NCC	284.214 / 10.8	123.354 / 5	355.063 / 13.6	129.991 / 5.0
Fats (g) / NCC	476.957 / 11.2	104.929 / 2.5	765.637 / 18.1	374.096 / 8.8
Fibres (g) /NCC	276.811 / 21.7	-	333.833 / 26.1	-

Table 7: Comparison of nutritional value produce between this study, Boulestreau (year 50) and Skrøder & Henriksen (2019). Both the total nutrient produce (in kg/ha except for energy which is in kcal/ha) as the nutritional carrying capacity (NCC: in number of persons per ha) is shown. The NCCs are normalized with the intake requirements used in the case study of plot *H2* to increase the comparability. Take notice that the fibres are not assessed in the other studies.

As can be noted in the table, the estimation of plot *H2* by far outperforms both the measurements for the *Garden Cottage Forest* as Boulestreau's estimation with the only exception being the carbohydrates produce in the *Garden Cottage Forest* around year 23 which is 18 % higher than plot *H2* in 2040. This can be attributed to several reasons: For example, plot *H2* includes a variety of high yielding species. This is reflected in the balanced and relatively high output of macronutrients. As stated by Skrøder & Henriksen (2019), a more balanced species distribution in the *Garden Cottage Forest* could have led to higher outputs in terms of proteins and fats although probably losing on the carbohydrate produce. Next to this, plot *H2* might be an overly optimistic estimation where all species are reaching a high potential. In reality some species may prefer the soil of food forest *Schijndel* while other will not. This point will be further outlined in the discussion (section 5.1.5). Unfortunately, soil conditions were not described in the study by Skrøder & Henriksen. Moreover, the difference in climate between Scotland and the Netherlands might play an important role in which the same species in the Netherlands may have given different results.

When comparing to Boulestreau's estimation for year 50, first it should be noted that higher estimations on several species have been used in plot *H2*. For example, the value used for the *Juglans regia* calculation for *Schijndel* was 37.5 kg/tree in year 50. This is significantly higher than the corresponding value used by Boulestreau: 23.5 kg/tree. Secondly, the higher count of nut species gives an additional reason behind the higher nutritional value of plot *H2* in 2067 versus year 50 (Boulestreau) when the nut species are expected to approach their full yield potential. Next to this, it seems that Boulestreau took different nutritional contents for the *Castanea sativa* (around half of the nutritional values used for plot *H2*) which might be attributed to the fact that Boulestreau & van Eck (2016) assumed 25 kg/tree as the fresh instead of dry yield yield. Subsequently, the nutritional output is roughly half in relation to this study where 25 kg/tree has been taken as the dried nut weight in accordance with *agroforestryvlaanderen.be (n.d.).* When examining this difference, this amounts to 7.6 instead of 7.1 persons/ha for kilocalories (Boulestreau) and can thus be regarded as a relatively minor difference.

Also two previous studies, mentioned by Skrøder & Henriksen, assessed the food production potential of a food forest in terms of calorific value supply. The first study, a B.Sc. thesis, concluded that a food forest was able to supply between 6 and 8 persons (Hansen, 2015). The second study resulted in an estimation of 10 persons per ha (Lavoll *et al.*, 2019). The latter study assessed a model food forest designed for optimizing both food production and carbon sequestration. The supply of calories by the studies corresponds with forest years 7 and 28 of plot *H2* respectively when species are 10 and 31 years old. Further comparison between the studies by Hansen (2015) and Lavoll *et al.* was not possible as the original papers could not be retrieved. It should be highlighted that this comparison represents just one aspect of a food forest and does not provide a full overview nutritional carrying 'potential' as mentioned above. See table 8 below for an overview of the calorific value between studies.

Output / ha	Skrøder & Henriksen (years 20-26)	Boulestreau & van Eck (year 50)	Hansen (2015)	Plot *H2* (in 2040)	Lavoll *et al.* (2019)	Plot *H2* (in 2067)
Energy (NCC)	5.4	7.1	6-8	9.8	10	13.5

Table 8: Comparison of calorific value between studies in NCC (in number of persons/ha/y). Take notice, Lavoll 2019, designed a model system for optimizing food production (and carbon sequestration) and thus has a comparable aim with plot H2. Other studies did not assess systems optimized for productivity. After correcting for the methodological difference of assuming 25 kg/chestnut tree as fresh yield (Boulestreau & van Eck, 2016) instead of dry yield (plot H2), the NCC would rise from 7.1 to 7.6 in the case of Boulestreau & van Eck (2016).

4.2.4 Conclusion on literature comparison

Skrøder and Henriksen (2019) is the only study, thus far, that provides measurements from a real temperate food forest. The scaled nutritional value results of their Scottish *Cottage Garden forest*, as opposed to fresh weight production, are significantly lower than plot *H2* except for the carbohydrate supply around the compared years (when species are 23 years old). Based on previous studies regarding the nutritional value supply, that have all lower outputs than plot *H2,* it can be assumed that plot *H2* is on the higher end of the spectrum of yield estimations and results may in practise be lower. However, given the differences in climate, soil conditions, and species distributions the explanatory power of this comparison is limited and can thus be regarded as an initial range for temperate food forests with regards to productivity and nutritional value supply. In the discussion, this topic will be further outlined.

4.4 Comparison with temperate agricultural systems

There is a lot of uncertainty whether alternative production systems such as food forests will actually be able to feed us and the comparison is usually made with conventional farming systems. Within this section, an attempt was made to compare the outputs of a food forest in terms of dry weight and ability to feed persons (NCC) with conventional food systems. The results are presented below:

Fruits

The food forest is only competitive with the red berry and gooseberry systems with regards to the dry edible weight production: *I.e.* a 15 % lower and 128.5 % higher production are reached respectively for the food forest in 2049. As shown in figure 9 below, the maximum dry weight production for quince and apple systems is much higher (‘*Conference*’: 214 %, ‘*Elstar*’ with irrigation: 186 %). Take into consideration, the ‘*Elstar*’ without artificial irrigation on a drought sensitive area yields 122 % better. The difference in yield between the two *‘Elstar’* systems is without taking into account future scenarios of climate change. Therefore, it gives an indication on the effect of drought vulnerability on yield performance which may increase under progressing climate change. Section 4.5.2 provides further insight into this subject. Besides, the food forest is the only cultivation system with a continuous yield as the quince, apple and berry cultivations need to be replanted at the end of their economic lifetime. It can be seen from the graph that replanting takes a couple of years until the yields are back on their maximum level. Accordingly, the yield on plot *H2* develops much more equal instead of the fruit systems which climb fairly quick towards their peak potential but do not maintain this output for the assessed time frame.

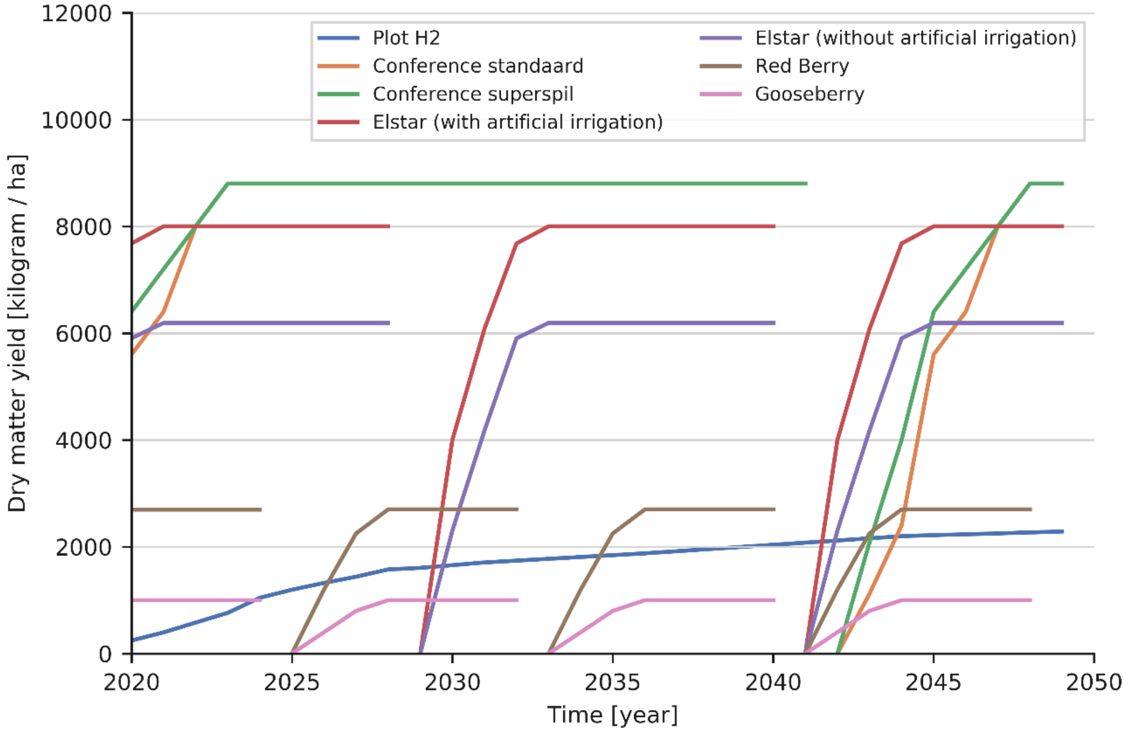

Figure 9: Fruits - Dry weight comparison over 2020-2050. Take notice that the extrapolation (2705 kg in 2067) has not been included.

More relevant in terms of nutritional value supplied by each system is to split the production in nutrients and see how many persons can be fed by the edible produce. The results are shown below:

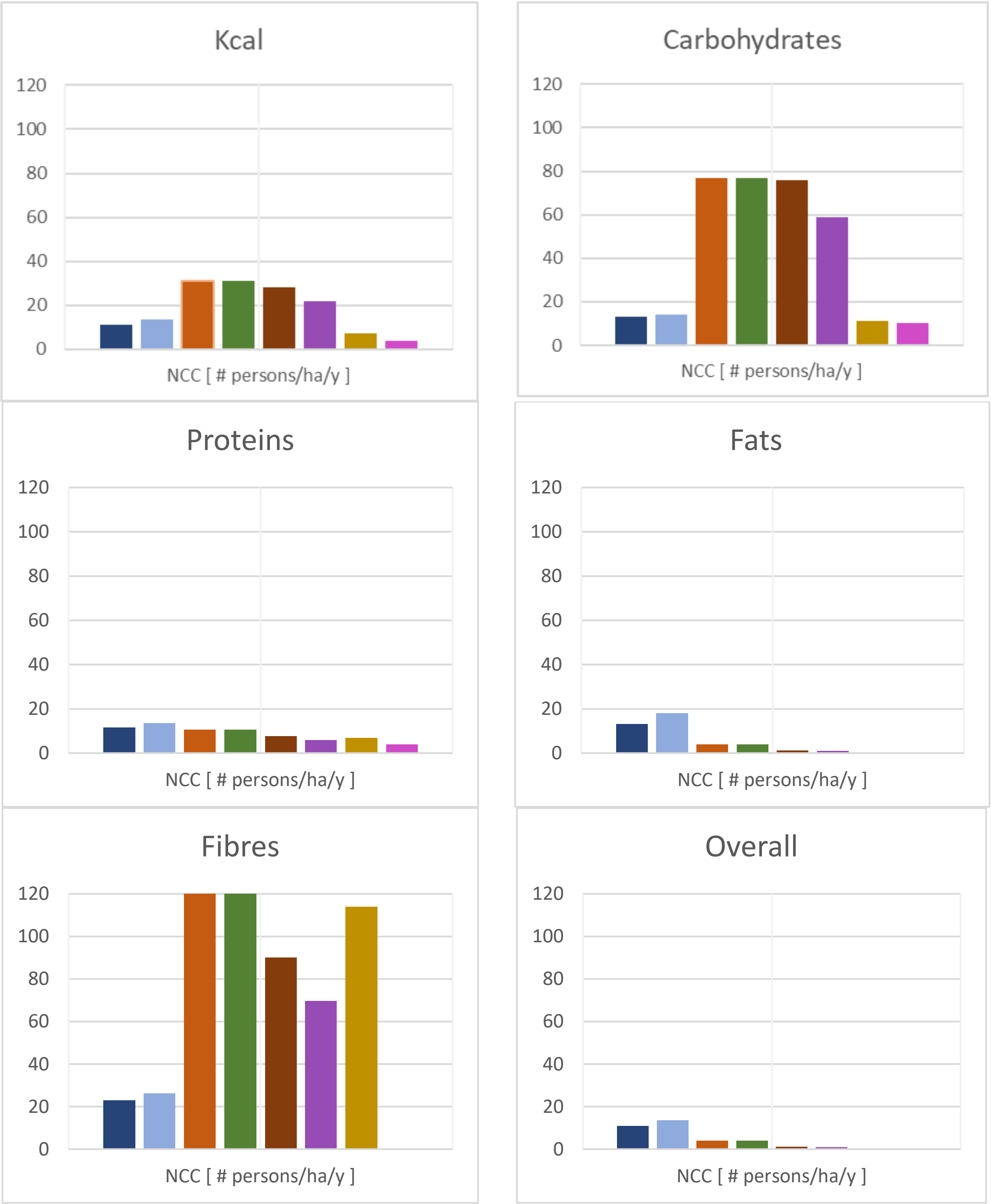

Figure 10: Nutritional carrying capacity - comparison between food forest plot H2 and (max of) fruit systems. Legenda: Dark blue: Plot H2 (2049), light blue: Plot H2 (2067), orange: Conference Standaard, Green: Conference Superspil, Brown: 'Elstar' with irrigation, Purple: 'Elstar' without irrigation on drought sensitive area, Ochre: Red berry, Pink: Gooseberry.

The food forest has the highest overall nutritional carrying capacity: 11.1 persons per ha (in 2049) versus 3.9 persons per ha for the Conference systems, 1.2 persons per ha for the *'Elstar'* with irrigation, 0.91 persons per ha for *'Elstar'* without irrigation and 0 persons per ha for the berry systems since there is no fat stored in the berries. Additionally, the food forest scores better among proteins and fats. As can be observed, the carbohydrate and fibre produce of the fruit cultivations greatly surpasses the food forest with the exception of the carbohydrate produce by the berry systems.

Carbohydrate crops

As shown in the graph below, the dry edible weight produce of plot *H2* will fall short in comparison with the yields (per ha) of potatoes and wheat. The potato and wheat production are respectively 250 % and 177 % higher than the estimated production of the food forest plot in 2067.

