Silvopastoral farming systems –

Consequences of trees on pastures for an organic dairy farm in North-Brabant, in the south of The Netherlands

Name student: Christine Franke

Period: 1st November 2016 – 30th April 2017

Farming Systems Ecology Group

Droevendaalsesteeg 1 – 6708 PB Wageningen - The Netherlands

Silvopastoral farming systems –

Consequences of trees on pastures for an organic dairy farm in North-Brabant, in the south of The Netherlands

Name student: Christine Franke
Registration number: 90051244060
Course code: FSE-80436
Period: 1st November 2016 – 30th April 2017
Supervisor(s): Walter Rossing (FSE) & Roos de Adelhart Toorop (FSE)
Professor/Examiner: Rogier Schulte (FSE)

Preface and Acknowledgements

Before I started my research on agroforestry systems, I heard more and more about Mark Shepard. John Heesakkers, the farmer who I am grateful for having had the opportunity to work out together a case study on agroforestry systems, has one of his books at home. Other friends of mine told me: "Mark Shepard is visiting. You should make sure that you see one of his presentations". I did not have the opportunity to see him in person, but reading his book is an inspiring experience:

> "Our culture, worldwide, has the power to utterly destroy the entire life support system upon which it depends. The simple act of eating is the keystone of this fact" and "[s]ince the annual plants are the staple foods that we eat, and necessity drives us to continue to eat, it is easy to assume that 'this is the way things have to be' and that 'this is the way things have always been'." (Shepard, 2013)

In a call for alternative ways of living which intend to bring back our focus on food and its core practices of eating and producing among others such as marketing products and sharing knowledge, his book describes a holistic approach that includes, rather than excludes, diversity. In my view, agroforestry is one such example that reflects its multiplicity in different regions, on different scales and under different motivations with a high relevance for the fields of social and natural sciences. This thesis was written with the support of my two supervisors Walter Rossing and Roos de Adelhart Toorop from the Farming Systems Ecology group that tries to bridge the gap between natural and social sciences on farming and agriculture. Without their keen interest in pushing this thesis forward to a particular and relevant level and their regular advice and guidance throughout the process, this thesis would not be written the way it is. Thank you very much for your support during the process of writing this thesis. Moreover, my thanks goes to John Heesakkers, without whom the topic of this thesis would not be existing and have developed as such. I am grateful for the warm welcome to his farm and for sharing his ideas and wishes with me. Two other people have shaped my thesis in particular ways: Laura van Vooren in Belgium and Alicia Ledo in the UK, two inspiring researchers who with others bring forward knowledge about agroforestry systems. Thank you for taking the time to answer my questions and sharing the knowledge about your research that had a great impact on the outcomes of the thesis. From the practical side, I would like to thank Marcus Nitzsche for the visit to the field that made me see trees on pastures the way they are beyond a scientific perspective. Lastly, I am grateful for the friends I have met at Wageningen University, for those that I could still see regularly and for those, who have already left to find a place somewhere in the world. I am especially grateful for Gabi, Juan and Silja for their immense academic and emotional support during the last phase of my time at Wageningen University.

Summary

Agroforestry systems receive increased attention in temperate regions as one potential pathway for transition towards more sustainable land use systems due to the multiple ecosystem services that they provide. Principles and designs of agroforestry systems vary widely dependent on region, woody species included and the interaction with other components of a farming system. For farmers, practical concerns and potential obstacles for the integration of trees in the farming system deal with the productivity of system components, cash flows and labour requirements. To support farmer decision making, this thesis aimed at investigating the potential of agroforestry systems for temperate dairy farms with regard to pasture productivity, profitability and carbon storage. Specific attention was given to the effects of tree density and tree height on relative pasture yield that served as a basis for answering the overall research question: How do different spatial configurations of trees on pastures affect the profitability and carbon storage of the agroforestry plot.

The material and methods comprised a mixture of quantitative and qualitative methods. A case study of an organic Dutch dairy farmer in North-Brabant, a province in the south of the Netherlands, served as the main focus of interest for which practical implications on profitability and carbon storage were evaluated. A literature review on studies that reported experiments of silvopasture systems in temperate regions resulted in 10 scientific sources of which 65 observations were analysed statistically with a mixed effects model in R. The statistical relation which described the effects of tree density, tree height and their interaction on relative pasture yield was operationalized in a tool for quantification of agroforestry systems, the silvopasture tool. This tool served as another output of this thesis, which was used to evaluate four different scenarios of tree spatial tree configurations. Data were collected for walnut, chestnut, cherry, pear, apple and plum. Tree density and tree height constituted the inputs for the silvopasture tool, from which profitability and carbon storage was calculated on the basis of changes in relative pasture yield over 15 years. The four scenarios differed in low versus high tree height and low versus high tree density to visualize the effects of each variable on pasture yield, profitability and carbon storage.

The statistical analysis presented negative correlations of tree height and tree age with relative pasture yield, whereas for tree density no significant effect on relative pasture yield was found. Tree density together with tree height and in interaction with each other showed a significant effect on relative pasture yield. In contrast to the effects of tree height and tree age alone, this relation indicated positive interactions between trees and pasture in the first years after planting. This meant that in the first years after tree establishment pasture yield in the agroforestry plot was slightly higher than in open pasture before it started to decrease after a certain year, dependent on the tree species included in the system. Competition for light capture by tree canopies was identified as the main factor reducing relative pasture yield, whereas assumptions on positive interactions between trees and pastures were made with regard to improved microclimates and below-ground interactions.

In the operationalization of different spatial tree configurations through scenarios, configurations with low tree density and low tree height were identified to best meet the two objectives of minimizing pasture yield loss and maximizing profitability. In contrast, carbon storage was maximized in scenarios of high tree density and constituted a trade-off to minimum pasture yield loss. The quantification of carbon storage comprised a potential source for economic revenue in form of carbon credits. In none of the spatial tree configurations a considerable profit is made beyond 5% of the Business As Usual scenario. This is why initial financial incentives are essential for farmers to be able to make a smooth transition to agroforestry systems.

A novel insight of this thesis is the finding that tree density showed an effect on relative pasture yield if considered in interaction with tree height. In this interaction, positive effects between trees and pastures on pasture yield were identified in the first few years after tree establishment. Literature on temperate silvopasture systems was very scarce. This is why an in-depth investigation of tree density, tree height and other relevant factors such as the distance to the tree is recommended for future research with an emphasis on facilitation effects between trees and pastures.

Table of Contents

List of Figures

List of Tables

1. Introduction

Agroforestry, simply understood as the integration of trees in the farming system, is commonly defined as a “land-use system(.) in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both; [in which there are] usually both ecological and economic interactions between the trees and other components of the system” (Lundgren, 1982). Agroforestry practices vary widely in scale, species of crops, trees and animals, in managing interacting farm components and in spatial and temporal configurations that show specific and complex demands for resources (Luedeling, 2016). Instead of reducing complexity, agroforestry systems attempt to manage complexity as its most powerful feature. Associated with agroforestry are a number of ecosystem services like biodiversity conservation, soil enrichment, air and water quality, and carbon sequestration (Jose, 2009). Agroforestry received increased attention in tropical regions, where small-scale and subsistence farmers gain from enhanced food security through more resilient and diverse agricultural practices. For temperate regions, Long and Nair (1999) suggested that agroforestry systems largely represented economic opportunities for higher profitability and market diversification, with the long-term goal of adapting to more sustainable farming practices. Three forms of agroforestry practices were evident in temperate regions: intercropping annual and woody species, silvopastoral practices, where forestry is combined with grazing animals, and windbreaks or shelterbelts (Long & Nair, 1999). In this thesis, the silvopastoral system, which consists of animal, pasture and tree components, was investigated. In line with the overall concept of agroforestry systems, silvopasture attempts to optimize the “interactions among pasture plant species, woody perennials, and grazing animals, to increase production efficiency and sustainability of the entire system” (Bambo et al., 2009).

Historically, agroforestry practices are not new, but have regained popularity in the last decades due to their potential to provide alternatives to a highly industrialized farming system which causes a wide range of negative environmental externalities (Smith et al., 2012). One specific design of silvopastoral systems is the German ‘Streuobst’. As a low-input system, it is similar to an alley cropping design that integrates fruit trees such as apple (*Malus domestica* Borkh.), pear (*Pyrus communis* L.), plum (*Prunus domestica* L.) and mazard cherry (*Prunus avium* L.) on grassland, which might additionally be grazed by animals. Also other trees like peach (*Prunus persica* (L.) Batsch), Persian walnut (*Juglans regia* L.), sweet chestnut (*Castanea sativa* Mill.) or mulberry (*Morus* spp.) are not uncommon in ‘Streuobst’ systems (Herzog, 1998). On the political agenda, the implementation and maintenance of this system reflects a desire of reintegrating cultural landscape elements in the region and profiting from their associated benefits of biodiversity and nature conservation

(Naturschutzbund Deutschland e.V., 2017). Similarly, Shepard (2013) as one of many others suggested an agroforestry design under the heading of restoration agriculture that does not only conserve nature, but also produces fruits and nuts. In the Netherlands, 'Streuobst' agroforestry designs nearly vanished because of the intensification of fruit production in orchards (Herzog, 1998). More recent, there is an interest of reintegrating cultural landscape elements and adapting more sustainable land-use systems. For instance, *Brabants Landschap*, a Dutch nature organization in the province of Brabant in the south of the Netherlands, collaborates with farmers to implement measures that contribute to nature and landscape conservation. One particular initiative is the subsidy scheme STIKA (in Dutch: Subsidieregeling Groen Blauw Stimuleringskader) that helped farmers in Brabant to integrate different landscape elements in their farming system (STIKA, 2017). By integrating landscape elements such as trees and shrubs, a farmer makes the link between agricultural production and nature conservation.

Agroforestry systems fit well to organic or agroecological practices that attempt to mimic the structure and functioning of natural ecosystems, but a careful design and management of these systems is needed to obtain their associated benefits (Smith et al., 2012). Especially, the integration of perennial farm elements like trees and shrubs must be preceded by a proper long-term planning. Large investments are made during the planting phase and economic profits are only obtained years after. Accordingly, Graves et al. (2011) argued that financial feasibility and return are the main criteria for farmers to decide on alternative land uses such as agroforestry. Concerns are for instance the productivity of crops, labour demand for the additional farm activity and available cash flow at the beginning of the planting period and per year. These practical concerns were addressed in this thesis by investigating the productivity of agroforestry systems in terms of profitability. Moreover, ecological consequences on carbon storage were examined since agroforestry systems have the potential to sequester carbon and offset greenhouse gas emissions (Cubbage et al., 2012). This is one of the benefits associated with agroforestry systems. In contrast to profitability, the carbon storage of trees is rarely a primary concern of farmers as opportunities to economically account for ecosystem services such as carbon storage are limited. Montagnini and Nair (2004) argued however that carbon storage could be a considerable additional output of farming systems, which could be accredited as 'carbon credits'.

The following section presents available scientific information on the productivity of agroforestry systems consisting of trees and crops with an emphasis on tree-crop interactions. This leads to the formulation of the objective of this thesis, from which specific research questions are drawn. The introduction ends with an outline of the thesis.

1.1. Scientific background

One of the characteristics of agroforestry is the interplay of complex competitive and facilitative interactions between trees and crops. Vandermeer (1990) argued that competition takes place “where two species attempt to use the same resource pool, while facilitation occurs, where one species alters the environment of the other in a positive way”. To illustrate, trees may affect crops negatively in competition for light, water and nutrients and positively by increased leaf and root biomass that may enhance the nutrient cycling in the agroforestry system (Rao et al., 1998). Central to the interactions between two species in an agroforestry system is the hypothesis that “benefits of growing trees with crops will occur only when the trees are able to acquire resources that the [other species] would not otherwise acquire” (Cannell et al., 1996). Usually denoted as complementarity, this interaction may be spatial or temporal. Spatially, trees and crops differ in their rooting systems with trees exploiting water and nutrients beyond the roots of the crop and temporally, if greater resource demands occur during different times of the growing seasons (Luedeling et al., 2016).

Rao et al. (1998) summarized the main tree-soil-crop interactions as effects on chemical, physical and biological soil fertility, resource competition, conservation, change in microclimate, weeds, pests and diseases and allelopathy. With a focus on above-ground interactions, light capture is one of the major competitive factors constraining growth in agroforestry systems. Light capture is affected by “tree leaf area, leafing phenology, crown structure and crown management” (Luedeling et al., 2016). Positively, an improvement of microclimate may occur, which is caused by reduced solar radiation, a more moderate temperature regime, higher humidity, lower rates of crop transpiration, and higher soil moisture levels (Singh et al., 2012). Most evident are reduced soil and air temperature and protection from wind, which is especially beneficial for animals in the agroforestry system. Below-ground, rooting systems of trees and crops are essential for nutrient and water capture. General processes involved in agroforestry systems are “soil carbon enrichment through root turnover, the interception of leached nutrients, or the physical improvement of compact soil layers” (Schroth, 1999). While competition for light can be manipulated by changing tree configurations and by thinning tree canopies through management practices, controlling negative effects on crop growth by manipulating the rooting system through fertilization is challenging (ibid.).

Productivity of agroforestry systems is believed to be overall higher due to niche differentiation, meaning that “different species obtain resources from different parts of the environment” (Smith et al., 2012). Sharrow et al. (1996) showed that agroforestry systems had the potential for higher yields of trees and pasture together than monocultures of their components, estimating 102-103% tree production compared to forests and 90% grass production compared to open pastures. Moreover, Douglas et al. (2001) argued for agroforestry sites in New Zealand that if trees were not in leaf in late autumn and winter in New Zealand, "differences between yields of swards beneath trees and in the open were negligible". In contrast, in spring and summer temperate pasture yield was reduced by 70 % (Douglas et al., 2001) Translating productivity into financial terms, Van Vooren et al. (2016) calculated the profitability of an alley cropping and hedgerow system on arable land in Belgium. In a literature meta-analysis the authors found positive and negative tree-crop interactions on productivity dependent on the distance from the tree row and the height of the tree row. In the study, variables like crop type, tree line width, and tree line orientation were not assessed. Van Vooren et al. (2016) differentiated between three different zones of tree-crop influence: first, the zone in which crop yield was lost due to the replacement of crop plants by trees, second, the affected zone close to the tree, in which the authors identified positive interactions between trees and crops and third, the unaffected zone where crop yield was 100% because there was no tree-crop interaction. Relative yield, described as the fraction of the crop yield in the agroforestry site compared to the crop yield on an arable plot, was a function of the ratio H. The ratio H equalled the distance from the tree row relative to the tree row height (distance to tree/tree row height). The impact from the tree row on crop yield decreased with an increase of H. Figure 1 shows schematically how the ratio H changes with increasing distance from a tree.

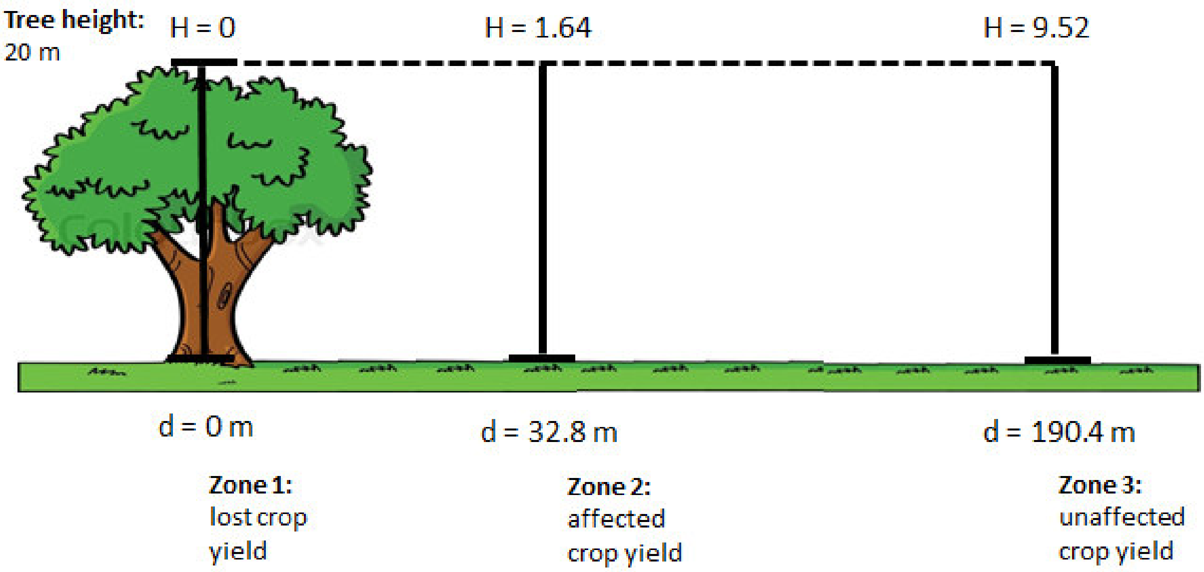


Figure 1: Visualization of the ratio H used by Van Vooren et al. (2016), with H equalling the distance from the tree relative to the height of the tree, adapted by Franke (2017). For poplar trees (*Populus* sp.) together with crops like winter wheat, winter barley, maize, sugar beet and potatoes, Van Vooren et al. (2016) calculated the negative effect zone 1 to occur between H=0 and H=1.64, the affected zone 2 between H=1.64 and H=9.52, and zone 3 outside of tree influence for H>9.52.

In this thesis, the findings of the Van Vooren et al. (2016) study were used as a foundation for further knowledge expansion on agroforestry systems and more specifically on interactions between trees and pasture. Due to very limited availability of data on silvopastoral systems, tree density and tree height were the variables investigated in this study, to determine the effect of trees on relative pasture yield. Compared to existing literature, this thesis presents novel findings on positive tree and pasture interactions with regard to the productivity of agroforestry systems. The integration of fruit and nut trees in a silvopastoral system was elaborated as part of a case study for an organic dairy farm in the Netherlands. The following section presents the overall research objective and research questions, with a focus is on profitability and carbon storage in agroforestry systems. This is followed by outlining the set-up of the thesis report.

