Measuring carbon sequestration and soil fertility in Swedish forest gardens
– a methodological study

Elsa Lagerquist

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Abstract

Agroforestry is an old agricultural practice which has got renewed interest during the last decades as an alternative to industrialized agriculture. Agroforestry is a practice with potential to promote several ecosystem services, e.g. carbon sequestration and soil improvement. This study looks into how carbon sequestration and soil fertility can be measured in one of the most diverse agroforestry systems; forest gardens. Five forest gardens located in southern Sweden were included in the study; Tystinge (T), Rikkenstorp (R), Hånsta Östergärde (H.Ö.), Holma skogsträdgård (H.o.) and Klockaregården (K), representing different soils, climates and managements. Standing biomass was estimated for herbs, trees and shrubs. Herbal vegetation was harvested and brought back to the lab, while trees and shrubs were measured in the field and biomass was calculated by using allometric equations. Soil samples were collected to estimate root biomass, respiration, carbon content and C/N ratio. A soil profile description was performed, and a method to estimate mychorrizal colonization was also tried out. It was shown that the biomass production and carbon in standing biomass varies depending on site and management. Previous land use will determine whether the establishment of a forest garden will improve or impair biomass production. Herbal biomass was twice as high at T compared to H.Ö. Biomass of trees and shrubs varied as well, with the highest woody biomass being more than twice as high as the lowest, found at H.o. and K respectively. After the forest gardens had been established root biomass decreased with 60% at R, while it increased with 50% at H.Ö. At all sites soil respiration was lower in the forest garden than at reference spots outside the garden. The forest gardens seemed to favor earthworm activity, while no changes in carbon content or C/N ratio were seen. C/N ratios were strongly connected to the respective sites. For proper estimations of above- and belowground biomass of trees and shrubs more specific allometric equations needs to be developed, suiting the species of relevance and the climatic conditions. A similar method would also provide the best estimation of herbal biomass. Carbon content in soils changes slowly and to see whether the forest gardens have had a long-term impact on carbon content new measurements needs to be made in the future. Respiration should be measured several times a year for reliable modeling of carbon sequestration to be possible. Data on degradation rates of different plant components are also needed for proper models on carbon flows to be developed. Better understanding of the components of forest gardens, and their interactions, would help in finding the potentials of forest gardens in Sweden.

Keywords: biomass production, allometric equations, soil science, carbon cycling, agroforestry

Populärvetenskaplig sammanfattning

MILJÖVÄNLIGARE OCH KLIMATSMARTARE JORDBRUK MED AGROFORESTRY

Kan träd och buskar i odlingslandskapet vara en lösning på jordbrukets negativa påverkan på miljö och klimat? Och hur kan detta mätas vetenskapligt? Metoder för att mäta kollagring och markbördighet har undersökts i denna uppsats, och agroforestry-systemen visar potential att binda mer kol, både i biomassa och i mark, än alternativ landanvändning.

Idag är det få som inte känner till jordbrukets negativa påverkan på miljön. Förluster av biologisk mångfald, vattenekosystem skadade av övergödning och bekämpningsmedel, och utarmning av våra marker, de som ska förse oss människor med den essentiella produkten *mat*. Och så klimatförändringen, där jordbruket är en av orsakerna, men också kan motverka den.

Agroforestry är en gammal jordbruksmetod, där träd och buskar integreras med växtodling och/eller djurhållning. Det diversifierar landskapet, förbättrar vattenkvaliteten och ger en ökad produktion av biomassa. I Sverige är det ännu en rätt ovanlig jordbruksmetod, men initiativ poppar upp här och var, liksom forskningsprojekt. I studien som presenteras här undersöktes metoder för att mäta kollagring både i biomassa och i mark, samt olika markbördighetsparametrar i skogsträdgårdar, en typ av agroforestry-system.

Skogsträdgårdarna med sina träd och buskar visade sig, ha en större ovanjordisk biomassa jämfört med alternativ markanvändning; permanent gräsmark och åker. Därmed binder de mer kol ovan jord. När det gällde rotbiomassa var denna störst i de permanenta gräsmarkerna, följt av skogsträdgårdarna. Metoden som användes inte lyckades fånga rotbiomassan hos träd och buskar, vilken underskattades i denna studie. Att göra en tillförlitlig bestämning av mängden vedbiomassa, både ovan och under jord, var dock inte möjlig eftersom det kräver beräkningar för varje enskild art, något som är mycket tidskrävande och kostsamt.

Globalt sett är marken den överlägset största lagringspoolen för kol, men potentialen att lagra kol varierar mellan olika jordar och markanvändning. För totalt markkol kunde ingen trend urskiljas. Förändringar i markkol är dock en mycket långsam process. Det kan ta 10-20 år efter en föränding i markanvändning innan förändringen kan mätas, och 50-100 år innan jämvikt har uppstått. Detta beror på att det är relativt lite kol som binds in i marken jämfört med vad som redan finns lagrat där. Odlingssystemets potential att lagra kol kan dock förutsägas genom modellering om mängden producerad förna från olika vegetationstyper, dess nedbrytningshastighet och markens mikrobiella aktivitet är kända. Mer data behövs för detta, men studien visade på en intressant trend att respirationen var lägre i skogsträdgårdarna än vid referenspunkterna. Det tyder på att mer kol stannar i marken i skogsträdgårdarna. Något som skulle vara intressant att titta närmare på.

Nyckelord: biomassa, allometriska ekvatoner, markvetenskap, kolcykel, agroforestry

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1   Introduction

Agroforestry is a practice where agriculture, in terms of growing crops, keeping livestock, or both, and forestry are combined either in space or time (World Agroforestry Center, 2013). According to World Agroforestry Center it is

> a dynamic ecologically based, natural resource management system that, through integration of trees on farms and in the agricultural landscape, diversifies and sustains production and builds social institutions (World Agroforestry Center, 2013).

The concept and practice of agroforestry is old, and in many European countries trees have been an important part of agriculture. However, intensification of agriculture led to a decrease of trees integrated on farmland (Nerlich et al., 2012). The term *agroforestry*, however, appeared when the practice of combining trees with food crops and/or animals was developed in the tropics to provide smallholders and poor farmers a more secure livelihood (Gordon and Newman, 1997; Carton, 2011). Due to land shortage it has been of importance to utilize the land efficiently, but simultaneously in a sustainable way. In agroforestry systems, trees provide food, timber or other commodities, energy, medicines or animal feed (World Agroforestry Center, 2013). Integrating trees into agriculture has also been shown to promote beneficial ecological interactions such as stabilizing the soil and therefore protecting the land from erosion, and to have yield improving interactions like nitrogen fixation and allelopathy (Gordon and Newman, 1997). With the increase in human population and the fact that many agricultural practices are depleting the soil of its fertility new management practices are adopted and developed, one of them is agroforestry (Carton, 2011; Nerlich et al., 2012). The practice of agroforestry has been revitalized in Europe, and previous studies has shown that agroforestry can be more biological productive, more profitable and more sustainable than forestry or agriculture monocultures in temperate regions too (Gordon and Newman, 1997). One of the benefits with regards to sustainability is that the systems can provide ecosystem

services. These services could be carbon sequestration, biodiversity conservation, soil enrichment and air and water quality (Jose, 2009).

Agroforestry can be practiced in several ways. Alley-cropping, silvopastoral systems, forest grazing, integrated riparian systems, and windbreak systems are some examples (Gordon and Newman, 1997). Another practice is forest gardening. In an edible forest garden the forest ecosystem is mimicked by using plants of different size to create several layers to capture all the incoming sunlight and utilize the soils nutrients efficiently (Jacke and Toensmeier, 2005). In Sweden there are yet few examples of agroforestry, and studies of these systems by the academia have been even fewer. One of the pilot projects in the field, however, is the participatory learning and action research project "Sustainable food production in Sweden – the potential of agroforestry systems?" at Örebro University. The project involves a group of thirteen farmers and gardeners and a few affiliated researchers. The aim of the project is to investigate the possibilities to develop productive and economically viable agroforestry systems for food production in Sweden (Örebro Universitet, 2015). Hereafter this project is referred to as *The Project*. There is also an interest in studying the ability of the systems to provide ecosystem services, for the farm and the region, and maybe even on a global scale. One of the systems studied in this project is edible forest gardens in which trees and shrubs, bearing fruits or nuts, or having other functions such as nitrogen fixation, timber production, wind protection and nutrient accumulation (Jacke and Toensmeier, 2005), are grown together with perennial herbaceous plants, smaller fruit plants, climbers and creepers.

Agroforestry systems in general, and edible forest gardens in particular, are complex systems, which make any measurements of functions difficult. To understand these systems renewed approaches for studying and evaluating interactions between agriculture and the environment are needed (Carton, 2011). The diversity of trees, crops and/or animals in space or time adds several parameters to the study, parameters that interact and respond to each other. Studies of each component (crops, trees and/or animals) in isolation will not tell much about the performance of the mix (Gordon and Newman, 1997). This study focus on the two ecosystem services carbon sequestration and soil fertility, as they both are crucial for sustainable agriculture and because they are interlinked with each other. A fertile soil will increase crop growth and thereby carbon input to the system, and high crop growth will increase the input of biomass to the system, which improves soil fertility. Under Swedish conditions this has not been investigated yet, neither in parts nor in the mix.

The aim with this study was to try out and analyze methods for measuring carbon sequestration and soil fertility in The Projects edible forest gardens, hereafter just

called *forest gardens*. Questions to be answered were: How easily are the methods applied? How valid is the gathered data? What further knowledge is needed to improve the measurements? As The Project is participatory it is also of interest to look into the possibilities of the participants to be involved in the measurements. The questions presented above were answered by conducting both field and laboratory work. Vegetation and soil samples were collected to estimate above- and below-ground biomass, as well as carbon and nitrogen content in the soil, soil respiration and abundance of mycorrhiza. Data from within the forest gardens and outside them (hereafter referred to as *reference spots*), which were representing earlier land use, were compared.

The aim was to investigate the impact of an established forest garden on carbon sequestration and soil fertility parameters compared to earlier land use. In addition, the impact of different sites, e.g. climate, soil and/or management, and by the vegetation, was studied.

This work will also provide data of height and diameter of trees, shrubs and herbal vegetation, as well as soil data to The Project, which can be used in future comparisons and evaluations of the system. Due to the difficulties of measuring carbon sequestration and soil fertility in a representative way, and the fact that the sites are very young and under development (established in 2011), this study focus on getting start-up reference values and begins to explore methods that could be used to measure these services in the future.

In this study, data has been collected from five forest gardens that are part of The Project to analyze carbon pools of the forest gardens, and look into how these flows can be modeled. This was done by collecting vegetation and soil samples to estimate biomass, carbon content in the soil and respiration at the sites. To estimate soil fertility a soil profile description was conducted and the C/N ratio was measured. A method for estimating mycorrhizal colonization was also tried out.

2 Background

2.1 Carbon sequestration

Carbon sequestration is a complex process of biomass production, litter enrichment to the soil (e.g. leaves, roots, woody debris and dead microbes) and degradation of this litter. To understand these flows and get at better overview of the processes involved as well as the contribution of different inputs the use of models is widely adapted. They can be simple and static, as allometric equations (Trotta et al., 2013), or more complex and dynamic modeling programs. (de Coligny et al., 2002; Masera et al., 2003; van der Werf et al., 2007).

Methods for measuring biomass, and thereby carbon stocks, in trees have been developed in forestry research (Zianis et al., 2005; Picard et al., 2012) and for agroforestry systems in the tropics (Chave et al., 2005; Segura et al., 2006; Youkhana and Idol, 2011; Negash et al., 2013;Tumwebaze et al., 2013; Saj et al., 2013). Carbon stocks in forests can be measured by field inventories, airborne lasers or radar, and by satellite remote sensing. All these methods require having trees measured and weighed in the field, which is an expensive and time consuming procedure (Picard et al., 2012). From field inventories allometric equations can be developed. This was the method used to calculate biomass of trees and shrubs in the forest gardens.

2.1.1 Allometric equations – their use and development

Allometric equations are built on the relationship between *independent variables*, those that are measured (e.g. diameter at breast height (dbh), height (h), crown diameter, crown height and branch diameter), and *dependent variables*, those that are calculated (e.g. volume or biomass of stem, crown, branches or the whole tree, Lott et al., 2000; Zianis et al., 2005; Snorrason and Einarsson, 2006; Picard et al., 2012; Negash et al., 2013). Allometry describes the growth of trees with either a linear or a non-linear correlation, therefore the dependent variable, e.g. biomass of a tree, can be determined by one or more independent variables, as long as they are within the range of the independent variables used to develop the equation (Picard et al., 2012).

Most equations only use diameter at breast height as an independent variable. Height and diameter at breast height are closely correlated to each other and therefore the addition of height contributes little to the fit of a model (Lott et al., 2000; Ketterings et al., 2001; Segura et al., 2006). However, in some cases the correlation between height and diameter at breast height is low, and thereby the inclusion of height in

the model is important. This could be explained by management, for example pruning (Segura et al., 2006; Tumwebaze et al., 2013) and morphology (Zianis et al 2005; Tumwebaze et al., 2013), both of which could determine how biomass is allocated. Furthermore, it has been argued that when calibrating a model to fit another environment the relationship between diameter at breast height and total height of the tree is important (Picard et al., 2012). If models involve several different trees, mixed-species models, the inclusion of height can also improve the equations (Chave et al., 2005).

Allometric equations are either built up by power models or logarithmic models. Equation 1 shows the power function and its parameters

$$Y = b \times x_1{}^a \times x_2{}^c \qquad \text{Eq 1}$$

where Y is the dependent variable, e.g. volume, or biomass of stem, crown, branches or the whole tree, x is an independent variable, e.g. diameter at breast height (dbh), height (h), crown diameter, crown height and branch diameter, and a, b and c are parameters determined by abiotic and biotic factors which changes with species, species varieties, climate, soil, etc. (modified from Picard et al., 2012). In some studies, the logarithmic function showed a better fit between independent and dependent variables (e.g. Snorrason and Einarsson, 2006). Whether the power function or the logarithmic function is used depends on the type of forest or agroforestry system, i.e. species and management, and the type of biomass that should be estimated, i.e total tree, stem, foliage, branches or roots. To find the most reliable function the goodness of fit of each function is evaluated statistically by various statistical tools (e.g. the coefficient of determination, sum of squares of the residuals, residuals mean square, standard error of estimate, see for example Youkhana and Idol, 2011; Negash et al., 2013). A cohort approach can also be used when developing allometric equations, which can reduce the work load of developing the equations. A cohort is a group of individual trees or a stand of different species which is treated as single entities by the model. The cohorts could for example be the different stratas in a multi-strata agroforestry system (e.g. understory, middle layer, upper layer; Masera et al., 2003).