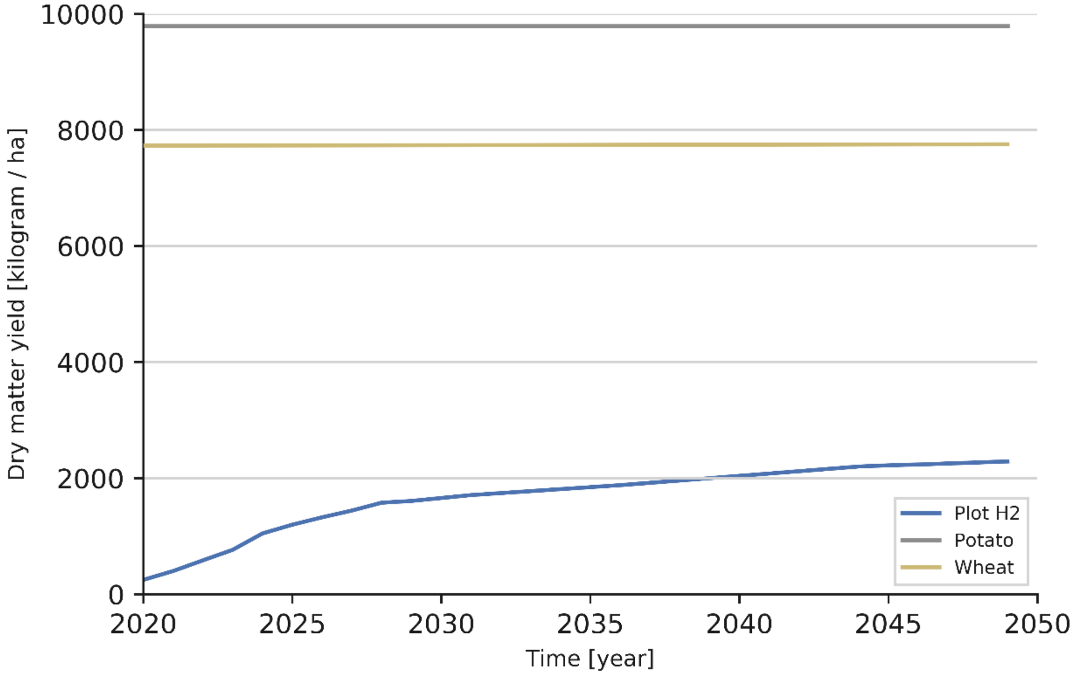

Figure 11: Dry weight comparison - Carbohydrate crops. Take notice that the extrapolation (2705 kg in 2067) has not been included.

However, when looking at the nutritional carrying capacities of the three systems, the following can be concluded:

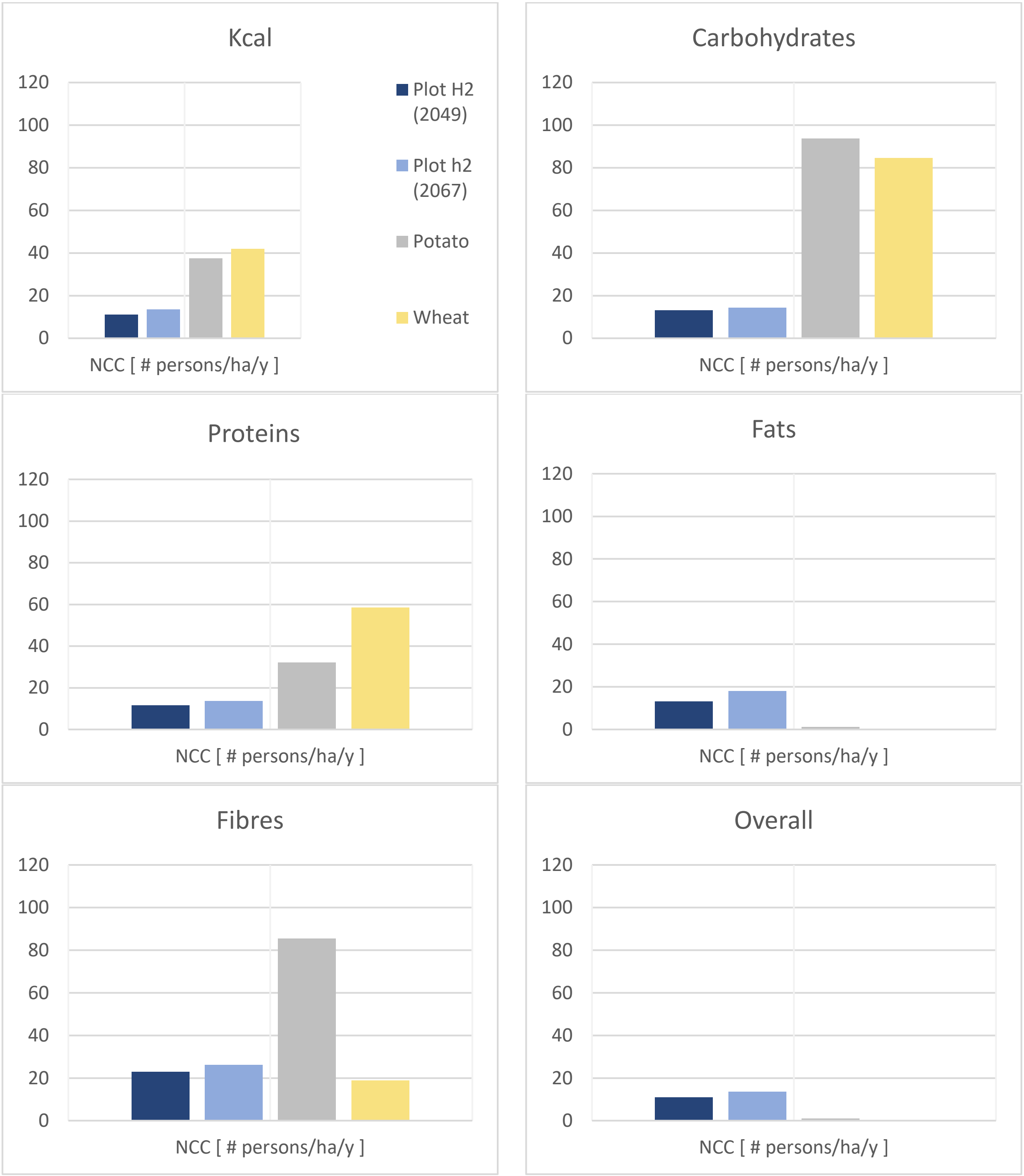

Figure 12: Nutritional carrying capacity - comparison between food forest plot H2 and carbohydrate crops.

The energy and carbohydrate produce of the potato and wheat crops is much higher than plot *H2*, 5.6 and 4.9 times for carbohydrates and 1.8 and 2.1 times for energy (kcal) respectively. As can be seen, the wheat cultivation scores high on supplied protein as well, 58.3 persons per ha. This is no surprise as wheat provides around 20 % of both energy and protein worldwide and is considered an important staple crops (Heuze, Tran, Renaudeau, Lessire, & Lebas, 2015). Take notice that the overall carbohydrate produce of wheat is much higher (6.652 kg per ha) than protein (1.551 kg per ha) but the results are normalized towards the recommended intake for humans per macronutrient. What can be observed is that both carbohydrate crops fall short in the category of fats. Concerning fibres, the potato scores very high but wheat scores less than the food forest both in 2049 as 2067. Overall, both carbohydrate crops perform low on overall nutritional carrying capacity by the limiting macronutrient fats.

Nuts

As shown in the figure below the food forest plot performs better than both chestnut and hazelnuts-orchard with respect to the dry edible weight production. From 2025 onwards the dry weight production also surpasses the hazelnut orchard. The dry weight production of the food forest plot in 2067 is 115 % higher than the chestnut production and 132 % higher than the hazelnut orchard. Take notice that for both nut orchards species age has been assumed 3 years in 2020 to allow for a comparable scenario between the food forest and the nut orchards.

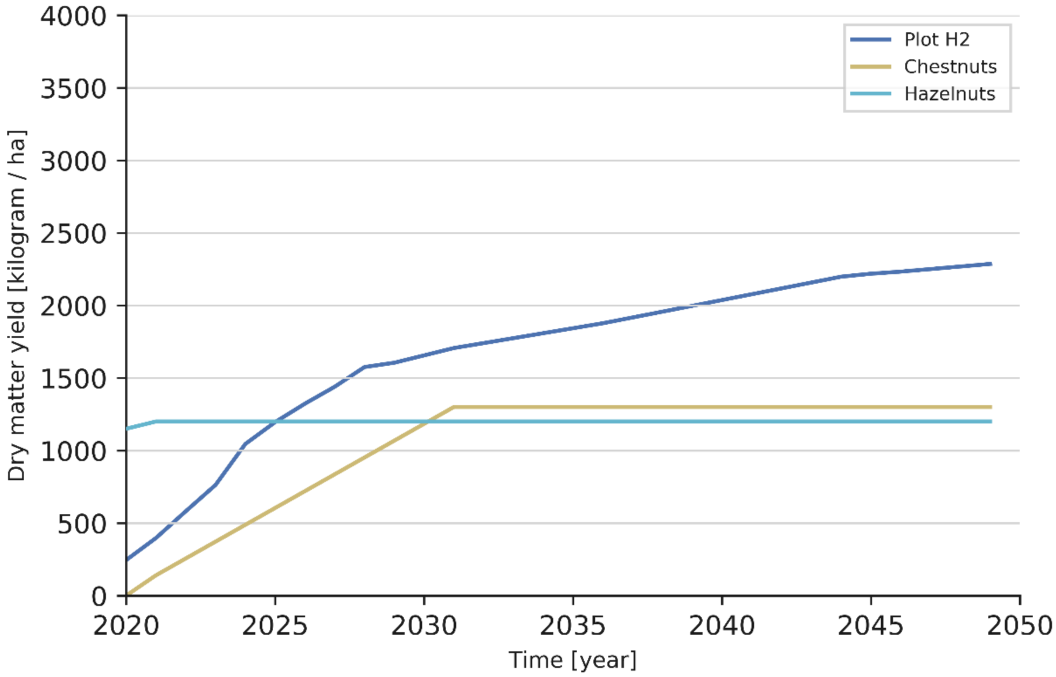

Figure 13: Dry weight comparison - Nuts. Take notice that the extrapolation to 2067 for plot H2 (2705 kg) has not been included.

The nutritional value comparison shows the following results: The nuts score significantly less on energy produce, *i.e.* both around 65 % lower than plot *H2* in 2067. The chestnuts score relatively high on carbohydrates: 11.9 persons per ha versus 13.1 persons per ha and 14.3 persons per ha for plot *H2* in 2049 and 2067 respectively. This can be attributed by the fact that sweet chestnuts are atypical nuts with a relatively high carbohydrate- (72 %) and low protein (8.2 %) and fat content (4.1 %). The hazelnut orchard has a high fat production, 17.8 persons per ha which makes it the second best performing system on fats just behind the food forest in 2067: 18.1 persons per ha. Lastly, both nut orchards score low on fibre produce.

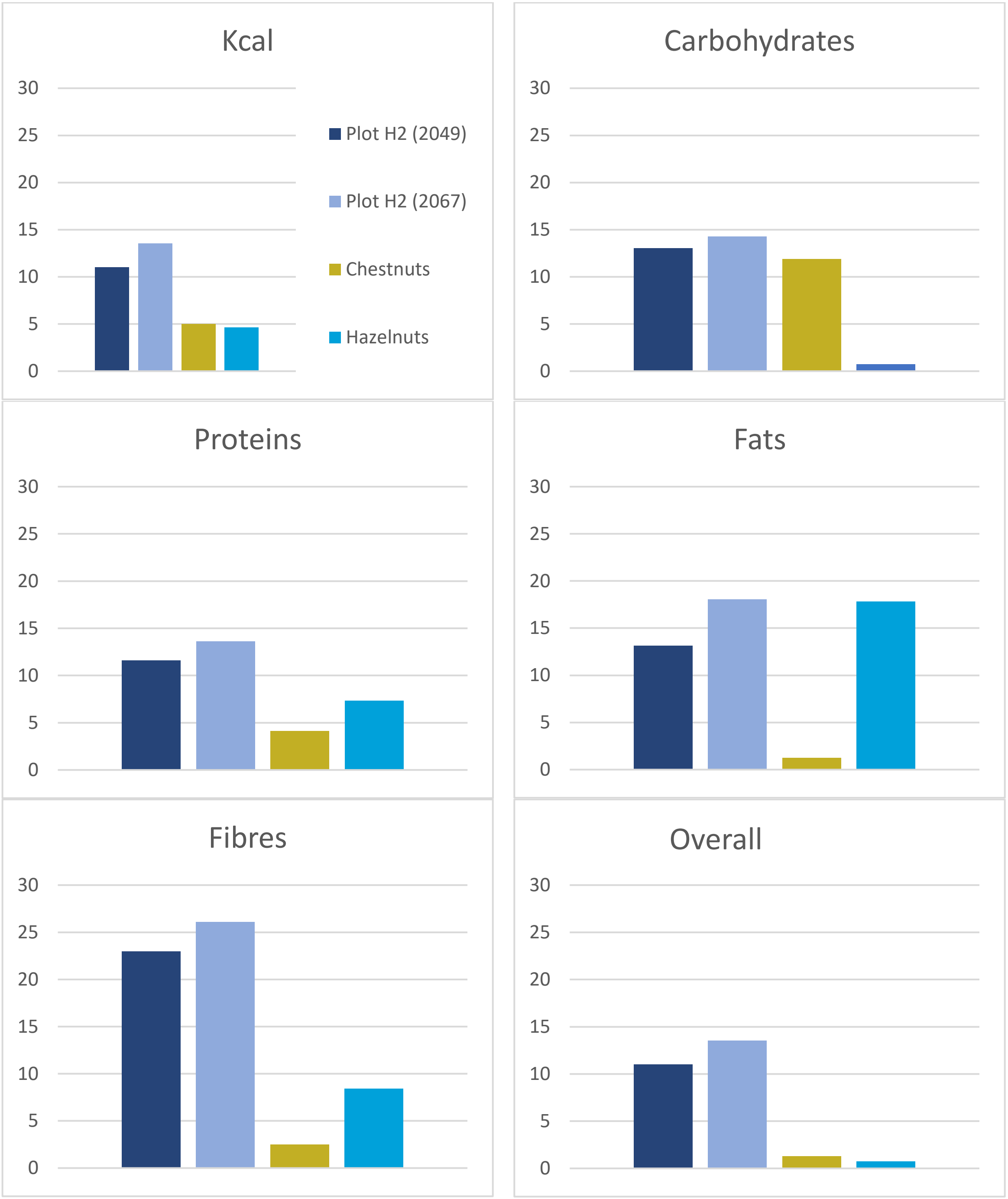

Figure 14: Nutritional carrying capacity - comparison between food forest plot H2 and nut orchards. Consider that the y-limit has been changed to 30 (instead of 120 for fruits and carbohydrate crops) to allow for a more detailed view.

Meat

As can be noticed in the graph below, the dry weight comparison between the two meat systems and the plot *H2* is favourable for the food forest from the second year onwards. The dry weight productivity per hectare is 580 % higher than poultry and even 1780% times higher than beef.