1.2. Objective and research questions

This thesis aimed at investigating the potential of agroforestry systems for temperate dairy farms, with specific attention for the effects of tree density and tree height on system productivity over 15 years. The time frame corresponded to a typical economic life of fruit orchards and shed light on consequences of trees still early in their growth to full maturity.

The objective led to the following overall research question:

How do different spatial configurations of trees on pastures affect the profitability and carbon storage of an agroforestry plot?

Specific research questions were:

1. **How much temperate pasture yield is produced in an agroforestry plot with trees of different height and at different density over a time frame of 15 years?**
2. **What are financial costs and revenues of temperate silvopastures that differ in tree height and tree density over a time frame of 15 years?**
3. **How much carbon is stored in trees in temperate silvopastures with different tree height and tree density over a time frame of 15 years?**

1.3. Setup of thesis report

The thesis comprises four chapters. The (current) first chapter introduces and defines agroforestry as an alternative land use concept for sustainable farming and summarizes scientific knowledge about the productivity of temperate agroforestry systems. The objective and research questions are outlined. The second chapter on methods and materials describes the case study of a Dutch dairy farm in the south of the Netherlands, used to investigate interactions between trees and temperate pastures. The second section of the chapter describes the methods used to review the literature on effects of trees on pasture yield. It explains how scientific sources were selected, statistically analysed and reviewed to understand the mechanisms behind the effect of trees on pastures. Secondly, a tool for quantitative evaluation of agroforestry systems is introduced, which operationalizes the effect of trees on relative pasture yield. The conceptual basis of the tool is outlined and the assumptions made for inputs and outputs of the tool are justified. Chapter three displays the results of the analyses and is divided into two sections. The first section describes the results of the literature review on the effect of trees on pasture yield and serves as a foundation for the second section, where the relation is operationalized for fruit and nut trees on an agroforestry plot. Four different scenarios are evaluated with regard to three different objectives: minimum pasture yield loss, maximum profitability and maximum carbon storage in trees. In chapter four, the results of the thesis are discussed by critically assessing the outcomes of the research. Results are compared to existing literature, practical implications are drawn and recommendations are made for further scientific research.

2. Materials and methods

This section is separated into four parts. The first part introduces the case study of the Dutch dairy farmer in North-Brabant, in The Netherlands. The second part deals with the review of the effect of trees on relative pasture yield by outlining the selection of scientific sources, the statistical analysis and the qualitative review of literature. The third part presents the tool for quantification of agroforestry systems and the evaluation of four different scenarios with regard to three objectives: minimum pasture yield loss, maximum profitability and maximum carbon storage in trees. The last part explains how qualitative data from semi-structured expert interviews and field visits were obtained to complement the quantitative findings.

2.1. Case study

John Heesakkers is an organic dairy farmer who started an extensive dairy farming system in the province of Brabant, in the south of The Netherlands in 2006. John is a proactive and innovative farmer, interested in a transition towards combining organic agriculture with nature conservation. This is due to his personal interest in nature and his goal to bring back historical landscape elements for more biodiversity in and around his farm. He took several initiatives towards agroforestry with the support of *Brabants Landschap* and through the subsidy program STIKA. Among the measures he implemented were an amphibian and meadow bird pond, a walking path, arable wildflower and fauna strips, natural stream banks for wet grasslands, shrubbery at field margins, solitary trees and rows of trees (Figure 2).

Figure 2: Overview of John Heesakkers' farm with integrated landscape elements. The box in light blue marks the borders of the agroforestry plot where John wishes to integrate fruit and nut trees with pasture.

The farm comprises 58.61 ha agricultural land, of which 38.61 ha is under pasture. The remaining 20 ha are natural grass areas. The pasture is a combination of ryegrass, white clover, red clover, timothy grass, herb mix, oats and other pasture species (Table 21 in Appendix 2). Pasture yield amounts up to 10,000 kg DM/ha. In the near future, he plans to focus more on meat production. This change results in a herd composition of 70 Fleckvieh-Brown Swiss dairy cows, 18 calves, 17 heifers, ten bulls between 1-2 years and ten bulls younger than one year. Furthermore, he considers taking up six horses as an additional element to his farm.

Figure 3: Agroforestry plot of 6.89 ha, marked by yellow lines. White arrows outline the length and width of the rectangular field used in the quantification of agroforestry systems with a length of 292 m and width of 228 m. Source: downloaded from boerenbunder (2017).

Figure 3 shows the field of 6.89 ha, on which the farmer wishes to include trees for a silvopasture system. For quantifying the effect of trees on pasture, a rectangular shape was assumed. The rectangular field comprises 6.66 ha, with a length of 292 m and a width of 228 m. The field has a sandy soil and the plot was converted from maize production to grassland in 2014. The following list summarizes John Heesakkers' wishes and concerns for the agroforestry plot:

- **Agroforestry design**: Two or three double rows of trees that connect the two bordering forest areas. Pasture will be used to graze young bulls
- **Tree row width**: Dependent on type, the width of machinery amounts to 6 and 7.2 m. The turning of the machines between the rows and at the end of the field need to be considered
- **Tree species**: Mixed fruit and nut species like walnut and apple
- **Labour availability**: Focus on low labour intensity because is an additional farming activity to the production of milk and meat
- **Economics**: Profitability is not the highest priority, but costs should be at least balanced by the production of trees

2.2. Review of effect of trees on pasture yield

Selection of literature

The Web of Science gave 683 hits of scientific peer reviewed articles in December 2016, using the following search criteria:

	agroforestry OR silvopast*	(Topic)
AND	yield OR prod*	(Topic)
AND	grass* OR pasture	(Topic)

From these hits, the search was restricted to studies that carried out experiments on silvopasture systems in temperate regions such as United States, New Zealand, Canada or parts of Western and Northern Europe. Tree species predominantly comprised pine, poplar, willow and Douglas fir. The intention was to follow the approach of Van Vooren et al. (2016) and investigate the effect of distance from tree on relative pasture yield. Apart from Sharrow (1991) and DeBruyne et al. (2011), no pasture yield measurements were reported at different distances from trees. In other studies, pasture productivity was assessed by the effect of tree density, tree height or tree age. This brought down the number of studies usable for further assessment to ten. All of these studies reported on the effect of either tree age or tree height. Tree density, if not explicitly mentioned in the experimental design was calculated from the row spacing and number of tree rows on the experimental plot.

Table 1 presents an overview of the ten scientific sources that comprised 65 observations. For each study, the values for tree age, tree height and tree density are indicated. Tree height for pine (*Pinus radiata*) (Brack & Wood, 1997) and Douglas fir (*Pseudotsuga menziesii*) (Flewelling et al., 2001) was estimated from tree age.

Table 1: Overview of the ten scientific sources where Obs. represents the number of observations in each study. Tree height for *Pinus radiata* and *Pseudotsuga menziesii* (marked with *) were estimated on tree age. Sources: Brack & Wood (1997), Flewelling et al. (2001).

Source	Author(s)	Year	Obs.	Tree species	Tree age (year)	Tree height (m)	Tree density (trees ha^{-1})
1	Bambo et al.	2009	2	Loblolly pine (*Pinus taeda* L.)	18	-	225
2	Burner & Brauer	2003	14	Loblolly pine (*Pinus taeda* L.)	7	4, 9	1764, 1176, 840, 830, 664, 581, 498
3	Guevara-Escobar et al.	2007	6	Poplar (*Populus* spp.)	29, 40	28, 32	37, 40
4	Hawke	1991	16	Pine (*Pinus radiata*)*	3, 6, 8, 10, 13,	2, 4, 5, 7.5, 13, 14	50, 100, 200, 400

					15		
5	Hussain et al.	2009	3	Willow (*Salix* spp.); Poplar (*Populus* spp.)	2	1,9	6889
6	Peri et al.	2007	1	Pine (*Pinus radiata*)	10	13,3	200
7	Sharrow et al.	1996	10	Douglas fir (*Pseudotsuga menziesii*)*	6, 7, 8, 9, 10	1.14, 1.56, 1.99, 2.56, 3.13	890, 1600
8	Sibbald et al.	1991	9	Sikta spruce (*Picea sitchensis*)	-	3,5,8	156, 278, 625
9	Varella et al.	2011	1	Pine (*Pinus radiata*)	-	11	200
10	Yunusa et al.	1995	3	Pine (*Pinus radiata*)	-	2,69, 2,73, 2,91	1000

Statistical analysis

Relative pasture yield (RY) was defined as

$$RY = \frac{pasture\ yield\ in\ agroforestry\ plot}{pasture\ yield\ in\ open\ pasture/control\ plot}$$

Relations among tree density, tree age and tree height were evaluated by plotting the data and by calculating correlations. The effects of tree density, tree age and tree height on relative pasture yield were tested individually and in a stepwise approach including interactions. Appendix 1 presents a detailed overview of the relative pasture yield per observation in Table 18 and Table 19.

A mixed effects model was used to account for the multilevel structure in the data. To account for the hierarchical nature and non-independence of the data, scientific source was included as a random effect. The model assumes that the observations are likely to be more related with each other if within the same scientific source (Zuur et al., 2009). Practically, this meant that aspects like tree species, pasture composition and climatic characteristics of the same scientific source were taken into account. The characteristics of the scientific source are expressed by a random factor that results in a variation around the intercept per scientific source (ibid.). Using the command *lme* in R, the procedures used in the statistical analyses of mixed effects are described in Table 2.

Table 2: Commands used in R for the statistical analysis of the effect of tree density, tree age and tree height on relative pasture yield represented by the variable Ratio. The random factor of the mixed effects model is represented by Author which stands for the scientific source analysed

Tested variable	**Command in R**
Tree density	mixed<-lme(Ratio ~Density, random=~1 |Author, method="REML", data=table)
Tree age	mixed<-lme(Ratio ~Age, random=~1 |Author, method="REML", data=table)
Tree height	mixed<-lme(Ratio ~Height, random=~1 |Author, method="REML", data=table)
Tree age on height	mixed<-lme(Height ~Age, random=~1 |Author, method="REML",

	data=table)
Height and density: stepwise	mixed<-lme(Ratio ~Height + Density, random=~1 |Author, method="REML", data=table)
Height and density: interacting variables	mixed<-lme(Ratio ~Height*Density, random=~1 |Author, method="REML", data=table)

Additionally, the variance was calculated to judge the accuracy of the mixed effects model. This was done by using the command **r.squaredGLMM(mixed)** for each of the tested variables. The results present the variance for the fixed effects and the variance for the fixed and random effects. It is expected that the second variance that includes the random factor is higher because the relatedness of the scientific source is taken into account.

Review of literature

The ten scientific sources were reviewed qualitatively to identify underlying mechanisms that gave potential explanations about the effects on relative pasture yield. An overview of the tree species, experimental design, experimental factors and outcomes of the studies was established. In the experimental design, the location of the experiment and the experimental set-up was taken into account. The experimental factors were identified and, as far as stated in the scientific source, potential mechanisms added. The research outcomes referred to the arguments given by the authors of the scientific sources on pasture yield productivity in agroforestry plots. A particular focus was given to observations where relative pasture yield was almost equal to or higher than 1.

2.3. A tool for quantification of agroforestry systems

Conceptual basis of tool

The statistical relation which described the effect of tree density (trees ha^{-1}) and tree height (m) on relative pasture yield was operationalized in a tool for quantification of agroforestry systems. The tool was based on the excel tool by Laura Van Vooren (Van Vooren et al., 2016), which quantified the effects of poplar trees on the productivity of different crops in Belgium. Similar to Laura van Vooren's tool, the silvopasture tool served as a calculation device for scientific purposes and as a decision tool for farmers. The main difference between these tools was the adjustment towards silvopasture systems, with multiple tree species on pastures. Six different tree species were chosen. Cherry, apple, pear and plum were common fruit tree species of 'Streuobst' agroforestry systems and walnut and chestnut trees were added additionally to the selection options.

The silvopasture tool was divided into the following sections, which represent the tabs in excel:

- **Tab 1 - Definition:**
    - Background and organization of tool
    - Definition of tabs
- **Tab 2 - Agroforestry plot**:

    - Length (m) and width (m) of agroforestry plot and length (m) of tree row
    - Number of tree rows per tree species
    - Pasture area reduced by trees (ha) calculated by tree row width of 1.5 m
    - Conditions set for maximum number of tree rows possible on agroforestry plot for given tree row spacing
- **Tab 3 - Relative pasture yield:**
    - Tree height (m) per tree species over 15 years
    - Relative pasture yield dependent on tree height (m) and tree density (trees ha^{-1})
- **Tab 4 - Carbon sequestration:**
    - Diameter of tree trunk (cm) per tree species for 15 years
    - Carbon sequestered (kg) per tree species and overall agroforestry plot for 15 years
- **Tab 5 - Economics trees:**
    - Revenue and costs (€) per tree species
    - Revenue and costs (€) for overall agroforestry plot (Agroforestry Scenario for trees)
- **Tab 6 - Economics pasture:**
    - Revenue and costs (€) for pasture on plot without trees (Business As Usual for pasture)
    - Revenue and costs (€) for pasture on overall agroforestry plot (Agroforestry Scenario for pasture)
- **Tab 7 - Comparison of BAU & AS:**
    - Discounted gross margin (€) and present net value (€) for Business As Usual (BAU)
    - Discounted gross margin (€) and present net value (€) for Agroforestry Scenario (AS)

Tree density (trees ha^{-1}) and tree height (m) are the main input variables needed in the silvopasture tool because they determine the effect on relative pasture yield. Tree density (trees ha^{-1}) is determined by the user in the choice of the number of tree rows to be planted on the agroforestry plot (Tab 2: Agroforestry plot), while tree height is determined beforehand (Tab 3: Relative pasture yield). The size of the agroforestry plot with regard to its length (m) and width (m) is defined by the user, as well as the length (m) of the tree row (Tab 1: Agroforestry plot). The loss of pasture area (ha) is calculated assuming a tree row width of 1.5 m, which is multiplied by the selected number of tree rows and tree row length (m).

One output of the silvopasture tool is the carbon sequestered (kg) on the agroforestry plot (tab: Carbon sequestration), which was based on the diameter of the tree trunk (cm). The second outcome of the tool is the comparison of the Business As Usual (BAU) and Agroforestry Scenario (AS) with regard to gross margin (€) and present net value (€) (Tab 7: Comparison of BAU & AS). This was based on the calculations of revenue and costs of trees (Tab 5: Economics trees) and the calculations of pasture yield, determined by the effect of tree height and density on relative pasture yield (Tab 6: Economics pasture).

The following sections shed light on the assumptions made on tree density based on within tree row spacing and tree height based on specific tree height growth rates per year. Moreover, assumptions were made with regard to profitability (costs and revenues) and carbon storage of trees. These are explained in the last two sections.

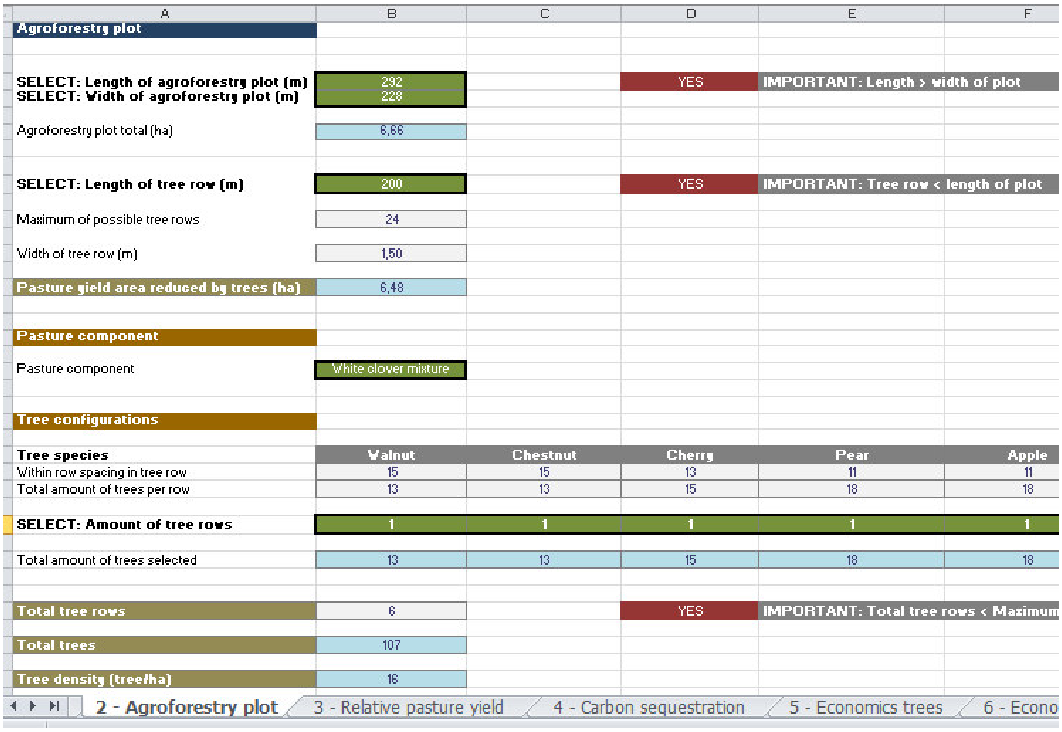
Tree density determined by number of tree rows

Common rules for tree densities in practice are 100 fruit trees or 75 fruit and nut trees combined per ha (Nitzsche, 2017, personal communication). This was taken as a target for setting the within row spacing for tree rows per tree species. Table 3 displays the spacing for walnut, chestnut, cherry, pear, apple and plum trees as trees of standard 1.8 m tree height (Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, 2009).

Table 3: Within row spacing of walnut, chestnut, cherry, pear, apple and plum trees. *The within row spacing for chestnut was not stated. Due to its similar height to walnut trees, the same spacing is assumed. Source: Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen (2009)

Tree species	Within row spacing (m)
Walnut	15
Chestnut*	15
Cherry	12-14
Pear	10-12
Apple	10-12
Plum	6-8

The width between the tree rows was set to a distance of 12 m, to ensure sufficient space for the trees when the maximum tree height is reached (Nitzsche, 2017, personal communication). Within row spacing in the silvopasture tool was determined by dividing the length of the tree row by the adequate within row spacing. The result is the maximum number of tree rows possible on the agroforestry plot. Figure 4 shows Tab 2 – Agroforestry plot, where the size of the agroforestry plot is defined and the number of tree rows is selected.