For root biomass the development of a regression relation is a two-step process. First, a relation between individual root diameter and root mass should be found and thereafter between stump diameter and predicted root mass (Youkhana and Idol, 2011). Very few studies have considered root biomass in their development of biomass equations, due to the complexity of collecting data of roots (Picard et al., 2012).

Most studies investigating biomass equations in temperate regions have been conducted in forest systems, or plantations for bioenergy (Nordh and Verwijst, 2004; Zianis et al., 2005; Picard et al., 2012). Some studies of carbon sequestration or timber production in agroforestry systems have been conducted also in temperate regions, focusing on alley cropping (Palma et al., 2014) and shelterbeds (Zhou et al., 2007). Agroforestry systems differ from forests in their management and diversity (Lott et al., 2000; Segura et al., 2006; Tumwebaze et al., 2013). Therefore, if investigations of biomass are to be performed in agroforestry systems models need to be developed for each type of system, depending on density and thereby competition (there will be more competition for water, light and space in a dense forest garden than in an alley cropping system), and management (pruning, coppicing etc.; Lott et al., 2000). Furthermore, as studies of agroforestry systems mainly have been conducted in the tropics, the lessons learned from those cannot be directly applied into the context of Swedish agroforestry, but can serve as guidance. Furthermore, the effect of management practices that are used for the specific purpose of the agroforestry system should be taken into account when models are developed (Saj et al., 2013).

2.1.2 Modeling carbon flows

A more dynamic way to study forests and agricultural practices is by calibrating more elaborate mathematical models implemented in computer simulations (de Coligny et al., 2002). There are several computer models developed for studying the dynamics of forests, agriculture or agroforestry (de Coligny et al., 2002; van der Werf et al., 2007; Negash and Kanninen, 2015). The models can be used to calculate the effect of thinning on tree growth (Courbaud et al., 2001), the diameter increment of trees over time (Gourlet-Fleury and Houllier, 2000), or estimating productivity in alley cropping systems (van der Werf et al., 2007). The model can be distance dependent, which means that the model takes into account the distance between the trees when modeling systems' functions (Gourlet-Fleury and Houllier, 2000; Courbaud et al., 2001). Some models however are independent of distance between trees (de Coligny et al., 2002). The models require data on biomass of the different tree components or cohorts (Masera et al., 2003; van der Werf et al., 2007; Negash and Kanninen, 2015), and are most reliable when inventories are made at the studied site (Negash and Kanninen, 2015). The models also include growth parameters of trees and crops, such as irrigation, radiation and soil water potential (Courbaud et al., 2001; van der Werf et al., 2007; Negash and Kanninen, 2015). To estimate carbon sequestration turnover rates are calculated for the different components (foliage, branches and roots), for which empirically determined turnover coefficients are used

(Masera et al., 2003). Turnover times vary between different plant components and have to be estimated individually.

3 Materials and methods

3.1 Site description

In this study, five forest gardens were included: Tystinge (T), Rikkenstorp (R), Hånsta Östergärde (H.Ö.), Holma skogsträdgård (H.o.) and Klockaregården (K). The locations of the sites are shown in Figure 1. During the year of establishment a textural analysis were made which is shown in Table 1. These textural analyses were made at all sites except K. The sites were chosen to cover the broad spectra of climates and soils that are represented in The Project. All sites have the same design (see Figure 3) and the same size (60 m^2), but they have been established in different ways and are surrounded by different environments. One was established on an agricultural field and four were established at different types of grasslands.

Table 1. Soil properties of the sites Rikkenstorp, Hånsta Östergärde, Tystinge and Holma.

Site	Clay (<0.002mm)	Silt (0.002-0.2mm)	Sand (0.2-2mm)	Humus	pH
R	6.5	68.2	25.3	8.3	5.2
H.Ö.	32.0	66.6	1.3	1.8	6.2
T	14.8	28.4	56.8	8.9	5.3
H.o.	9.5	40.1	50.5	8.4	5.8

Rikkenstorp is the northernmost located site, about 30 km west of Ludvika. The forest garden is sited on a slight slope with some older trees above it and pastureland below. The soil is clayey moraine silt, rich in humus from improvements some years ago when it was used as a potato field. So far, only trees, shrubs and some comfrey have been planted at the site and the rest of the ground is covered by grass. Hånsta Östergärde is located outside of Vattholma, about 20 km north of Uppsala. The forest garden is sited on a former agricultural field, and it is a quite open and windy spot. This year winter wheat was grown on the surrounding field, which was used as the reference. The soil is a medium clay soil, poor in humus. At this site, trees, shrubs and herbal layer are planted. Tystinge is located 10 km west of Hallsberg. The forest garden is sited on former lay and there is a big tree some meters away. The soil is clayey moraine sand, rich in humus, with a layer of slate at about 30-40 cm depth. At this site, trees and shrubs have been planted, and about half of the site has an established herbal layer. The rest is covered by folding boxes, garden fabric and straw. Holma is located in Höör. The forest garden is sited at the edge of a larger forest garden and is therefore surrounded by trees and shrubs on two sides. The soil

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is a humus rich, clayey moraine soil with little structure and at some places there are layers of gravel that have been used to cover pathways in the older forest garden. At this site, trees, shrubs and a few herbs have been planted, but most of the ground is still covered by newspaper and straw. Klockaregården is located in Norra Mellby, about 20 km north of Höör. The forest garden is sited on meadowland, and is surrounded by other trees and shrubs on two sides. The soil is silty but has some structure, which decreases with depth. At this site trees, shrubs and a few herbs have been planted, but the main part of the area is covered by grass. At the time of sampling, the grass had been cut and was used as mulch and to suppress weeds. Hereafter the sites are named by their abbreviations.

3.2 Data collection

During the autumn in 2015 biomass and soil samples from the experimental sites were collected. The procedure of data collection is described below.

3.2.1 Biomass

Biomass in the forest garden consists of two components, aboveground and belowground biomass. Aboveground biomass can be further divided into herbal and woody biomass (trees and shrubs), while belowground biomass is made up of roots and soil organisms. In this thesis only roots are considered below ground. The following description of the methods used divides biomass into (1) herbal biomass, (2) biomass of trees and shrubs and (3) root biomass.

Herbal biomass
The method for sampling of herbal biomass was changed during the course of field work, as the second method was considered more precise and suitable. Both of the methods are described below, as herbal biomass estimation 1.0 and 2.0.

The idea of using the second method for estimation of aboveground herbal biomass arose during field work at the third forest garden (H.o.) where the ground was mostly covered by newspaper and straw. At this site it was not possible to use the first method. At the other sites the first method was also considered not to provide reliable results as the sites are so heterogeneous. Heterogeneity is the foundation of agroforestry systems, but the heterogeneity also makes randomized sampling less suitable for studies of the system (Schroth and Sinclair, 2003). The second method was influenced by the work with allometric equations.

Figure 1. Location of the five sites.

Herbal biomass estimation 1.0

Biomass was collected in ten randomly selected squares of 25x25 cm within a grid, Figure 2. The size of the total grid (big square) was 2,5x2,5 m and was placed at a spot at the experimental site that was seen as most representative of an established forest garden, i.e. with well-developed layers of vegetation. As one of the aims of this study was to investigate biomass production of the forest gardens, choosing a spot that represented a fully established system at this stage of development was of importance. The grid was also placed not closer than one meter from the end of the long sides and not closer than two meter from the end of the short sides to minimize the edge effects. For random selection of the squares each square in the grid got a number, out of which ten were blindly picked. For location of the grids at the specific sites see Appendix 1. Planted vegetation and weeds (plants that was not planted on purpose) were harvested in the randomly selected squares (filled squares in Figure 2), put into separate bags and taken to the lab for drying and weighing. The height of the plants in each square was also noted in the field. Parts of vegetation that was outside of the square were cut off and not collected. This method to estimate herbal biomass was used at three sites, R, H.Ö. and T. At the two other sites, this method was not possible to use as the ground was covered by magazine paper and straw. Raw data of herbal vegetation from this method is to be found in Appendix 2. The same procedure was done with vegetation from 3 plots outside the forest gardens. The reference spots were placed randomly. At R there were very little space outside of the forest gardens and the reference spots were very close to the forest gardens. At H.Ö. the reference spot was the neighboring agricultural field and here samples were collected about two, twelve and twenty two meters into the field. At T there was also more space and the reference spots were within five meters of the forest gardens, on different sides of it. Vegetation samples were also collected at the reference spots of H.o. and K. At H.o. there was very little space and soil samples had to be collected very close to the forest garden whilst at K there were more space and the soil samples were collected within 5 meter from the forest garden.
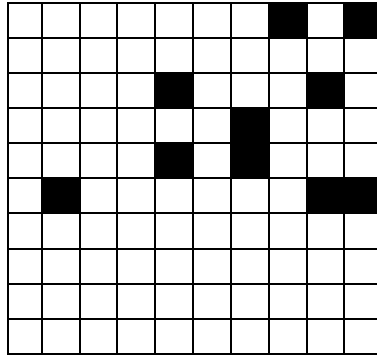
Figure 2. Grid with marked squares from where biomass was collected.

<u>Herbal biomass estimation 2.0</u>
The second estimation of herbal biomass was done by clipping two squares of biomass (25x25cm) of each planted herb at four sites (H,Ö., T, H.o., K). These samples were collected in different bags and brought to the lab for drying and weighing. Raw data of herbal vegetation form this method is to be found in Appendix 3.

Biomass of trees and shrubs
For estimation of biomass of trees and shrubs diameter, height and crown width were measured in the field at three sites, H.Ö., H.o. and K. Diameter was measured just beneath the canopy's branches as the trees were too small for measuring diameter at breast height. For the shrubs height, width and diameter of approximately half of the branches were measured.

Root biomass
See the paragraph *Soil sampling* further down.

3.2.2 Soil profile description
Soil profile descriptions were conducted at one spot in the forest gardens at H.Ö., T, H.o. and K, and their references, down to a depth of 50 cm. At H.o. no profile description was done at the reference spot. The description was conducted with regards to fine roots and earthworm cavities according to Friedel (2011). Inside of the forest gardens, the profile description was done at the same relative location for all gardens (spot three in Figure 3).

3.2.3 Soil sampling
Soil samples were collected at five places within the forest gardens (Figure 3) and at three reference spots. Within the forest gardens the samples were first collected from a transect, shaped as a "w". However, after the visit to the first site (R) the method was slightly changed and thereafter the samples were collected close to the

same woody plant species as they had been at R (see Figure 3). This was to enable comparison between different species and see whether they had any general impact on the studied parameters. For the names of the plants in English and Latin see Table 2. Soil samples from the reference spots were collected from the same spots as the vegetation samples.

Soil samples were collected with a cylinder, 10 cm in height and 7,5 cm in diameter, at 0-10, 20-30 and 40-50 cm depth. At H.o. where the soil was very stony a smaller cylinder was used, with a diameter of 4.8 cm. At some spots the cylinder could not go down to 10 cm due to the stones, in these cases the smaller volume was taken into account when calculating bulk density. Four samples were collected at each depth; one for measuring bulk density (always with the cylinder; for bulk density see Appendix 4), one for root biomass, one for mycorrhiza and one for measuring respiration. The samples collected for respiration measurements were stored in a cool box to quickly reduce the metabolic activity (Schinner et al., 1995). Samples collected for investigation of root biomass, mycorrhiza and respiration were put into a plastic bag and mixed, and subsamples were taken from this mix. This was done to obtain values representing a larger sampling area (Schroth and Sinclair, 2003). The samples were stored cold before taken to the laboratory for analysis. Analysis of carbon and nitrogen was conducted on subsamples of the samples used for estimating bulk density.

Figure 3. Forest garden design, and spots for soil sampling.
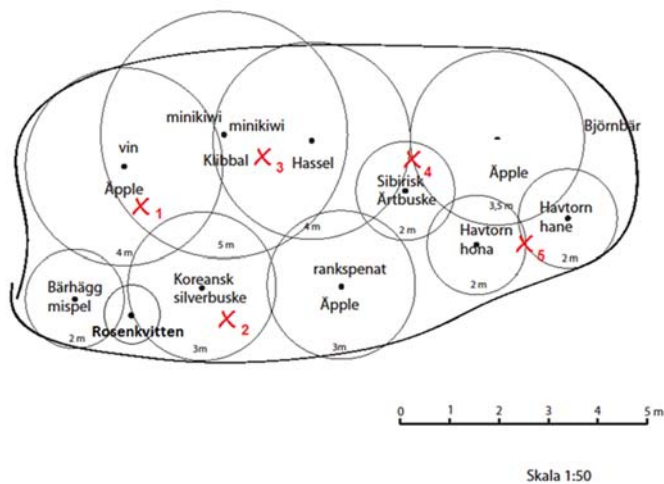
Table 2. Species name in Swedish, English and Latin.

Swedish	English	Latin
Äpple	Apple	*Malus domestica*
Klibbal	Common alder	*Alnus glutinosa*
Bärhäggmispel	Saskatoon service berry	*Amelanchier alnifoila*
Koreansk silverbuske	Autumn olive	*Elaeagnus umbellata*
Hassel	Hazel	*Corylus avellana*
Rosenkvitten	Flowering quince	*Chaenomeles sp.*
Sibirisk ärtbuske	Siberian peashrub	*Cargana arborescens*
Havtorn	Sea-buckthorn	*Hippophaë rhamnoides*
Björnbär	Blackberry	*Rubus subg. Rubus*
Minikiwi	Hardy kiwi	*Actinidia arguta*
Vinranka	Vine	*Vitis vinifera*

3.3 Data preparation and analysis

3.3.1 Above ground biomass

The harvested herbal biomass was weighed, dried at 50ºC for 48 hours and weighed again for biomass estimation in grams of dry biomass. Mean values of gram biomass per m^2 were calculated. In the first version of herbal biomass estimations, the values from each sampled square were summed up and divided by the number of squares. In the second version of herbal biomass estimations, mean values for each species were calculated and then used to estimate herbal biomass in the forest garden by estimating the relative coverage of each species at the site. Carbon content was calculated by multiplying biomass with 0.475, assuming biomass contain 47.5% carbon (Saj et al. 2013).