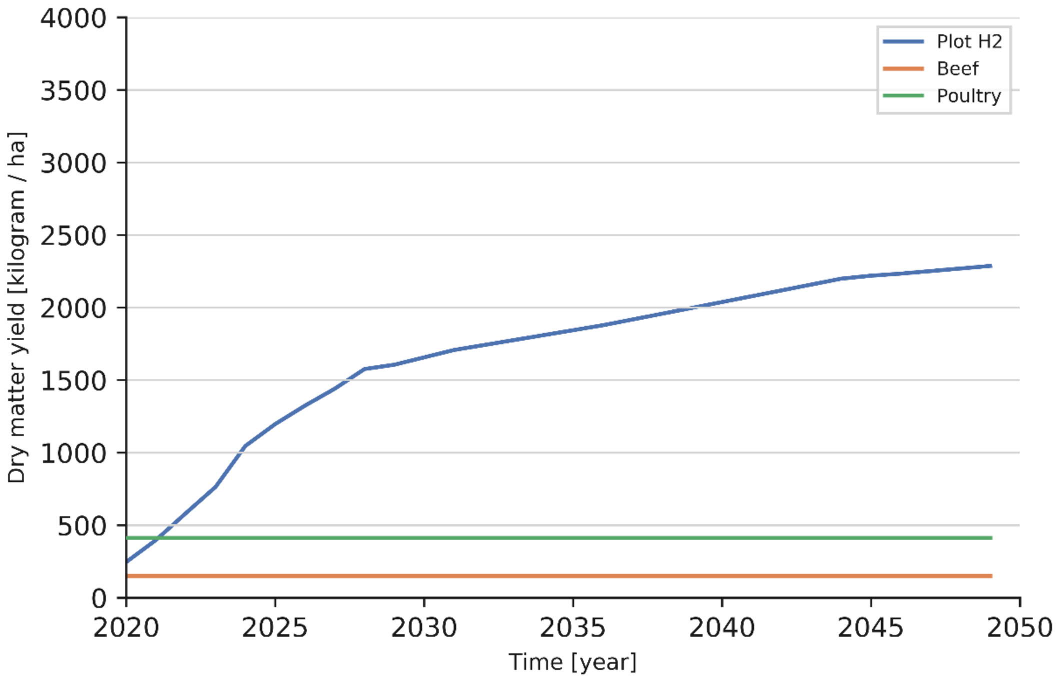

Figure 15: Dry weight comparison between food forest plot H2 and meat production systems. Take notice that the extrapolation for plot H2 to 2067 (2705 kg) has not been included.

However with respect to macronutrients the results show that especially poultry systems are still competitive with regards to protein (under the condition that a vegan dietary pattern requires 1.3 times more protein intake). The protein carrying capacity is 6 persons per ha for beef meat and 13.3 persons per ha for poultry versus the NCC – protein for the food forest in 2049 of 11.6 persons per ha and 13.6 persons per ha in 2067.

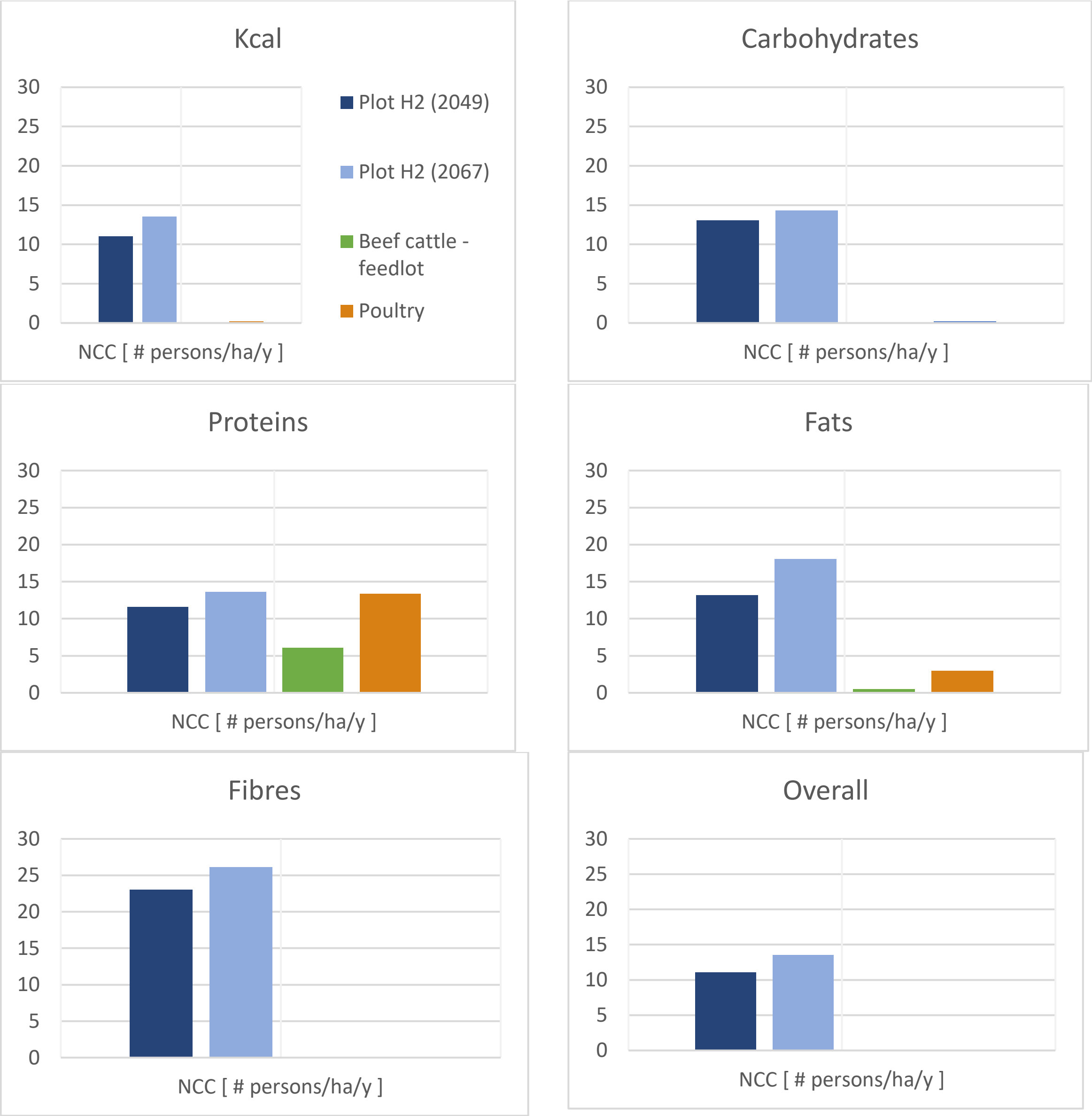

Figure 16: Nutritional carrying capacity - comparison between food forest plot H2 and (maximum of) meat systems. Consider that the y-limit has been adapted to 30 (instead of 120 for fruits and carbohydrate crops) to allow for a more detailed view.

As can be noted from figure 16, the occurrence of other nutritional carrying capacities is virtually non-existent in the meat systems with all the nutritional produce being able to feed <1 persons per ha except for fats in the poultry system (2.9 persons per ha per year).

4.4.2 Summary of results

The annual productivity can be scored as follows: Potatoes (9.8 t DM/ha), *‘Conference’* (both: 8.8 t DM/ha), *‘Elstar’* with irrigation (8.0 t DM/ha), wheat (7.8 t DM/ha), *‘Elstar’* without irrigation (6.2 t DM/ha), plot *H2* 2067 (2.7 t DM/ha), red berry (2.7 t DM/ha), plot *H2* 2049 (2.3 t DM/ha), chestnuts (1.3 t DM/ha), hazelnuts (1.2 t DM/ha), poultry (0.41 t DM/ha) and beef (0.15 t DM/ha).

When evaluating the annual NCC (in number of persons per ha), the following can be concluded: the food forest has by far the highest overall NCC, *i.e.* 11 and 13.5 for 2049 and 2067 respectively. The other systems score in this way: Conference (both: 3.9), Chestnuts (1.3), *'Elstar'* with irrig. (1.2), Potato (1), *'Elstar'* without irrig. (0.9), Hazelnuts (0.7), Wheat (0.2), Red berry (0), Gooseberry (0), Beef cattle – feedlot (0), Poultry (0). The findings do not include extra losses of systems yet (such as losses due to conservation or bird consumption). This and other points regarding this comparison will be further outlined in the discussion. The NCC results per category are summarized below. See for a complete overview appendix E.

Rank	Category									
	Carbohydrates		Proteins		Fats		Fibres		Kcal	
	System	NCC	System	NCC	System	NCC	System	NCC	System	NCC
1	Potato	93.7	Wheat	58.3	*H2* 2067	18.1	Conference	120.4	Wheat	42
2	Wheat	84.6	Potato	32.2	Hazelnut	17.9	Red berry	114	Potato	37.3
3	Conference	76.7	*H2* 2067	13.6	*H2* 2049	13.1	Elstar +	90	Conference	31
4	Elstar +	76	Poultry	13.3	Conference	3.9	Potato	85.4	Elstar +	28.3
5	Elstar -	58.3	*H2* 2049	11.6	Poultry	2.9	Elstar -	69.6	Elstar -	21.9
11	Hazelnuts	0.7	Elstar -	5.9	Wheat	0.2	Beef	0	Gooseberry	3.8
12	Poultry	0.2	Chestnuts	4.1	Red berry	0	Poultry	0	Poultry	0.2
13	Beef	0	Gooseberry	3.8	Gooseberry	0	Gooseberry	0	Beef	0.1

Table 5: Overview of NCCs per category indicating the 5 best- and 3 worst performing systems. Elstar (+) is with artificial irrigation, Elstar (-) is without irrigation – on drought sensitive area.

4.5 Environmental assessment

This environmental assessment is structured among nutrients, water and a general conclusion will be drawn on the potential advantages of a food forest system over conventional annual cropping systems.

4.5.1 Nutrients

Soil nutrient demand has greatly increased over the past century together with mineral fertiliser application and subsequent increase in global food production termed the *Green Revolution* (Foley, 2011; Jones, Cross, Withers, Deluca, *et al.*, 2013). However, major global problems have arose as a result of this agricultural nutrient use (Jones, Cross, Withers, Deluca, *et al.*, 2013). That is, the current agricultural system results in geographical nutrient imbalances. A fundamental gap exists between the nutrient in- and export on agricultural lands with the main reason of high nutrient losses through harvest that are not replenished on the same area of land. As such, the nutrients need to be artificially replenished in large quantities by fertiliser or manure applications resulting in leaky systems with high nutrient losses or it leads to nutrient depletion which poses long term soil productive failure especially in third world countries (Jones, Cross, Withers, Deluca, *et al.*, 2013; Van Der Pol & Traore, 1993). Moreover, the nutrients consumed by humans are subsequently lost to places where it is not possible anymore to efficiently retrieve those nutrients, *i.e.* long term losses of macro- and micronutrients in human excretions towards the ocean (Jones, Cross, Withers, Deluca, *et al.*, 2013).

For the problem of nutrient pollution, many policies have come into place since the 1990s (Boone & Dolman, 2010). Nonetheless, studies show that the problem of nutrient pollution in freshwater and coastal zones is ever present around the world (Glibert *et al.*, 2018) including the Netherlands (van

Galen *et al.*, 2015). The issue of nutrient depletion has been recently stated as a top priority by experts (Scherer *et al.*, 2020).

The issues of nutrient pollution and depletion will be further discussed in the paragraphs below together with other hazardous impacts related to the application of fertiliser and manure. Here, a food forest will be assessed on nitrogen (N) and phosphorus (P) as being the only nutrients that are currently included in the planetary boundary assessment for the category of biogeochemical cycles (Steffen *et al.*, 2015).

Nitrogen

Nitrogen is an essential element for high crop yields and the critical limiting nutrient for most plants due to their large role in plant growth (Vance, 2001; Vitousek *et al.*, 2009). Several large environmental problems relate to the use of nitrogen specifically. As aforementioned, the planetary boundary for the disruption of the N cycle has already been exceeded. That is, the current amount of N_2 which is annually removed from the atmosphere, N-fixation by the Haber-Bosch process being by far most significant, equals ~150 Tg N per year with the boundary set on 62-82 Tg N per year (Steffen *et al.*, 2015). As stated by Rockström *et al.* (2009), much of this removed nitrogen ends up in the environment, polluting waterways and coastal zones, accumulating in land systems and adding a number of gases to the atmosphere. This poses *e.g.* risks for aquatic eco-systems that are undergoing eutrophication with severe consequences for the health of these eco-systems (Pavlidis & Tsihrintzis, 2018). Another important issue are the N_2O emissions from manure applications to grasslands and synthetic fertiliser applications both during manufacturing and use which contribute to global warming and ozone depletion (Rockström *et al.*, 2009; Velthof & Rietra, 2018). In fact, N_2O contributes approximately 6 % radiative forcing to the total anthropogenic GHG emissions with agriculture being the most important emitter (Velthof & Rietra, 2018). Next to this, N_2O emission is currently the single most dominant cause of ozone depletion (Velthof & Rietra, 2018). The fact that the manufacturing of especially N fertiliser is an energy intensive process further contributes to global warming (Toensmeijer, 2016, p. 20). Other negative impacts from fertiliser use and manure applications include ammonia (NH_3) volatilization (Bealey *et al.*, 2016) which could be toxic and are accompanied by CO_2 emissions by the soil. Therefore, a food forest would pose advantages over traditional agricultural systems if it: (1) has a higher nitrogen use efficiency (NUE) thereby avoiding N discharge to terrestrial and aquatic eco-systems, (2) lower gaseous emissions (*e.g.* N_2O and NH_3) (3) has reduced needs for fertiliser and manure applications thereby avoiding other related ecological impacts such as described above.

Assessing a food forest system regarding N cycling

When examining the situation regarding nitrogen cycling, the following can be distinguished: the N-administration, NUE, and land management which affects the previous aspects:

In regard to the first aspect, a food forest is a natural resource management system which means that it provides its own N through *i.a.* N-fixing species (and mining from the soil stock). Therefore, a food forest lacks ecological impacts accompanied by manure and fertiliser applications (Pavlidis & Tsihrintzis, 2018). Nonetheless, ecological impacts can still arise from N_2O release resulting from biological N-fixation. Although, as explained by Pepels (2019), these N_2O emissions are considerably less in well-aerated soils such as in food forests.

Nonetheless, targeted biological N-fixation will also result in a disruption of the global N-cycle and is included in the planetary boundary assessment (Steffen *et al.*, 2015). Thus, when the amount of N that gets supplied with targeted biological fixation can be kept lower than what has to be supplied in industrial agriculture, a food forest can be regarded more favourable as well with respect to maintaining the natural N-cycle. In this light, it is necessary to assess the NUE of a food forest in comparison with conventional mono-cultivations.

With regards to the NUE, several positive influences can be attributed to the integration of trees within in a farming system. Namely, biomass decomposition of mainly leaf litter and tree roots together with plant root exudates will result in an increased soil organic matter (SOM) (Nelissen *et al.*, 2017; Toensmeijer, 2016, p. 22). As a result, biological, chemical and physical characteristics of the soil change and agroforestry systems have been found with improved aggregate forming and a more permeable soil structure (Nelissen *et al.*, 2017). The improved soil quality is also a result of increased activity of soil organisms (Rao *et al.*, 1998). With respect to the subsequent nutrient availability the following aspects are worth noting: the above mentioned decomposition of dead biomass will result in nutrients becoming available in the upper soil layers which can be reused by plants (Nelissen *et al.*, 2017). In addition, nutrients that have been moved to deeper soil layers can be taken up by deep tree roots and become available again via the leaf litter or dying tree roots (Nelissen *et al.*, 2017; Rao *et al.*, 1998). This mechanism is known as the tree root safety net (Rowe, 1999) and described by Rao *et al.* (1998) as deep soil N capture which reduces leaching and improves NUE. This is an important difference with an annual system where plant root depth is considerably less and thus the plants are not able to take up nutrients from soil layers that perennial systems such as food forests can acquire (Pepels, 2019). An extra factor explaining the reduced leaching reduced leaching rates is the fact that perennial crops use nutrients all year around while annual crops use nutrients for a limited portion of the year (Toensmeijer, 2016, p. 56). This creates a more synchronous uptake (Pepels, 2019).