A	B	C	D	E	F
Agroforestry plot					
SELECT: Length of agroforestry plot (m)	292		YES	**IMPORTANT: Length > width of plot**	
SELECT: Width of agroforestry plot (m)	228				
Agroforestry plot total (ha)	6,66				
SELECT: Length of tree row (m)	200		YES	**IMPORTANT: Tree row < length of plot**	
Maximum of possible tree rows	24				
Width of tree row (m)	1,50				
Pasture yield area reduced by trees (ha)	6,48				
Pasture component					
Pasture component	White clover mixture				
Tree configurations					
Tree species	**Walnut**	**Chestnut**	**Cherry**	**Pear**	**Apple**
Within row spacing in tree row	15	15	13	11	11
Total amount of trees per row	13	13	15	18	18
SELECT: Amount of tree rows	1	1	1	1	1
Total amount of trees selected	13	13	15	18	18
Total tree rows	6		YES	**IMPORTANT: Total tree rows < Maximum**	
Total trees	107				
Tree density (tree/ha)	16				

Figure 4: Tab 2 – Agroforestry plot of the silvopasture tool by Franke (2017). It shows the selection options for tree rows per tree species and as outputs the total trees on the agroforestry plot and the tree density (trees ha^{-1})

Tree height determined by fixed tree growth rates

To calculate the relative pasture yield in the silvopasture tool, tree height per year per tree species is determined. Literature on growth rates of trees is scarce because the growth of tree height depends highly on "initial spacing and treatment, silvicultural treatment, artificial thinning and pruning, site conditions and climatic conditions" (Brack & Wood, 1997). For fruit and nut trees data on growth was not found in literature, with only indications on maximum tree height. Table 4 presents tree height (m) for fruit and nut trees with a focus on timber production (Wiselius, 2005).

Table 4: Tree height (m) and maximum height (m) for walnut, chestnut, cherry, pear and apple trees for timber production. Source: Wiselius (2005).

	Tree height (m)	Maximum tree height (m)
Walnut	15 – 30	
Chestnut	15 – 25	30
Cherry	18 – 25	
Pear	9 – 12	18
Apple	5 – 6	9

The initial approach was to estimate the rate by which the tree grows in height based on the year in which the tree species reaches maximum tree height. Data on that could not be found as references in literature were limited. Experts from tree nurseries and practitioners were consulted for estimations on maximum tree height, the year in which that height is reached and rates by which the tree grows per year (Appendix 2). Because the responses varied widely, the tree growth curve by

Brack and Wood (1997) was adapted as a second approach to estimate tree heights. To simplify the curve, the tree height curve was split into phases of growth (youth, mature and senescent) and described through linear functions of minimum, maximum and most likely growth rates.

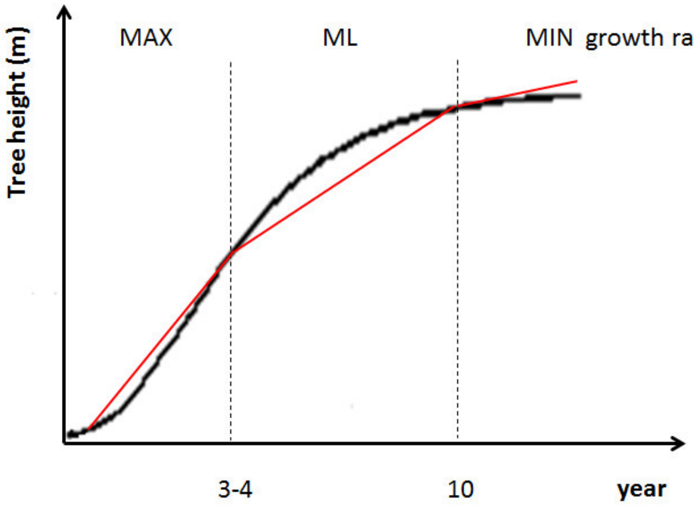


Figure 5: Tree height growth (m) adapted by Franke (2017) from Brack and Wood (1997). Three phases of growth were distinguished: youth with a maximum growth rate (MAX), mature with a most likely growth rate (ML) and senescent with a minimum growth rate (MIN).

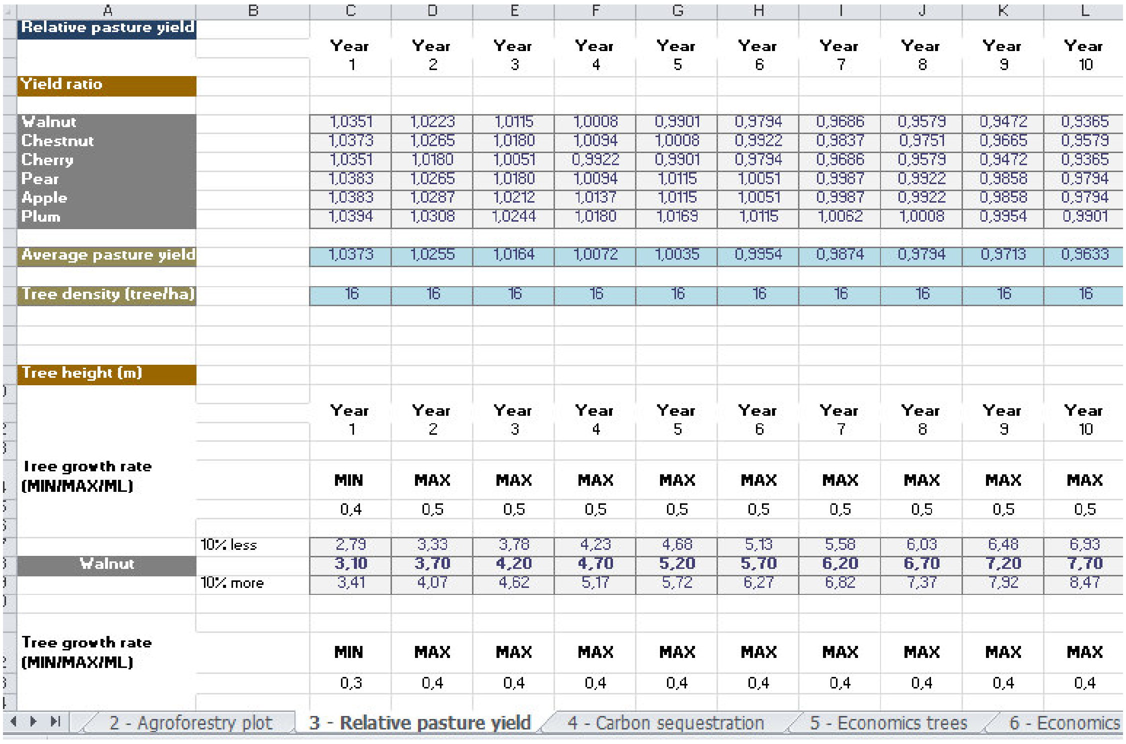
The maximum growth rate corresponded to Brack and Wood's (1997) juvenile phase with an accelerated rate of growth, the most likely growth rate to the mature phase in which a constant rate of growth was expected and the minimum growth rate referred to the senescent phase with a decelerating rate of growth (Figure 8). In year 2, a maximum growth was anticipated that was enhanced by pruning that usually takes place after the first year of planting (Friedrich, 1961). In year 3-4, fruit production was expected to increase and shoots develop from a horizontal growth to a more vertical growth (ibid.). This was described by the most likely growth rate. Derived from literature, this was the phase of yielding fruits (Friedrich, 1961). Approximately in year 10, pruning management changes from yielding to maintaining which was depicted by the minimum growth rate for tree height. Table 5 presents an overview on the minimum, most likely and maximum tree growth rate, based on the estimations given by experts (Table 20 in Appendix 2).

Table 5: Tree growth rates per tree species, distinguishing minimum (MIN), most likely (ML) and maximum (MAX) tree growth rates (cm) per year

	Tree growth rate MIN (cm)	**Tree growth rate ML (cm)**	**Tree growth rate MAX (cm)**
Walnut	40	45	50
Chestnut	30	35	40
Cherry	40	50	60
Pear	25	30	40

Apple	25	30	35
Plum	20	25	30

Trees are planted with a trunk height of 1.8 m and a crown height of 0.8 – 1m (Kraus, 2017, personal communication). The total height of 2.7 m was used as the starting point for the tree curve. It was assumed that the growth in year 1 is at minimum because the tree invests more energy in root growth after being planted in the new site (Kraus, 2017, personal communication). The tree curve in Figure 5 supported well the growth of fruit trees, but nut trees grow much larger than fruit trees over a larger amount of time. This is why it was assumed that walnut and chestnut trees started the mature phase with a most likely tree growth rate in year 10 (Friedrich, 1961). Figure 6 shows the calculations in the silvopasture tool on Tab 3 – Relative pasture yield. Based on the specific relative pasture yield per tree species, an average of these values is calculated for the overall agroforestry plot.



A	B	C	D	E	F	G	H	I	J	K	L
Relative pasture yield											
		Year 1	**Year** 2	**Year** 3	**Year** 4	**Year** 5	**Year** 6	**Year** 7	**Year** 8	**Year** 9	**Year** 10
Yield ratio											
Walnut		1,0351	1,0223	1,0115	1,0008	0,9901	0,9794	0,9686	0,9579	0,9472	0,9365
Chestnut		1,0373	1,0265	1,0180	1,0094	1,0008	0,9922	0,9837	0,9751	0,9665	0,9579
Cherry		1,0351	1,0180	1,0051	0,9922	0,9901	0,9794	0,9686	0,9579	0,9472	0,9365
Pear		1,0383	1,0265	1,0180	1,0094	1,0115	1,0051	0,9987	0,9922	0,9858	0,9794
Apple		1,0383	1,0287	1,0212	1,0137	1,0115	1,0051	0,9987	0,9922	0,9858	0,9794
Plum		1,0394	1,0308	1,0244	1,0180	1,0169	1,0115	1,0062	1,0008	0,9954	0,9901
Average pasture yield		1,0373	1,0255	1,0164	1,0072	1,0035	0,9954	0,9874	0,9794	0,9713	0,9633
Tree density (tree/ha)		16	16	16	16	16	16	16	16	16	16

Tree height (m)											
		Year 1	**Year** 2	**Year** 3	**Year** 4	**Year** 5	**Year** 6	**Year** 7	**Year** 8	**Year** 9	**Year** 10
Tree growth rate (MIN/MAX/ML)		**MIN**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**
		0,4	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
	10% less	2,79	3,33	3,78	4,23	4,68	5,13	5,58	6,03	6,48	6,93
Walnut		**3,10**	**3,70**	**4,20**	**4,70**	**5,20**	**5,70**	**6,20**	**6,70**	**7,20**	**7,70**
	10% more	3,41	4,07	4,62	5,17	5,72	6,27	6,82	7,37	7,92	8,47
Tree growth rate (MIN/MAX/ML)		**MIN**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**	**MAX**
		0,3	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4

Figure 6: Tab 3 – Relative pasture yield in the silvopasture tool by Franke (2017). It shows the relative pasture yield for specific tree species and calculates the average for the overall agroforestry plot.

Profitability based on revenue and costs

To assess the profitability of agroforestry systems, data on the revenue and costs for pasture was needed to calculate the profitability of the Business As Usual and to adapt pasture production in the agroforestry plot by the relative pasture yield. Table 6 describes the revenue based on the assumption that 10,000 kg pasture DM amounted to € 1100 revenue. Costs for seeds and contract work per ha were given by the farmer.

Table 6: Revenue and costs for pasture production of John Heesakkers' farm. Source: Heesakkers (2017, personal communication)

PASTURE	**Value (ha)**
Pasture yield DM	10000 kg
Price per uni	0.11 €
Seeds	252,47 €
Fertilizers	-
Crop protection	-
Contract work	235 €

For the Agroforestry Scenario (AS), the production of trees and the costs for implementation, maintenance and harvest were determined per tree species. Table 7 presents an overview on the production (kg) per tree, based on Heijerman-Peppelman and Roelofs (2010). In the tool, the revenue is calculated per year from the production of fruits (kg/tree) times the cost price (€/kg). For nut trees, harvest was not expected before year 10. Due to the similarity in growth and management to cherry trees, similar production rates were adopted for nut trees for every second year after year 10. Also for costs, values for cherry trees were used. Data on costs for walnuts and chestnuts were limited. This is why a similar price to cherries was assumed for walnuts, while for chestnut a slightly lower price was expected.

Table 7: Fruit production per tree species per year and corresponding cost prices. For pear the type Conference, for apple the type Elstar and for plum the type Opal St. Julien A were defined. The other fruit types remained undefined. Source: Heijerman-Peppelman & Roelofs (2010).

TREES	**Walnut**	**Chestnut**	**Cherry**	**Pear**	**Apple**	**Plum**
Cost price per fruit (€/kg)	4.00	2.00	4.76	0.73	0.74	1.54
Year 1 (kg/tree)	0	0	0	0	0	0
Year 2 (kg/tree)	0	0	0.8	2.8	5.33	0
Year 3 (kg/tree)	0	0	2.4	6	9.67	3.01
Year 4 (kg/tree)	0	0	5.6	14	13.67	6.02
Year 5 (kg/tree)	0	0	8	16	14.33	9.04
Year 6(kg/tree)	0	0	9.6	20	14.33	12.05
Year 7 (kg/tree)	0	0	10.4	22	14.33	18.07
Year 8 (kg/tree)	0	0	10.4	22	14.33	27.11
Year 9 (kg/tree)	0	0	10.4	22	14.33	27.11
Year 10 (kg/tree)	2.4	2.4	10.4	22	14.33	27.11
Year 11 (kg/tree)	2.4	2.4	10.4	22	14.33	27.11
Year 12 (kg/tree)	5.6	5.6	10.4	22	14.33	27.11
Year 13 (kg/tree)	5.6	5.6	10.4	22	14.33	27.11
Year 14 (kg/tree)	8	8	10.4	22	14.33	27.11
Year 15 (kg/tree)	8	8	10.4	22	14.33	27.11

Costs differed per tree species and per year. An overview for each tree species was established, which was split into labour activities and labour hours needed per tree. Activities in the implementation phase in year 1 comprised planting trees and setting wooden poles. As material costs in the implementation phase, wooden poles were calculated at a cost of € 70, fruit trees at € 50 and nut trees at € 50, when planted by Nitzsche (2017, personal communication). For the case study, lower prices were assumed. The wooden poles were calculated at a cost of € 50, fruit trees at € 20 and nut trees at € 50.

From year 2, the maintenance of trees started, where pruning, thinning out and cancer protection were involved. It was assumed that trees needed to be pruned each year to ensure proper fruit production (Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, 2009). From year 10, pruning took place every 3-5 years and was added by activities of thinning out and cancer protection. Harvest was divided into preparing the harvest (spreading boxes and harvest material, instructing pickers, control, administration and providing packaging), picking and sorting fruits from approximately year 4. Each of these activities were split according to skilled labour with a cost of € 26.28, lesser skilled and irregular labour with a cost of € 16.00 and unskilled labour of € 9.12 (Spruit & Van der Voort, 2015). Table 8 shows an example on pear trees. The cost overview for the other tree species is found in Table 22 to Table 26 in Appendix 2.

Table 8: Cost overview example for a pear tree, distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Source: Heijerman-Peppelman & Roelofs (2010).

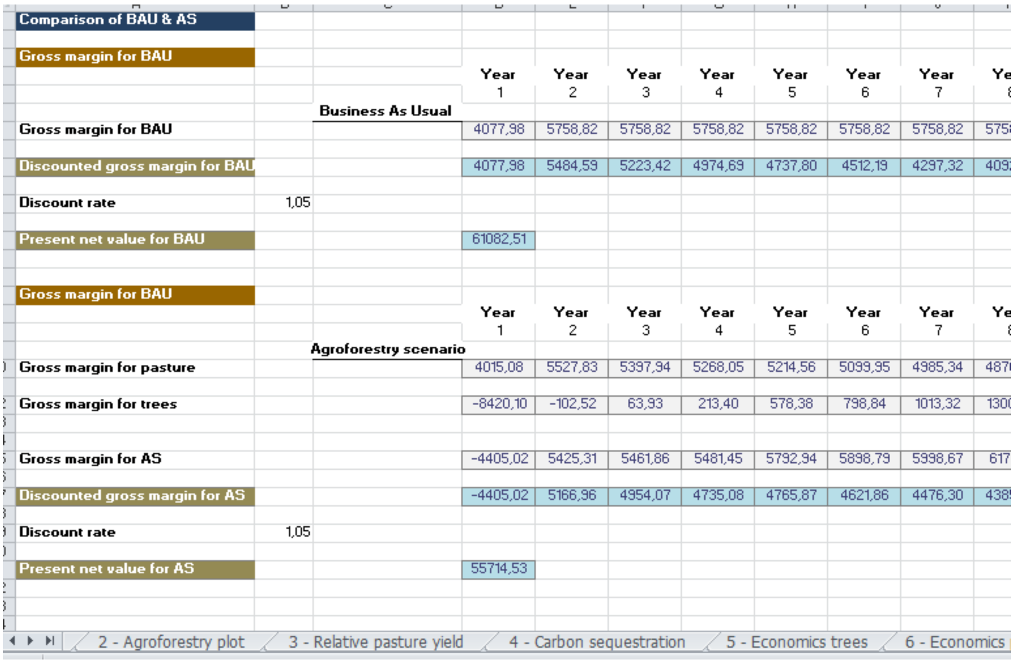
PEAR	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.022	0.58		
	Setting wooden poles	0.0168	0.44		
Maintenance (from year 2)	Pruning	0.04	1.05		
Maintenance (from year 4)	Thinning out and cancer protection	0.024	0.63		
Harvest (from year 4)	Preparing harvest	0.0076	0.2		
	Picking (for max. 900 kg)	0.024			0.22

Additional to these costs, the lost pasture area was accounted for as trees are planted in a tree row width of 1.5 m. The lost area was subtracted from the total area and translated into pasture yield (kg) DM that was thought to be imported to meet the requirements of animal feed under Business As Usual conditions.