Biomass of trees and shrubs was estimated by allometric equations (Table 3). As no equations have been developed for most of the tree and shrub species in the forest gardens, equations developed for other species were used. These equations were chosen to fit the morphology, growth pattern and climate conditions of the species and sites within the project. The first two were equations for birch (*Betula pendula*) and alder (*Alnus glutinosa*) growing on abandoned farmland, calculating biomass in kg dry weight (DW)/ha (Johansson, 1999; Johansson, 2000). To be able to calculate the amount of biomass in kg DW/tree an equation for beech (*Fagus sylvatica*) was used (Nihlgård, 1972). This equation was also thought to better fit the morphology of apple trees, as the morphology of apple trees is more similar to that of beech than of birch. The calculated values were used to assess differences in biomass between the sites, and the contribution of each plant or type of vegetation to the total biomass of the forest gardens.

For the shrubs, an equation for *Salix sp.* was used as it is a very branchy tree, and in bioenergy production they do not get very large either. An equation developed on Iceland was used (Snorrason and Einarsson, 2006), which might better mimic the growth of the shrubs, as Salix sp. otherwise grows very fast. Raw data of trees and shrubs are presented in Appendix 5.

Again, the carbon content was calculated by multiplying biomass with 0.475, estimating a carbon content of 47.5 % C/g dry biomass (Saj et al., 2013).

Biomass of foliage was calculated for both trees and shrubs to estimate litter production from woody plants.

Table 3. Allometric equations used to estimate a) total biomass and b) leafy biomass of trees and shrubs. B = total biomass, DBH = diameter at breast height (in this case the diameter had to be measured just underneath the crown as the trees were too small), H = total height of tree or shrub, D0.5 = branch diameter at 0.5 m height (in this case the diameter was measured at about 0.1 m as the shrubs were too small), F = biomass of foliage.

a)

Author	Equation	Species
Johansson, 1999	$B=0.00087*(DBH)^{2.28639}$	*Betula pendula*
Nihlgård, 1972	$B=LOG10(DBH^2*H)*1.0414-1.7194$	*Fagus sylvatica*
Johansson, 2000	$B=0.00079*(DBH)^{2.28546}$	*Alnus glutinosa*
Snorrason and Einarsson, 2006	$B=0.0348*D_{0.5}^{(1.9123)}*H^{(0.8904)}$	*Salix sp.*

b)

Author	Equation	Species
Johansson. 1999	$F=0.00371*(DBH)^{1.11993}$	*Betula pendula*
Johansson, 2000	$F=0.00239*(DBH)\sim1.32535$	*Alnus glutinosa*

3.3.2 Below ground biomass

Below ground biomass was estimated by weighing roots that were washed out from soil samples. The soil samples were soaked in water for at least 24 hours to make separation of roots from the soil easier. The roots were then washed out of the soil with a 0.63 mm sieve. The roots were dried and weighed. Root biomass was estimated per m^2 based on measurements of soil density.

3.3.3 Respiration

Respiration was measured according to Rowell (1994). This method was further developed during this work, with assistance from researchers at Örebro University as described below.

The soil was sieved through a 2 mm sieve and was incubated for approximately a week to stabilize carbon fluxes. For measuring respiration, a water content of 60% of field capacity was desired (Rowell, 1994). The initial water content was estimated by drying subsamples of soil from all sampling spots. For most samples the water content was already close to 60% of field capacity, but for some samples water had to be added with a spray bottle, and the flasks were swirled around to mix soil and water. Approximately 50 g soil was put into flasks, which were sealed with a plastic cork. To the plastic cork a small glass jar was attached, containing 10 ml 0.01 M NaOH. Respired CO2 was collected during a three hours incubation period.

BaCl was added to the NaOH-solution in the jars when they were taken out of the flasks to stop the NaOH-solution from reacting with CO_2 in the air. Respired CO_2 was then measured by titrating 0.0025 M HCl into the NaOH solution until pH was neutral. Respiration estimates were presented as gCO_2/m^2h. Bulk densities without stones (sieved with a 2 mm sieve) were used for these estimations, as the soil used for respiration measurements had been sieved.

3.3.4 Total C/Total N

Soil samples were dried at 105°C and sieved on a 2 mm sieve. The samples were analyzed for carbon and nitrogen on a CN analyzer (LECO, St. Joseph, MI, USA). The amount of carbon was estimated per m^2, whilst the C/N was estimated by an average across the soil horizons and presented per m^2. Bulk densities without stones (sieved with a 2 mm sieve) were used for these estimations, as the soil used for this analysis had been sieved.

3.3.5 Mycorrhiza

The roots were thoroughly cleaned from soil by washing. First, roots were separated from the soil by soaking the soil sample in water for a minimum of 24 hours. Roots were washed in a 0.63 mm sieve, put into tubes with water and stored in a cooling room until staining. For mycorrhizal staining solutions of 10% KOH, 5% acetic acid and a 3:2 dilution of H_2O_2 were prepared. The roots were colored with ink according to the procedure, developed by Vierheilig et al. (1998), described below.

Subsamples of the roots were put into small tubes where they were cleaned in de-ionized water. After drying of excess water, the roots were cleared by incubation in

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10% (wt/vol) potassium hydroxide (KOH) at 90° C for 15 minutes in a heating cupboard. The roots were then rinsed with de-ionized water several times and dried of excess water again. The roots were put back into the tubes and a 5% ink-vinegar solution (5% acetic acid) was added to the tubes, which were incubated at 90ºC for 3 minutes. The roots were de-stained by being washed with water and put into de-ionized water with a few drops of acetic acid (5%) and left in room temperature for 20 minutes. The acid also helped to fix the ink in the fungal tissue. Lastly, roots were cleaned with water at 90°C. The roots were stored in tap water in the refrigerator. Dark root tissue had to be bleached with H_2O_2 overnight. For roots that were bleached, the cleaning procedure was repeated. The roots were studied under microscope to evaluate the degree of mycorrhizal colonization and abundance of arbuscules.

3.4　Statistical analysis

The impact of an established forest garden on root biomass, total carbon, respiration and C/N ratio, was compared to former land use, as well as within and between each site. Weighted mean values of the studied parameters from each layer within and outside of the forest garden were calculated. Samples collected within the forest gardens were weighted according to the percent of coverage this spot was estimated to represent, whilst the three sampling spots outside the forest gardens were considered to be of equal weight in this analysis. To analyze differences both within and between forest gardens weighted values from all sampling spots and depths were used for the analysis. The data was assumed to be normally distributed and two factor ANOVA was used. The statistical analysis was conducted with the program R Studio.

4 Results

4.1 Pools and flow of Carbon

4.1.1 Herbal biomass

Version 1.0, randomly selected squares

According to the measurements of herbal biomass from randomly selected squares, the potential of the forest garden to increase biomass of non woody vegetation varies between the sites. At H.Ö. and T, where the herbal layer had been established, herbal biomass was higher within the forest garden than at their reference spots. At R, biomass was higher outside of the forest garden. However, the herbal layer was not planted yet, so this site cannot be seen as a representative forest garden with regards to herbal biomass. Figure 4 also show that biomass varied substantially between the two established forest gardens, H.Ö. and T, with T having about twice as much biomass than H.Ö. Thus, site seems to have a crucial impact on biomass production in the forest gardens.
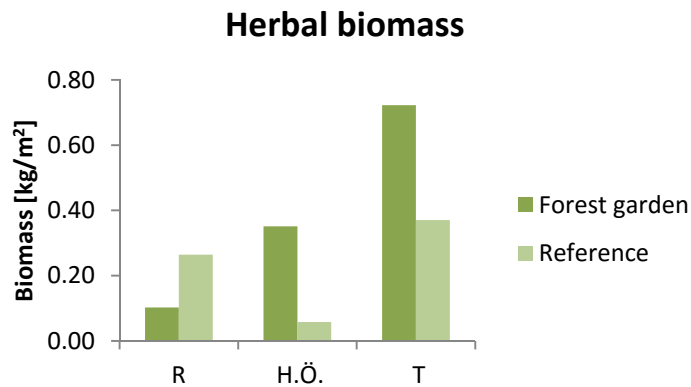
Figure 4. Herbal biomass [kg/m^2] collected at Rikkenstorp (R), Hånsta Östergärde (H.Ö.) and Tystinge (T) from within and outside of the forest gardens.

Version 2.0, species specific biomass

Biomass estimations for the different herbs ascribed different values to different plants (Figure 5). Vegetation was collected, dried and calculated for most of the herbs in the forest garden. The exceptions were adder's wort (*Persicaria bistorta*), chive (*Allium schoenoprasum*) and day lily (*Hemerocallis sp.*), which were not harvested because those plants were more expensive or they were not so commonly occurring in the forest gardens.
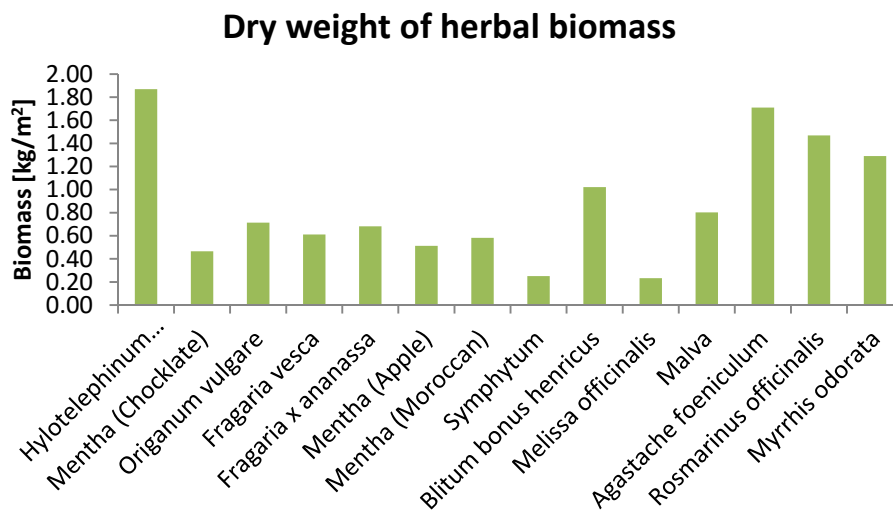
Figure 5. Average dry weight [kg/m^2] of herbal plants in the forest gardens. Species names in Swedish and English are to be found in Table 4.

Table 4. Species names, herbal biomass, in Swedish, English and Latin.

Swedish	English	Latin
Kärleksört	Orphine	*Hylotelephium telephium*
Mynta (Choklad)	Mint (Chocklate)	*Mentha*
Oregano	Oregano	*Origanum vulgare*
Smultron	Wild strawberry	*Fragaria vesca*
Jordgubb	Strawberry	*Fragaria x ananassa*
Mynta (Äpple)	Mint (Apple)	*Mentha*
Mynta (Maroccansk)	Mint (Moroccan)	*Mentha*
Vallört	Comfrey	*Symphytum*
Lungrot	Good-King-Henry	*Blitum bonus henricus*
Citron meliss	Lemon balm	*Melissa officinalis*
Malva	Mallow	*Malva*
Anissop	Anise hyssop	*Agastache foeniculum*
Rosmarin	Rosemary	*Rosmarinus officinalis*
Spansk körvel	Myrrh	*Myrrhis odorata*

Compared to other land use (reference spots) the herbal layer of the forest garden (H.Ö.) produced more biomass (DW) than vegetation at its reference (agricultural cropping field). The forest garden at H.Ö. also produced more biomass than the grazed grassland (reference at T) and the untouched grassland (reference at R; Table 5). Furthermore, biomass production was almost the same as for the reference spot at K whilst it was less than on the reference spot at H.o. Table 5 show that biomass varied considerably depending on land use at the reference spots. H.Ö. is used as an example as this was one of the well-established forest gardens. Carbon content in standing biomass was also calculated, and as the same amount of carbon was assumed for each herb, carbon content follows the same trend as biomass production (Table 5).

Table 5. Herbal biomass at H.Ö. and the five reference spots.

Herb	Area covered	Biomass	Carbon	Biomass
	m2	kg	kg	kg/m^2
Symphytum	9	2.26	1.07	
Fragaria x ananassa	9	6.14	2.92	
Rosmarinus officinalis	1.8	2.64	1.26	
Hylotelephium telephium	0.3	0.56	0.27	
Mentha (Chocklate)	6	2.79	1.33	
Mentha (Moroccan)	2.7	1.57	0.75	
Myrrhis orodata	4.8	6.19	2.94	
Blitum bonus henricus	3	3.07	1.46	
Sum	36.6	25.23	11.98	0.69
Reference H.Ö.	36.6	2.11	1.00	0.058
Reference T	36.6	11.74	5.58	0.32
Refernce R	36.6	9.68	4.60	0.27
Reference H.o.	36.6	32.38	15.38	0.89
Reference K	36.6	23.87	11.34	0.65

4.1.2 Biomass of trees and shrubs

Comparing the biomass obtained from the same equations but from different sites showed that tree biomass at H.o. was largest, followed by H.Ö. and K (Table 6, Figure 6). It is also worth noticing that biomass of woody plants was only calculated at these three sites. At H.o. biomass also differ a lot between the three apple species (Figure 6 a). This could be because the ground was covered at some part of the forest garden and at others not. Even though the alder was not planted at K it does not seem to be the main cause of the lower tree biomass at this site, as the apple trees already show much lower biomass at this site compared to the two others. Table 6 also shows that the two equations by Johansson give slightly different biomass estimations.

The biomass of shrubs was substantially lower at K (Figure 6 b), compared to the two other sites, which were almost the same (Table 7, Figure 6 b)).

Table 6. Biomass of trees from Hånsta Östergärde, Holma and Klockaregården us-
ing three different equations (Nihlgård, 1972; Johansson, 1999; Johansson, 2000).
For names in Swedish and English see Table 3. d = diameter just under the crown,
h = height of the tree.