Next to that, there is a difference in land management between conventional agriculture and food forestry as no tillage is done in the latter one. This means that the soil is not ploughed or treated otherwise. The reduction or elimination of tillage increases the complexity and diversity of soil life, notably the arbuscular mycorrhizal (AM) fungi as the fungal hyphae are kept intact (Toensmeijer, 2016, p. 55; van der Heijden et al., 2015). As been described before, mycorrhizae fulfil an essential role in assisting the plants with its nutrient uptake by capturing and transferring nutrients to the plant. Tillage also decreases the amount of SOM and no-till is considered effective in erosion prevention (Arshad, Schnitzer, Angers, & Ripmeester, 1990). Although, it has to be noted that the literature remains ambivalent towards the effect of no-till on N leaching with a couple of studies showing marginal positive results in the context of annual monocultures (Constantin et al., 2010; Es et al., 2020). For this studies it should be considered that the effect of using catch crops on leaching reduction was way more significant together with different soil types and rates of N application. Lastly, research on tillage in conventional systems may not be easily translated into a food forest since its inherently different design.

Two illustrative studies, as highlighted by Pepels (2019), are worth mentioning: the first study included experiments with Spanish olive tree orchards. On a number of plots annual fertiliser treatment was given. Control plots did not receive fertiliser whatsoever. After 13 years, foliar nitrogen concentration were measured. Results showed that also in the unfertilised plot, there was no nitrogen deficiency. Additionally, there was no drop in production for the unfertilised plots with a N-amount in harvest of 13.5 kg N/ha. The researchers attributed this to the fact that plant-available N must have increased in the soil. Additionally, the leaching losses were very low, 2.2 to 2.9 kg N/ha compared to leaching rates from 14.1 up to 117.4 kg N/ha for the fertilised plots. Also, the rate of the earlier described ammonia emissions were insignificant in the unfertilised plots and were already compensated by inputs from N in rainwater. Lastly, net mineralisation was decreased when fertiliser was applied and net mobilization increased. The researchers concluded that the application of N was unnecessary in fertile soils for achieving high yields and could cause damage to eco-systems (Fernández-Escobar, García-Novelo, Molina-Soria, & Parra, 2012).

Another study, assessing German forests, found that N leaching ranged between 0 and 26.5 kg N/ha/y (Borken & Matzner, 2004). The higher leaching compared with the Spanish olive orchards can be attributed to the fact that higher N deposition rates are found in North-Western Europe which can lead to surpassing a threshold (Borken & Matzner, 2004). These findings are in line with Gundersen (1991) who stated that temperate forest eco-systems are traditionally efficient in retaining their N through internal cycling and keeping losses through leaching and volatilization low but that they can become 'N-saturated' once receiving significant additional N-inputs (such as through atmospheric deposition).

Self-sufficiency of a food forest regarding N

When examining the self-sufficiency of a food forest, the N-balance should be evaluated. Pepels (2019) set up such N-balance in his exploration of the question: *'do food forests need fertiliser?'* The *considered inputs* were: Atmospheric deposition, migrating animals, rock weathering and N-fixation. The *considered outputs* were: Harvest losses, leaching, erosion and gaseous emissions. First, a chestnut system, with an annual mature yield of 2 t DM/ha (= 21 kg N/ha) was examined over different scenarios. This led to the conclusion that it takes >400 years for the model chestnut system for the N soil stock (depth: 0-2 m) to halve in the scenario of no inputs and no other outputs. Over multiple scenarios with different input- and output parameters, time was between ~400-600 years for the stocks to halve with one scenario including high inputs and high outputs, indicating a net positive balance which means accumulation of N in the soil-stock instead of depletion. Pepels (2019) did the same exercise for a high yielding hazelnut system (2 t DM/ha/y) with a significantly increased N-removal (51 kg N/ha/y). Now, it only takes ~70 years for the N-stock to halve in the scenario of no inputs and (other outputs). Average timespans over the different scenarios have been lowered to ~150 to 250 years. Here it should be noted that the used value for N deposition of 9 kg N/ha/y is considerably lower than the average N deposition in the Netherlands (Marra, 2018). Given, the high uncertainty and variability in the described in- and outputs, these explorations should be interpretated as an indication for the order of magnitude.

When applying the concept of N-balancing to our case study, the following can be noted: Annual harvest losses, using a conventional protein to nitrogen conversion factor of 0.16 (van Gelder, 1981), were between 10.7 to 48.4 kg N/ha/y from 2020 to 2049 (and thus comparable to the hazelnut system towards later years). However, when taking the average Dutch N deposition of 25 kg N/ha/y in 2020, this means that harvest N losses are compensated by N deposition alone until year 4. Additional inputs such as mineralization and biological N-fixation are responsible for rebalancing the harvest losses after year 4 plus the other losses. Given the high Dutch N deposition, an adequate number of N-fixating species and soil N-stocks in temperate forests, in range of ~2.600-26.000 kg N/ha (depth: 0-2 m) (Pepels, 2019), a food forest may well be long term self-sufficient in regard to N making application indeed not required. However, more research need to be conducted towards the effects of inputs such as N deposition on soil processes (especially related the loss routes). Moreover, yearly N harvest losses are at the higher side of the spectrum of described systems above making a food forests even more of an 'open system'. The effects of higher N-harvest losses on soil processes thus long term N plant-availability have to be studied yet.

Lastly, there are other advantages of a food forest over traditional monocultures with regards to nitrogen. For example, the planting of trees is considered a good strategy to take up ammonia from the air (Bealey *et al.*, 2016). Therefore, the trees in a food forest can be used to tackle air pollution by ammonia thereby providing air quality regulation. At large, the application of trees has been used to tackle pollution by industry, vehicles and buildings (Smith et al., 2013). However, further elaboration is beyond the scope of this thesis.

Phosphorus

Phosphorus is a fossil mineral that is nowadays mainly mined from rock deposits (Rockström *et al.*, 2009). Similarly to nitrogen, the use of phosphorus and other minerals in the form of artificial fertiliser is widespread in agriculture (Vitousek *et al.*, 2009). With respect to sustainability of the use of P the following comments can be made: First, for phosphorus the disruption of the global phosphorus cycle is also at 'high risk' of exceeding the planetary boundary (Steffen *et al.*, 2015). This entails an enormous annual transfer of P from watersheds to oceans leading to eutrophication with almost all the P of leaching to watersheds coming from fertilisers (Steffen *et al.*, 2015). Furthermore, there is the problem of freshwater eutrophication by the transfer of P to those watersheds (Carpenter & Bennett, 2011). In addition, there are indications that the global P demand will exceed the supply which poses a risk to global agricultural production (Carpenter & Bennett, 2011). As P is mined from finite rock deposits, it is projected that with the current rate of withdrawal, P deposits will run out within 50-100 years from now (Willett et al., 2019).

Both from a perspective of P discharge as well as a shortage in P supply it would thus be favourable if a food forest is: (1) more efficient with its phosphorus to avoid discharge of P to watersheds as much as possible and thus be (2) less dependent on external P input and not placing additional pressure on the P supply chain and (3) using the excess P in arable land and preventing it from leaching to groundwaters.

Assessing a food forest system regarding P cycling

When examining a food forest, no external administration of P is planned in design or in management. Therefore, the uptake rate of P from the soil stock needs to be sufficient to compensate for the annual losses by the harvest that leave the farming system. With respect to this aspect, Rao *et al.* (1998) describes that less available inorganic P forms can be transformed into readily plant-available forms in (tropical) agroforestry systems. Micro-organisms, especially mycorrhizae, fulfil an important role here as described before. However, concerning the supply of P, the soil P stock is the only significant supply of P and thus needs to be of abundant quantity. Pepels (2019) demonstrates that this is the case, with an average found soil stock of ~*13.300* kg P/ha (depth: 0-2 m) with additional mechanisms such as bedrock weathering, facilitated by mycorrhizae, which contribute to the overall accessible soil P stock (similarly to N). Moreover, specifically for the Netherlands, there is a long time positive P balance resulting from the large dairy sector (Jongeneel, Daatselaar, Leeuwen, & Silvis, 2017). This excess P has been dumped in the form of manure on arable lands across the Netherlands and therefore a high P soil stock is expected. His explorations regarding P were based on a similar balance as for N except for N-fixation and gaseous which are non-relevant for P. Based on the same model chestnut system, the annual harvest losses equalled 2.5 kg P/ha. Under a similar scenario of nu inputs and negligible outputs (other than harvest losses) his calculations led to ~*2600* years before the P stock would be halved. In one scenario, including inputs such as from migrating animal excretions or weathering a positive P balance is achieved (similarly to N). In this case P (or N) would accumulate in the soil stock and thus at least the abundance of those nutrients would not pose a sustainability issue.

Based on these explorations, it can thus be concluded that the long term sustainability of P supply might even be less of a problem then for N. However, there is a difference between stock abundance and nutrient availability for the plant. Ultimately, studies conducted on the productivity of millennia old soils have found a decreasing biomass production based on P limitation, *e.g.* as of depletion of rock-derived P (De Jong *et al.*, 2015; Pepels, 2019). Another reason were increasing fungal-bacteria ratios together with a decreasing plant-availability of P (De Jong *et al.*, 2015). Additionally, Pepels (2019) mentions the fact that an annual P removal of 2.5 kg is low in contrast to annual systems that can remove tens of kg P per ha. It can be assumed that annual P harvest losses in a food forest are considerably higher as well based on this low P removal of chestnuts (Pepels, 2019). This would alter the situation where, despite the described mechanisms for obtaining P, the question can be asked: are the natural soil web processes of a food forest able to compensate high annual P harvest losses? At some point fertilisation might be needed for (sustaining) high yields within a food forest. As of now it remains difficult to provide final answers as ample research exist.

4.5.2 Water

From all water reservoirs, only 2.5 % is freshwater next to oceans (96.5 %) and brackish water (1 %) (Steinfeld *et al.*, 2006). Furthermore, 70 % of the freshwater resources are stored in glaciers, permanent snow or the atmosphere (Steinfeld *et al.*, 2006). At the same time, the world is globally moving towards a shortage and scarcity of freshwater (Steinfeld *et al.*, 2006). Agriculture is the dominant cause in this shortage, *i.a.* by the irrigation of crops, and consumes more freshwater than any other source on earth (Ridoutt & Pfister, 2009; Steinfeld *et al.*, 2006). Thus, the amount of freshwater stays roughly the same but competition for it increases each year with agriculture being the principal cause for this increased human demand for freshwater.

Simultaneously, an increase in extreme drought events is projected in Europe (Grillakis, 2019). As a low soil moisture content is a principal issue by having direct consequences for plant growth and agricultural crop yields, farmers are increasingly forced to apply irrigation in order to avoid future yield losses or have to take other measures such as cultivation of different crop varieties (Grillakis, 2019). Therefore, it would be beneficial if a food forest: (a) has an improved on-farm storage capacity which induces resilience against droughts and flooding, (b) thus requires less water thereby putting less stress on the freshwater resources and (c) pollutes watersheds less by having a lower nutrient leaching rate.

Assessing a food forest system regarding water quality

As been discussed in the section above the leaching rates of nutrients are stated to be lower in agroforestry systems than industrial agricultural systems. This will result in less nutrient pollution of watersheds when cultivating a food forest instead traditional annual crops in a monoculture. When looking at the literature a meta-analysis carried out in 2018 by Pavlidis & Tsihrintzis concluded that tree roots in agroforestry systems could reduce nitrogen and phosphorus residues in soils by 20 to 100 %. Although, no studies regarding multi-layered food forests were included.

Assessing a food forest system regarding on-farm water characteristics

With regards to water availability the following can be derived from literature. The improved aggregate forming together with overall higher SOM content, and more permeable soil structure are accompanied by an improved water infiltration and water holding capacity (Nelissen *et al.*, 2017). Both will result in an increased on-farm availability (Toensmeijer, 2016, p. 56). Hereby, a food forest can be seen as a more sophisticated, natural alternative to mulching, *i.e.* covering the ground with organic matter for retaining moisture (Foley, 2011).

Besides, very important when assessing any perennial over annual cropping system are the deep tree roots which have been already discussed in the *nutrient* section. In fact, the nutrient uptake by those deep tree roots is facilitated through hydraulic lift. Hereby, hydraulic lift can result in an increase of water content in the upper soil layers of between 28 % and 102 % with a mean value across studies of 52 % (Sardans & Peñuelas, 2014).

Furthermore, as soil compaction is reduced, the soil is also better equipped for periods of flooding. Given these benefits, agroforestry is regarded more climate resilient than regular monocrop farming which means it is more resilient to future periods of drought and flooding (Intergovernmental Panel on Climate Change, 2014, pp. 846, 883).

Also, no external irrigation is planned within a food forest. This means that the total water input, and thus stress on freshwater availability, will be substantially lower compared with traditional arable systems. However, whether a temperate food forest can cope with this reduced water input and can sufficiently employ its benefits to avoid losses in crop yield due to water shortage is a question that has not been sufficiently addressed in academic literature.

Thus far, literature evidence in the context of Dutch food forests remains scarce and anecdotal at best. For example, Wouter van Eck reported that food forest *Ketelbroek* was preserving way more moisture than its surrounding fields during periods of drought in 2014. An initial report from *Van Hall Larenstein University of Applied Sciences* on *Ketelbroek* concluded that the water holding capacity of *Ketelbroek* may be higher compared with an acre nearby due to the larger depth of the tree roots (Siepel, Velthuis, Zondergeld, Schiemmel, & Wiesje, 2018) but no actual measurements of soil moisture content were performed yet.

4.5.3 Conclusion on nutrients and water

Concerning *nutrients,* there are multiple (expected) benefits of a food forest over conventional annual monocultures. These are : *(1)* reduced nutrient leaching, *(2)* fewer N_2O emissions, *(3)* fewer NH_3 emissions, *(4)* fewer CO_2 emissions during manufacturing of fertiliser *(5)* lower disturbance of the natural N- and P- cycle, and *(6)* tackling NH_3 pollution. These improvements are mainly facilitated through avoided fertiliser (and manure) use *(1-5),* a deep root network *(1,5)*, increased activity of soil organisms, most notably the mycorrhizae *(1,5)*, together with an increased SOM content *(1,5)*, year long nutrient uptake by perennials *(1,5),* a well aerated soil *(2),* and the tree component (*6*)*.* Several mechanisms indirectly affect *(5)* as a higher nutrient efficiency and retention could reduce the need for fertilisation such as by biological N-fixation. However, whether a food forest is able to bear optimal yields without external N or P application is a question that cannot be fully answered yet. As of now, there is a substantial body of literature regarding low leaching rates in natural (unfertilised) forests and agroforestry systems and high leaching rates in monocultures and/or intensively managed systems. However, no studies have been conducted to measure such losses for a (temperate) food forest. Therefore, it would be beneficial to study *e.g.* leaching rates in relation to arable fields with similar soil and climate conditions to allow for a valid comparison.