To calculate the present net value (€) for Business As Usual and the Agroforestry Scenario, the discounted gross margin was estimated using a discounting factor of 1.05. The following formula was used:

$$\text{Discounted gross margin in year n} = \frac{\text{Gross margin of year n}}{1.05^{n-1}}$$

For the net present value, the outputs of the discounted gross margin were added up for 15 years. Figure 7 shows Tab 7 – Comparison of BAU & AS, where the profitability of agroforestry systems is presented.



Comparison of BAU & AS

Gross margin for BAU

Business As Usual		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Gross margin for BAU		4077,98	5758,82	5758,82	5758,82	5758,82	5758,82	5758,82
Discounted gross margin for BAU		4077,98	5484,59	5223,42	4974,69	4737,80	4512,19	4297,32
Discount rate	1,05							
Present net value for BAU		61082,51						

Gross margin for BAU

Agroforestry scenario		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Gross margin for pasture		4015,08	5527,83	5397,94	5268,05	5214,56	5099,95	4985,34
Gross margin for trees		-8420,10	-102,52	63,93	213,40	578,38	798,84	1013,32
Gross margin for AS		-4405,02	5425,31	5461,86	5481,45	5792,94	5898,79	5998,67
Discounted gross margin for AS		-4405,02	5166,96	4954,07	4735,08	4765,87	4621,86	4476,30
Discount rate	1,05							
Present net value for AS		55714,53						

Figure 7: Tab 7 – Comparison of BAU and AS in silvopasture tool by Franke (2017), showing the discounted gross margin (€) and net present value (€) for the Business As Usual and the Agroforestry Scenario

Carbon storage based on diameter of tree trunk

To calculate the carbon storage of trees in the agroforestry plot, the Cool Farm Tool, an online greenhouse gas and biodiversity calculator for farmers was used. One of the components of the tool is the calculation of carbon sequestration in trees, based on the diameter of tree trunk (cm). The following formula is used for temperate US eastern hardwoods (Van Tonder & Hillier, 2014).

$$\text{Carbon storage (kg/tree)} = 0.5 + \frac{25000 * DBH^{2.5}}{DBH^{2.5} + 246872}$$

Where DBH represents the diameter of tree trunk (cm) at breast height

Because the formula was based on the measurements of natural forests in the United States, the outputs of carbon sequestration in kg per fruit and nut trees were often not correctly represented (Ledo, 2017, personal communication). A new approach takes into account the below and above ground biomass of apple trees. These values are irrespective of the growth of the tree trunk because biomass was weighed to estimate the parameters that described the growth curve of apple trees. The following formula was used to account for carbon storage in apple trees.

$$\text{Carbon storage (kg/tree)} = \alpha * \text{AGE}^{\beta}$$

Where AGE represents the age of trees and α and β are specific parameters to describe the growth curve of the tree. Source: Ledo (2017, personal communication)

As values were only available for apple and citrus trees, the old formula was adopted in this thesis. The difference in carbon storage outputs for apple trees in both approaches was compared in the discussion section. For this, the diameter of the tree trunk (cm) per year was needed. Similarly to tree heights, there are no accurate values available in literature. Table 9 shows an overview on the maximum diameter for available tree species and Table 10 the estimations of Zapfe (2017, personal communication) on how the diameter of tree trunk grows with increasing tree height.

Table 9: Diameter (cm) of tree trunk for carbon storage calculations. Source: Wiselius (2005)

	Diameter (cm)	**Maximum diameter (cm)**
Walnut	50 – 90	150
Chestnut	60 – 100	150
Cherry	60 – 80	
Pear	30 – 40	70
Apple	20 – 30	40

Table 10: Overview on diameter (cm) growth of tree trunk with regard to tree age and tree height. Source: Zapfe (2017, personal communication)

Year	**Height (m)**	**Diameter (cm)**
3	3	7 – 8 8 – 10
6	4 – 5	12 – 14 14 – 16
9-10	6 – 7	16 – 18 18 – 20

Based on these estimations, a linear relation between tree height (m) and diameter (cm) growth was established (Appendix 2), which was described as:

$$DBH = 2.8531 * HEIGHT$$

Where DBH represents the diameter of tree trunk (cm) at breast height and HEIGHT represents tree height (m)

2.4. Evaluation of different tree configurations

The excel tool was used to evaluate four scenarios that differ in tree density (trees ha^{-1}) and tree height (m). The establishment of the scenarios was based on the assumption that tree height and tree density affected relative pasture yield differently. Moreover, by identifying the best spatial tree configurations for concrete objectives, farmers were thought to be able to rank them according to their practical concerns. As Figure 8 presents, four different scenarios were established in line with low to high tree height and low to high tree density. In line with the three research questions, the following objectives were identified, which were evaluated through the four scenarios:

1. Minimize pasture yield loss
2. Maximize profitability
3. Maximize carbon storage in trees

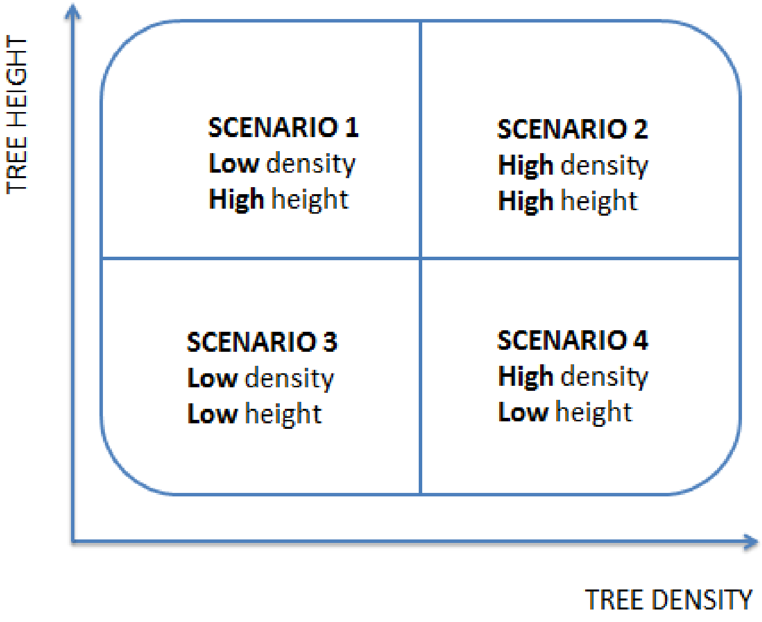


Figure 8: Four scenarios for evaluating tree configurations with regard to tree density (trees ha^{-1}) and tree height (m) by Franke (2017). Scenario 1: high tree height, low density; Scenario 2: high tree height, high density; Scenario 3: low tree height, low density; Scenario 4: low tree height, high tree density

As features for the scenarios, low tree density was set at 6 tree rows and high tree density at 24 tree rows. Tree height differed by the choice for smaller trees opposed to taller trees. For the scenarios of small tree species pear, apple and plum trees were chosen and for the scenarios of tall trees all trees were included in the agroforestry system, meaning walnut, chestnut, cherry, pear, apple and plum trees. Table 11 presents the features of the scenarios based on number of tree rows, total amount of trees, tree density (trees ha^{-1}) and maximum tree height (m) after 15 years.

Table 11: Overview of the four agroforestry scenarios differing in number of tree rows, total number of trees, tree density (trees ha-1) and maximum tree height (m) in year 15

	Number of tree rows	**Total number of trees**	**Tree density (trees ha^{-1})**	**Maximum tree height (m) in year 15**
Scenario 1: Low density High height	6	107	16	9.45
Scenario 2: High density High height	24	428	64	9.45
Scenario 3: Low density Low height	6	130	20	6.45
Scenario 4: High density Low height	24	519	78	6.45

For each objective of minimum pasture yield loss, maximum profitability and maximum carbon storage the four scenarios for evaluated for year 1-5, for year 6-10, for year 11-15 and in total.

2.5. Expert interviews and field visits

Farmer interviews and farm visits

The contact with John Heesakkers was arranged by Roos de Adelhart Toorop from Wageningen University through the Climate CAFÉ project that focused on climate change adaptation of organic farms in the Netherlands in collaboration with other research organization in Europe. In October 2016, John Heesakkers and two other farmers who were known to be interested in adapting agroforestry practices were visited. From the visits, it became clear that John Heesakkers had clear design ideas in mind for one particular plot that was adopted as a case study in this thesis. From this initial meeting, a more regular contact via email and two more farm visits emerged. In the second meeting in February 2017, first insights were discussed and new directions taken on in the research process explained. John invited a landscape designer from his personal network, with whom ideas for the design were discussed. Shortly, before finishing the thesis a last meeting was arranged in March 2017 in which the final results of the thesis were presented. The intention of this meeting was to gain feedback from the farmer on how the scientific insights served his interests in implementing an agroforestry design. Before all meetings topic lists were prepared and all interviews took place in Dutch. The conversations were in an informal setting, where the interviews were mostly semi-structured and in a form of a dialogue, in which information was shared by both sides. The meetings were recorded and transcribed in form of short summaries to English.

Regular expert contact about profitability and carbon storage

Through Walter Rossing the contact to Laura van Vooren and Bert Reubens from Van Vooren et al. (2016) was established via Skype in November 2016. During the meeting, the idea emerged to expand Laura's work to the effect of trees on temperate pastures. Questions about the findings of the research and how the research was undertaken were addressed. Support was offered by Laura van Vooren via Skype and email, from which a regular contact emerged along the several steps of the economic analysis. For calculations on carbon storage, Alicia Ledo from the Cool Farm Tool was contacted via email. Similarly as with Laura van Vooren, a contact emerged first via email and then via skype in which questions about the research on greenhouse gas emissions of perennials were addressed. This opened the opportunity to use the formulas on carbon sequestration of trees and add insights of the new approach on calculating carbon from above and below ground biomass of apple trees, that she and her team were working on during the process of writing this thesis.

Semi-structured expert interviews via phone and e-mail

Additional knowledge was sought from experts on plant-soil interactions to gain more understanding about tree-pasture interactions affected by tree density and tree height. This was done via email, where the plotted data from the statistical analysis were displayed and asked whether the experts could make assumptions on the interactions between trees and pastures in temperate regions. For a few of these contacts, a short sending back and forth of questions developed. For tree heights, maximum height and growth rates, observations were collected at tree nurseries and from a practitioner from the personal network of the author of this thesis via email and phone. Once, first observations were collected, they were sent via email to the experts for verification. This showed to be less time consuming for the experts. Table 12 summarizes the expert contacts.

Table 12: Overview on expert interviews with regard to expertise and collected data

Reference	Expertise	Data
Postma, J.	Plant Sciences	Potential tree pasture interactions
De Deyn, G.	Soil quality	Potential tree pasture interactions
Cortois, R.	Plant-soil interactions	Potential tree pasture interactions
Kraus, S.	Tree nursery, Germany	Growth rate for tree height
Zapfe, S.	Tree nursery, Germany	Maximum tree height, height after 10 years, diameter of tree trunk in relation to tree height
Heyland, J.	Practitioner, Germany	Growth rate for tree height

Two days excursion to ‘Streuobst’ agroforestry systems in Germany

Through the professional network of the author of this thesis to gardeners, a contact to the landscape gardener Marcus Nitzsche was established. He takes care of the implementation and maintenance of ‘Streuobst’ agroforestry systems in the further surroundings of Cologne in the western part of Germany. After initial email contact, the opportunity opened up to join him at his work for two days in March 2017. Several agroforestry sites were visited which differed between recently planted young trees and mixed sites where young and old trees were found. Some of these sites were accessible for cows. Others were public natural area planted with trees. The quality of the agroforestry designs on different sites was assessed together with regard to distances between trees and the tree protection against cows. The researcher assisted at pruning activities and gained insights about the management of trees. These practical insights pathed the way to adopt the concept of the ‘Streuobst’ agroforestry system with the focus on fruit and nut trees as the core of this thesis.

3. Results

The first part of this chapter explores the effect of trees on temperate pastures, by investigating the effects of tree density, tree height and tree age on relative pasture yield. Plotted data from scientific sources and statistical correlations are shown for these relations. Moreover, interactions between trees and pasture are interpreted and reviewed in literature. In the second part, one relation, which through tree height (m) and tree density (trees ha^{-1}) in interaction showed a significant effect on relative pasture yield, is presented and operationalized.

3.1. Effect of trees on relative pasture yield

This chapter assesses the effect of tree density, tree height and tree age on relative pasture yield, which formed the foundation for addressing the research questions in the second part of this chapter.

Statistical analysis of tree density, tree height and tree age

Table 13 summarizes the statistical relations tested for the effect of trees on relative pasture yield. The output of the mixed effects model is found in Table 27-34 in Appendix 3. The explanatory variables were tree density (trees ha^{-1}), tree age (years) and tree height (m). Additionally, the relation between tree age and tree height was tested as both variables were found to have a significant effect on relative pasture yield. Since no significant effect of tree density on relative pasture yield was found, tree density was examined stepwise and in interaction with tree age and tree height as both affecting relative pasture yield. The variables tree density and tree height interacting with each other were found to have a significant effect on relative pasture yield.

Table 13: Overview on explanatory variables and regression equations analysed with regard to significance and variance. The results for variance R^2c takes into account the random factor of the scientific source. Where RY represents relative pasture yield, DENSITY represents trees per ha (trees ha^{-1}), AGE represents tree age (years) and HEIGHT represents tree height (m)

Explanatory variables	Regression equation	Significance (p-value)	Variance (R^2m) for fixed effects	Variance (R^2c) for fixed and random effects
Tree density Figure 9	**RY** = 0.75 (±0.073) – 0.000009 (±0.00003) * DENSITY	NO: p = 0.78	R^2m = 0.002	R^2c = 0.3
Tree age Figure 10	**RY** = 0.98 (±0.08) – 0.02 (±0.05) * AGE	YES: p = 0.0005	R^2m = 0.318	R^2c = 0.436
Tree height Figure 11	**RY** = 0.9 (±0.06) – 0.02 (±0.05) * HEIGHT	YES: p = 0.0002	R^2m = 0.286	R^2c = 0.39
Tree age on height Figure 12	**HEIGHT** = 0.49 (±1.48) – 0.8 (±0.05) * AGE	YES: p = 0.0000	R^2m = 0.811	R^2c = 0.976
Age and	**RY** = 1.1 (±0.11) – 0.02	NO:	R^2m = 0.378	R^2c = 0.528

density: stepwise (AGE + DENSITY)	($\pm$0.006) * AGE - 0.00005 ($\pm$0.00003) * DENSITY	p = 0.0002 (AGE); p = 0.099 (DENSITY)		

Age and density: interacting variables (AGE * DENSITY)	**RY** = 1.21 ($\pm$0.014) – 0.024 ($\pm$0.007) * AGE + 0.00001 ($\pm$0.00005) * DENSITY – 0.00003 ($\pm$0.00002) * AGE * DENSITY	NO:
		p = 0.0011 (AGE);
		p = 0.8482 (DENSITY);
		p = 0.0416 (AGE * DENSITY)
			$R^2m = 0.31$	$R^2c = 0.662$

Height and density: stepwise (HEIGHT + DENSITY)	**RY** = 0.98 ($\pm$0.08) – 0.02 ($\pm$0.006) * HEIGHT - 0.00004 ($\pm$0.00003) * DENSITY	NO: p = 0.0002 (HEIGHT); p = 0.16 (DENSITY)	$R^2m = 0.322$	$R^2c = 0.471$

Height and density: interacting variables (HEIGHT * DENSITY)	**RY** = 1.08 ($\pm$0.01) – 0.02 ($\pm$0.007) * HEIGHT + 0.0001 ($\pm$0.00006) * DENSITY – 0.00009 ($\pm$0.00003) * HEIGHT * DENSITY	YES:
		p = 0.0043 (HEIGHT);
		p = 0.0415 (DENSITY);
		p = 0.0003 (HEIGHT * DENSITY)
			$R^2m = 0.388$	$R^2c = 0.654$

Figure 9 presents the data of relative pasture yield (RY) as a function of tree density (trees ha^{-1}) (relation not significant, cf. Table 13). Since no significant effect was found, the equation of density on RY was not plotted. The variance for fixed effects was very low ($R^2m = 0.002$), but the extent to which the mixed effects model accounted for the variation of RY was improved when the random factor per scientific source was taken into account ($R^2c = 0.3$).

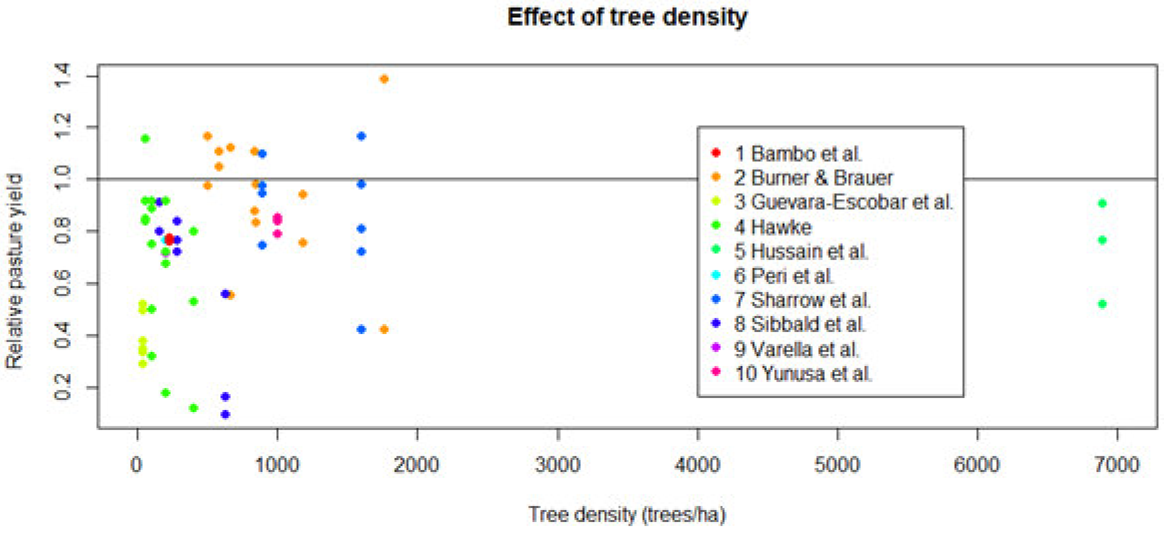


Figure 9: Relative pasture yield as a function of tree density (trees ha^{-1}) in the agroforestry plot: no significant relationship with p = 0.78. Sources included: Bambo et al. (2009), Burner & Brauer (2003), Guevara-Escobar et al. (2007), Hawke (1991), Hussain et al. (2009), Peri et al. (2007), Sharrow et al. (1996), Sibbald et al. (1991), Varella et al. (2011), and Yunusa et al. (1995)

Figure 10 and Figure 11 display the data of the effect of tree age (years) and tree height (m), respectively, on relative pasture yield. Both variables showed a significant effect on relative pasture yield (AGE: p = 0.0005, HEIGHT: p = 0.0002). Comparing the variances for fixed and random effects for both variables showed that variation of relative pasture yield was better captured by the effect of tree age on RY than by the effect of tree height (AGE: $R^2c = 0.436$; HEIGHT: $R^2c = 0.39$).