Species and Site	Equation	d	h	Biomass	Carbon
		cm	m		
Malus domestica (Amorosa)	Johansson, 1999			kg DW/ha	kg/ha
H.Ö.		3.50	200	2.96	1.41
H.o.		5.03	215	6.77	3.22
	Johansson, 2000				
H.Ö.		3.50	200	2.68	1.27
H.o.		5.03	215	6.12	2.91
	Nihlgård, 1972			kg DW/tree	kg/tree
H.Ö.		3.50	200	64.70	30.73
H.o.		5.03	215	148.31	70.45
Malus domestica (Astrakan)	Johansson, 1999			kg DW/ha	kg/ha
H.Ö.		3.25	215	2.49	1.18
H.o.		4.30	145	4.72	2.24
	Johansson, 2000				
H.Ö.		3.25	215	2.25	1.069
H.o.		4.30	145	4.27	2.028
	Nihlgård, 1972			kg DW/tree	kg/tree
H.Ö.		3.25	215	59.61	28.31
H.o.		4.30	145	70.91	33.68
Malus domestica (Alice)	Johansson, 1999			kg DW/ha	kg/ha
H.Ö.		3.79	200	3.54	1.68
H.o.		2.74	200	1.68	0.8
K		2.42	219	1.27	0.6
	Johansson, 2000				
H.Ö.		3.79	200	3.20	1.52
H.o.		2.74	200	1.52	0.72

				kg DW/tree	kg/tree
K		2.42	219	1.15	0.55
	Nihlgård, 1972				
H.Ö.		3.79	200	76.21	36.2
H.o.		2.74	200	38.75	18.41
K		2.42	219	32.92	15.64
Malus domestica (unknown)	Johansson, 1999			kg DW/ha	kg/ha
K		2.80	177	1.77	0.84
K		2.71	185	1.64	0.78
	Johansson, 2000				
K		2.80	177	1.61	0.76
K		2.71	185	1.48	0.7
	Nihlgård, 1972			kg DW/tree	Kg/tree
K		2.80	177	35.79	17
K		2.71	185	34.87	16.56
Alnus glutinosa	Johansson, 1999			kg DW/ha	kg/ha
H.Ö.		3.57	200	3.081	1.46
H.o.		4.20	312	4.49	2.13
	Johansson, 2000				
H.Ö.		3.57	200	2.79	1.33
H.o.		4.20	312	4.06	1.93
	Nihlgård, 1972			kg DW/tree	
H.Ö.		3.57	200	67.17	31.91
H.o.		4.20	312	150.29	71.39

Table 7. Biomass of shrubs from Hånsta Östergärde, Holma and Klockaregården using the equation from Snorrason and Einarson, 2006. For names in Swedish and English see Table 3. d = diameter at approx. 0.1 m heitht, h = height of the shrub.

Species and site	Equation	d	h	Biomass	Carbon
	Snorrason and Einarsson, 2006	cm	cm	kg DW/shrub	kg/shrub
Elaeagnis um-bellata					
H.Ö.		2.4	165	16.9	8.028
H.o.		2.5	200	18.2	8.65
K		4	92	1.8	0.86
Corylus avellana					
H.Ö.		1.8	140	8.6	4.085
H.o.		2.4	141	12.9	6.13
K		7	178	6.4	3.04
Cargana arbore-scens					
H.Ö.		2.5	150	17.2	8.17
Hippophaë rhamnoides					
H.Ö. (male)		2.5	125	15.3	7.27
H.Ö.(female)		2.6	150	18.5	8.79
H.o. (male)		7	80	2.4	1.14
H.o. (female)		3	200	44.6	21.19
K (unknown sex)		1.1	43	1.2	0.57
K (unknown sex)		1.2	89	2.7	1.28
Rubus subg. Ru-bus					
K		2.7	167	22.3	10.59

a)

Relative woody biomass, trees

b)

Relative woody biomass, shrubs
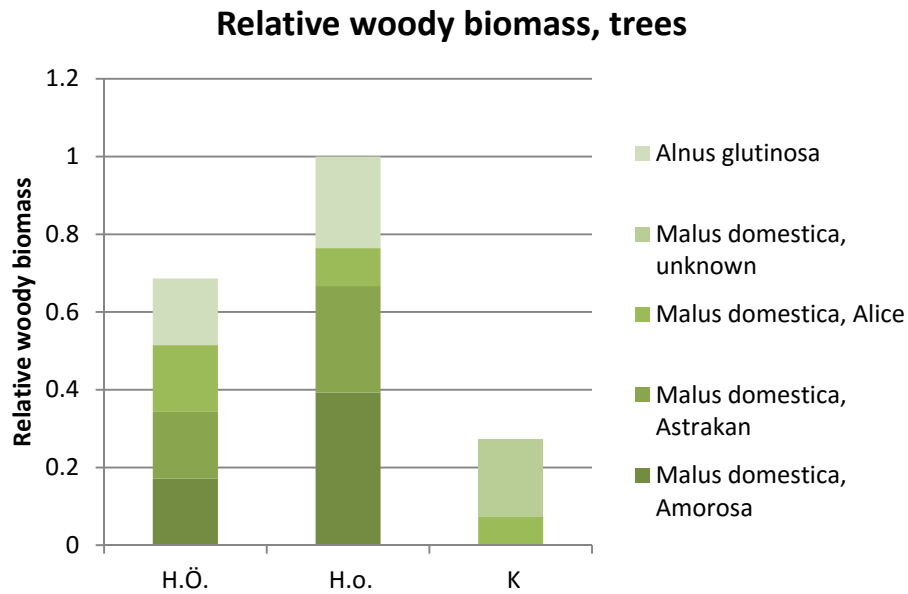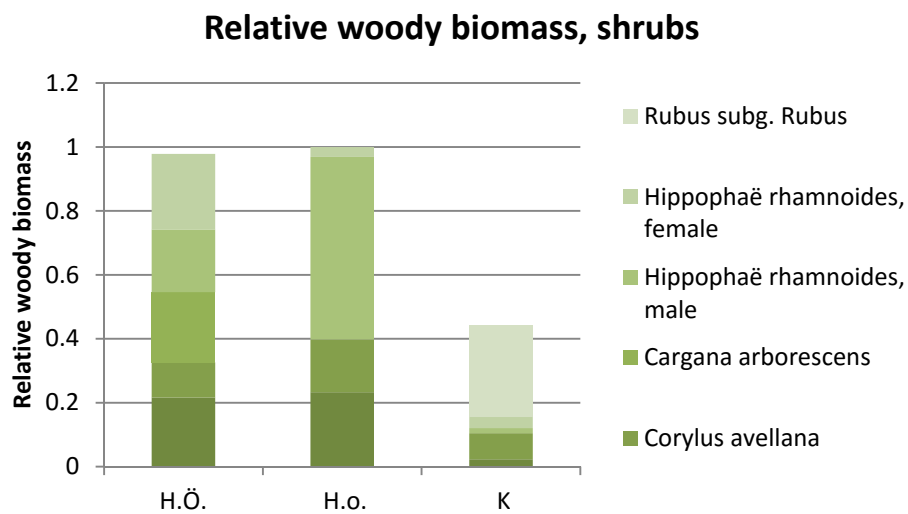
Figure 6. Relative values (H.o. set to 1) of woody biomass for a) trees and b) shrubs. Equations used for the calculations are Johansson, (1999) for apple trees (Malus domestica), Johansson (2000) for alder (Alnus glutinosa) and Snorreson and Einarsson (2006) for shrubs. For names in Swedish and English see Table 3.

4.1.3 Total aboveground biomass

The contribution of each type of vegetation to aboveground biomass of the forest garden varied. Trees contributed most to forest garden biomass, followed by shrubs (Figure 7). This is not very surprising because of the different sizes of these vegetation types. To estimate the contribution of each vegetation type, equations calculating biomass per tree or shrub were used, together with the second method to estimate herbal biomass.
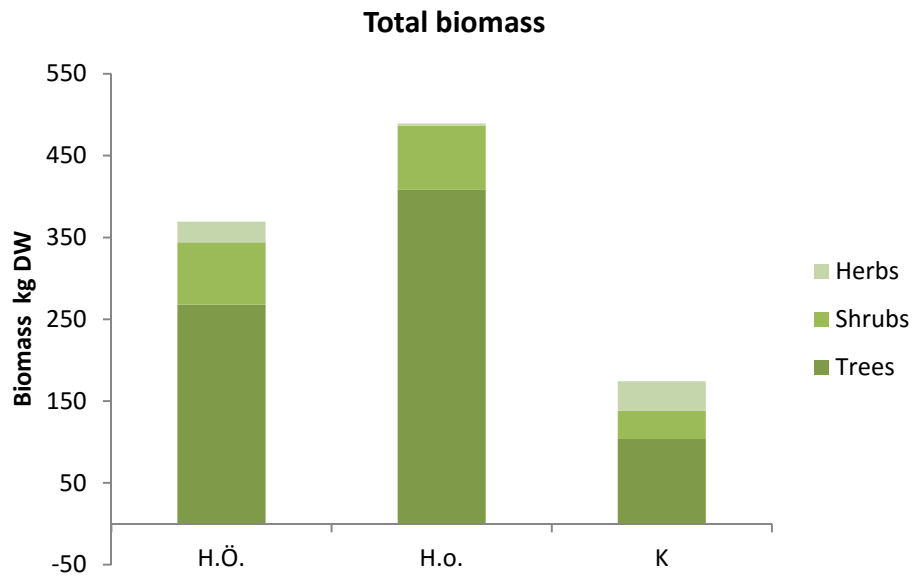
Total biomass

Figure 7. Total biomass at H.Ö., H.o. and K calculated by equations from Nihlgård, (1972) for trees and Snorrason and Einarsson, (2006) for shrubs. For each component see Appendix 6.

However, when comparing litter production with the methods used in this study (Table 3; Appendix 7), the relations are the contrary, with K having the highest litter production and H.o. the lowest. Out of the data obtained from this study, herbal biomass production was the main contributor of litter production, which is probably explained by the combination of young trees and shrubs, with yet a small total production of leaves, and allometric equations with an imprecise fit. At this stage herbal biomass is probably the main contributor of litter production, but not to that extent, according to visual observations.

4.1.4 Roots biomass

When comparing the forest gardens with their reference spots it was clear that the alternative land use had an impact on the root biomass at this stage of development

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of the forest gardens (Figure 8 a-c). Grasslands, particularly at R, had the highest biomass production, and more than the forest garden at those sites (R and T). Root biomass in the grasslands is concentrated in the top layer, just under the soil surface and decreases drastically with depth. At the forest gardens and the agricultural field (reference spot at H.Ö.) root biomass is more evenly distributed throughout the soil profile. Root biomass was considerable higher at R compared to the other sites. It was twice as high as root biomass at T, both within and outside of the forest garden, and up to over 26 times higher than root biomass at H.Ö. Comparing the two forest gardens that had their herbal layer established (H.Ö. and T), Figure 8 b) and c) also reveal differences in root biomass between these sites, with T having more than three times higher root biomass in the top layer. In the lower layers the difference decreases. The forest gardens at H.Ö. and T were established to the same extent, but this data indicates that there is a difference in growth conditions at the site. For raw data on root biomass see Appendix 8.

a)

b)

c)

Tystinge

Root biomass [g/m²]

Legend:
- 0-10
- 20-30
- 40-50
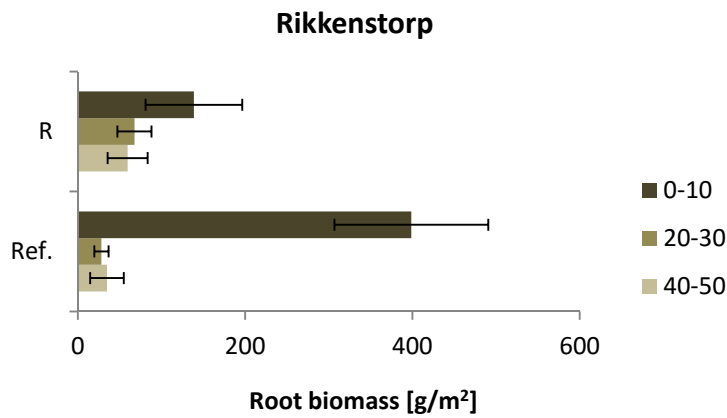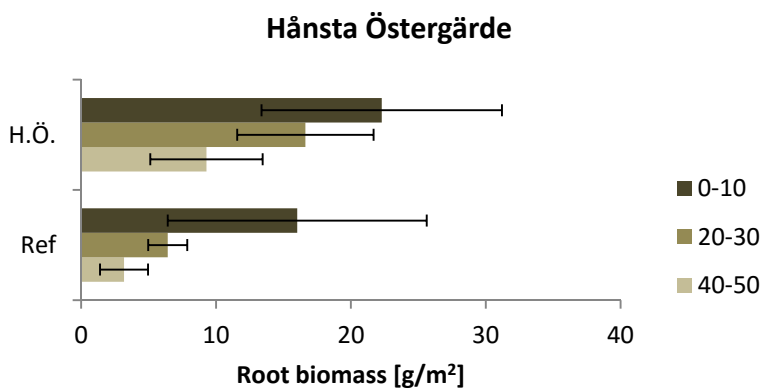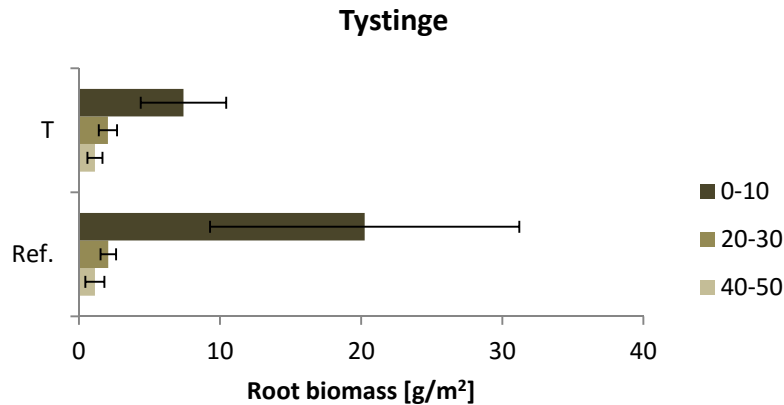
Figure 8. Root biomass expressed in gram per m² for the forest gardens at a) Rikken-storp, b) Hånsta Östergärde, and c) Tystinge and their reference spots. Error bars show standard error of the mean.

Only at H.Ö. there was a significant difference between the forest garden and its reference spot with regards to root biomass, as well as with depth (P<0.01; Table 8).

An ANOVA analysis of the three forest gardens compared showed that there were significant differences in root biomass between the forest gardens (P<0.1) as well as between the depths (P<0.01). However, no significant differences were found between the sampling spots within the forest gardens (Table 8).