With respect to the *long term nutrient sustainability,* the first explorations indicate that the soil stock is of abundant quantity for sustaining yields over centuries (N) or even millennia (P) across multiple input- and output scenarios regarding in a temperate setting. Extra inputs, such as N- or P-deposition or N-fixation could prolong the timespan or even lead to a net accumulation of nutrients. Although, given the earlier described uncertainties, research should be redirected to gain an improved understanding on the effects of an ‘open forest system’ together with inputs as atmospheric deposition on soil processes regarding nutrient availability and loss routes.

Regarding *water*, many studies indicate improvements for agroforestry practises such as on-farm water availability and reduced risk to flooding making a food forest potentially more climate resilient. However, what could theoretically be a problem is competition for water between species of a food forest particularly in times of water stress. If the production can be sufficiently or fully sustained under most or even extreme weather conditions, it would give a competitive edge over traditional agricultural systems. Furthermore, the lack of external irrigation in a food forest in comparison with traditional agricultural systems places less stress on the freshwater supply thereby increasing the freshwater availability for all users. Research need to be redirected towards comparing a temperate food forests with adjacent arable fields on features such as soil moisture and yields, particularly in periods of droughts. These yield numbers can also be compared with the yield performance during droughts of conventional cultivations systems.

5. Discussion

The aim of this study was to evaluate the production potential of a temperate food forest in comparison with conventional agricultural systems, together with indicating environmental advantages over conventional monocultures in the domains of nutrient management and water. The results show very clearly that a food forest is a more balanced producing system, in terms of *macronutrients* and *energy* in comparison with conventional fruit-, nut-, carbohydrate cropping- and meat systems. Although, the estimated NCCs of plot *H2* are in general significantly higher than few previous studies on this subject and further losses have not been accounted for yet. Moreover, an explorative assessment of the environmental characteristics regarding nutrients (N, P) and water show that, in comparison with conventional monocultures, food forests may well pose advantages such as reduced leaching and gaseous emissions, a higher NUE, and may be self-sufficient for centuries (N) to millennia (P). However, regarding this self-sufficiency, there is considerable uncertainty on total stock quantity (including the bedrock layer) and even more on (long-term) potential to acquire sufficient nutrients for high yields (in particularly for P). Furthermore, several effects, such as high N deposition, on the nutrient balance are largely unaddressed in literature and can change these parameters. In addition, a food forest is less prone to drought and flooding although further research need to test for the productivity in times of water stress. Overall, these results suggest that food forests can become a worthwhile addition to the agricultural landscape but some more practical and scientific work needs to be done to support this idea. Below, I elaborate on some important remarks and limitations. Afterwards, the inclusion of agroforestry in the Dutch agricultural landscape is discussed before a final conclusion is given together with recommendations for further research.

5.1 Remarks and limitations

Regarding the used (adjusted) yield model, several notes on the accuracy can be made: First, data on yield performance was not readily available for quite a number of species. Therefore, data on related species (*e.g. Juglans regia* instead of *Juglans cinerea*) or yield numbers from other countries (*e.g.* numbers from South-Estonia for *Cydonia oblonga* or even numbers from Egypt for the *Ficus carica*) had to be used several times to complement the model or an assumption had to be made for several parameters. More accurate data on the yield of several species, especially in a food forest configuration, could significantly benefit this and future yield models. See appendix B.2 for further documentation.

Second, yield data was used regardless of fertiliser treatment which is generally non-existent in a food forest setting. This was done since no other data could be retrieved. While a food forest may provide a sufficiently fertile soil in itself to sustain a high production, species such as within the KWIN are likely to be optimally fertilised according to nutrient requirement. In addition, it is unrealistic to assume that all species will thrive under the same soil and climate conditions. Although, it can be argued that some species will have an increased/decreased affinity with the local soil and climate of *Schijndel* as compared to the underlying conditions of the used yield data. Based on the variability of those underlying conditions, it is difficult to predict the net effect of not taking this aspect into account.

Furthermore, the included dynamics of the food forest are largely grounded in expert knowledge and could not always be substantiated with studies given the premature body of literature on certain topics. Prime examples are the yield reduction rates as of shading for which no clear numbers could be retrieved from literature together with the effect of build-up of natural pollinator populations which has not been taken into account in this study.

Finally, it is worthwhile to mention that the yield estimation has been done for a single plot of food forest *Schijndel.* Other plots could give different results given different species distributions. For an overview of limitations of the adjusted yield model, see appendix F.

5.1.2 Nutritional carrying capacity

In regard to calculating the NCCs, there were several hurdles as well. Most notably, data on nutritional content was not readily available for all species. Given the (scientific) interest in food forests in the Netherlands, it would be useful to measure the nutritional content of those species and to make data open available.

In this study, the NCC has been expressed in the number of persons whose annual intakes can be met per ha and compared with the NCC of several conventional systems. What could be done in future research is comparing the edible produce to a diet such as the Lancet diet (Willett *et al.*, 2019), possibly by assessing to what extent a food forest can fulfil such dietary recommendations. An alternative is calculating the NCC over the inputs (*e.g.* irrigation or nutrients). Here, a food forest is likely to score very well given the lack of artificial inputs. Other metrices are potentially valuable as well such as the *Cumulative NCC* which would evaluate the total nutritional capacity of a food system.

When looking more qualitatively at the results, the following is worth mentioning: The carbohydrate produce can be split up in short- (sugars) and long carbohydrates (starch). The results of plot *H2* show an 51 % share of sugars in 2049 which means that almost half of the produce are long carbohydrates. Regarding plot *H2*, a large share in long carbohydrates (~40%) comes from chestnuts (*Castanea sativa*) which have a 50 % long carbohydrate content. It could be valuable to look at other species that can be grown in a food forest to diversify the species that provide a (long) carbohydrate supply. Regarding fats, it is expected that the distribution for *plot H2* is high in unsaturated fats which is considered healthy. However, no quantification has been made mainly due to time limitations and the fact that the fatty acid distribution could not be retrieved for all species.

As hypothesized before, a food forest is expected to be a diverse producing system as well for micronutrients such as vitamins and minerals (Boulestreau & Van Eck, 2016). However, in this study an analysis of the micronutrients could not be completed, mainly due to lack of data and time constraints. In addition to this point, several other health promoting properties exist, that cannot easily be put into the main macro- and micronutrient categories. For example, the sea buckthorn (*Hippophae rhammnoides)* is historically known for its therapeutical and nutraceutical properties (Fatima *et al.*, 2012).

5.1.3 Comparison with temperate agricultural systems

Regarding the comparison of conventional systems, it is worth emphasizing that the comparison does not include all categories. An important omission is the category of *vegetables*. Within this category, the inclusion of *e.g.* soy cultivation would have given additional insights to what is possible in terms of a plant based protein versus animal protein supply. Also, no other full organic farming methods were included. Regarding the included systems among *fruits, carbohydrate crops, nuts and meat*, the following notes can be made on the interpretation:

For the *fruit* systems, there was a high intra-categorial variation. In particularly, the '*Conference'* systems scored high to very high on DM yield, fibre, carbohydrates and kcal produce and the berry systems scored significantly lower in all categories than plot *H2* except for the red berry system that scored very high on fibres and the DM yield is also a bit higher compared with plot *H2* in 2049. The food forest plot scored considerably better among proteins and fats. The data on fruit yields can be considered accurate since aggregated numbers from the Dutch fruit sector were used (Heijerman-peppelman & Roelofs, 2010).

The *carbohydrate cropping* systems scored very high on kcal (both), carbohydrates (both), protein (both) and fibres (potato). For other aspects, such as fats, plot *H2* scored way better. If a food forest would score better on vitamins and minerals, this suggests that the outputs can be complementary to a carbohydrate cropping system. Data for the assessed carbohydrate crops, could be regarded reliable since the average Dutch harvest numbers on potato and wheat where used (Hendriks-goossens, 2009; *'StatLine - Akkerbouwgewassen; voorlopige en definitieve oogstraming,' 2020)*.

The *nut* systems scored very low on overall NCC. Although, the fat produce of hazelnuts is competitive and the second highest of all systems just below the extrapolation of plot H2 in 2067 and above the results for plot H2 in 2049. For the chestnut system, the fat and protein producing capacity is rather low although the carbohydrate production is on par with the food forest. Regarding the location of the hazelnut orchard, *Zeeland* was not indicated as the best production region (Verdonckt *et al.*, 2016). Therefore, numbers might be lower than the maximum potential of hazelnut cultivation in the Netherlands. Inclusion of a walnut orchard would have been interesting although no numbers on Dutch walnut cultivation could be obtained in the given time frame. Nonetheless, Pepels (2019) pointed out a study showing high yields for *Juglans regia* in France of 4.8 t DM/ha/y. This will not likely take place in the Netherlands but it shows a considerable yield variety for nut systems. Besides, the fact that no info was obtained on fertilisation status of the compared orchards is a shortcoming. As indicated by the owner of nut orchard *Bisschop*, there is a considerable lower production potential of (Dutch) nut trees when not applying fertiliser although this is within a non-agroforestry scenario. Hence, more solid estimations of the output of nut orchards in the Netherlands could help to test the conclusions of this comparison.

Regarding *meat* systems, the only significant macronutrient output is protein. Here, poultry (13.3 persons per ha) scores better than the protein supply of plot H2 in 2049 (11.6 person per ha) and slightly below the extrapolated value of 13.6 persons per ha in 2067. For beef meat, the protein carrying capacity was significantly less: 6 persons per ha. This is under the condition of a 1.3 higher required protein intake for a plant-based diet (Hautvast, 2001). Considering micronutrients, two main nutritional advantages can be attributed to meat systems: First, the iron from animal tissue is of different origin, *i.e.* containing a high amount of haem-iron, and studies show a 1.8 higher required iron intake from non-haem sources although a debate exist on this topic (Panel & Nda, 2015). Therefore, meat systems may be better equipped to provide an adequate supply of iron but this could not be tested in this research. Second, of all compared systems only meat delivers vitamin B12, a vital element for *i.a.* neural functioning and the prevention of vascular disease (Stover, 2010). However, direct supplementation to humans is shown to deliver an adequate status of vitamin B12 as well (Rizzo *et al.*, 2016). Regarding the accuracy of the comparison: The land use intensity is the only indirect value in this comparison. This can be attributed to the fact that the animal feed needs to be grown elsewhere or the animals are kept on pastures with limited or zero external food requirements. Nevertheless, the used numbers for beef-feedlot and poultry represent averages for the considered system/species (Westhoek *et al.*, 2011) and can be regarded accurate in that sense.

Nonetheless, for a full comparison among the supply chain, also the losses should be evaluated. That is, for all systems, further losses take place. For example, the KWIN does report on several conservation losses for fruit systems in ranges of ~10-25% (Heijerman-peppelman & Roelofs, 2010). Also for the meat systems, further losses from retail towards consumption are in place and assumed to be 20% (Blonk *et al.*, 2008). With regards to a food forest, losses through bird consumption are likely to occur (Pepels, 2019). Moreover, inferior quality due to disease and other abnormalities could make the products from a food forest unsuitable for *e.g.* markets where a high standardization is required. The lack of losses, both directly as well as by subpar quality, in the analysis hampers the explanatory power of this study when evaluating the net yield potential. However, accurate estimations for losses in a food forest could not be made given the time span of the study and premature literature body on this subject. Therefore, the results need to be interpreted as the gross nutritional carrying capacity of different food systems.

Important as well is the fact that a food forest is a considerably better equipped system to prevent nutrient depletion and soil erosion (Torralba *et al.*, 2016). As a result, land degradation can be prevented for a food forest and the system can be regarded more sustainable regarding this aspect. When a crop cannot be grown on the land for a couple of years, this requires additional arable land for a system to be grown on. Moreover if, with progressing land degradation, it may be not possible to grow any crop on the land for a period of time, this aspect should be considered in a yield comparison and would favour a food forest. Next to this aspect, and not explicitly mentioned within this research yet, are the improved (natural) pest and pathogen control of agroforestry systems (Torralba *et al.*, 2016). Yield losses due to pest and pathogens may thus be minimalized when comparing with other organic farming methods. However, it is unclear whether a food forest is also more effective in pest and pathogen control than the use of pesticides, common in conventional agriculture.

Furthermore, it is worth noticing that breeding as been done extensively for *e.g.* wheat (Sakamoto & Matsuoka, 2004) is expected to be less advanced for food forest species as well (Pepels, 2019). Whether the route of genetic breeding is desirable or not, considerable yield increases can be expected, especially when certain complementary traits will be reinforced between the intercropped species. This can be done both by breeding as selecting and testing for specific tree-crop combinations (Brooker *et al.*, 2015). In addition, genetic enhancements could potentially aid in *e.g.* conservation.

5.1.4 Yield estimation: realistic or overly optimistic?

When evaluating the yield performance of a food forest, it is worth summarizing the following points for the yield estimation of plot *H2* being overly optimistic: (1) A food forest receives no artificial fertiliser input and irrigation but still same yield numbers were used from those data sources, for example for berry systems. As aforementioned, it can be considered optimistic, and at least undemonstrated, that species will perform as well in a food forest as they will do in an (optimally) managed monoculture. (2) A fungal dominant system has been associated with a lower net primary production than a bacterial dominant system such as in most intensively managed agricultural systems (De Jong *et al.*, 2015). Although, it is important to mention that this claim has not been verified in a food forest context and contrasting information exist with other studies mentioning a higher nutrient availability and overall soil fertility. (3) A number of sources were used with data from other climates, such as from Egypt for the *Ficus carica.* (4) The yields of the *Corylus avellana* might be lower in practise as well. (5) The nutritional value results are significantly higher compared with previous studies although the fresh yields are comparable; (6) The planting distance could be suboptimal in plot *H2* for yield results. Hence, plot *H2* may perform less in practise than these yield estimations, either by a slower succession of the forest or one of the other limiting factors described above.

5.1.5 Environmental assessment

The environmental assessment shows multiple potential improvements of a food forest in the domains of *nutrient management* and *water* although more research is needed to substantiate these advantages with evidence. Regarding future research, it is important to analyse aspects such as local climate and soil conditions (Kettler *et al.*, 2001). This means that a food forest on a sandy soil can perform worse than a food forest on a different location with a more clay rich soil or even an (unfertilised) monoculture on such clay rich soil. Other inputs which could steer past the threshold of (significant) leaching are N deposition for which the values in the Netherlands are currently very high and are projected to remain high until at least 2030 despite measures (Marra, 2018). Within this thesis (section 4.5.1), a brief calculation was included showing that N deposition alone was enough to compensate for the N harvest losses for the first 4 years of plot *H2*. Although, further work needs to be done to improve the N-balance based on an enhanced understanding of the effects of N deposition on the N-balance and soil processes in a food forest context.

Next to major macronutrients such as *N* and *P*, there are other mineral nutrients, important for crop growth, which get depleted by the current agriculture (Jones, Cross, Withers, DeLuca, *et al.*, 2013). Of these depleted nutrients belong micronutrients such as selenium (Se) which pose risks to the adequate nutritional supply in both developed as developing countries (Jones, Cross, Withers, Deluca, *et al.*, 2013; Rayman, 2000). It is worthwhile to redirect attention both to other macronutrients as well as to the issue of micronutrient depletion, possibly in the context of food forests.