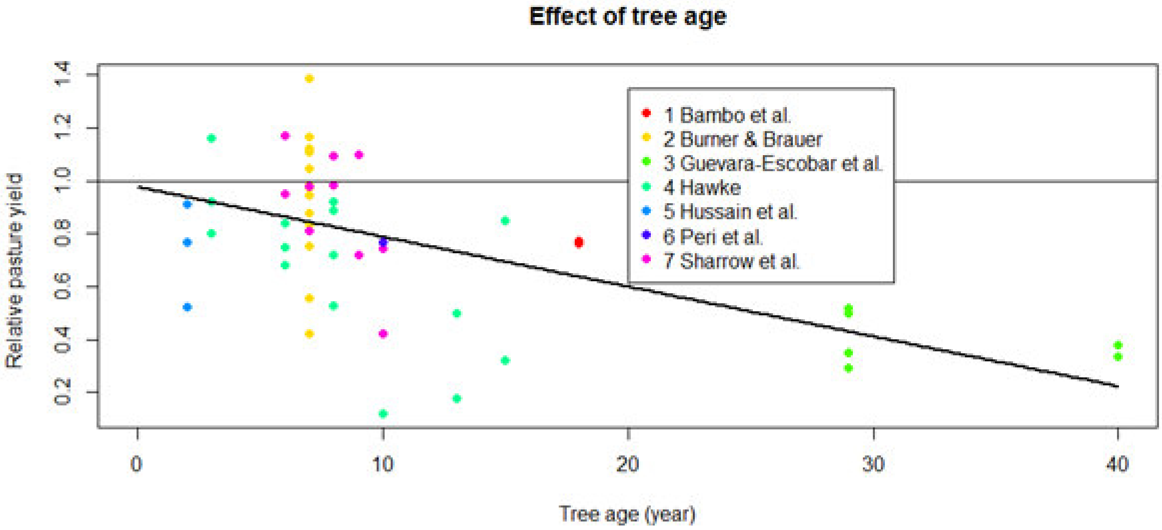


Figure 10: Effect of tree age (year) on relative pasture yield (t ha^{-1}) in the agroforestry plot: significant relationship with p = 0.0005. Sources included: Bambo et al. (2009), Burner & Brauer (2003), Guevara-Escobar et al. (2007), Hawke (1991), Hussain et al. (2009), Peri et al. (2007), Sharrow et al. (1996)

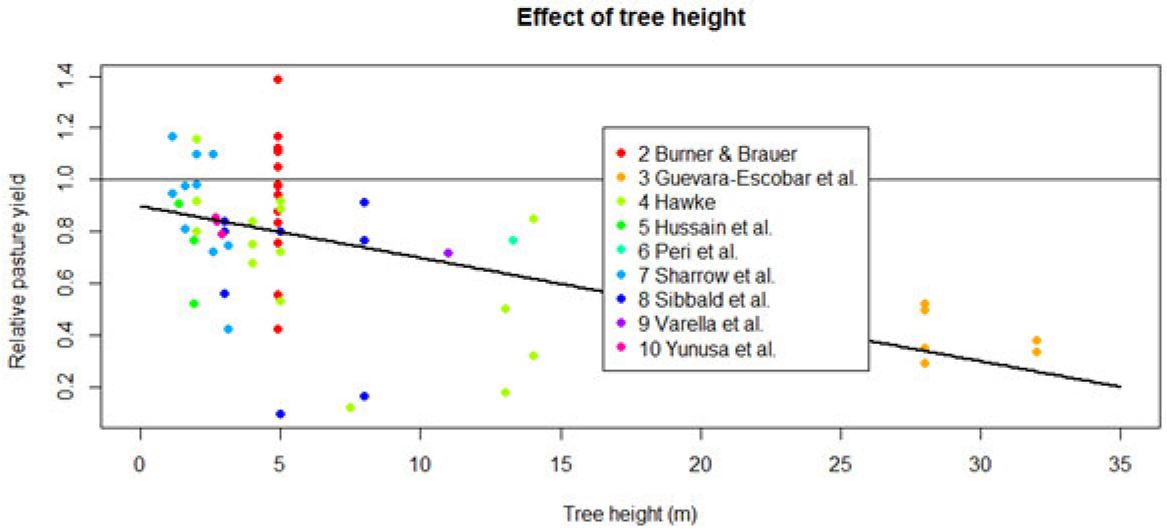


Figure 11: Effect of tree height (m) on relative pasture yield (t/ha^{-1}) in the agroforestry plot: significant relationship with p = 0.0002. Sources included: Burner & Brauer (2003), Guevara-Escobar et al. (2007), Hawke (1991), Hussain et al. (2009), Peri et al. (2007), Sharrow et al. (1996), Sibbald et al. (1991), Varella et al. (2011), and Yunusa et al. (1995)

Figure 12 shows the relation between tree age (years) and tree height (m), which was found to be significant (p = 0.0000) and expressed through a high variance ($R^2m = 0.811$; $R^2c = 0.976$). The plotted line indicated that tree height increased with tree age.

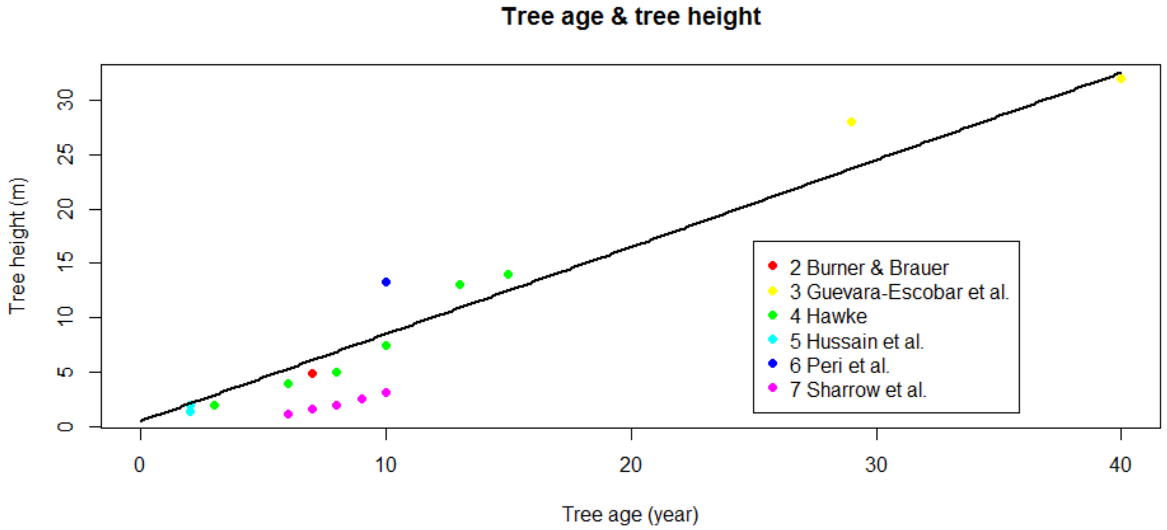


Figure 12: Effect of tree age (year) on tree height (m): significant relationship with p = 0.0000. Sources included: Burner & Brauer (2003), Guevara-Escobar et al. (2007), Hawke (1991), Hussain et al. (2009), Peri et al. (2007), and Sharrow et al. (1996)

Tree density was investigated further in relation to tree age and tree height. When considering the additive effects of tree age and tree density on RY, no significant relation was found. Even though the p-value for tree age indicated a significant effect (AGE: p = 0.0002), the p-value for tree density did not (DENSITY: p = 0.099). This meant that the addition of tree density to tree age was not meaningful as changes in RY could not be attributed to changes in tree density. The same accounted for a stepwise approach for tree height and tree density, where the relation was not found to have a significant effect on relative pasture yield (HEIGHT: p = 0.0002; DENSITY: p = 0.16).

The effects of tree density and tree age in their interaction on RY showed no significant effect because tree density did not show a significance (DENSITY: p =0.85). In contrast, the effects of tree height and tree density in their interaction on RY showed a significance of all factors (HEIGHT: p = 0.0043; DENSITY: 0.0415; HEIGHT * DENSITY: p = 0.0003)**.** The slopes of the equation indicated that at increasing tree density relative pasture yield went up (slope 0.0001 ±0.00006), while for increasing tree height relative pasture yield went down (slope -0.02 ±0.007). The strength of the slope indicated that the effect of tree height was 200 times higher than the effect of tree density. The interaction of tree height and tree density resulted in a negative effect on relative pasture yield (slope -0.00009 ±0.00003), which was even lower than the slopes of tree height and tree density separately. From these results, it was assumed that a scenario of high tree densities at low tree height has a higher relative pasture yield than a scenario, where there is a smaller density of tall trees. The variance of fixed and random effects of tree density and tree height in interaction was the highest (R^2c = 0.654) compared to the effects of tree height and tree age alone. This led to the decision to operationalize the effects of tree height and tree density in their interaction on RY and to analyse the outcomes of different spatial tree configurations.

Reviewing tree-pasture interactions

Despite of the gradual reduction of relative pasture yield in the agroforestry plot at increasing tree height (m) and tree density (trees ha^{-1}), some observations showed to be higher or almost equal to 1 (Figure 9, Figure 10, Figure 11). For these observations, the agroforestry plot yielded more pasture yield than the open pasture under same conditions. This is similar to the findings of Van Vooren et al. (2016), who showed a positive effect of trees on crop productivity, dependent on the distance from and the height of the tree row. Table 14 presents an overview on the experimental design, the experimental factors assessed in the research and the outcomes of the scientific sources analysed statistically in the previous section. The grey marked sources 2, 4 and 7 stand for observations almost equal or higher to the yield in open pasture. Tree density, tree height and tree age are stated in capital letters to better relate the scientific sources to the variables tested statistically.

Table 14: Overview of the ten scientific sources with regard to tree species, experimental design, experimental factors and outcomes of study.

Source	Tree species	Experimental design	Experimental factors	Outcomes of study
1	Pine	US: Four different forage	*(focus on forage*	Open pasture on average

		treatments arranged randomly within tree configuration; control	*species)*	more DM
2	Pine	US: Randomized complete block design; different within-row and alley spacing; control	Row spacing (DENSITY)	Row spacing affected the yield, quality, and botanical composition
3	Poplar	NZL: Three livestock farms with mature trees, not replicated on control	Tree canopy growth (AGE) and soil water	Greatest effect of poplar on pasture production due to shading
4	Pine	NZL: Randomized block design; different stems per ha; open pasture	DENSITY; AGE	Pasture growth decline with increasing tree stocking and age
5	Willow, poplar	NZL: Randomized complete block design; densely planted young trees; control	Tree canopy cover (DENSITY); Tree species	Significant reduced pasture growth; more prominent under willow due to larger canopy
6	Pine	NZL: different light transmission regimes for open and silvopasture	Shading (artificial)	Lower DM production rates in heavily shaded pastures
7	Douglas fir	US: Grid plot and cluster plot design resulting in different densities	Tree canopy cover (DENSITY; AGE)	Understory forage production no substantial decrease until tree canopy cover exceeds
8	Sitka spruce	UK: Transferred boxes sown with pasture; trees with different heights at different spacing; control	DENSITY; HEIGHT; pruning	Herbage production significantly reduced by trees of all heights
9	Pine	NZL: Split-split plot randomized block with artificial shade structures	Shading (artificial)	The mean dry matter yield under trees less than in open pasture
10	Pine	NZL: Randomized complete block design of treatments at young tree age	AGE; Seasonality	Little effect by the presence of trees, but seasonal trends

Competition for light

In all sources in Table 14, pasture yield was reduced by shading due to increased competition for light by increasing tree canopy cover. Clearly in line with the statistical findings that showed an effect on relative pasture yield when tree density and tree height were interacting with each other, tree density, tree height and tree age were the main experimental factors examined in the ten scientific sources. Burner & Brauer (2003) in source 2 concluded that yield decreases with decreasing row spacing. Presenting the same line of argumentation, Hawke (1991) in source 4 stated that pasture growth declined with increased tree densities and tree age. These two factors determine the transmission of light onto the pasture. Sharrow et al. (1996) in source 7 showed that for a tree canopy cover of 19%, pasture yield was almost the same as for open pasture, while an increase of cover to 49% and 74% resulted in a pasture yield for the agroforestry plot that produced only 70%

pasture yield for nine year old trees and 40% pasture yield for ten year old trees. In contrast, wider spaced configurations yielded more because canopy cover reached only 24%, when trees were ten years old (Sharrow et al., 1996). Similarly, Varella et al. (2011) in source 9 examined that pasture yield amounted to 72% compared to the yield of open pasture due to light transmittance of 49% under trees. Furthermore, Peri et al. (2011) in source 6 calculated a reduction of 22% pasture yield due to a light transmittance of 58% under trees.

Explanatory factors for other research outcomes besides the competition for light capture, either through tree density, tree height or tree age were almost not stated in the scientific sources. To illustrate, pruning had a significant effect on light capture at agroforestry sites in New Zealand as stated in source 4 (Hawke, 1991) and seasonality showed different temporal demands of trees and plants in source 10 (Yunusa et al., 1995). In contrast, soil water did not show a significant effect on pasture yield in New Zealand as was concluded in source 3 (Guevara-Escobar et al., 2007). In short, the light transmission limited by the growing tree canopy over time or by a large canopy cover through increased tree densities confirmed the findings of a gradual reduction of pasture yield expressed by the statistical relationships calculated in the previous section.

Potential mechanisms for enhanced pasture productivity

Understanding the competition for light through the tree canopy as one interaction between trees and pastures does not explain why some observations at low tree density and tree height result in relative pasture yield greater than 1. This was found in the experiments of Burner & Brauer (2003), Hawke (1991) and Sharrow et al. (1996). Hawke (1991) in source 4 claimed that trees at low densities may reduce the effects of other factors reducing pasture yield, referring to the improvement of the microclimate. For a density of 50 trees per ha, pines at the age of three years yielded 116% of pasture compared to open pasture, while at 13 years, pasture was reduced by 15 % in the agroforestry plot (Hawke, 1991). Burner and Brauer (2003) claimed that there are nearly no effects on pasture yield for young trees, but they do not report why pasture yield in the agroforestry plot is higher in some observations of the same tree age and for others it was not. Sharrow et al. (1996) also did not explain potential mechanisms behind the few observations of pasture yield scoring better in an agroforestry plot.

Experts in the field of plant-soil interactions were asked to present assumptions on these findings. Postma (2017, personal communication) concluded that trees may increase pasture yield due to shading and hydraulic lift, dependent on tree density, distance to the tree, major wind direction and water availability. Similarly, De Deyn (2017, personal communication) argued that pasture might profit from beneficial effects of trees by the uplift of water and nutrients, taken place indirectly by tree litter. Litter composition is, however, a gradual process that makes nutrients only available upon mineralization, which may take time depending on climatic conditions. Accordingly, Cortoir (2017, personal communication) argued that the effect of increased nutrient availability of plant litter would not be relevant for increased pasture yield. For answering how pasture yield was affected, especially in the first years of tree growth where tree litter is limited, more knowledge on (micro)climatic conditions of the scientific sources would be needed. This is why the improvement of microclimates remained one potential explanation for the positive results on relative pasture yield in agroforestry plots.

3.2. Quantification and evaluation of different spatial tree configurations

This part addresses the three research questions by evaluating four different scenarios of spatial tree configurations with regard to the objectives to minimize pasture yield loss, to maximize profitability and to maximize carbon storage in trees. The following three sections show in detail how the scenarios differ in their outputs profitability and carbon sequestration and compare them to the Business As Usual (BAU) scenario.

Objective 1: Minimize pasture yield loss

The absolute and relative differences between BAU and each of the four scenarios were calculated in Table 15.