At the moment, grassland seem to be the land use with the largest root biomass, mainly because of the thick root-mat at the top 0-10 cm (Figure 8 a) and c)). However, this is only one part of biomass production in the system. Root biomass of the whole forest garden (60 m²) between 0-50 cm was calculated to be about 16, 3 and 6 kg for R, H.Ö. and T respectively (Appendix 9). These numbers are quite small compared to the total above ground biomass calculated for H.Ö., H.o. and K, ranging from 170 kg (K) to 340 kg (H.o.; Figure 7). Also when comparing root biomass with annual production of litter, the roots represent a quite small part of the biomass production, with annual production of litter estimated to range from 3 kg (H.o.) to 36 kg (K; Appendix 7). However, in the estimation of root biomass larger roots of trees and shrubs were not considered as they could not be harvested. Hence, root biomass is larger than calculated here and might be equal to or even larger than litter production. Other studies has shown that root biomass is a major contributor of organic matter and carbon to the soil, especially in grassland (Paul, 2015).

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Table 8. Probability values and significance levels of root biomass, carbon content, respiration and C/N ratio.

Hypothesis and site		Root bio-mass		Carbon content		Respi-ration		C/N	
Forest garden vs. reference		p-value		p-value		p-value		p-value	
R	Location	0.55		0.078		0.44		0.034	*
	Depth	0.16		0.0083	**	0.039	*	0.0061	**
H.Ö.	Location	0.0095	**	0.59		0.17		0.62	
	Depth	0.0036	**	0.0075	**	0.43		0.041	*
T	Location	0.42		0.47		0.93		0.62	
	Depth	0.11		0.097		0.015	*	0.041	*
H.o.	Location	-		0.72				0.89	
	Depth	-		0.0074	**			0.97	
K	Location	-		0.018	*			0.57	
	Depth	-		0.00094	***			0.48	
Comparison between forest gardens									
	Location	0.014	*	1.79e-10	***	0.026	*	2.86e-08	***
	Depth	0.0087	**	2.26e-12	***	0.00019	***	0.070	
	Sample	0.95		0.15		0.25		0.50	
	Location:Depth	0.44		0.11		0.0011	**	0.0011	**
	Location:Sample	0.92		0.00024	***	0.19		0.052	
	Depth:Sample	0.99		0.35		0.012	*	0.95	
	Location:Depth: Sample	0.88		0.44		0.62		0.77	

4.1.5 Total C

Carbon content was highest at R, T and H.o., and lowest at H.Ö. and K (Figure 9). This coincides with the general picture of the productivity of the sites that was found for biomass, i.e. high above and/or below ground biomass at R, T and H.o., and less at H.Ö. and K. Carbon content was highest in the uppermost layer and decreased with depth at all sites. The difference in carbon content with depth was significant for R, H.Ö., H.o. and K ($P<0.01$). Differences between the forest gardens and their references varied. At R and K, carbon content was higher in the forest gardens than at the reference spots, while at H.Ö., T and H.o., carbon content was highest at the reference spots. Only at K a significant difference was seen between the forest garden and its reference ($P<0.05$), The differences between the five forest gardens was highly significant ($P<0.0001$). The difference within each forest garden was not significant.

a)

Rikkenstorp

b)

Hånsta Östergärde

c)
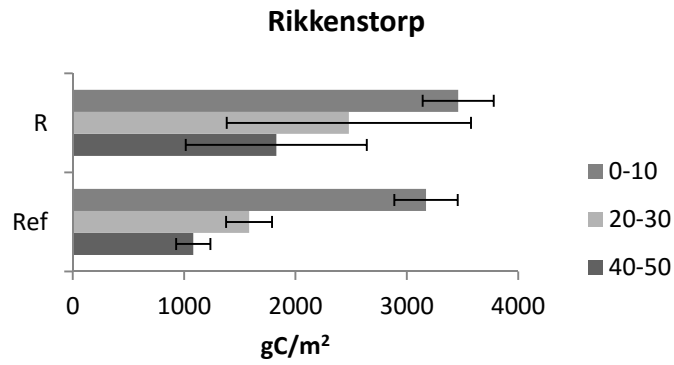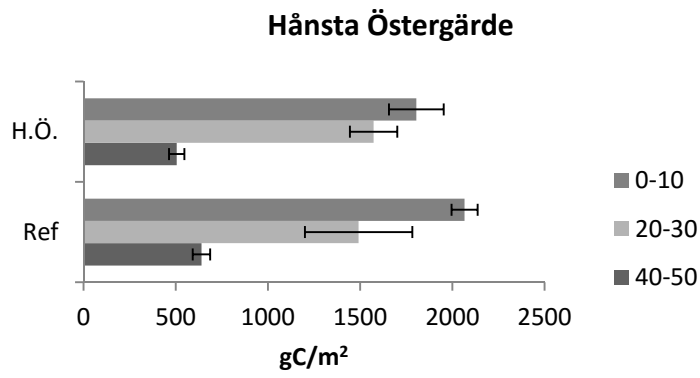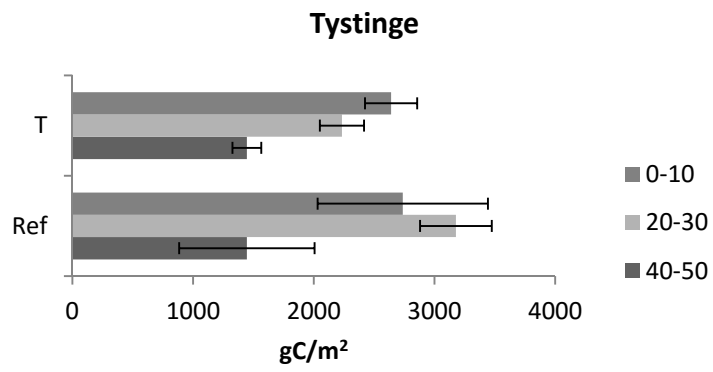
Tystinge

d)
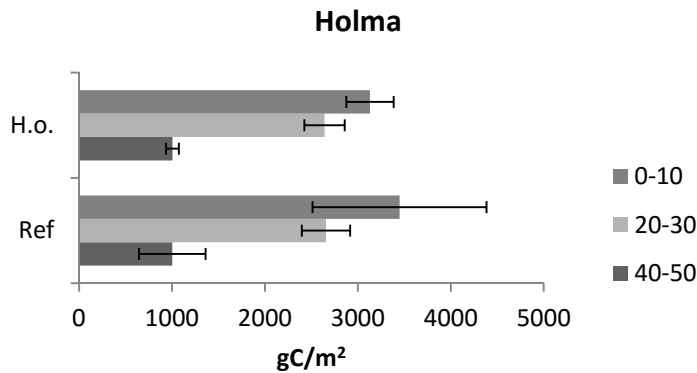
e)
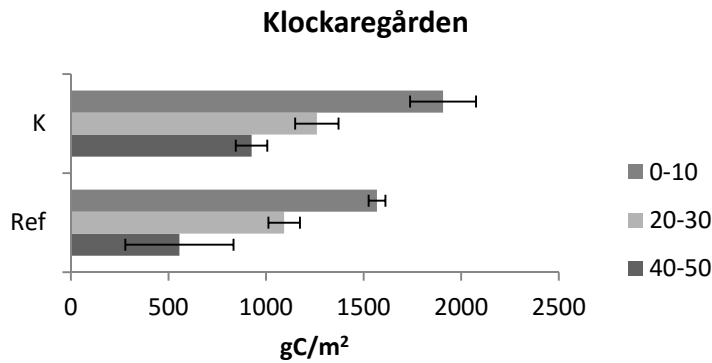
Figure 9. Carbon content per m² in the soil profile at a) Rikkenstorp, b) Hånsta Östergärde, c) Tystinge, d) Holma and e) Klockaregården. Error bars show standard error of the mean.

4.1.6 Respiration

Soil respiration was measured throughout the whole soil profile for the sites R, H.Ö., and T. At T, respiration was almost the same in the forest garden as at the reference spot (Figure 10 c)), while at R and H.Ö. respiration was higher at the reference spot (Figure 10 a) and b)).

For R and T the respiration trend in the soil profile followed what would be expected, with a higher respiration in the top layers and a decrease with depth (Paul, 2015). Respiration values at H.Ö., however, showed an unexpected pattern, with increasing respiration with depth, and relatively high respiration in the middle and lower layers, compared to the two other sites. This could be because the samples

were taken out of and put back into the fridge a couple of times before respiration were measured. It was estimated that it would be possible to measure respiration from samples from four sites during the first laboratory session of two days, so samples from R. H.Ö., H.o. and K were prepared. However, it took longer than expected to prepare the soil samples and it was also difficult to establish appropriate respiration times, so the samples had to be put back into the fridge for about a week. When the soil samples are taken out from the fridge, respiration rates accelerates. Therefore, the samples have to acclimatize to room temperature for about a week before respiration is stable (Rowell, 1994). To have had respiration accelerated twice could have affected the respiration measurements, and might be the reason for the peculiar observations from H.Ö. On the other hand, respiration at R does not seem to have been affected by this treatment. The unexpected respiration rates at H.Ö. could also be due to uneven water content. Almost all soil samples from H.Ö. had lower water content than the desired 60% of field capacity and therefore needed to be rewetted. This was difficult to accomplish as clay soils get very sticky when water is added. Therefore, soil moisture might have differed within the sample.

a)

b)

Rikkenstorp

$gCO_2/m^2\ h$

c)

Hånsta Östergärde

$gCO_2/m^2\ h$

38
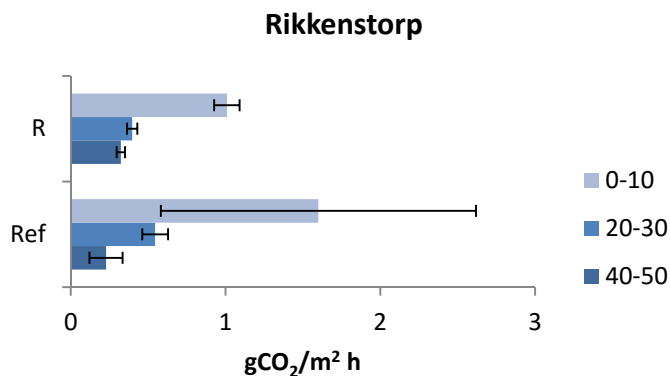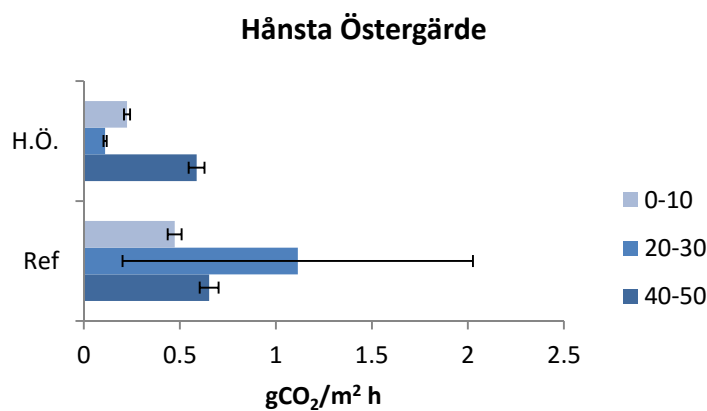
Figure 10. Respiration in gCO₂ per m² and hour at the three depths at a) Rikken-

storp, b) Hånsta Östergärde and c) Tystinge. Error bars show standard error of the mean.
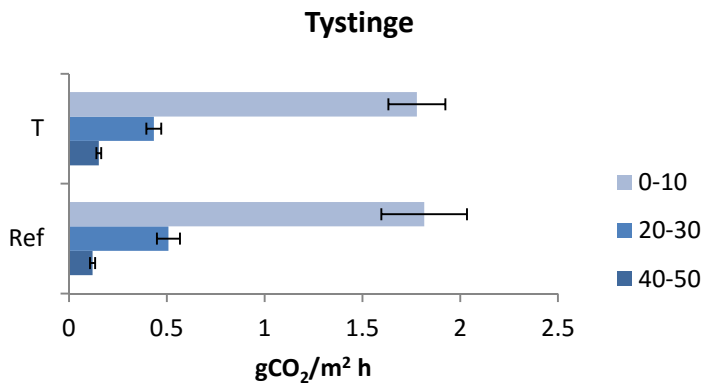
At H.o. and K respiration were only measured on samples from the top layers due to lack of time. As microbial activity is highest in the top soil (Paul, 2015) these samples were chosen for the analysis. The measurements from the top layers show that respiration is highest at the reference spot for all forest gardens (Figure 11). It seems, however, as if respiration was higher in grassland soil (with the exception of K), and under the well-established forest garden at T. At H.o., respiration was expected to be low as the ground was covered by newspaper and straw, thereby having little input of easily decomposable litter. This was also what the measurements showed, with a lower respiration rate at H.o., both compared to the reference spot, which was not covered, and the forest gardens at R and T.

When compared to measurements that were made on soil samples collected from all forest gardens one year earlier, the respiration rates varied more or less between the sample sets (Table 9). At R, H.o. and K mean respiration was quite similar between the two data sets. At T mean respiration was considerable higher in this study compared to the samples collected in 2014, and at H.Ö. mean respiration was twice as high in the samples collected in 2014. The samples from 2014 were not put back into the fridge after they had acclimatized to room temperature, but were analyzed directly. Therefore these results might be more reliable. Furthermore, the differences in respiration between the two sample sets could be caused by differences in sampling depth. The samples collected during 2014 were taken within a depth of 0-20 cm whilst the samples collected for this study and used in this analysis were collected from the top 10 cm. As shown in Figure 10 respiration decreases sharply with depth at R and T, and this might explain the lower respiration rates, especially

at T. Even though no consistent similarities were seen between the two sample sets, the trend in respiration rate is the same, with R and T having the highest respiration rates, and the other three considerably lower.

Figure 11. Respiration gCO_2 per m^2 and hour at the top layer for all forest gardens
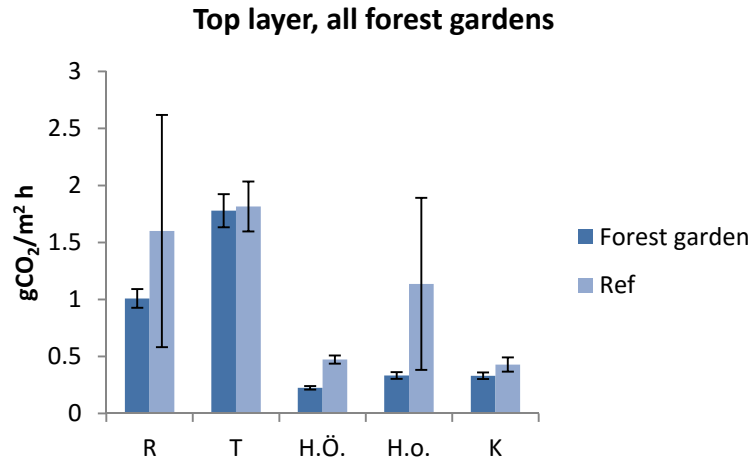
and their reference spots. Error bars show standard error of the mean.