5.2 The inclusion of agroforestry practises in the Dutch agricultural landscape

Evaluating the future role of agroforestry practises, in particularly food forests, in the Dutch agricultural landscape, a competitive yield performance should be demonstrated. Competitive, in this sense, means through achieving a high (net) edible yield, quantitatively and/or by growing high quality products (such as valuable herbs), or by considering other goods of a food forest (such as timber) including low losses such as by inferior quality or bird consumption. Below, I consider the future role of agroforestry for two scenarios in which food forests either have a competitive yield performance (5.2.1) or a non-competitive yield performance (5.2.2).

5.2.1 Competitive yield performance

When assuming a competitive yield performance, the overall economic feasibility is the next critical objective. First, the production costs need to be kept low for a good business case. In this light, the following can be stated: While *cost savings* can be achieved due to avoidance of tillage, fertiliser-, herbicide- and pesticide use, an important drawback could be the *high labour demand* related to activities such as weeding and harvesting of products in a food forest (Brooker *et al.*, 2015). Besides, *mechanisation* is considerably more difficult to develop for these systems given the small spatial scales and complex configurations in which machinery has to operate (Brooker *et al.*, 2015). In this light, it can be stated that a design such as for plot *H2* would pose fewer constraints then a less structured food forest and/or with higher species varieties (each with different patterns of harvesting and conservation). Considering a local food supply, a possible solution can be realised through offering subscriptions by which citizens pay for accessing the harvests throughout the year as well as experiencing a food forest. However, for other supply chains (*e.g.* high volume delivery to a supermarket or for the export) a low labour demand is crucial for competitive pricing. This is in line with a report from *HAS University of Applied Sciences* after the economic feasibility concluding that is necessary for a profitable business case to ask premium prices in a short supply chain (van Namen & Willems, 2019). Next to no-profitable scenario in the 'global market', it is also uncertain how markets would respond to an increase in food forest products (Doomen, van Leeuwen, & Pluhe, 2019). Among reasons for not starting a food forest were the fact that the development of a food forest is 'knowledge-intensive' together with a long return on investment for which growing annuals, as been done on plot *H2,* is indicated as a partial solution (Doomen et al., 2019; van Namen & Willems, 2019).

Next to a strong business case, several policies and legal adjustments could foster the spreading of food forests over the Netherlands, as described in the *GreenDeal Voedselbossen* (Wiebes *et al.*, 2016). For example, an exemption on the obligation for replanting for a food forest would give food forest owners more freedom to operate. Also, the fact that there is a strong legal division between nature and agricultural area in the Netherlands can be considered a burden (Selin Norén, 2019). For instance, nature area has a 2.5 to 3 times lower value than agricultural land which can make it unattractive to start a food forest. It is possible to ask for a compensation although strict regulations apply with regards to *e.g.* species distributions (Selin Norén, 2019). Apart classifications for a food forest, as being the bridge between nature and agricultural land, with flexible regulations could erase constraints.

5.2.2 Non-competitive yield performance

Evaluating a scenario in which the edible yield of a food forest is non-competitive, it does not mean that a food forest is unvaluable, in contrast to annual monocultures that offer little value outside food production. Nonetheless, it becomes more important to reckon other ES of a food forest. For example, Baptist *et al.* (2019) chose an important role for agroforestry, in their vision of the Netherlands in 2120, with food forests located around cities offering localised production together with recreation, biodiversity, carbon sequestration and a way to combat heat stress from the cities.

A broader perspective is adopted as well by Kay *et al.* (2019), who distinguishes between marketable eco-system (ES) services (*e.g.* biomass production) and non-marketable services (*e.g.* carbon sequestration) provided by agroforestry systems. The aim of the study was to evaluate the profits of an agroforestry systems when including the non-marketable ES in the market system and putting penalties on dis-services (*e.g.* soil nutrient loss). The studied *services* and used monetary value entailed: Biomass production (0.43-802.6 €/t, depending on crop and country), groundwater recharge (0-4 €/m^3, depending on country) and carbon storage (5 €/t C). The *dis-services* entailed: Nutrient loss (- 4 €/kg N), soil loss (-6.41 €/t) and pollination deficits (0.43-802.6 €/t, depending on crop and country). Afterwards, it was shown that a land use change towards agroforestry would be economically favourable for several Continental and Atlantic regions in Europe when the monetized ES would be incorporated in the market. Interestingly, by embodying a monetary value on *e.g.* carbon sequestration, this would lead to an increase in economic performance of both agroforestry as well as non-agroforestry systems. Kay *et al.* (2019) stated that the chances of actually including non-marketable ES into funding for farmers become higher nowadays. For example, the financial support as part of the current CAP includes an increasing emphasis on environmental performance (pillar II cross compliance) (Kay *et al.*, 2019). In addition, addressing climate change is likely to further link agricultural policy to environmental performance in the next funding period (post 2020) (Kay *et al.*, 2019). Resulting from the strong ES delivery of a food forest, expanding the marketable ES would thus greatly benefit future revenue models and decrease the dependence on edible yield production.

5.2.3 Technological or ecological route

Finally, it can be questioned what kind of direction the food sector should take towards sustainable transformation. In contrast to the route of ecological intensification, the route of technological advancement could also be a possible direction. That is, highly technological innovations such as lab cultured meat are approaching the market soon and totally change *e.g.* land use equations (Bryant, 2020). A combination of routes is potentially viable in which food forests can offer a diverse landscape, increased biodiversity, balanced and (probably) durable production, and other improvements such as reduced nutrient pollution. Agroforestry can thus fulfil a role amidst (environmentally) improved cropping systems and innovative technologies that provide a high supply of specific nutrients such as fats (*e.g.* food forest), proteins (*e.g.* lab cultured meat or improved nut systems) and carbohydrates (*e.g.* wheat cultivation). As mentioned by Toensmeijer (2016), there are several gradations of land management in agroforestry systems. Technological advancements and land management could thus be integrated with food forests such as growing genetically enhanced species, defending yields by animal protective equipment, and developing specialized machinery solutions that would improve the (cost-) and labour efficiency of food forest farming.

6. Conclusion

This study aimed to answer the research question: *How can the edible production of a temperate food forest contribute towards a sustainable Dutch food sector in 2050?*

To this end, research has been divided into two parts in which a focal study plot of food forest *Schijndel* has been analysed on yield and nutritional value provision in comparison with conventional temperate cultivation systems together with an explorative assessment of environmental advantages in the domains of nutrient management (N,P) and water.

The yield results showed a slow but steady yield increase with a balanced nutritional supply in terms of nutritional carrying capacity (NCC) for kcal (11.0 persons/ha), carbohydrates (13.1 persons/ha), proteins (11.6 persons/ha), fats (13.1 persons/ha) and fibres (23.0 persons/ha). Fresh weight- and dry weight yields were 7.2 t/ha and 2.3 t/ha respectively in 2049. The comparison with conventional cultivation systems, in the categories of fruits, carbohydrate crops, meat and nuts, revealed that the study plot had the highest overall NCC. Furthermore, the study plot scored high for fats, modest for proteins and was not competitive with the best performing systems among carbohydrates, fibres and kcal produce. It is hypothesized that a food forest has a high micronutrient provision as well, although this could not be substantiated in this study. The nutritional value results were significantly higher than previous studies on this subject while the comparison with previous studies showed comparable fresh yields. The main limitations included the fact that yield data representing other countries had to be used on several occasions, assumptions had to be made for several parameters, together with assumptions for yield decline rates as of shading due to a premature literature body. Besides, the analysis did not account for losses for all systems making the comparison between conventional systems a gross yield comparison.

The explorative assessment regarding nutrient management (N, P) and water indicated that multiple environmental benefits can be expected in comparison with heavily managed monocultures, most notably fewer nutrient leaching, long term self-sufficiency (in range of centuries for N and millennia for P), and improved on-farm water cycling making a food forest less prone to drought and flooding. Although, effects such as high annual nutrient removal and high N deposition such as in the Netherlands on the dynamics of a food forest are yet insufficiently understood. Further research is needed to improve the understanding of the dynamics a food forest as well as actual measurements of nutrient leaching and soil moisture content (in particular during periods of drought).

Overall, through offering more balanced, continuous and (probably) durable yields, and enhanced environmental ES delivery, these results suggest that food forests can become a worthwhile addition to the Dutch agricultural landscape although more practical research is needed to support this idea. Most notably, yield estimations made by this and other models need to be verified, together with a further economic assessment for which this study can provide a basis. This research can contribute to the scientific basis on the quantification of yields and nutritional value provision for temperate food forests, and to a lesser extent to the understanding of environmental aspects as well as interpreting the role of a food forests in the Dutch food supply by providing the first nutritional comparison between a food forest and conventional cultivation systems. See chapter 7 for the full recommendations.

7. Recommendations

The recommendations based on this study are presented below among research (productivity and environmental performance) and policy:

Research - Productivity:

- Measure actual harvest numbers on *plot H2* or other study plots and compare these yield measurements to validate this and/or other yield models.
- Invest in tracking the yields of food forests in general.
- When evaluating the yields of a food system, choose a metric such as the NCC which can normalize the outputs of a system instead of just looking at the (fresh) edible yields.
- Analyse different plots/species distributions to obtain more insight in NCC potentials.
- In addition to the previous point, other metrics than just the NCC could be used such as the *Cumulative NCC*: $\Sigma NCC(i)$ with (i) being the assessed nutrient category to gain insight into the total production potential of a system; *Nutrient use efficiency:* Output [kg] / Nutrient input (i or Σi) [kg] with (i) being the assessed nutrient or *Cost efficiency*: Output [kg] / Costs [€].
- Estimate losses due to bird consumption or due to inferior quality (when considering channels where standardized product are required, *e.g.* selling products to supermarkets).
- Include micronutrient provision (vitamins and minerals) in future nutritional analyses.
- Take contextual factors such as soil properties, local climate and spacing into account when comparing yields between systems.
- Study the effects of fungal dominant systems on yields in particularly regarding a food forest context), most notably in comparison with bacteria dominant systems.
- Take the effects of climate change into account in future comparisons between systems.

Research - Environmental characteristics:

- Conduct experiments on water availability under different climate conditions (*e.g.* periods of drought) and compare this to equivalent arable fields.
- Conduct research to measure losses such as leaching within Dutch food forests and compare these numbers with equivalent arable fields.
- More research should be done into the long term sustainability of food forests, in particular in the category of nutrient mining, as a food forest is an open (perennial) system but has several efficiency- and loss preventing mechanisms such as described in this thesis.
- Pay attention to other nutrients including the issue of micronutrient depletion in order to gain a deeper understanding on loss mechanisms as has been established for N and P.

Policy:

- Remove governmental and legal barriers for applying agroforestry and food forestry in particular such as constraining landscape norms.
- Steer towards a compensation based on environmental ES delivery of (agricultural) systems including ES such as carbon sequestration or recreation and apply penalties on dis-services.

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Appendices

Appendix A. Design of plot H2

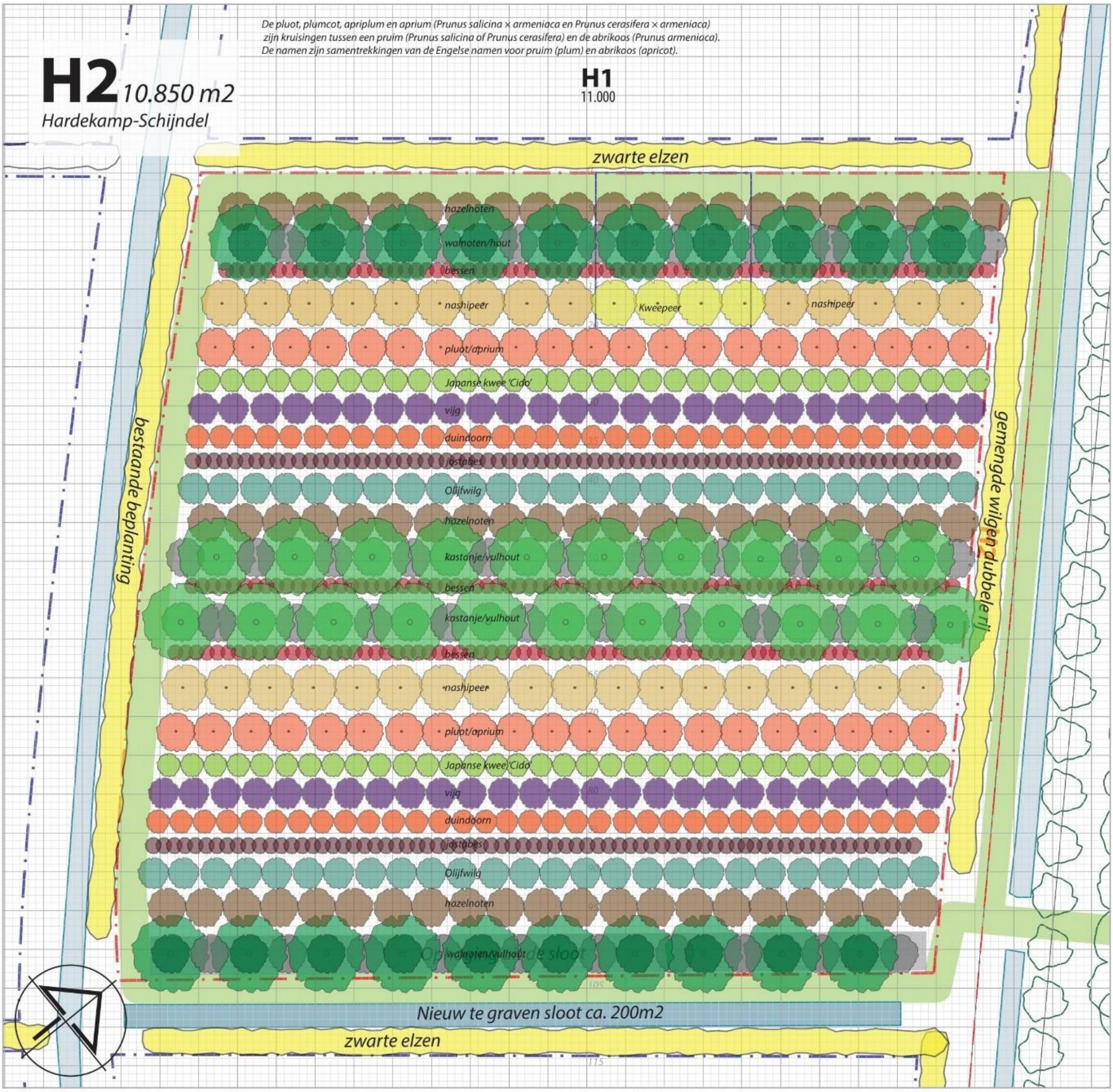

Figure A.1: Design of H2. Take notice that for several species, a different number was finally planted. The definitive numbers have been included in table 3.