Table 15: Outputs of silvopasture tool on minimum pasture yield loss (t DM/ha) for four agroforestry scenarios differing in tree height (m) and tree density (trees ha^{-1})

		Year 1 – 5	Year 6 – 10	Year 11 – 15	TOTAL
Business As Usual	Pasture yield t (DM/ha)	50	50	50	150
Scenario 1:	Pasture yield t (DM/ha)	49	48	46	143
Low density	Absolute difference t (DM/ha)	-1	-2	-4	-7
High height	Relative difference (%)	98%	96%	92%	95%
Scenario 2:	Pasture yield t (DM/ha)	45	43	41	129
High density	Absolute difference t (DM/ha)	-5	-7	-9	-21
High height	Relative difference (%)	90%	86%	82%	86%
Scenario 3	Pasture yield t (DM/ha)	50	48	48	146
Low density	Absolute difference t (DM/ha)	0	-2	-2	-4
Low height	Relative difference (%)	100%	96%	96%	97%
Scenario 4	Pasture yield t (DM/ha)	45	43	42	130
High density	Absolute difference t (DM/ha)	-5	-7	-8	-20
Low height	Relative difference (%)	90%	86%	84%	87%

The difference between scenarios 1 and 3 and scenarios 2 and 4 was the greater loss of pasture area due to greater tree density. For scenarios 1 and 3 this amounted to 6.48 ha of in total 6.66 ha agroforestry plot available for pasture production, while for scenarios 2 and 4 only 5.94 ha were available. Over the years and in total, scenario 3 minimized pasture loss because it included smaller trees that have a smaller effect on pasture yield. Overall, there was only a difference of 97% of pasture production with BAU, which translated into 4 t DM/ha that needed to be imported to meet animal feed requirements of the agroforestry plot. Slightly more import was needed in scenario 1, where relative pasture yield was affected by the greater height of walnut, chestnut and cherry trees compared to scenarios 3 and 4. This amounted to 1 t DM/ha additionally needed feed. Both of these scenarios, however, showed a small reduction of overall pasture yield compared to BAU. In contrast, scenarios 2 and 4 with tree densities of 64 and 78 trees ha^{-1} respectively, resulted in 90% reduction of pasture production after 5 years. Averaged over 15 years pasture production was reduced by 86% and 85% of BAU, respectively. In sum, scenario 3 and scenario 1 would be the best options for a farmer who wishes to minimize pasture yield loss. A motivation for choosing such a spatial configuration would be the financial cost of having to import additional feed for dairy cows.

Objective 2: Maximize profitability

For determining the profitability of agroforestry systems, the discounted gross margin (€) was compared between BAU and the four agroforestry scenarios. For the scenarios, the costs of buying feed due to pasture yield loss, the costs of implementing and maintaining trees and the revenues of fruit and nuts were included in Table 16.

Table 16: Outputs of silvopasture tool on maximum profitability (€/plot) for four agroforestry scenarios differing in tree height (m) and tree density (trees ha^{-1})

		Year 1 – 5	Year 6 – 10	Year 11 – 15	TOTAL
Business As Usual	Discounted gross margin (€/plot)	24498	20512	16072	61082
Scenario 1	Discounted gross margin (€/plot)	15217	21954	18543	55714
Low density	Absolute difference (€/plot)	-9281	1442	2471	-5368
High height	Relative difference (%)	62%	107%	115%	91%
Scenario 2	Discounted gross margin (€/plot)	-17093	28469	30446	41822
High density	Absolute difference (€/plot)	-41591	7957	14374	-19260
High height	Relative difference (%)	-70%	139%	189%	68%
Scenario 3	Discounted gross margin (€/plot)	15211	25620	21733	62564
Low density	Absolute difference (€/plot)	-9287	5108	5661	1482
Low height	Relative difference (%)	62%	125%	135%	102%
Scenario 4	Discounted gross margin (€/plot)	-18031	40867	40568	63404
High density	Absolute difference (€/plot)	-42529	20355	24496	2322
Low height	Relative difference (%)	-74%	199%	252%	104%

In years 1-5, all scenarios showed a financial loss due to implementation costs in year 1. Scenarios 1 and 3 with lower tree densities recovered some of the costs later on and had a discounted gross margin of 62% of BAU. Scenarios 2 and scenario 4 had a financial loss of more than half of what was earned by pasture production in BAU due to high tree densities. From year 5 onwards, a recovery of cash flow took place for scenario 4 where the revenue of pear, apple and plum production balanced the initial implementation costs. Overall, scenario 4 had the highest profitability after 15 years with 104% of BAU. After this followed scenario 3 with 102% of BAU, while scenarios 1 and 2 only reached 68% of the profitability in BAU. Scenarios 3 and 4 included pear, apple and plum trees that were able to cover costs earlier than scenarios 1 and 3, where all trees were added to the spatial design. The difference in profitability was caused by walnut and chestnut trees as the revenue of nut production was obtained only later on. In none of the scenarios profitability exceeded BAU by more than 4 %.

Objective 3: Maximize carbon storage in trees

Carbon storage in t per ha and for the overall agroforestry plot was calculated for all four scenarios. Absolute values and the proportion of the total are shown in Table 17.

Table 17: Outputs of silvopasture tool on maximum carbon storage in trees (t) for four agroforestry scenarios differing in tree height (m) and tree density (trees ha^{-1})

		Year 1 – 5	**Year** 6 – 10	**Year** 11 – 15	**TOTAL**
Scenario 1	Carbon storage (t/ha)	3	8	13	24
Low density	Carbon storage (t/plot)	23	56	87	166
High height	Proportion of total (%)	13%	33%	54%	100%
Scenario 2	Carbon storage (t/ha)	17	34	52	103
High density	Carbon storage (t/plot)	91	225	347	663
High height	Proportion of total (%)	17%	33%	50%	100%
Scenario 3	Carbon storage (t/ha)	7	8	11	26
Low density	Carbon storage (t/plot)	24	50	70	144
Low height	Proportion of total (%)	27%	31%	42%	100%
Scenario 4	Carbon storage (t/ha)	14	30	86	130
High density	Carbon storage (t/plot)	95	198	280	573
Low height	Proportion of total (%)	11%	23%	66%	100%

Over 15 years, scenarios 2 and 4 had the highest amount of carbon stored in tree biomass. This was because these two scenarios had a high tree density compared to the other two. After 10 years, scenario 4 produced more biomass than scenario 2 because in total more trees could be planted. This were 478 trees for scenario 2 and 519 trees for scenario 4 because smaller trees demanded smaller distances between trees in a row. Overall, scenario 4 stored 130 t carbon per ha and 573 t carbon on the agroforestry plot. In comparison, scenarios 1 and 3 stored only a fifth of what was stored in scenario 4, 24 t per ha and 26 t per ha respectively.

4. Discussion and conclusions

The following section discusses and critically assesses the findings of this thesis. Practical implications for John Heesakkers are addressed and recommendations made for future research. The conclusions briefly summarize findings and reflect on the societal relevance of this research.

4.1. Discussion

Effect of trees on relative pasture yield

Selected and analysed data

Ten scientific sources of silvopastoral experiments were analysed for the effect of tree density, tree age and tree height on relative pasture yield In contrast to common statements in scientific literature (Burner & Brauer, 2003; Hawke, 1991; Hussain et al., 2009; Sharrow et al., 1996 and Sibbald et al., 1991), no significant effect of tree density alone on pasture yield was found. One concern in the analysis of tree density was the intercept of the function, which for tree density at 0 did not start at 1, but at 0.75. An intercept of approximately 1 was expected since it was assumed that for tree density at 0 100% pasture yield would be evident. This could be explained by the poorly specified experimental designs, which required tree density to be calculated based on tree row spacing and available tree rows. Moreover, only a very limited amount of data was available for statistical analysis since silvopasture systems were scarce in scientific literature.

Using the relation between relative pasture yield and tree age or tree height alone would have resulted in a reduction of pasture yield over time which corresponded to the majority of available data in literature (Guevara-Escobar et al., 2007; Hawke 1991; Sharrow et al., 1996 and Yunusa et al., 1995). This approach however would have neglected the positive interactions of trees and pastures found for young trees, which were also found by Van Vooren et al. (2016) on the distance to the tree. This is why the operationalization of the relation of tree height and tree density in their interaction on relative pasture yield was chosen. Nevertheless, a prudent interpretation of tree density as an explanatory factor on relative pasture yield is needed and more research should be done to understand under which circumstances relative pasture yield might potentially yield more pasture in the agroforestry plot than in pastures without trees.

Review on potential mechanisms for tree-pasture interactions

In the second part of the study on the effect of trees on relative pasture yield, scientific sources were reviewed to identify the underlying mechanisms for tree-pasture interactions. Due to the high variation of experimental designs and lack of explicit information in the scientific sources it was not possible to identify concrete mechanisms that gave explanations for the effects of tree density and height in interaction. Increased tree canopy cover was identified as the main mechanism responsible for an overall reduction of relative pasture yield in the agroforestry plot over time. Improved microclimate due to the integration of trees on pastures was a hypothesis that emerged as a potential explanation from the scientific sources and from the expert interviews on soil-plant interactions. Stigter (2015) summarized the main factors influencing microclimates as the energy balance of trees and crops by a different interception of solar radiation, the precipitation due to modified interception of rainfall and the wind protection resulting in different flows upwards, downwards and among the trees. Positive effects of improved microclimate would be expected after a mature growth of tree canopy that modifies solar radiation, rainfall and wind on pastures. These assumptions could therefore not be confirmed with the positive interactions found for trees low tree height.

Fernández et al. (2002) concluded that pasture yield reduction in the agroforestry plot might occur a few years after planting if the sites are highly productive. They specified that “when trees are young and small, facilitation may be more important than competition; as trees become larger, competition may overshadow facilitation and adversely affect herbaceous production” (Fernández et al., 2002). Similarly, Tian et al. (2015) found that two experimental sites in the Unites Stated showed negative effects on pasture yield only after the fourth and sixth year of planting loblolly pine with switchgrass. An investigation of below-ground interactions between trees and pastures might help to understand these interactions. For instance, Gao et al. (2013) concluded for apple-soybean and apple-groundnut agroforestry systems in China that soil moisture was the primary factor affecting crop yield, which was followed by light interception and soil nutrient deficiency dependent on the crop type in the system. These findings corresponded to the conclusion of Jose et al. (2004) that the competition for water is the strongest driver for interspecific below-ground interactions in agroforestry systems as temperate pastures are usually well supplied with high inputs of nutrients. Of the scientific sources only one investigated the effect of soil water which was found to be similar on the agroforestry site and open pasture (Guevara-Escobar et al., 2007).

Gao et al. (2013) stated that both systems in China showed to be “beneficial” in the region if spacing was adjusted adequately to prevent competition among species. As with other scientific sources, it remained unclear to what extent and under which mechanisms these systems were ‘beneficial’. Moreover, it referred to tree density as being one of the main factors influencing relative pasture yield (Gao et al., 2013). Due to the poor quality and limited data of the scientific sources that were investigated in this thesis on the effect of trees on pasture productivity, it is therefore too soon to entirely neglect that density does not have an effect on pastures. In fact, it was presented that tree density in interaction with tree height affected relative pasture yield. More research on the quantification of positive tree-crop and tree-pasture interactions is therefore needed with a specific research emphasis on facilitation in agroforestry systems.

Quantification and evaluation of different spatial tree configurations

Assumptions for silvopasture tool inputs

The tool for quantification of agroforestry systems was adapted from the tool of Laura van Vooren from Van Vooren et al. (2016) and included the parameters tree height of six different tree species and tree density which was selected by the user. For each of the tree species, tree height was established per year which showed to be challenging due to an apparent lack of data. It became clear that fruit and nut trees received only very limited attention in scientific literature on agroforestry systems, whereas willow, poplar and pine were more popular. Despite of the lack of data, it was decided that a tree growth curve would more adequately describe the change of tree height over years than a linear regression. To acknowledge the effect of other factors on tree height such as climatic conditions at the agroforestry site, the silvopasture tool displayed a difference of 10% more or 10% less growth per year on Tab 3 – Relative pasture yield. Taking these ranges into account would be a way of critically assessing the change of tree height on profitability and carbon storage in the future.

For the calculations on carbon storage, tree height was used to estimate diameter of the tree trunk by a linear regression. Ledo et al. (2016) concluded that the calculation of carbon storage often is not adequately represented when tree aboveground biomass was calculated by estimating the diameter of tree trunk as a function of tree height. The results of this thesis for apple trees was compared to the calculations made by Ledo (2017, personal communication), who estimated the carbon storage of an apple tree after 5 years at 11 kg, after 10 years at 40 kg and after 15 years at 80 kg per tree. The comparison showed a large underestimation of represented carbon storage in trees because it was calculated in the silvopasture tool that 18 kg carbon can be stored in a 15 year old apple tree. This meant that the results of above ground carbon storage in apple trees in this thesis might be around four times larger than calculated by the diameter of tree trunk. Assessing carbon storage with the new approach in the future would help to make more realistic assumptions and could be further expanded to integrate overall GHG emissions for agroforestry systems.

For the calculations on profitability, the values for cost prices were based on research reported in 2010 by Heijerman-Peppelman and Roelofs. It needs to be taken into account that the cost prices do not reflect cost prices of more recent years, nor were cost prices for organic production considered. It would therefore be assumed that the farmer could ask a higher cost price for organic products which are sold at the farm directly to the consumer. Additionally, the production volumes of fruits in the research of Heijerman-Peppelman and Roelofs (2010) assumed production to end at year 8.

Bader and Kriesel (2005) estimated an average of 15-40 kg apple, 10-30 kg pear , 10-30 plum, 15-30 cherry and 10-30 walnut production per tree for full grown trees. This meant that the revenue of fruit production could even be higher than estimated in the silvopasture tool.

Reflection on evaluation of different spatial tree configurations

In the evaluation of different spatial tree configurations in light with the three objectives of minimizing pasture loss, maximizing profitability and maximizing carbon storage in trees, it was shown that the best-fitting scenarios differed for each objective. For minimizing the loss of pasture yield, low tree density contributed to a higher relative pasture yield than the scenarios of high tree density. For maximizing profitability, low tree height showed to have the best effect on economic calculations because pear, apple and plum trees produced earlier more fruits than as when cherry, walnut and chestnut trees were included. This was irrespective of the tree density, since the revenue from tree production covered the initial implementation costs in both cases. For maximum carbon storage, high tree density was the determining feature for a spatial design. If this criterion was met, there was no trade-off between profitability and carbon storage if the farm is able to cover the initial costs in the planting phase (scenario 4). In addition, a low tree density combined with low tree height did not result in a trade-off between profitability and pasture yield. Only the objectives of maximum carbon storage and minimum pasture yield are not met under the same conditions. This showed that spatial tree configurations are highly relevant for practical farm management decisions.

In the statistical analysis, where the effect of tree height and tree density in interaction was investigated, tree density did not have such a strong effect on relative pasture yield as tree height. This was shown in the interpretation of the slopes. In contrast, the tool of quantification showed that a change in tree density from low to high affected relative pasture yield immensely. To illustrate, high tree density resulted in a loss of pasture yield three times higher than in scenarios of low tree density. In comparison, tree height did not differ as much between the two scenarios of same density because the range of modification for tree height was more limited than the range of modification of tree density. In the scenarios low tree density from 16 and 20 trees ha^{-1} ranged to high tree density of 64 and 78 trees ha^{-1}, whereas tree height differed between low tree height and high tree height only by 3 metres. This thesis was limited to 15 years, but a more severe effect of tree height would be expected after 20-30 years when maximum tree height is reached for all trees included in the agroforestry design. Tree density was therefore not as irrelevant as was interpreted in the slope of the effects of tree height and tree density in interaction on relative pasture yield.

Practical implications

For farmers like John Heesakkers spatial tree configurations differing in tree height and tree density have significant effects on pasture yield, profitability and carbon storage. The silvopasture tool is a helpful tool to support decisions related to different practical concerns. A drawback of this tool is the restriction of selecting a tree row per tree species instead of the number of trees per tree species to be planted on an agroforestry plot. The core idea of this tool was to account for the relative pasture yield loss and for the spatial design of tree rows on pasture. A simpler version of this tool could focus on costs and revenues and carbon storage per tree species, whose amount is individually selected by the farmer. Though this would give insights into answering practical questions of profitability and carbon storage, important considerations of lost pasture area and changes in relative pasture yield would not be included in a simplification.

For John Heesakkers, a consideration of high or low density was less relevant since he envisioned 2-3 double tree rows at the moment of undertaking research. This corresponded best to the scenarios of low tree density. Scenario 1 included all tree species, whereas scenario 3 only pear, apple and plum trees. Both scenarios scored well for the objective of minimizing pasture yield loss due to the low tree density. Profitability was maximized in scenario 3 with a profit of 2%, whereas scenario 1 made a loss of 9%. This indicated that initial costs could be balanced, but a considerable profit not made from the integration of trees in the farming system. The quantification of carbon storage was considered by John Hesakkers as a potential economic output in the form of carbon credits. Though carbon storage would not be his main objective to define spatial tree configurations, it could serve as an additional source of revenue in the future. Additionally, initial implementation costs could be balanced by the introduction of a tree layer system that integrates shrubs like blackberry, gooseberry, blueberry or raspberry. A similar design was introduced by Shepard (2013).

The economic findings of this thesis confirmed the conclusions of Van Vooren et al. (2016) who called for the provision of extra financial stimuli for farmers to invest into agroforestry systems. Though costs were balanced after 15 years for two presented spatial tree configurations, the farmer would not be able to make a considerable profit from the additional farming activity. Graves et al. (2011) argued that profitability is the main decisive factor for farmers to integrate agroforestry systems. In the case of John Heesakkers, subsidies would balance the investments of € 8240 in the initial phase of planting trees. Considering positive tree-pasture interactions detected in this thesis and the quantification of carbon storage in trees as an ecosystem service constitute substantial benefits of agroforestry systems. These outputs should be considered in policy strategies of providing financial stimuli for sustainable land-use systems.

Limitations and recommendations for scientific research

The goal of this thesis was to assess the productivity of temperate pastures in different spatial tree configurations over the time frame of 15 years. It showed that this time frame was rather short to account for the consequences of full grown trees on pastures as especially walnut and chestnut trees were not yet producing. After 15 years, it would be expected that pasture yield decreases further, while profitability and carbon storage would increase. Considering a longer time frame might affect the objectives prioritized by farmers. This is why it is suggested that an investigation of effects after 20-30 years would be essential to identify consequences for trees as part of a more permanent integrated agroforestry system. For John Heesakkers, 15 years showed to be practically relevant since it was expected that someone else would take over the farm management in around 15 years from the moment of writing the thesis.