Table 9. Mean respiration in the top soil, measured from soil samples from this study (2015) and from samples collected one year earlier (2014).

Site/Sampling year	2015 μmol/g h	2014 μmol/g h
R	0.29	0.2
T	0.91	0.3
H.Ö.	0.048	0.1
H.o.	0.084	0.13
K	0.079	0.1

ANOVA analysis of respiration data showed no significant differences in respiration between the forest garden and its reference for any of the sites. With depth however, significant differences were seen for both R and T ($P<0.1$). When the top layers at all five sites were analyzed with ANOVA, significant differences were found between the five sites ($P<0.1$), as well as between sampling spots within the forest gardens ($P< 0.1$).

The ratio between respired CO_2 and soil carbon was also calculated. For R and T, the whole profile was taken into account (Figure 12), whilst when comparing all sites only the top layers were considered (Figure 13). H.Ö. was excluded due to the

unrealistic values of CO_2 released form the soil. At R the ratio of respiration-to-soil carbon differs more between the forest garden and the reference spot, at the first two layers in the soil profile, than respiration alone did. At T, the respiration-to-soil carbon ratio almost did not differ at all with any of the measurements. However, in general, respiration [gCO_2] per g soil carbon is larger outside of the forest gardens than within them (Figure 13). Note that respiration is presented as respired CO_2, and not respired carbon.

a)
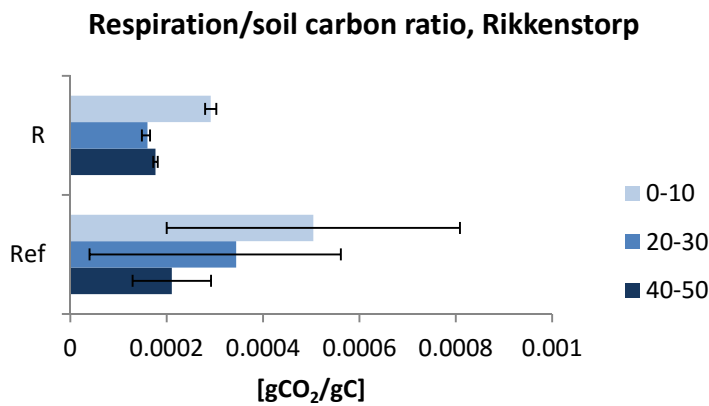
b)
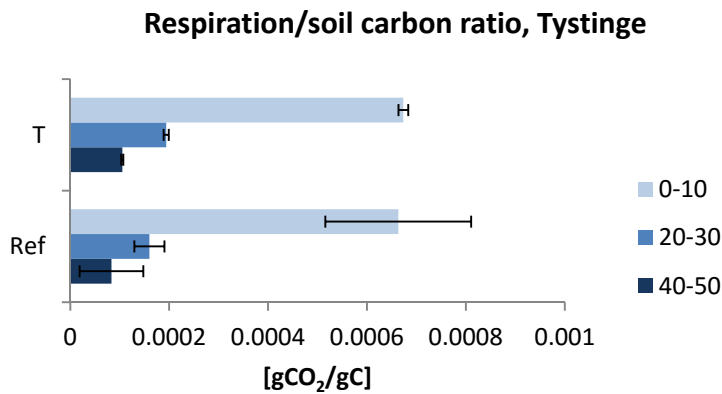
Figure 12. Respiration/soil carbon ratio [gCO2/gC] for the whole soil profile at a) Rikkenstorp and b) Tystinge. Error bars show standard error of the mean.

Respiration/soil carbon ratio
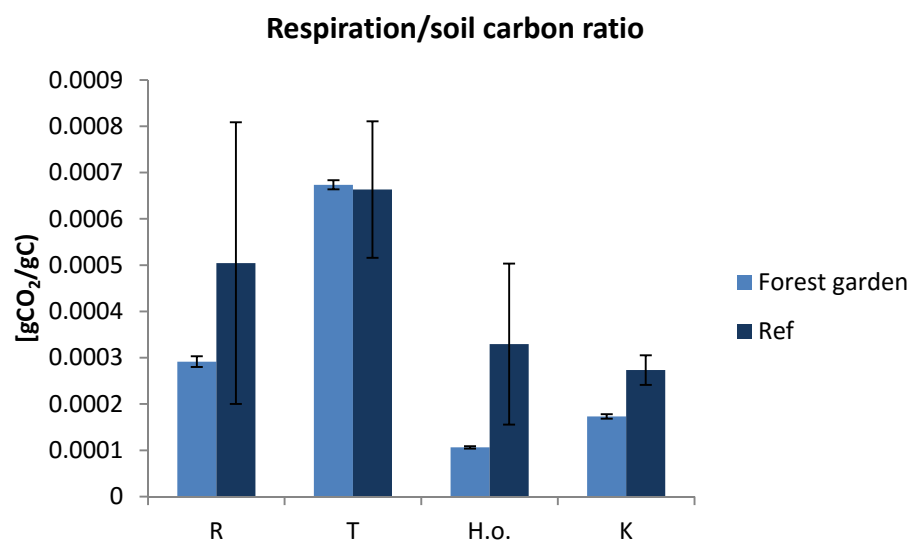
Figure 13.Respiration/soil carbon ratio [gCO₂/gC] for the uppermost soil layer at Rikkenstorp, Tystinge, Holma and Klockaregården. Error bars show standard error of the mean.

4.2   Soil fertility parameters

4.2.1   Soil profile description

At H.Ö. the forest garden seems to have had a positive impact on fine roots compared to the control, increasing the amounts of fine roots found (Table 10). At T, the impact of the forest garden seems to have been negative, with a decrease in the number of fine roots, especially in the uppermost layer (Table 10). The forest gardens also seem to have had a positive impact on the abundance of earthworms at H.Ö. and T, the two forest gardens with the most established herbal layers (Table 10). At T the hole that was dug to conduct the soil profile description was just about 30 cm deep as there was a slate layer at this depth.

Table 10. Number of fine roots and earthworm channels estimated from soil profile descriptions at Hånsta Östergärde, Tystinge, Holma and Klockaregården and their references.

Depth [cm]/Site	Number of fine roots						
	H.Ö.	**H.Ö. Ref.**	**T**	**T Ref**	**H.o.**	**K**	**K Ref**
0-10	20-50	19	10	20-50	20-50	20-50	20-50
11-20	20-50	9	13	10	20-50	20-50	20-50
21-30	20-50	20-50	11	9	15	7	7
31-40	7	14	11	10	10	7	9
41-50	0		8	5	0	5	3

Depth [cm]/Site	Number of earthworm channels						
	H.Ö.	**H.Ö. Ref.**	**T**	**T Ref**	**H.o.**	**K**	**K Ref**
0-10	3	0	2	0	0	2	0
11-20	2	0	4	4	0	0	1
21-30	5	0	7	3	0	0	0
31-40	1	2		1	0	0	0
41-50	1	0		0	2	0	0

4.2.2 Total carbon and nitrogen

At most places, the C/N ratio increased with depth (Figure 14.). Consequently, there is more nitrogen in the top soil than further down in the soil profile. The exceptions are the forest garden at T, the forest garden and reference spot at H.Ö. and the reference spot at H.o. At R, T and K, C/N ratios were higher at the reference spots than inside the forest gardens. At H.Ö. and H.o. the C/N ratios are very similar between the forest gardens and their reference spots.

a)

Rikkenstorp

C/N ratio

b)

Hånsta Östergärde

C/N ratio

c)

Tystinge

C/N ratio

d)

Holma

44
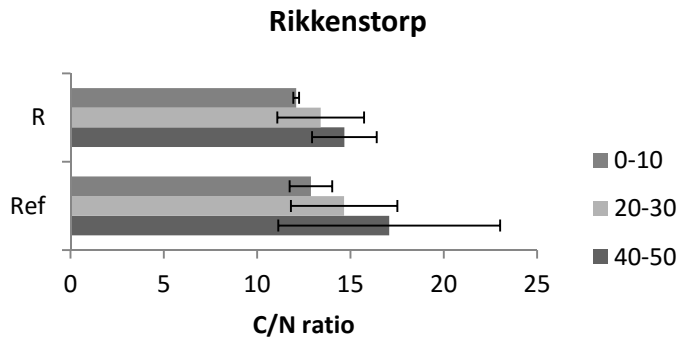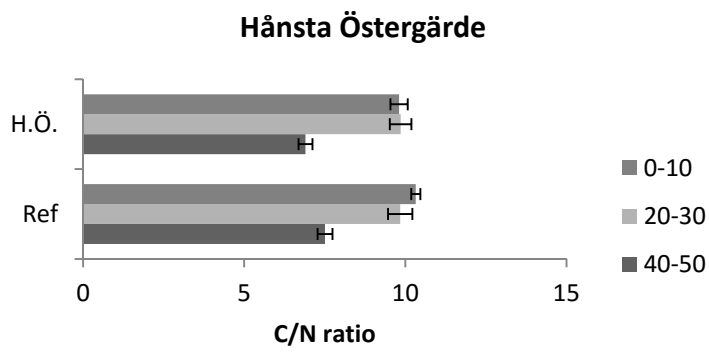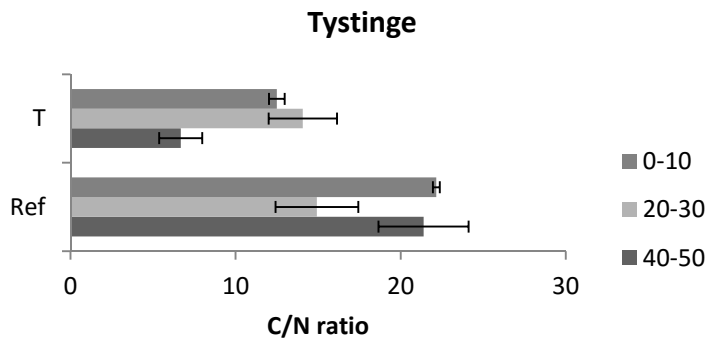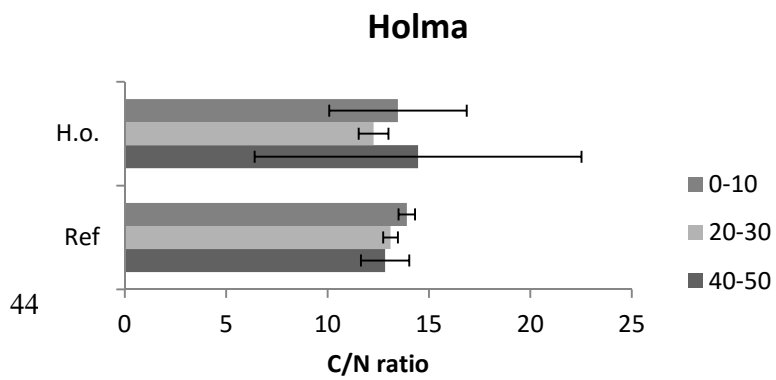
C/N ratio

e)
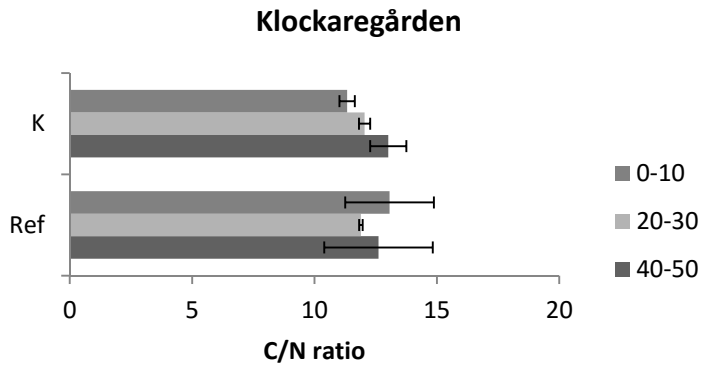
Figure 14. C/N ratios for a) Rikkenstorp, b) Hånsta Östergärde, c) Tystinge, d) Holma and e) Klockaregården. Error bars show standard error of the mean.

ANOVA analysis of the C/N ratios showed significant difference with depth for R ($P<0.01$) and H.Ö. ($P<0.05$). R also showed a slight significant difference between the forest garden and its reference spots, R ($P< 0.05$; Table 8).
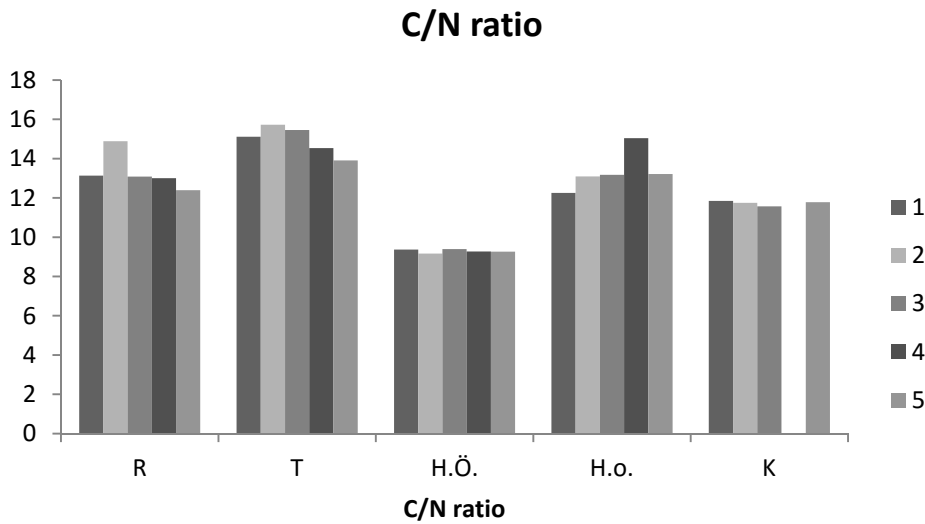
Figure 15. C/N ratios at each sampling spots (1-5) for all forest gardens. C/N ratios are calculated for all layers at each site.

According to Figure 15 C/N ratios are relatively stable within the forest gardens, while it varies somewhat between them. An ANOVA analysis of the C/N ratios confirms this visualization. There is a strong significant difference between the five

sites ($P<0.0001$). There is however no difference in C/N ratio between the different sampling spots (Table 8).