Appendix B. Data collection and choices for yield models

B.1 Non-specific yield model

Scientific name	English name	Data collection and modelling choices
Castanea sativa	European chestnut	The middle of the literature range (20 kg/tree) has been chosen as mature productivity after 14 years (Boulestreau & Van Eck, 2016; *'Tamme kastanje (Castanea sativa)* in agroforestry - *Agroforestry Vlaanderen*,' n.d.).
Juglans cinerea	White walnut	Data of the related *Juglans regia* (Boulestreau, 2016; *Agroforestry Vlaanderen*, n.d.) has been used. For, the white walnut, characterized as a relatively fast growing species (Burns & Honkalasell, 1990; van Eck, 2020) the short end of the years to productivity (4 years) is assumed.
Cydonia Oblonga	Quince	Production numbers from a mid-range performing quince species (*'Doyenne du Comice'*, system: 2500 low stem branches per ha) have been taken from the KWIN. After economic lifetime of 25 years for a quince planting, the species are assumed to loose 25 % of max productivity.
Prunus salicina x Prunus armeniaca	Pluot/aprium	For the hybrid species *Prunus salicina x Prunus armeniaca,* data of the European plum (*Prunus domestica*) from the KWIN has been used as of data availability. The mean yield of the two systems (St-Julien A, system: 830 trees per ha 4x3m and St.-Julien B, system: 1250 trees per ha 4x2m) has been taken from the KWIN. After the economic lifetime of 18 years the species are assumed to have lost 25% of their maximum productivity.
Pyrus pyrifolia	Asian pear	Similar to the *Cydonia oblonga*, production numbers from a mid-range performing quince species (*'Doyenne du Comice'*, system: 2.500 low stem branches per ha) have been taken from the KWIN. After the economic lifetime of 25 years for a pear cultivation, the quince species are assumed to have lost 25 % of their maximum productivity.
Corylus avellana	Hazelnut	Estimation from Boulestreau & Van Eck (2016) of 9 kg/tree.
Elaegnus umbellata	Autumn olive	The middle of the literature range has been chosen as maximum productivity. After the economic lifetime of 30 years, the species are thought to have lost 25% of their maximum productivity.
Ficus carica	Fig	The maximum yield number 14.3 kg/plant from Abo-El-Ez, Mostafa, & Badawy (2013) has been used together with estimations on years to productivity taken from Boulestreau & Van Eck (2016).
Hippophae rhamnoides	Sea buckthorn	For the sea buckthorn, 1 in every 7 species has been assumed to be a male plant and will therefore not bear any fruits. This has been applied in the adjusted model The maximum yield number 11.5 kg/plant from Jalakas, Kelt, & Karp, (2003) has been taken.
Chaenomeles speciosa	Japanese quince	For this species, the time till maximum output from the KWIN has been used (7 years, system: 'Conference' superspil, 5000 plants per ha, planting distance: 2,80x0,71 m). The maximum yield has been used from (Rumpunen, 2002) thereby given a more tailored yield towards this plant but with the dynamics of a cultivar bred in a conventional fruit system.
Ribes x nidigrolaria	Jostaberry	This is a hybrid species between a black berry, gooseberry and Worchester berry. Here, the mean productivity numbers from the black berry and gooseberry were taken from the KWIN
Ribes rubrum	Red berry	Information on productivity from the KWIN has been used.

Table B.2: Data collection and modelling choices for non-specific yield model.

B.2 Adjusted yield model

Scientific name	English name	Description of modelling choices
Castanea sativa	European chestnut	Prolonged time until first harvest (7 years). Also, the maximum productivity of the literature range (25 kg/tree – dry weight without shell) has now been taken since chestnuts have an assumed high performance in a food forest (Boulestreau & Van Eck, 2016) and perform generally well (expert knowledge from the owner of Dutch nut orchard *Bisschop*. The max productivity is now assumed to get reached by year 30 as the canopy species within a food forest are slow starters (van Eck, 2020).
Juglans cinerea	White walnut	Prolonged time until first harvest (6 years). As pointed out by van Eck (2020), canopy species have a continuous growth in a food forest until at least 50 years if given enough space. Therefore, the productivity is assumed to continue with a growth rate of 1.95 kg/y after forest year 27.
Cydonia Oblonga	Quince	In this food forest plot high-stem quince cultivars are planted in contrast to normal cultivation systems with a high density of low-stem branches. Therefore, the growth dynamics are different. Similar to the canopy species, the high stem quince cultivars are expected to start slowly and grow continuously beyond the timespan of 30 years. As a result, a linear yield increase has been assumed from age 4 (2 kg/tree) until maximum productivity of 48.5 kg/tree in forest year 47 (Radović *et al.*, 2016).
Prunus salicina x Prunus armeniaca	Pluot/aprium	This species has been assumed to maintain its maximum output. No further adjustments have been made compared with the non-specific yield model.
Pyrus pyrifolia	Asian pear	Similar to the *Cydonia oblonga*, production numbers from a mid-range performing quince species (*'Doyenne du Comice'*, system: 2500 low stem branches per ha) have been taken from the KWIN. After the technical lifetime of 25 years for a pear cultivation, the quince species are assumed to have lost 25 % of their maximum productivity.
Corylus avellana	Hazelnut	The *Corylus avellana* is shade tolerant, however for a high fruit productivity, light is a requirement (Hampson, Azarenko, & Potter, 1996). Therefore, a gradual yield decline of -1 %/y of the normal production potential has been assumed from 2027-2049 when the chestnut trees start producing. Furthermore, the hazelnut has been characterized by van Eck (2020) to start bearing fruits later. Therefore 5 years until first harvest has now been assumed instead of the initial 3 years.
Elaegnus umbellata	Autumn olive	In consultation with Wouter van Eck (2020) the autumn olive production has been assumed to take longer before the maximum has been achieved and can produce more than the initial literature value. Therefore the maximum yield is increased from 7.5 kg/plant in year 8 to 10 kg/plant in year 15.
Ficus carica	Fig	In consultation with Wouter van Eck (2020) the yield has been assumed to stay the same after the maximum production has been reached. In addition, as can be seen on the plot design (Appendix A.1) there is probably no issue with shade as the fig will be planted in between the sea buckthorn and the Japanese quince. Therefore, from forest year 8 onwards the yield is calculated at 14.3 kg/plant.
Hippophae rhamnoides	Sea buckthorn	The species has been assumed to maintain its maximum productivity.

Chaenomeles speciosa	Japanese quince	For the *Chaenomeles speciosa*, the 'high but realistic' number of 6 kg/tree from Rumpunen (2002) has been used. Rumpunen (2002) also hinted at a breeding cultivar which reached 8-10 kg/plant (more in line with the productivity from the KWIN for low stem-cultivars). Furthermore, no end of economic age has been assumed in line with earlier species and therefore the maximum yield continued in the model. Also, the plant has been assumed to start bearing fruits in forest year 4 in consultation with Wouter van Eck (2020).
Ribes x nidigrolaria	Jostaberry	The *Ribes x nidigrolaria* grows amidst higher species and is therefore expected to lose the competition for light. A yield reduction of 1 %/y of the normal production potential has been assumed assumed from forest year 2023 until 2049.
Ribes rubrum	Red berry	The *Ribes rubrum* is planted under the canopy species. Therefore, a high limitations in yield is expected when the canopy species are growing over time. Hence, a reduction of yield 3 %/y of the normal production potential has been assumed from 2025 when the chestnut trees start producing until 2049.

Table B.2: Modelling choices for adjusted yield model.

Appendix C. Used nutritional contents

Scientific name	Edible portion	Water portion	Kcal (/kg)	Carbohydrates (portion)	Proteins (portion)	Fats (portion)	Fibres (portion)	Sources
Castanea sativa	0,8	0	3686	0,72	0,082	0,041	0,13	FoodData Central (‘European chestnuts, dried including 9 g water’)
Juglans cinerea (data from *Juglans regia)*	0,5	0	6540	0,051	0,16	0,68	0,067	Voedingscentrum.nl (‘Walnut’)
Cydonia oblonga	1	0,84	570	0,15	0,004	0,001	0,028	FoodData Central (‘Quinces, raw’)
Prunus salicina x Prunus armeniaca (data from prunus domestica)	1	0,845	560	0,12	0,07	0,002	0,007	(Elzebroek & Wind, 2008), voedingswaardetabel.nl (‘Prum, fresh’)
Pyrus pyrifolia	1	0,84	540	0,11	0,005	0,003	0,028	Voedingscentrum.nl (‘Pear’)
Corylus avellana	0,5	0	6670	0,05	0,16	0,63	0,09	Voedingscentrum.nl
Elaeagnus umbellata	1	0,714	908	0,136	0,04	0,023	0,059	Khanzadi (2012), Parmar & Kaushal (1982)
Ficus carica (Kadota)	1	0,823	640	0,13	0,014	0,002	0,021	Voedingscentrum.nl
Hippophae rhamnoides	1	0,8	1030	0,074	0,014	0,071	0,008	*Houtwal.be* (‘Sea buckthorn’)
Chaenomeles speciosa/japonica	1	0,88	570	0,03	0,0025	0,008	0,039	Watychowicz *et al.* (2017), kcal (quince)
Ribes x nidigrolaria	1	0,9	360	0,08	0,01	0	0	Voedingswaardetabel.nl (‘gooseberry’)
Ribes rubrum	1	0,85	380	0,048	0,01	0	0,081	Voedingswaardetabel.nl (‘red berry’)
Triticum (dry matter)	1	0	4346	0,723	0,165	0,01	0,03	Heuze *et al.* (2015), Boulestreau & van Eck (2016) (fats)
S. Tuberosum	1	0,767	850	0,176	0,02	0,001	0,026	Voedingswaardetabel.nl (‘potato, raw’)
Malus domestica ‘Elstar’	1	0,84	540	0,12	0,004	0,001	0,023	Voedingscentrum,nl (‘apple’)
Ribes crispa uva	1	0,9	360	0,08	0,01	0	0	Voedingswaardetabel.nl (‘gooseberry’)
Bos taurus	1	0,738	119	0,002	0,212	0,036	0	FoodData Central (‘beef for manufacturing imported from New Zealand)
Gallus gallus domesticus	1	0,732	143	0,0004	0,1744	0,081	0	FoodData Central (‘chicken, ground, raw’)

Table D.1: Used nutritional values for species.

Appendix D. Compared agricultural systems

D.1 Fruit systems

Scientific name species	System name	System details	Sources
Pyrus communis 'Conference'	Conference standard	2500 plants per ha (3,25x1,25m), economic lifetime is 25 years, the Netherlands	(Heijerman-peppelman & Roelofs, 2010)
Pyrus communis 'Conference'	Conference superspil	5000 plants per ha (2,80x0,71 m), economic lifetime is 25 years, the Netherlands	(Heijerman-peppelman & Roelofs, 2010)
Malus domestica 'Elstar'	Elstar (with external irrigation)	3000 trees per ha (3,10 x 1 m), economic lifetime is 12 years, the Netherlands	(Heijerman-peppelman & Roelofs, 2010)
Malus domestica 'Elstar'	Elstar (without external irrigation - on drought sensitive area)	3000 trees per ha (3,1 x 1m), on drought-sensitive areas (10 % lower production than no irrigation on drought-resistant , areas), economic lifetime is 12 years, the Netherlands	(Heijerman-peppelman & Roelofs, 2010)
Ribes rubrum	Red berry	6670 plants per ha (2,50x0,60m). Cultivated in ground temporary covered with rain-protection, two-branch plant, the Netherlands	(Heijerman-peppelman & Roelofs, 2010)
Ribes uva crispa	Gooseberry	8000 plants per ha (2,50x0,50m), cultivation in ground without protection, manual harvesting for fresh consumption , the Netherlands	(Heijerman-peppelman & Roelofs, 2010)

Table D.1: Compared fruit systems.

D.2 Carbohydrate crops

Scientific name species	System name	System details	Sources
S. Tuberosum	Potato	Mean of potato cultivation in Holland (2009/2010), similar to cultivation in 2019.	(Hendriks-goossens, 2009), CBS
Triticum	Wheat	Mean of definitive harvest numbers of wheat cultivation in Netherlands over 2017, 2018 & 2019 (including parcels that were not suitable for harvesting but were sowed), moisture content is 16 %; 2017: 9.1 t/ha, 2018: 8.8 t/ha, 2019: 9.6 t/ha.	(*'StatLine - Akkerbouwgewassen;* 2020)

Table C.2: Compared carbohydrate cropping systems.

D.3 Nut systems

Scientific name species	System name	System details	*Sources*
Castanea sativa	Chestnut (orchard)	Orchard with 70 trees per ha. First production after 5 years. Max production in year 15. Mean production: 1.3 t/ha, dried without shell. A linear yield increase has been assumed and a starting output of 2 kg/tree	*('Tamme kastanje (Castanea sativa) in agroforestry - Agroforestry Vlaanderen,' n.d.)*
Corylus avellana	Hazelnut (orchard)	*Corylus avellana* orchard in *Gunslebert* in the province of *Zeeland*: 1100 trees/ha; production after 3 years = 1 t DM/ha dry, mean production during 10 years 1.2 t/ha/y.	(Verdonckt *et al.* , 2016)

Table C.3: Compared nut systems.

D.4 Meat systems

Scientific name species	System name	System details	Sources
Bos Taurus	Beef cattle (feedlot)	Mean number (=17.5 m2/kg) for beef feedlot systems from Westhoek *et al.* (2011).	(Westhoek *et al.* , 2011)
Gallus gallus domesticus	Poultry	Mean value of land use range from studies mentioned by Westhoek *et al.* (2011): i.e. 5-8 m^2/kg; in line with Blonk *et al.* 2008 (4.5-6.5 m^2/kg)	(Westhoek *et al.* , 2011)

Table D.4: Compared meat systems.