The focus in this thesis was the quantification of pasture yield, profitability and carbon storage. No emphasis was given to other farm components such as the consequences of trees on feed quality and animal productivity. Burner and Brauer (2003) and Hawke (1991) concluded that feed quality decreased with tree spacing. This suggests that more forage might be needed to meet feed requirements of grazing animals, which would result in an additional economic cost for the farmer. Moreover, animals were affected by the presence of trees on pastures. Similar to pasture production, high tree densities (Hawke 1991) and growing tree heights 6 years after tree establishment (Teklehaimanot et al., 2002) affected animal productivity negatively. Though positive interactions between trees and animals are known in form of shelter effects, negative interactions could affect the profitability of other farm components. The understanding and quantification of how interactions between trees and pastures and trees and animals relate to each other would provide a deeper analysis for farmers to make well-informed decisions in the future. The profitability with regard to changes in relative pasture yield and costs and revenues associated with trees constituted a first core element in an overall farm system evaluation.

The silvopasture tool comprised six tree species specifically intended to deliver fruits and nuts as an additional farm activity. It was supposed that walnut, chestnut, cherry, pear, apple and plum trees fitted well to the climate in the province of Brabant. Other tree and shrub species could be added easily to the excel tool if the costs of implementation, maintenance and revenues of production are known. A more detailed economic analysis of processing and marketing activities could be included to improve the findings of this thesis especially tailored to organic farmers in the Netherlands.

The following recommendations for future research were made:

- More quantitative information is needed on the growth of fruit and nut trees over years with regard to tree height (m), diameter of tree trunk (cm) and biomass (kg), to better assess the effects of trees on temperate pastures;

- More carefully designed experiments of temperate silvopasture systems are needed, to investigate in more depth tree height, tree density and other relevant such as the distance to trees explanatory variables affecting relative pasture yield;
- More investigation on the effects of trees on feed quality and animal productivity is needed, to examine the consequences of agroforestry systems for the overall farming system.

4.2. Conclusions

This thesis aimed at investigating the potential of agroforestry systems for temperate dairy farms with specific attention for the effects of tree density and tree height on profitability and carbon storage of trees. The results showed that a tree configuration of low tree density with no more than 6 rows of pear, apple and plum trees in the agroforestry plot presented the best-fitting scenario for minimum pasture yield loss and maximum profitability. Maximal profitability in comparison to Business As Usual without trees meant that initial costs for planting and maintaining trees in the first five years were balanced by the revenue of fruit production later in the rotation of total 15 years. It was found that for none of the tree configurations a significant profit could be made by the integration of agroforestry. This is why initial support in the form of financial subsidies is essential to stimulate the transition towards more sustainable land use systems and ease the implementation of such designs. The quantification of carbon storage which constituted another element of this thesis is helpful to present the benefits of agroforestry systems in terms of their ecosystem services.

Novel in this thesis were the findings about the effect on relative pasture yield by tree density and tree height which were contrasting to scientific literature. Tree density alone did not show significant results in the statistical analysis and only seemed to affect relative pasture yield when tree density was in interaction with tree height. When different scenarios of tree height and tree density were operationalized, tree density showed to have a much stronger effect in practice than tree height due to the wider range of modification for tree density. Until a few years after planting dependent on tree species, this relation indicated positive interactions between trees and pastures that resulted in higher relative pasture yield in the agroforestry plot than in open pasture. Since literature on temperate silvopastures was very scarce and the majority of recent scientific sources focused on the reduction of light capture by tree canopies as a competing factor, the mechanisms behind positive interactions between trees and pastures seem to have had only limited attention. Due to the very limited data available for the investigation in this thesis on silvopasture systems, a more detailed investigation of these variables is recommended with an emphasis on facilitation between trees and pastures in temperate agroforestry systems.

References

Bader, R. & Kriesen, M. (2005). Richtlinien für die Ernteerhebung: Obst. Retrieved 18 March from Statistik Austria http://www.auerbach.ooe.gv.at/gemeindeamt/download/222923484_1.pdf

Bambo, S. K., Blount, A. R., Nowak, J., Long, A. J., Myer, R. O., & Huber, D. A. (2009). Effects of annual cool-season forage on bahiagrass production in silvopastures. *Journal of Sustainable Agriculture*, *33*(4), 418-434.

Boerenbunder. (2017). Kenmerken retrieved February 25th 2017 from https://boerenbunder.nl/#b/51.55294,5.59184/2016/15/kenmerk

Brack, C. L., & Wood, G. B. (1997). Tree growth and increment. Retrieved 12 February 2017 from http://fennerschool-associated.anu.edu.au/mensuration/BrackandWood1998/T_GROWTH.HTM

Burner, D. M., & Brauer, D. K. (2003). Herbage response to spacing of loblolly pine trees in a minimal management silvopasture in southeastern USA. *Agroforestry systems*, *57*(1), 69-77.

Cannell, M. G. R., Van Noordwijk, M., & Ong, C. K. (1996). The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. *Agroforestry systems*, *34*(1), 27-31.

DeBruyne, S. A., Feldhake, C. M., Burger, J. A., & Fike, J. H. (2011). Tree effects on forage growth and soil water in an Appalachian silvopasture. *Agroforestry systems*, *83*(2), 189-200.

Douglas, G. B., Walcroft, A. S., Wills, B. J., Hurst, S. E., Foote, A. G., Trainor, K. D., & Fung, L. E. (2001). Resident pasture growth and the micro-environment beneath young, wide-spaced poplars in New Zealand. In *PROCEEDINGS OF THE CONFERENCE-NEW ZEALAND GRASSLAND ASSOCIATION* (pp. 131-138).

Fernández, M. E., Gyenge, J. E., Dalla Salda, G., & Schlichter, T. M. (2002). Silvopastoral systems in northwestern Patagonia. I: growth and photosynthesis of Stipa speciosa under different levels of Pinus ponderosa cover. *Agroforestry systems*, *55*(1), 27-35.

Flewelling, J., Collier, R., Gonyea, B., Marshall, D., & Turnblom, E. (2001). Height-age curves for planted stands of Douglas-fir, with adjustments for density. *Stand Management Cooperative, College of Forest Resources, University of Washington, Seattle, Wash. SMC Working Pap*, (1).

Friedrich, G. (1961). Der Obstbau. Neumann: Radebeul.

Gao, L., Xu, H., Bi, H., Xi, W., Bao, B., Wang, X., ... & Chang, Y. (2013). Intercropping competition between apple trees and crops in agroforestry systems on the Loess Plateau of China. *PloS one*, *8*(7), e70739.

Graves, A. R., Burgess, P. J., Liagre, F., Terreaux, J. P., Borrel, T., Dupraz, C., ... & Herzog, F. (2011). Farm-SAFE: the process of developing a plot-and farm-scale model of arable, forestry, and silvoarable economics. *Agroforestry systems, 81*(2), 93-108.

Guevara-Escobar, A., Kemp, P. D., Mackay, A. D., & Hodgson, J. (2007). Pasture production and composition under poplar in a hill environment in New Zealand. *Agroforestry systems*, *69*(3), 199-213.

Hawke, M. F. (1991). Pasture production and animal performance under pine agroforestry in New Zealand. *Forest Ecology and Management*, *45*(1-4), 109-118.

Hussain, Z., Kemp, P. D., Horne, D. J., & Jaya, I. K. (2009). Pasture production under densely planted young willow and poplar in a silvopastoral system. *Agroforestry systems*, *76*(2), 351-362.

Heijerman-Peppelman, G., & Roelofs, P. F. M. M. (2010). *Kwantitatieve Informatie Fruitteelt 2009/2010* (No. 2009-41). Praktijkonderzoek Plant & Omgeving, Bloembollen, Boomkwekerij & Fruit.

Herzog, F. (1998). Streuobst: a traditional agroforestry system as a model for agroforestry development in temperate Europe. *Agroforestry systems*, *42*(1), 61-80.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry systems*, *76*(1), 1-10.

Jose, S., Gillespie, A. R., & Pallardy, S. G. (2004). Interspecific interactions in temperate agroforestry. In *New Vistas in Agroforestry* (pp. 237-255). Springer Netherlands.

Long, A. J., & Nair, P. R. (1999). Trees outside forests: agro-, community, and urban forestry. *New Forests*, *17*(1-3), 145-174.

Luedeling, E., Smethurst, P. J., Baudron, F., Bayala, J., Huth, N. I., van Noordwijk, M., ... & Sinclair, F. L. (2016). Field-scale modeling of tree–crop interactions: Challenges and development needs. *Agricultural Systems*, *142*, 51-69.

Lundgren, B. (1982). Introduction (Editorial). Agroforestry Systems 1:3–6.

Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen. (2009). Streuobstwiesenschutz in Nordrhein-Westfalen: Erhalt des Lebensraumes, Anlage, Pflege, Produktvermarktung. Retrieved 29 January 2017 from http://vns.naturschutzinformationen.nrw.de/vns/web/babel/media/broschuere_streuobstwiesenschutz_mkulnv_2009.pdf

Montagnini, F., & Nair, P. K. R. (2004). Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agroforestry systems*, *61*(1-3), 281.

Naturschutzbund Deutschland e.V. (2017). Was ist Streuobst? Retrieved 28 February 2017 from https://www.nabu.de/natur-und-landschaft/landnutzung/streuobst/streuobstwissen/streuobstbau.html

Peri, P. L., Lucas, R. J., & Moot, D. J. (2007). Dry matter production, morphology and nutritive value of Dactylis glomerata growing under different light regimes. *Agroforestry systems*, *70*(1), 63-79.

Rao, M. R., Nair, P. K. R., & Ong, C. K. (1997). Biophysical interactions in tropical agroforestry systems. *Agroforestry systems*, *38*(1-3), 3-50.

Schroth, G. (1998). A review of belowground interactions in agroforestry, focussing on mechanisms and management options. *Agroforestry systems*, *43*(1-3), 5-34.

Sharrow, S. H. (1991). Tree planting pattern effects on forage production in a Douglas-fir agroforest. *Agroforestry systems*, *16*(2), 167-175.

Sharrow, S. H., Carlson, D. H., Emmingham, W. H., & Lavender, D. (1996). Productivity of two Douglas fir/subclover/sheep agroforests compared to pasture and forest monocultures. *Agroforestry systems*, *34*(3), 305-313.

Shepard, M. (2013). *Restoration agriculture: Real-world permaculture for farmers*. Austin: USA.

Sibbald, A. R., Griffiths, J. H., & Elston, D. A. (1991). The effects of the presence of widely spaced conifers on under-storey herbage production in the UK. *Forest Ecology and Management*, *45*(1-4), 71-77.

Smith, J., Pearce, B. D., & Wolfe, M. S. (2013). Reconciling productivity with protection of the environment: Is temperate agroforestry the answer?. *Renewable Agriculture and Food Systems*, *28*(01), 80-92.

Spruit, J., & Van der Voort, M. (2015). Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt. *Praktijkonderzoek Plant & Omgeving, Wageningen, PPO report*, *634*.

Stigter, C. J. (2015). Agroforestry and micro-climate change. *Tree-Crop Interactions: Agroforestry in a Changing Climate. CABI*, 119-145.

Teklehaimanot, Z., Jones, M., & Sinclair, F. L. (2002). Tree and livestock productivity in relation to tree planting configuration in a silvopastoral system in North Wales, UK. *Agroforestry Systems*, *56*(1), 47-55.

Tian, S., Cacho, J. F., Youssef, M. A., Chescheir, G. M., & Nettles, J. E. (2015). Switchgrass growth and morphological changes under established pine-grass agroforestry systems in the lower coastal plain of North Carolina, United States. *Biomass and Bioenergy*, *83*, 233-244.

Vandermeer, J. H. (1989). The Ecology of Intercropping. Cambridge: Cambridge University Press

Tonder, C. v. and J. Hillier (2014). Technical documentation for the online Cool Farm Tool, Cool Farm Alliance.

Van Vooren, L., Reubens, B., Broekx, S., Pardon, P., Reheul, D., van Winsen, F., ... & Lauwers, L. (2016). Greening and producing: An economic assessment framework for integrating trees in cropping systems. *Agricultural Systems, 148*, 44-57.

Varella, A. C., Moot, D. J., Pollock, K. M., Peri, P. L., & Lucas, R. J. (2011). Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system?. *Agroforestry systems*, *81*(2), 157-173.

Wiselius, S. I. (2005). Houtvademecum. SDU: Den Haag.

Yunusa, I. A. M., Mead, D. J., Lucas, R. J., & Pollock, K. M. (1995). Process studies in a Pinus radiata-pasture agroforestry system in a subhumid temperate environment. 2. Analysis of dry matter yields in the third year. *Agroforestry Systems, 32:* 185-204

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., & Smith, G. M. (2009). Mixed effects models and extensions in ecology with R. New York: Springer. *574 p*.

Appendix

Appendix 1: Detailed overview of the relative pasture yield

Table 18: Detailed overview of scientific sources based on tree age (years), tree height (m), tree density (trees ha-1), pasture yield (t ha-1) and relative pasture yield for the sources Bambo et al. (2009), Burner & Brauer (2003), Guevara-Escobar et al. (2007) and Hawke (1991)

Source	Author	Year	Tree species	Pasture mixture	Tree age (years)	Tree height (m)	Tree density (trees ha-1)	Pasture yield (t ha-1) for agroforestry	Pasture yield (t ha-1) for open pasture	Relative pasture yield
1	Bambo et al.	2009	Pine	Bahiagrass	18		225			0,7634
1	Bambo et al.	2009	Pine	Bahiagrass	18		225			0,7752
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	1764	0,25	0,18	1,3889
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	1176	0,17	0,18	0,9444
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	840	0,15	0,18	0,8333
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	830	0,2	0,18	1,1111
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	664	0,1	0,18	0,5556
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	581	0,2	0,18	1,1111
2	Burner & Brauer	2003	Loblolly pine	Tall fescue	7	4,9	498	0,21	0,18	1,1667
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	1764	0,52	1,23	0,4228
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	1176	0,93	1,23	0,7561
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	840	1,21	1,23	0,9837
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	830	1,08	1,23	0,8780
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	664	1,38	1,23	1,1220
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	581	1,29	1,23	1,0488
2	Burner & Brauer	2003	Loblolly pine	Bermudagrass	7	4,9	498	1,2	1,23	0,9756
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	29	28	37	0,95	1,82	0,5207
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	29	28	40	0,513	1,755	0,2923
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	40	32	40	1,05	3,123	0,3362
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	29	28	37	0,77	1,54	0,4990
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	29	28	40	0,58	1,64	0,3509
3	Guevara-Escobar et al.	2007	Poplar	Browntop, ryegrass	40	32	40	0,74	1,95	0,3810
4	Hawke	1991	Pine	Ryegrass, whiteclover	3	2	50			1,1600
4	Hawke	1991	Pine	Ryegrass, whiteclover	6	4	50			0,8400
4	Hawke	1991	Pine	Ryegrass, whiteclover	8	5	50			0,9200
4	Hawke	1991	Pine	Ryegrass, whiteclover	15	14	50			0,8500
4	Hawke	1991	Pine	Ryegrass, whiteclover	3	2	100			0,9200
4	Hawke	1991	Pine	Ryegrass, whiteclover	6	4	100			0,7500
4	Hawke	1991	Pine	Ryegrass, whiteclover	8	5	100			0,8900
4	Hawke	1991	Pine	Ryegrass, whiteclover	13	13	100			0,5000
4	Hawke	1991	Pine	Ryegrass, whiteclover	15	14	100			0,3200
4	Hawke	1991	Pine	Ryegrass, whiteclover	3	2	200			0,9200
4	Hawke	1991	Pine	Ryegrass, whiteclover	6	4	200			0,6800
4	Hawke	1991	Pine	Ryegrass, whiteclover	8	5	200			0,7200
4	Hawke	1991	Pine	Ryegrass, whiteclover	13	13	200			0,1800
4	Hawke	1991	Pine	Ryegrass, whiteclover	3	2	400			0,8000
4	Hawke	1991	Pine	Ryegrass, whiteclover	8	5	400			0,5300
4	Hawke	1991	Pine	Ryegrass, whiteclover	10	7,5	400			0,1200

Table 19: Detailed overview of scientific sources based on tree age (years), tree height (m), tree density (trees ha-1), pasture yield (t ha-1) and relative pasture yield for the sources Hussain et al. (2009), Peri et al. (2007), Sharrow et al. (1996), Sibbald et al. (1991), Varella et al. (2011) and Yunusa (1995)