Differences in C/N ratio with depth, which was left out in Figure 15, are also significant ($P<0.0001$). There is also a correlation between site and depth in C/N ratios ($P<0.0001$; Table 8).

4.2.3 Mycorrhiza

Staining and de-staining of root tissues went well, for roots with dark pigment H_2O_2 had to be used to bleach the roots. Bleaching of roots with H_2O_2 was tried out both before and after staining and de-staining because it would have been convenient to bleach dark roots the night before the rest of the procedure. However, this did not work, as the roots got dark again when boiled in KOH.

Even though the staining and de-staining process went well, very few mycorrhizal structures were observed. Mycorrhizal tissues get degraded fast and, due to the time consuming procedure of washing out the roots, many of the structures were probably already degraded. The soil samples had been stored for about two months when the mycorrhizal analysis begun and some would be stored for an even longer time. The risk of having the structures degraded was substantial and this part of the project was terminated.

5 Discussion

5.1 Pools and flows of carbon

5.1.1 Herbal biomass

From the estimations of herbal biomass it was clear that the potential of this vegetation layer to contribute to increased biomass production, at this early stage of forest garden development, will depend on the former land use. As grasslands already have a high biomass production the changes, either it is an increase or decrease, are less than for the agricultural field (Figure 4). Only T and H.Ö. had their herbal layer established, and therefore indications on the effects of the herbal layer can only rely on them. Furthermore, standing biomass from annual production is dynamic. When the wheat crop at the agricultural field grows it will increase standing biomass at the reference spot at H.Ö., and the difference will decrease. At T, the reference spot was grazed grassland and calculation of total production at the different reference spots was beyond the scope of this project, as there were neither time nor experience to conduct such a model. Furthermore, to investigate carbon sequestration within the forest garden from carbon stored in herbal biomass, degradability of the different herbs, and their contribution to soil organic matter formation, have to be known.

The herbal layer of the forest gardens is not homogeneous and therefore investigation of herbal biomass with random selection is not suitable, as it would not provide representative estimates. Schroth and Sinclair (2002) also argue that agroforestry systems cannot be seen as homogeneous systems and that their diversity has to be taken into account in the analysis. In the forest gardens the species are clustered and selecting squares randomly would risk missing out on some species and might fail in covering their actual presence. As seen in Figure 5, the different plants contribute with different amounts of biomass. When comparing the results from the first and the second method of herbal biomass estimation, biomass production [kg/m^2] was estimated as twice as high with the second method (see Figure 4 and Table 5). As the second method is more precise than the first, this indicates that the use of the first method could lead to substantial under estimations of biomass production, or over estimations if the random selection favors spots with high biomass production. With data on biomass of different herbal species it is also easy to estimate the biomass production and carbon content at the different sites at any time, by just estimating or measuring the size of the area covered by different herbs. There is a risk

that this method is somewhat subjective, and estimation errors may occur if estimations are made by different people. To further increase reliability of these calculations more samples have to be collected to increase the data set.

Differences in biomass production could also depend on the site. Table 5 shows herbal or grass biomass, in 36.6 m^2, which was the area estimated to be covered by herbal vegetation at H.Ö., as well as per m^2, and how it varies between the different reference spots. This variation could be explained by management, the young winter wheat crop having substantially lower biomass production than grassland, or climate, with the southern sites showing highest biomass production, which decreases the more north the forest gardens are located. When comparing the two well-established forest gardens they also showed large differences in biomass production (Figure 4). This could be due to the sampling method, as these estimations were made with random selection and, as argued above, this could lead to substantial over- or under estimations of biomass production. Furthermore, as the design of the herbal layer varies between the sites random sampling will not give a comparable result. Even though vegetative samples were collected in the same way it is difficult to compare the systems, as their herbal layers were designed differently. However, in the field it was observed that the herbal layer was denser at T than at H.Ö. When comparing the soils at these sites (Table 1), H.Ö. seems to be the most favorable site of the two, with high clay and silt content compared to the low clay and silt contents and large amount of sand at T. H.Ö. also has a more favorable pH. On the other hand, at T humus content is higher, probably due that the forest garden is sited on a former old lay (Table 1).

As the forest gardens were established in different ways, biomass data could not be collected from all sites. Due to the small amount of data, major general conclusions cannot be drawn. More studies would be needed, with data from all forest gardens. With well-established and mature herbal layers, more qualified conclusions could be drawn.

5.1.2 Biomass of trees and shrubs

As the same equations were used to calculate biomass production at the different sites it is possible to compare the different forest gardens. Variations in standing biomass between the forest gardens were found for both trees and shrubs. The most probable explanation to these variations is competition with the ground covering plants. At K, the trees and shrubs were directly planted in the grass, while at H.o.the soil was covered, leading to less competition with other plants. Trees and shribs at K seems to have suffered from competition by the grass, while competition at H.o. was low, enabling greater growth of trees and shrubs. At H.Ö., the soil was tilled

48

and relatively free from weeds, but the herbal layer was planted which might have posed some competition. Surrounding vegetation could also have posed competition to the trees and shrubs in the forest gardens. All sites but H.Ö. had one or more trees or shrubs close to the forest garden, which might spread their roots into the forest garden. However, when comparing woody biomass at H.Ö. and H.o., competition from the surrounding forest garden at H.o. do not seem to have suppressed the growth of trees and shrubs in the studied forest garden. Climate is another factor that could explain the differences in biomass. At H.o. the growing season is longer than at H.Ö., which most probably will lead to a higher primary production at H.o. On the other hand, this does not hold when comparing H.o. and K, which are located very close to each other. Even though they have slightly different climatic conditions, this should not cause the large observed difference in woody biomass. Biomass production at K was the lowest of all three sites, while H.o. had the highest. At K, the low growth is probably best explained by competition.

As could be expected, the different equations gave varying results of tree biomass, showing the impact of different equations on the outcome. In this case the equation developed for *Betula pendula* gave about ten percent higher biomass than the equation for *Alnus glutinosa*. Morphology, growth pattern and wood density are factors that influence biomass estimations, and vary both between and within species. It could be genetic or have to do with age (Nordh and Verwijst, 2004; Segura et al., 2006; Picard et al., 2012; Jain and Ansari, 2013; Tumwebaze et al., 2013). Growth conditions, such as climate and soil fertility, vary between sites (Lott et al., 2000; Picard et al, 2012). As the trees are young and hence small the difference in calculated biomass also becomes small, but as the trees grow larger the difference in calculated biomass production will get larger too. This point to the importance of species specific equations, or at least equations developed for groups of species having similar morphology, growth pattern and wood density. Even though the equations were chosen to be as representative of the studied species as possible with regards to morphology, growth pattern and environment, trustworthy calculations of biomass production and carbon storage could not be obtained, as the models were developed for other species and under other conditions. Therefore, relative values were used when comparing woody biomass at H.Ö., H.o. and K (Figure 6).

5.1.3 Total aboveground biomass
Trees, shrubs and herbs contributed to total biomass in the forest gardens to varying extent. Trees contributed most, followed by shrubs. This is not surprising considering the size of the different plants. Figure 7 also indicates that the amount of herbal biomass will have an impact on biomass of trees and shrubs due to competition, as

argued in previous section. Covering the soil is a well-recognized management practice to reduce competition of ground vegetation on woody species when a forest garden is established (Jacke and Toensmeier, 2005), and the results obtained here support that theory.

The herbal layer does not have any large impact, and might be neglected, for estimation of standing biomass as it dies of and decomposes, releasing carbon to the atmosphere, each year. However, if modeling carbon flows in the system and the accumulation of carbon in the soil, it is of interest to consider herbal biomass too. Herbal biomass contributed significantly to annual litter production, and therefore carbon to the soil, compared to the trees and shrubs. This will be discussed further down in the section about carbon flows. As Table 5 shows, herbal biomass in the forest garden can also contribute to more biomass, and hence capture of carbon, than some alternative systems.

For estimation of carbon in biomass of trees, shrubs and herbs it was assumed that 47.5 % of the biomass is carbon, as it is in between the two commonly used assumptions of 45 and 50%, as argued by Saj et al. (2013) Carbon concentrations vary between species, and also between above- and belowground biomass (Alías et al., 2015). Carbon concentrations measured by Alías et al. (2015) were even lower than 45%, so the assumptions in this study might be an overestimation. However, the estimations of biomass production form the allometric equations is probably the main cause to inexact carbon estimations here. As long as the accuracy of the allometric equations are unknown more precise measurements of carbon concentration in dry matter will not contribute significantly to the over-all estimate.

5.1.4 Root biomass

The impact of a forest garden on root biomass seems to depend on alternative land use. Where the alternative land use was grassland, the establishment of a forest garden decreased root biomass two to three times. Where the alternative land use was an agricultural field, the differences were not as large, with the forest garden showing a higher root biomass than the reference spots. These roots were mainly from the previous crop, and had started to decay. When the root system is the largest the difference will be smaller. The distribution of roots in the soil profile also varies between the sites. At R and T, the roots were concentrated to the top soil, whilst at H.Ö. they were more evenly distributed. This could be because of soil improvements at both R and T, which probably have been focused on the top soil. Further down there are less nutrients, due to much silt and sand and low clay content. On the other hand, root biomass at R and T is similar to, or even larger than, that at H.Ö. at these depths. At R, the high root biomass can also be explained by that the ground cover

at R is grass, which quickly develops a large root system, maybe faster than herbs does. It is also worth noticing that at R, the herbal layer of the forest garden was not yet established, and this site can therefore not represent a forest garden.

One of the aims with including trees and shrubs into agricultural systems is to obtain better utilization of the soil profile in terms of nutrient uptake (Schroth and Sinclair, 2002), and a more even distribution of roots in the soil profile is to be expected in agroforestry plots compared to agricultural fields, lays and pastures without trees. At R and H.Ö., root biomass at the deeper layers was larger in the forest garden compared to the reference spots. However, for R and T root biomass decreased rapidly from 0-10 cm to 20-30 cm. Even though all sizes of roots were collected from the soil samples, no roots coarser than 4 mm where observed. Hence, this method underestimated root biomass as not many roots of trees and shrubs were collected during soil sampling. Similar to what was observed for R and T in this study, a Spanish study of a silvopastoral system also found roots to be concentrated to the top soil (Ferreiro-Domínguez et al., 2016). However, it was not clear from where these samples were collected. If they were collected in the pastoral strips between the tree rows, the influence of tree roots may be low, as could be the case also in this study. For better estimations of root biomass of trees and shrubs allometric equations could be developed.

When comparing the two well-established forest gardens there was substantial variation between the two sites. This goes in line with what was observed for above-ground herbal biomass, which was both measured and observed to be larger at T compared to H.Ö. These two sites are located in the same climatic zone so differences in root biomass between these sites could not be explained by climatic factor. The differences might be explained by competition between woody plants and herbs, at H.Ö. herbal vegetation might be suppressed by more competitive woody vegetation, with the contrary occurring at T. Unfortunately no measurements of trees and shrubs were made at T. It could however be hypothesized that herbal vegetation benefits form the more humus rich soil at T (Table 1), and hence can compete better with trees and shrubs. When taking other soil characteristics into account, soil properties seem to be more beneficial at H.Ö compared to T due to the large amount of sand and low amounts of clay and silt, as well as lower pH at T. Due to the profitable soil structure of the clay soil and its capacity to store and deliver plant nutrients (Eriksson et al., 2011), H.Ö. could be expected to promote root growth. However, this seems not to be the case. At least at this stage it seems as if humus content is what explains the better growth of roots in the forest garden T compared to H.Ö, when taking soil properties into account. Furthermore, the mechanical resistance that a clay soil poses could also be the cause of lower root biomass at H.Ö. (Eriksson

et al., 2011). Future studies of root biomass in forest gardens would be needed to conclude whether plant growth, and hence root biomass, mainly is controlled by climatic factors or soil properties.

Significant difference between forest garden and reference spot was only observed for H.Ö. The analysis was done for the whole profile, but when just comparing the uppermost layer there was a clear difference in root biomass between the forest garden and its reference, also at R and T. At H.Ö. the significant difference between the forest garden and its reference might diminish as the wheat crop grows and its root system gets larger. The large variation in data (Figure 8) points to that the systems are very heterogeneous with regards to root biomass.

5.1.5 Carbon

No clear trend of the impact of forest gardens on soil carbon content could be observed. At some sites carbon content has increased (R and K) whilst at the other sites it varied with depth (Figure 9). K was the only site where a significant difference between forest garden and reference spot could be demonstrated ($P<0.05$). This is somewhat strange, as the forest garden at K was the least changed from the former land use (grassland).

Increasing carbon content in the soil is a long-term process (Jarecki and Lal, 2003). Hence, it is not surprising that no major changes in carbon content between the forest garden and its reference were found. The potential of carbon sequestration in soil is also limited, and depends on soil, climate and management (Smith et al., 1997; Freibauer et al., 2004). Grassland has higher potential for carbon sequestration than cropland, because of less disturbance and therefore a possibility to grow deep roots (Freibauer et al., 2004). Veum et al. (2011) studied soil organic carbon under three different practices of conservation agriculture; grass vegetative filter strips (VFS), agroforestry VFS and no-till. Grass VFS had the highest amount and concentration of soil organic carbon, followed by agroforestry VFS and thereafter no-till. In the study by Veum et al. samples were only collected from the upper 13 cm. Analyzing the soil at deeper horizons could give different results, as trees will have an impact on the soil further down in the soil profile than grass roots. A greater utilization of the different soil layers from growing a combination of trees, shrubs and herbs might increase the potential of carbon storage at the site. To evaluate this, measurements need to be conducted when the forest gardens are older. It can take up to 25-50 years to reach a new equilibrium in the soil carbon content after management practices have shifted (Jarecki and Lal, 2003). However, a Spanish study on a silvopastoral system in which the trees had been planted seventeen years ago, also showed a de-

crease in carbon content with depth (Mosquera-Losada et al., 2015). The higher carbon content in the top soil and decrease with depth (down to 100 cm) was assumed to be because of litter fall. If the roots of trees and shrubs are able to utilize soil layers that cereal crops or grassroots may not, it could be hypothesized that agroforestry systems would increase the activity, and hence biomass production and soil carbon, in deeper layers. However, also another Spanish study on silvopastoral systems showed a similar decrease in carbon content with depth (Ferreiro-Domínguez et al., 2016), here it was argued that biological activity of the trees mainly affected carbon sequestration in the top layer, whilst in the deeper layers it was mainly explained by aggregate size. On the other hand, neither of these studies evaluated differences between the agroforestry system and alternative land use. Comparing the silvopastoral systems to grassland might have shown differences with depth between the two land uses. Therefore, for future evaluations of the effect of the forest gardens on soil carbon, reference spots should be included. This would both show if carbon content in the forest garden changes in the whole soil profile, and whether the reference spots are at equilibrium or if carbon content still changes here as well.