Appendix E. Full nutritional value results

E.1 Energy and macronutrient provision

E.1.1 Energy

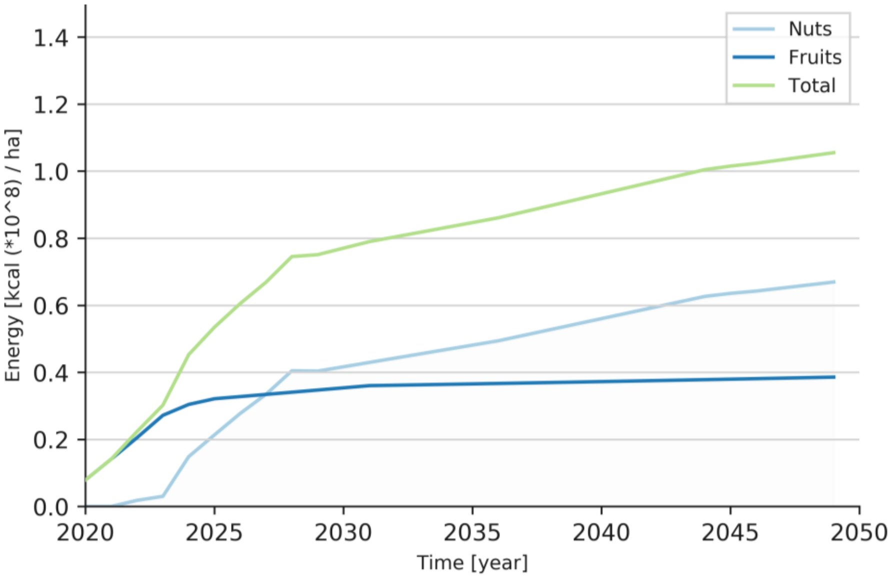

Table E.1.1: Energy production (in 10^8 kcal/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

E.1.2 Carbohydrates

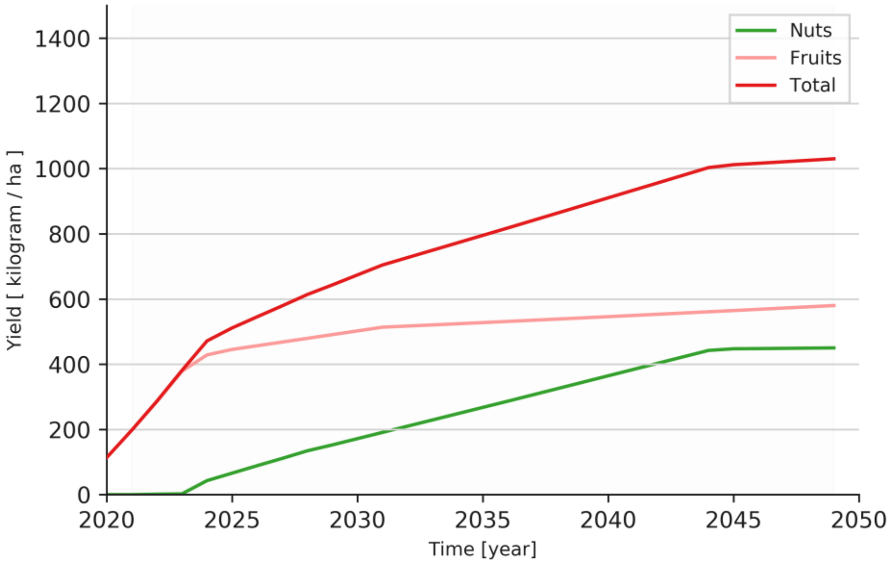

Table E.1.2: Carbohydrate production (in kg/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

E.1.3 Sugars

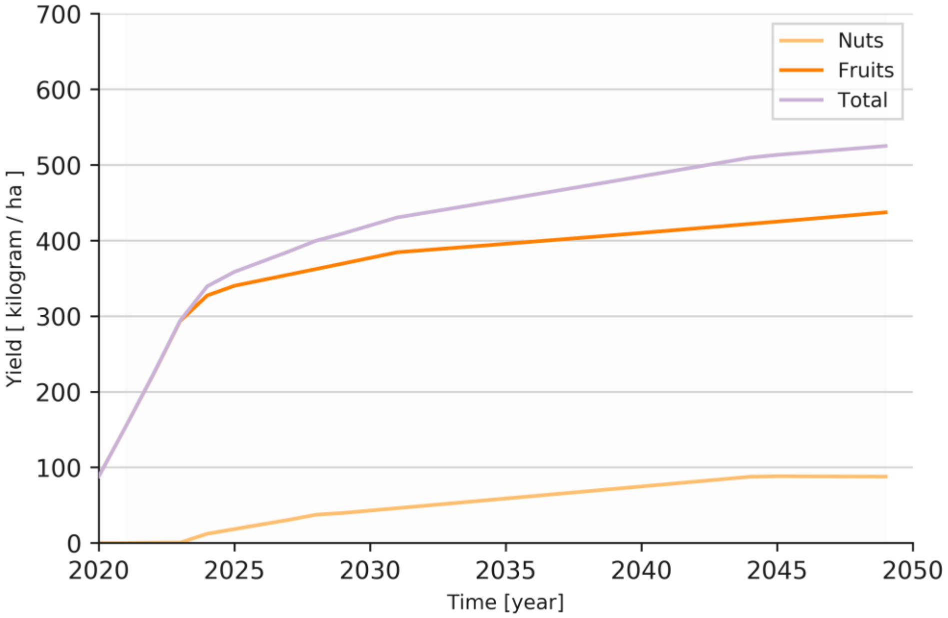

Table E.1.3: Sugar production (in kg/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

E.1.4 Proteins

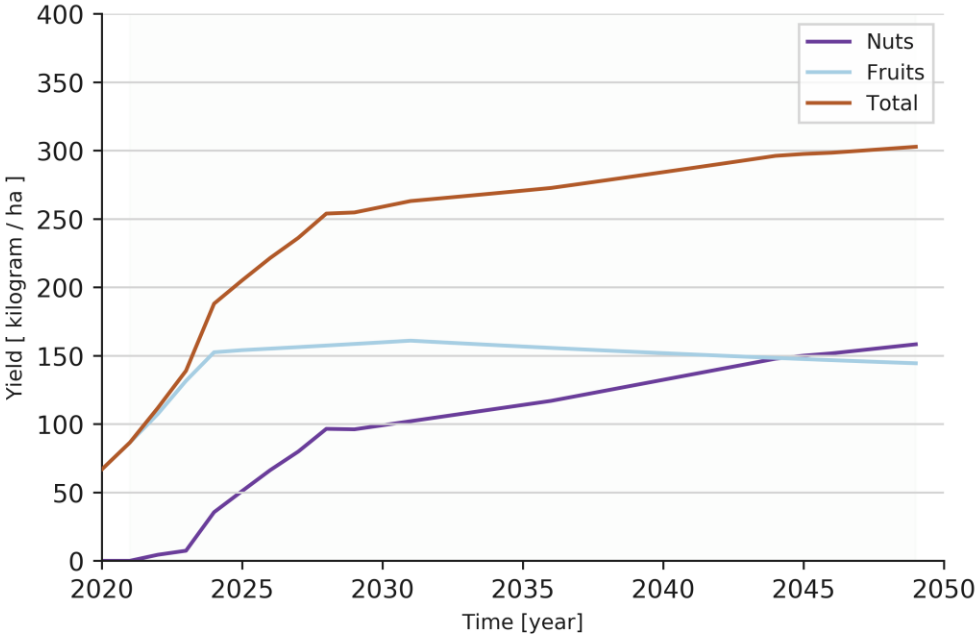

Table E.1.4: Protein production (in kg/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations. The slight drop in protein production regarding corresponds with % yield decline rates as of shading for *Ribes rubrum* (-3%/yr: 2025-2049) and *Ribes nidigrolaria x armeniaca* (-1%/y: 2023-2049).

E.1.5 Fats

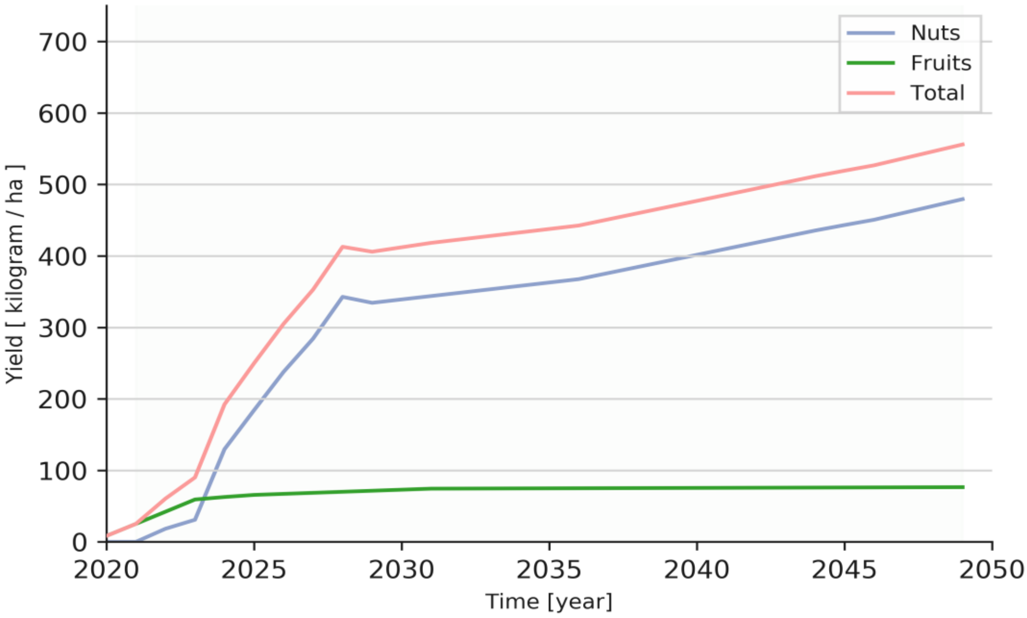

Table E.1.5: Fat production (in kg/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations. The drop in year 2028 regarding fat production (nuts) can be explained by a -1%/yr decline rate for the normal potential of hazelnut production as of shading starting from 2025.

E.1.6 Fibres

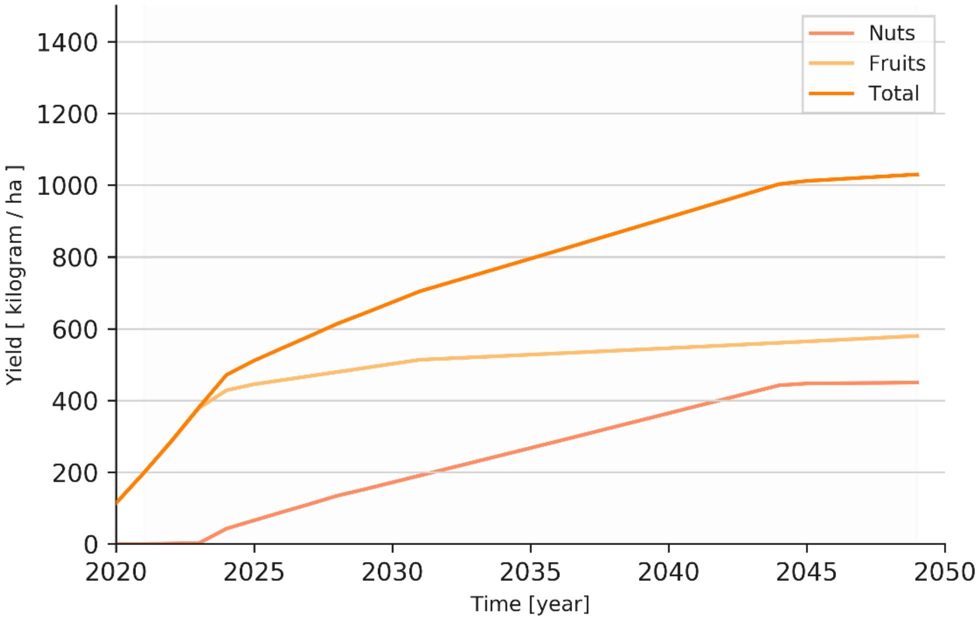

Table E.1.6: Fibre production (in kg/ha) of plot H2 over 2020-2049 differentiated into nuts and fruits. Take into consideration that only nut and fruit species are present for plot H2 (while excluding the annuals such as onions that will be planted in the early years and are considered a minority for the yield) and that other categories such as tubers, herbs and vegetables, are not present in plot H2 but can be present in other food forest configurations.

E.2 Macronutrients and energy - NCC

System	NCC					
	Carbohydrates	Proteins	Fats	Fibres	Kcal	Overall
Conference	76.7	10.5	3.9	120.4	31.1	3.9
Elstar +	76	7.7	1.2	90	28.3	1.2
Elstar -	58.9	5.9	0.9	69.6	21.9	0.9
Potato	93.7	32.2	1	85.4	37.3	1
Wheat	84.6	58.3	0.2	18.7	42	0.2
H2 2049	13.1	11.6	13.1	23	11	11
H2 2067	14.3	13.6	18.1	26.1	13.5	13.5
Chestnuts	11.9	4.1	1.3	2.5	5	1.3
Hazelnuts	0.7	7.4	17.9	8.4	4.6	0.7
Beef	0	6	0.5	0	0.1	0
Poultry	0.2	13.3	2.9	0	0.2	0
Gooseberry	10.1	3.8	0	0	3.8	0
Red Berry	11	6.9	0	114	7.2	0

Table E.2: Full results of comparison of NCC (in number of persons/ ha/y) with conventional systems indicating the top 3 best and worst performing systems. Take notice that for the overall NCC there are 4 systems that score 0 and thus have all been marked red. Elstar +) is with artificial irrigation, Elstar (-) is without irrigation – on drought sensitive area. Consider that the overall NCC of Boulestreau & van Eck (5) and even the NCC of the Garden Cottage forest (2.5) analysed by Skrøder and Henriksen (2019) would perform average among this comparison.

Appendix F. Shortcomings of adjusted yield model

Shortcoming	Explanation
Not taking into account local climate and soil aspects	Some species will perform better/worse in *Schijndel* compared with the underlying soil and local climate conditions for the obtained data. It is difficult to assess the net effect of not taken into account those conditions on the modelled yield.
Data from other countries	In addition, sometimes data had to be used from other countries where climate differences can be way larger. A prime example is data on the fig (*Ficus carica*) from a study from Egypt although the number of 14.3 kg/plant has been estimated as potentially applicable to a Dutch situation (van Eck, 2020).
Estimations (or estimation made in another study) for variables: [starting output], [max age] and [max productive from age]	*E.g.* regarding the *Ficus carica* - max productive from year 7 (estimated by Boulestreau); *Elaeagnus umbellata* - starting output of 0.5 kg/plant (own estimation) as of limited data availability. However for [maximum output] no estimations had to be made; therefore the overall yield potential is not affected by (direct or indirect) estimations.
Assumptions on yield reduction by shading	These assumption are based on the reasoning that yield will decrease by shading which is grounded in expert knowledge and literature. However the scale of the yield reduction is not empirically determined yet for these species, let alone in a Dutch situation. The applied yield reduction rates were -1 %/y (both for *Corylus avellana* as *Ribes x nidigrolaria* over 2022-2049) and -3 %/y (for *Ribes rubrum*).
Potential over-estimation of yield for several species given used data based on a fertiliser scenario	*E.g.* regarding the *Prunus salicina x armeniaca:* 23 kg/plant comes from the KWIN. It is unproven yet if the *prunus salicina x armeniaca* will perform near as good, especially given the fact that 23 kg/tree is likely achieved within a fertiliser scenario and that a much lower value of 7 kg/plant is used by Boulestreau & van Eck (2016).
Potential over-estimation of yield for *Corylus avellana*	Specifically regarding *Corylus avellana*, 9 kg/plant is probably an overestimation as pointed out by the owner of the Dutch nut orchard *Bisschop* who observed way lower outputs per plant in practise.
Insufficiently taking into account planting distance	If possible, the planting distance in the yield data has been compared with the planting distance on plot *H2.* Although, it can occur that the spacing of the plants does not allow for optimal yields. *E.g.* for the *Castanea sativa,* the recommended intra-row distance has been 12 metres by *agroforestryvlaanderen.be* versus the used 8 meter for plot *H2.*
Data on related species	Yield and nutritional data on: *Juglans regia* instead of *Juglans cinerea,* yield and nutritional data on: Prunus *domestica* instead of *Prunus salicina x armeniaca,* Yield data on *Pyrus pyrifolia instead of Cydonia oblonga.* Although this would only hamper the explanatory power for plot H2.

Table F.1: List of shortcomings of the adjusted yield model for estimating the yield on plot H2 for 2020-2050 plus extrapolation to 2067.