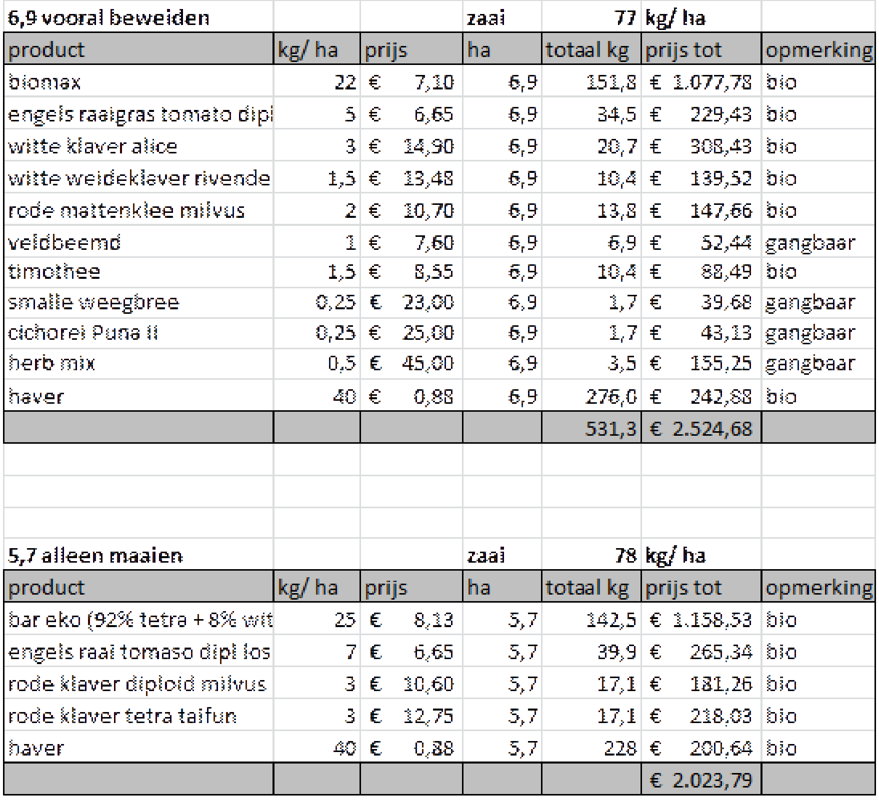
Source	Author	Year	Tree species	Pasture mixture	Tree age (years)	Tree height (m)	Tree density (trees ha-1)	Pasture yield (t ha-1) for agroforestry	Pasture yield (t ha-1) for open pasture	Relative pasture yield
5	Hussain et al.	2009	Willow	Ryegrass, Yorkshire fog, wh	2	1,9	6889	10,3	13,4	0,7687
5	Hussain et al.	2009	Poplar	Ryegrass, Yorkshire fog, wh	2	1,35	6889	12,2	13,4	0,9104
5	Hussain et al.	2009	Willow	Ryegrass, Yorkshire fog, bro	2	1,9	6889	5,6	10,7	0,5234
6	Peri et al.	2007	Pine	Cocksfoot	10	13,3	200	6,3	8,2	0,7683
7	Sharrow et al.	1996	Douglas fir	Tall fescue	6	1,137	1600	6,9	5,9	1,1695
7	Sharrow et al.	1996	Douglas fir	Tall fescue	7	1,5645	1600	7,7	9,5	0,8105
7	Sharrow et al.	1996	Douglas fir	Tall fescue	8	1,992	1600	6,1	6,2	0,9839
7	Sharrow et al.	1996	Douglas fir	Tall fescue	9	2,562	1600	3,6	5	0,7200
7	Sharrow et al.	1996	Douglas fir	Tall fescue	10	3,132	1600	2,5	5,9	0,4237
7	Sharrow et al.	1996	Douglas fir	Tall fescue	6	1,137	890	5,6	5,9	0,9492
7	Sharrow et al.	1996	Douglas fir	Tall fescue	7	1,5645	890	9,3	9,5	0,9789
7	Sharrow et al.	1996	Douglas fir	Tall fescue	8	1,992	890	6,8	6,2	1,0968
7	Sharrow et al.	1996	Douglas fir	Tall fescue	9	2,562	890	5,5	5	1,1000
7	Sharrow et al.	1996	Douglas fir	Tall fescue	10	3,132	890	4,4	5,9	0,7458
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		3	625	6,83	12,20	0,5600
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		5	625	1,17	12,20	0,0960
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		8	625	1,90	11,47	0,1660
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		3	278	10,25	12,20	0,8400
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		5	278	8,78	12,20	0,7200
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		8	278	8,78	11,47	0,7660
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		3	156	9,76	12,2	0,8000
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		5	156	9,76	12,2	0,8000
8	Sibbald et al.	1991	Sikta spruce	Ryegrass		8	156	10,49	11,47	0,9149
9	Varella et al.	2011	Pine	Alfalfa		11	200	13,33	18,57	0,7178
10	Yunusa et al.	1995	Pine	Ryegrass, clovers		2,91	1000	13,64	17,29	0,7889
10	Yunusa et al.	1995	Pine	Ryegrass		2,69	1000	8,64	10,1	0,8554
10	Yunusa et al.	1995	Pine	Lucerne		2,73	1000	20,31	24,21	0,8389

Appendix 2: Data for the silvopasture tool

Table 20: Estimations on tree (m) and tree growth rates (cm) per year. Sources: Kraus, Zapfe, and Heyland (2017, personal communication).

	Year	Tree height (m)	Height growth rate (cm/year)	Reference
Walnut			30 – 40	Kraus, 2017
Walnut	10	7 – 8		Zapfe, 2017
Walnut	20 – 30	15 – 20		Zapfe, 2017
Walnut			100 – 200	Heyland, 2017
Chestnut			25 – 30	Kraus, 2017
Chestnut	30	20 +		Zapfe, 2017
Chestnut			30 – 45	Heyland, 2017
Cherry			50	Kraus, 2017
Cherry	MAX.	20		Zapfe, 2017
Cherry			30 – 60	Heyland, 2017
Pear			25 – 30	Kraus, 2017
Pear	MAX.	12 – 14		Zapfe, 2017
Pear			30 – 40	Heyland, 2017
Apple			25	Kraus, 2017
Apple	MAX.	12 – 14		Zapfe, 2017
Apple			30 – 60	Heyland, 2017
Plum			20 – 25	Kraus, 2017
Plum	MAX.	12 – 14		Zapfe, 2017
Plum			20 – 40	Heyland, 2017

Table 21: Costs overview (€) for pasture seeds at John Heesakkers' farm. Source: Heesakkers (2017, personal communication)



6,9 vooral beweiden			**zaai**	**77**	**kg/ ha**	
product	kg/ ha	prijs	ha	totaal kg	prijs tot	opmerking
biomax	22	€ 7,10	6,9	151,8	€ 1.077,78	bio
engels raaigras tomato dipl	5	€ 6,65	6,9	34,5	€ 229,43	bio
witte klaver alice	3	€ 14,90	6,9	20,7	€ 308,43	bio
witte weideklaver rivende	1,5	€ 13,48	6,9	10,4	€ 139,52	bio
rode mattenklee milvus	2	€ 10,70	6,9	13,8	€ 147,66	bio
veldbeemd	1	€ 7,60	6,9	6,9	€ 52,44	gangbaar
timothee	1,5	€ 8,55	6,9	10,4	€ 88,49	bio
smalle weegbree	0,25	€ 23,00	6,9	1,7	€ 39,68	gangbaar
cichorei Puna ii	0,25	€ 25,00	6,9	1,7	€ 43,13	gangbaar
herb mix	0,5	€ 45,00	6,9	3,5	€ 155,25	gangbaar
haver	40	€ 0,88	6,9	276,0	€ 242,88	bio
				531,3	€ 2.524,68	
5,7 alleen maaien			**zaai**	**78**	**kg/ ha**	
product	kg/ ha	prijs	ha	totaal kg	prijs tot	opmerking
bar eko (92% tetra + 8% wit	25	€ 8,13	5,7	142,5	€ 1.158,53	bio
engels raai tomaso dipl los	7	€ 6,65	5,7	39,9	€ 265,34	bio
rode klaver diploid milvus	3	€ 10,60	5,7	17,1	€ 181,26	bio
rode klaver tetra taifun	3	€ 12,75	5,7	17,1	€ 218,03	bio
haver	40	€ 0,88	5,7	228	€ 200,64	bio
					€ 2.023,79	

Table 22: Cost overview for walnut trees distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Adapted from the cost overview of cherry trees. Source: Heijerman-Peppelman & Roelofs (2010).

WALNUT	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.0256	0.67		
	Setting wooden poles	0.024	0.63		
Maintenance (from year 2)	Pruning	0.04	1.05		
Harvest (from year 4)	Preparing harvest	0.0192	0.5		
	Picking*	12 kg/h			X

Table 23: Cost overview for chestnut trees distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Adapted from the cost overview of cherry trees. Source: Heijerman-Peppelman & Roelofs (2010).

CHESTNUT	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.0256	0.67		
	Setting wooden poles	0.024	0.63		
Maintenance (from year 2)	Pruning	0.04	1.05		
Harvest (from year 4)	Preparing harvest	0.0192	0.5		
	Picking*	12 kg/h			X

Table 24: Cost overview for cherry trees distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Source: Heijerman-Peppelman & Roelofs (2010).

CHERRY	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.0256	0.67		
	Setting wooden poles	0.024	0.63		
Maintenance (from year 2)	Pruning	0.04	1.05		
Maintenance (from year 4)	Attaching nets	0.064		1.02	
	Removing nets	0.02		0.32	
Harvest (from year 4)	Preparing harvest	0.0192	0.5		
	Picking*	12 kg/h			X
	Sorting*	20 kg/h			X

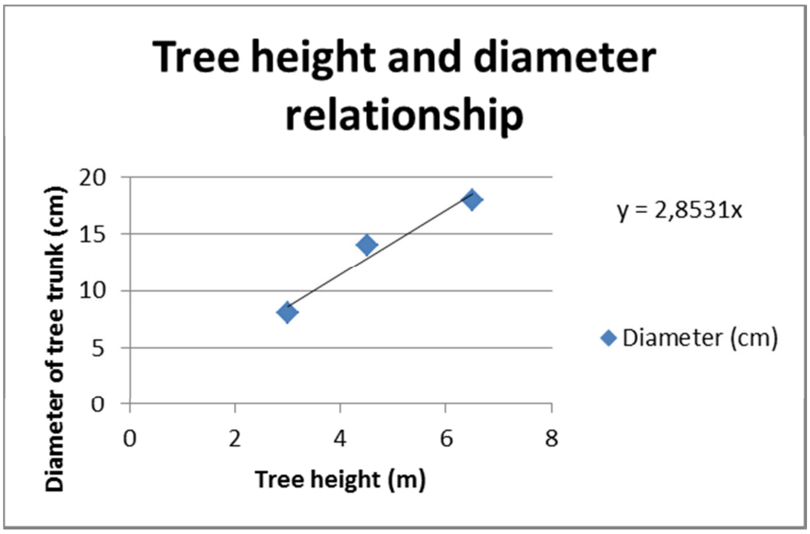
Table 25: Cost overview for apple trees distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Source: Heijerman-Peppelman & Roelofs (2010).

APPLE	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.02	0.53		
	Setting wooden poles	0.016	0.42		
Maintenance (from year 2)	Pruning (young age)	0.0067	0.18		

	Pruning (old age)	0.02	0.54		
Maintenance (from year 4)	Thinning out and cancer protection	0.011	0.3		
Harvest (from year 4)	Preparing harvest	0.0063	0.17		
	Picking (for max. 1100 kg)	0.027			0.25

Table 26: Cost overview for plum trees distinguishing between implementation, maintenance and harvest activities and corresponding costs for skilled, lesser skilled and unskilled labour. Source: Heijerman-Peppelman & Roelofs (2010).

PLUM	**Labour activities**	**Labour (tree/h)**	**Skilled €**	**Lesser skilled €**	**Unskilled €**
Implementation (year 0)	Planting trees	0.029	0.76		
	Setting wooden poles	0.025	0.66		
Maintenance (from year 2)	Pruning (young age)	0.048	1.26		
Maintenance (from year 4)	Thinning out	0.361	9.49		
Harvest (from year 4)	Preparing harvest	0.039	1.02		
	Picking (for max. 1000 kg)	0.016			0.15



Height (m)	Diameter (cm)
3	8
4.5	14
6.5	18

Figure 13: Linear relation of diameter at tree trunk (cm) based on tree height (m). Source: Zapfe (2017, personal communication)

Appendix 3: Results of mixed effects model in R

Table 27: Outputs of mixed effects model for the effect of tree density (trees ha^{-1}) on relative pasture yield

```
Random effects:
 Formula: ~1 | Author
        (Intercept)  Residual
StdDev:   0.1594276 0.2441104

Fixed effects: Ratio ~ Density
                 Value  Std.Error DF
(Intercept)  0.7493300 0.07349936 54
Density     -0.0000093 0.00003290 54
              t-value p-value
(Intercept) 10.195055  0.0000
Density     -0.283751  0.7777
 Correlation:
        (Intr)
Density -0.495

Standardized Within-Group Residuals:
       Min         Q1        Med
-2.3698019 -0.5119279  0.1995256
        Q3        Max
 0.6072643  1.9540304

Number of Observations: 65
Number of Groups: 10
```

```
Variance:
R2m        R2c
0.00208516 0.30046219
```

Table 28: Outputs of mixed effects model for the effect of tree age (years) on relative pasture yield

```
Random effects:
 Formula: ~1 | Author
        (Intercept) Residual
StdDev:   0.1026032 0.223973

Fixed effects: Ratio ~ age
                 Value  Std.Error DF
(Intercept)  0.9771277 0.08017638 44
age         -0.0188478 0.00498729 44
              t-value p-value
(Intercept) 12.187226   0e+00
age         -3.779175   5e-04
 Correlation:
    (Intr)
age -0.739

Standardized Within-Group Residuals:
       Min         Q1        Med
-2.5292406 -0.4170660  0.2213021
        Q3        Max
 0.5743770  2.0788400

Number of Observations: 52
Number of Groups: 7
```

```
Variance:
R2m       R2c
0.3176291 0.4359921
```

Table 29: Outputs of mixed effects model for the effect of tree height (m) on relative pasture yield

```
Random effects:
 Formula: ~1 | Author
        (Intercept)  Residual
StdDev:  0.09543126 0.2306742

Fixed effects: Ratio ~ height
                 Value  Std.Error DF
(Intercept)  0.8968625 0.06133669 53
height      -0.0199498 0.00504880 53
              t-value p-value
(Intercept) 14.621958   0e+00
height      -3.951392   2e-04
 Correlation:
       (Intr)
height -0.646

Standardized Within-Group Residuals:
       Min         Q1        Med
-2.6155107 -0.3540283  0.1689414
        Q3        Max
 0.5323333  2.0956610

Number of Observations: 63
Number of Groups: 9
```

```
Variance:
R2m      R2c
0.286090 0.390421
```

Table 30: Outputs of mixed effects model for the effect of tree age (years) on tree height (m)

```
Random effects:
 Formula: ~1 | Author
        (Intercept) Residual
StdDev:    3.240277 1.227801

Fixed effects: height ~ age
                Value Std.Error DF
(Intercept) 0.4867352 1.4781634 43
age         0.8007906 0.0534772 43
              t-value p-value
(Intercept)  0.329284  0.7435
age         14.974442  0.0000
 Correlation:
    (Intr)
age -0.409

Standardized Within-Group Residuals:
         Min           Q1          Med
-2.559852658 -0.313123478 -0.009857778
          Q3          Max
 0.168032472  2.156220982

Number of Observations: 50
Number of Groups: 6
```

```
Variance:
  R2m       R2c
0.8112597 0.9763032
```

Table 31: Outputs of mixed effects model for the effect of tree density (trees ha^{-1}) and age (years) on relative pasture yield: stepwise approach

```
Linear mixed-effects model fit by REML
 Data: Agroforestry_ratio_4L.age 
       AIC      BIC    logLik
  34.83018 44.28928 -12.41509

Random effects:
 Formula: ~1 | Author
        (Intercept)  Residual
StdDev:   0.1224549 0.2177335

Fixed effects: Ratio ~ age + Density 
                 Value  Std.Error DF
(Intercept)  1.0971129 0.11036235 43
age         -0.0234138 0.00581673 43
Density     -0.0000513 0.00003042 43
              t-value p-value
(Intercept)  9.941008  0.0000
age         -4.025254  0.0002
Density     -1.687055  0.0988
 Correlation: 
        (Intr) age  
age     -0.776      
Density -0.609  0.405

Standardized Within-Group Residuals:
       Min         Q1        Med 
-2.5226925 -0.5015610  0.1867793 
        Q3        Max 
 0.7198131  2.2716617 

Number of Observations: 52
Number of Groups: 7
```

```
     R2m       R2c 
0.3783484 0.5277287
```

Table 32: Outputs of mixed effects model for the effect of tree density (trees ha^{-1}) and age (years) on relative pasture yield: variables in interaction

```
Random effects:
 Formula: ~1 | Author
        (Intercept)  Residual
StdDev:   0.1909783 0.2058413

Fixed effects: Ratio ~ age * Density 
                 Value  Std.Error DF
(Intercept)  1.2112804 0.14190646 42
age         -0.0244938 0.00695693 42
Density      0.0000102 0.00005283 42
age:Density -0.0000320 0.00001524 42
              t-value p-value
(Intercept)  8.535766  0.0000
age         -3.520778  0.0011
Density      0.192652  0.8482
age:Density -2.102141  0.0416
 Correlation: 
            (Intr) age    Densty
age         -0.694              
Density     -0.297  0.360       
age:Density -0.166 -0.142 -0.701
```

```
Standardized Within-Group Residuals:
        Min          Q1         Med
-2.23060797 -0.56309744  0.08653291
         Q3         Max
 0.64062776  3.06204322

Number of Observations: 52
Number of Groups: 7
```

```
R2m       R2c
0.3706828 0.6618032
```

Table 33: Outputs of mixed effects model for the effect of tree density (trees ha^{-1}) and height (m) on relative pasture yield: stepwise approach

```
Random effects:
 Formula: ~1 | Author
        (Intercept) Residual
StdDev:   0.1199041  0.22606

Fixed effects: Ratio ~ height + Density
                 Value  Std.Error DF
(Intercept)  0.9715605 0.08439207 52
height      -0.0234396 0.00584226 52
Density     -0.0000411 0.00002926 52
              t-value p-value
(Intercept) 11.512462  0.0000
height      -4.012083  0.0002
Density     -1.403537  0.1664
 Correlation:
        (Intr) height
height  -0.679
Density -0.572  0.321

Standardized Within-Group Residuals:
       Min         Q1        Med
-2.5978708 -0.4036734  0.1563045
        Q3        Max
 0.5499845  2.2145007
Number of Observations: 63
Number of Groups: 9
```

```
Variance:
R2m       R2c
0.3222107 0.4710279
```

Table 34: Outputs of mixed effects model for the effect of tree density (trees ha^{-1}) and height (m) on relative pasture yield: variables in interaction

```
Random effects:
 Formula: ~1 | Author
        (Intercept)  Residual
StdDev:   0.1738888 0.1981623

Fixed effects: Ratio ~ height * Density
                     Value  Std.Error DF
(Intercept)      1.0758153 0.10231606 51
height          -0.0203862 0.00682820 51
Density          0.0001220 0.00005832 51
height:Density -0.0000971 0.00002510 51
                 t-value p-value
(Intercept)    10.514628  0.0000
```

```
height         -2.985591  0.0043
Density         2.091308  0.0415
height:Density -3.867186  0.0003
 Correlation: 
               (Intr) height Densty
height         -0.592              
Density        -0.240  0.391       
height:Density -0.097 -0.275 -0.818

Standardized Within-Group Residuals:
        Min          Q1         Med 
-2.41012276 -0.41826030  0.02140803 
         Q3         Max 
 0.48476844  3.86995897 
Number of Observations: 63
Number of Groups: 9 
```

```
Variance:
    R2m       R2c 
0.3875552 0.6539896
```