5.1.6 Respiration

As expected, soil respiration was highest at the top layer and decreased with depth at R and T (Figure 10). However, the forest garden at H.Ö. did not follow this pattern. The unexpected values for H.Ö. could be explained by the difficulties to accomplish a water content of 60% field capacity, or that the samples were put back into the fridge and taken out one week later, as explained in the results. On the other hand, if the cooling and rewarming would have affected respiration it should have been seen for the samples from R as well, which went through the same procedure. However, the procedure of wetting soil samples was mainly done at samples from H.Ö., and due to the high clay content wetting these samples was also the most difficult.

Respiration was consistently lower inside the forest gardens compared to their reference spots, both when only respiration was taken into account and for the respiration/soil carbon ratio. The impact of cooling and rewarming of the soil samples is assumed to be negligible, as all samples, except of those from T, were affected in the same way, and only H.Ö. showed this peculiar pattern in the soil profile. According to these results two contrary conclusions could be drawn. The first one is that the establishment of a forest garden will decrease carbon losses through microbial respiration. Together with a higher production of aboveground biomass, which was shown in previous sections, this points to that the establishment of a forest garden will increase carbon sequestration. The respiration/soil carbon ratio show that there is a lower respiration per gram soil carbon inside the forest gardens compared

to the reference spots, which supports this theory. The lower respiration within the forest garden might be due to the structure of carbon compounds and chemical properties of the herbal plants, affecting degradability of the organic matter (Berg and McClaugherty, 2003). This would however need to be further investigated. On the other hand, the result only show respiration under laboratory conditions, where temperature is kept at a favorable level for respiration (Luo and Zhou, 2006). Hence, differences in temperature, an important factor regulating respiration in the field, are not taken into account. With regards to temperature and vegetation period over the year, annual respiration should be expected to be lowest at R and highest at H.o. and K. However, in Figure 11 the contrary is shown. This might be explained by an accumulation of organic material at R, leading to more material for the microbes to consume when conditions are more favorable. Following this argument it would also mean that the higher respiration at the reference spots is an indication of that there is more organic material to consume here, as a consequence of accumulation under field conditions. This thesis is supported by field studies of respiration, showing that pasture land has lower respiration rates than both forests and cultivated land (Luo and Zhou, 2006; Emran et al., 2012), while the results obtained here show highest respiration from grassland (Figure 11; reference spots at R, T and H.o., with K being an exception). Furthermore, the temperature under which these measurements were made occurs during summer and Figure 11 would then point to higher respiration and carbon loss during summer time from the reference spots as argued above. However, the respiration/soil carbon ratio do not indicate that the higher respiration rates at the reference spots are due to accumulation of organic material in the soil here. A correlation between C/N ratio and respiration was also sought, but no significance was found ($P > 0.1$, data not shown).

Compared to studies under similar climatic conditions, respiration rates at R (1 and 1.6 gCO_2/m^2h), T (1.8 gCO_2/m^2h, for both forest garden and reference spot) and the reference spot at H.o. (1.1 gCO_2/m^2h) were relatively high, while respiration rates at H.Ö. (0.2 and 0.5 gCO_2/m^2h) and K (0.3 and 0.4 gCO_2/m^2h) as well as in the forest garden at H.o. (0.3 gCO_2/m^2h) were relatively low. Flanagan and Johnson (2005) measured a maximum respiration of 1.4 and 0.8 gCO_2/m^2h in northern temperate grassland at two different years. Han et al. (2007) measured soil respiration in a temperate zone maize field to be 0.5 gCO_2/m^2h in September. As respiration in the forest garden samples was assessed at room temperature, quite high respiration rates, as those for in the study by Flanagan and Johnson, could be assumed. R and T showed respiration rates close to those. The lower respiration rate for H.Ö., H.o. and K might be explained by that these samples were warmed up twice. Respiration data from this study were also compared to measurements that were made on soil samples collected one year earlier (2014) from all forest gardens. There was a slight

trend in respiration rates when respiration measurements were compared between the two sampling years (Table 9).

5.2 Soil fertility

5.2.1 Soil profile description

In general, observations from the soil profile description goes in line with measurements of root biomass, for the two sites (H.Ö. and T) where both methods had been used, and hence indicating that the alternative land use determines whether there will be an increase or decrease in belowground biomass production after the establishment of a forest garden. At H.Ö., the forest garden root biomass had increased, whilst at T root biomass has decreased in the top 10 cm. The large amount of fine roots at the reference spot at H.Ö., on the depth of 21-30 cm, was probably old roots from the previous crop that has not yet decomposed. On the contrary, the lower amount of fine roots at T compared to H.Ö. contradicts the results from the estimations of belowground biomass, where T had more than twice as high belowground biomass compared to H.Ö. (Figure 8). This could be due to that what was considered as fine roots in the soil profile description was just a fraction of roots present in the soil. For belowground biomass estimation, all sizes of roots were included. However, no roots wider than 4 mm in diameter were found in the soil samples. At T, the top soil was rich in organic material, making it more difficult to estimate fine root abundance compared to the clay soil at H.Ö. Hence, root abundance at T might be underestimated.

At H.o. and K, where the herbal layer had not yet been established, roots were abundant in the top 20 cm, and for K root abundance is very similar between the forest garden and its reference. At H.o., the ground was covered by newspaper and straw but the initial vegetation underneath had not been removed, and at K the ground was still covered by grass.

Earthworms seem to have been favored by the establishment of a forest garden. Earthworm channels were more abundant in the forest garden compared to the reference spots at both T and H.Ö. The increase was greater at H.Ö., which could be explained by the unfavorable conditions for earthworms in the yearly plowed agricultural field (the reference). Earthworm activity could also be observed at the soil surface, which was full of earthworm feces. At T it was difficult to see structures of earthworm channels, as the top soil was very porous. Hence, earthworm channels might be underestimated here. At K, the forest garden did not differ a lot from its reference with regards to earthworm channels (Table 10). The lack of structure in

the soil that was observed below the top 10 cm could be an explanation to this low amount of observed earthworm channels, as the earthworm channels may collapse when the structure is poor and the soil is dug in. No earthworm channels were identified when the soil profile description was performed at H.o., but during soil sampling many earthworms were observed. Poor soil structure is a possible explanation to the lack of detectable earthworm channels at this site too.

There is a risk of subjective estimations when working with visual estimations of structures in soils. If each participant would estimate the abundance of roots and earthworm channels in their own forest garden, comparison of data will be even less reliable. However, it is an easy method that, with a low workload, can provide an overview of the state of the soil. Furthermore, visual observations can be helpful when the results are to be analyzed or to decide what parts of the soil profile is interesting to take into account for further studies.

5.2.2 C/N

The C/N ratios indicate good fertility at all sites. C/N ratios lower than 25 stimulate mineralization of nitrogen, and makes nitrogen available to plants (Paul, 2015). The lower the C/N ratio, the more nitrogen is mineralized from that substrate. In agricultural fields the C/N ratio is usually around 10, and in acidic forest soils it ranges from 20 to 50 (Eriksson et al., 2011). The C/N ratio was below 25 in all forest gardens. At T and K, the establishment of a forest garden seems to have decreased the C/N ratio in the top 10 cm drastically. At T this could be explained by the change in vegetation, whilst at K vegetation was not much changed. At H.Ö. the C/N ratio was almost the same in the forest garden and at the reference spot. At this site it seems as if the establishment of a forest garden had little impact on the C/N ratio, either due to slow changes in the C/N ratio, or due to the properties of the soil.

5.2.3 Mycorrhiza

The abundance of mycorrhizal associations could not be analyzed due to lack of time for the laboratory work. The risk of having mycorrhizal structures degraded during preparation of the root samples was another reason for this part of the study to be terminated.

5.3 Improvements for further research

5.3.1 Herbal biomass

To be able to better estimate production of herbal biomass in the forest gardens and to obtain a better understanding of the factors influencing biomass production at the

different sites, vegetation data from more forest gardens has to be collected. However, this data should not be collected until the herbal layers are well-established and mature.

Future studies should address decomposition rates of litter from the different herbal species, to be able to model carbon flows and sequestration.

5.3.2 Biomass of trees and shrubs

For carbon sequestration to be determined, biomass production has to be better estimated, with regards to growth of trees and shrubs as well as wood densities of the different species. However, the workload of developing allometric equations is high (Picard et al., 2012), and ways to minimize it should be considered. Collection of data over a large geographical area, and from a wide range of tree and shrub sizes, will reduce the workload substantially. When the relation between diameter at breast height and height is known the equations can be used for a wide range of environments (Picard et al., 2012). With time, the equations could be refined into different geographical areas with similar climate zones and vegetation period (e.g. south, middle and north of Sweden).

Biomass estimations of trees and shrubs point to that there are some differences in the growth conditions at the sites. Annual measurements of height and stem diameter would provide better understanding of annual growth and potential competition in, as well as management influences on, the forest gardens. The Project provides a great opportunity for such data to be collected, not only in the forest gardens but also from other agroforestry practices.

5.3.3 Root biomass

The roots collected for this analysis was of all sizes, but no larger roots were present in the soil samples even though they were collected close to trees and shrubs. Estimation of root biomass would probably be improved if allometric equations were developed for root biomass of trees. At the moment there are few existing equations for root biomass, and development of these are even more difficult and time consuming than those for above ground biomass (Zianis et al., 2005). However, if allometric equations are to be developed for aboveground biomass, belowground biomass should be considered as well, to get the most out of this destructive sampling procedure.

As the procedure of washing roots out of the soil was very time consuming, estimation of herbal root biomass could be done in a similar way as for trees and shrubs. By collecting data on total root biomass from the different herbs, estimates of root-

shoot ratios could be established. This will probably also be a difficult and time consuming task, but when the data is collected it will be very useful. The development of allometric equations for root biomass and root-shoot ratios would also improve knowledge about the morphology and distribution of roots in the soil profile, which would lead to better understanding of the interactions between the plants in the system and be useful in the design of forest gardens or other agroforestry systems.

5.3.4 Respiration

To estimate whether carbon is stored in the soil or lost in respiration more data on both carbon inputs and outputs are required. Inputs to this system are litter from both woody vegetation (leaves and dead branches) and herbal biomass (whole plants). To model turnover of litter, litter decomposition rates have to be known, and the partitioning of biomass between different fractions of organic carbon. Decomposition rates vary between plant compartments (e.g. leaves, stems, thorns, etc.), and should therefore be estimated separately (Berg and McClaugherty, 2003). Investigation of decomposition rates of herbal species is of importance, as litter from the herbal layer makes up the main part of the annual litter production in the system today (see Appendix 7). For comparison with alternative land use, better knowledge about the degradability of straw and grasses could also explain differences in respiration rates between the forest garden and its reference, and is thus of importance to be able to draw any conclusion on improved or impaired carbon sequestration.

In this study, respiration was measured with alkali trapping of CO_2 in the lab. However, for estimation of carbon sequestration to be as accurate as possible, respiration should be measured in the field. Due to the spatial and temporal variations in respiration, measurements should be made at different spots and at different time of both the day and the year (Luo and Zhou, 2006). The alkali trapping method can also be used in the field. However, more reliable methods exists, which are infrared gas analysis and gas chromatography (Bekku et al., 1996; Emran et al., 2012). Hence, for future studies other measurement tools should also be considered (see for exmaple. Bekku et al., 1996; Davidsson et al., 2002; Davidsson et al., 2006; Luo and Zhou, 2006; Emran et al., 2012).

6 Conclusions

Agroforestry is an agricultural practice that has shown to be both more productive and more environmentally sustainable than conventional monocultures, in many parts of the world. In Sweden, there are few scientific studies of these systems, and still a lot to be known about their productivity as well as ecosystem services. This study demonstrates that the establishment of a forest garden at the studied sites lead to an increase in aboveground biomass, with regards to both herbal and woody plants. However, whether root biomass in the forest garden increases or decreases depends on alternative land use. Where the alternative land use was grassland, root biomass decreased after the forest garden was established, while it increased when the alternative land use was an agricultural field. For carbon sequestration to be estimated carbon losses through respiration at different parts of the year is needed, as well as decomposition rate of different herbal species and woody plant compartments. An easier way to estimate soil carbon is to simply measure carbon content in the soil. However, carbon content in soil changes slowly and it can take up to 50 years to reach a new equilibrium. With data on carbon in- and outputs, as well as decomposition rates, carbon flows and potential carbon sequestration could be predicted by modeling. This study, however, has provided valuable reference data on the forest gardens in their early phases.

The forest gardens seem to have increased earthworm abundance at the two sites where they were well-established, especially compared to the agricultural field. No changes in C/N ratio were observed, but C/N ratios were shown to be site specific.

For better understanding of the forest gardens, and of any agroforestry systems under Swedish conditions, further studies are needed. For estimation of yearly biomass production and standing biomass, annual increment of tree stems and shrub branches, allometric equations for trees and shrubs, as well as data on species specific biomass for herbal plants are needed. For estimations of carbon flows and sequestration, decomposition rates of herbal plants and plant components, as well as carbon losses through respiration have to be known. Mychorrhizal colonization of plant roots is another area that could be interesting to look into, both with respect to general abundance, but also what species occurs and with which plants they interact. The Project, and its forest gardens, provide a great opportunity to conduct these studies, but more initiatives are welcomed to increase the knowledge of how these systems works, and what they can provide to agriculture in a Swedish context.

7 References

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8 Acknowledgement

9 Appendix

9.1 Appendix 1. Placement of grids for herbal estimation version 1.0

Figure A1. Placement of grids for herbal biomass estimation 1.0 at a) Rikkenstorp, b) Tystinge and c) Hånsta Östergärde

9.2 Appendix 2. Raw data of herbal vegetation, version 1.0

Table A2. Raw data of herbal vegetation at Tystinge (T), Rikkenstorp (R) and Hånsta Östergärde (H.Ö.), from herbal biomass estimation 1.0, randomly selected squares. For calculation of herbal biomass per m2, mean values of herbal biomass
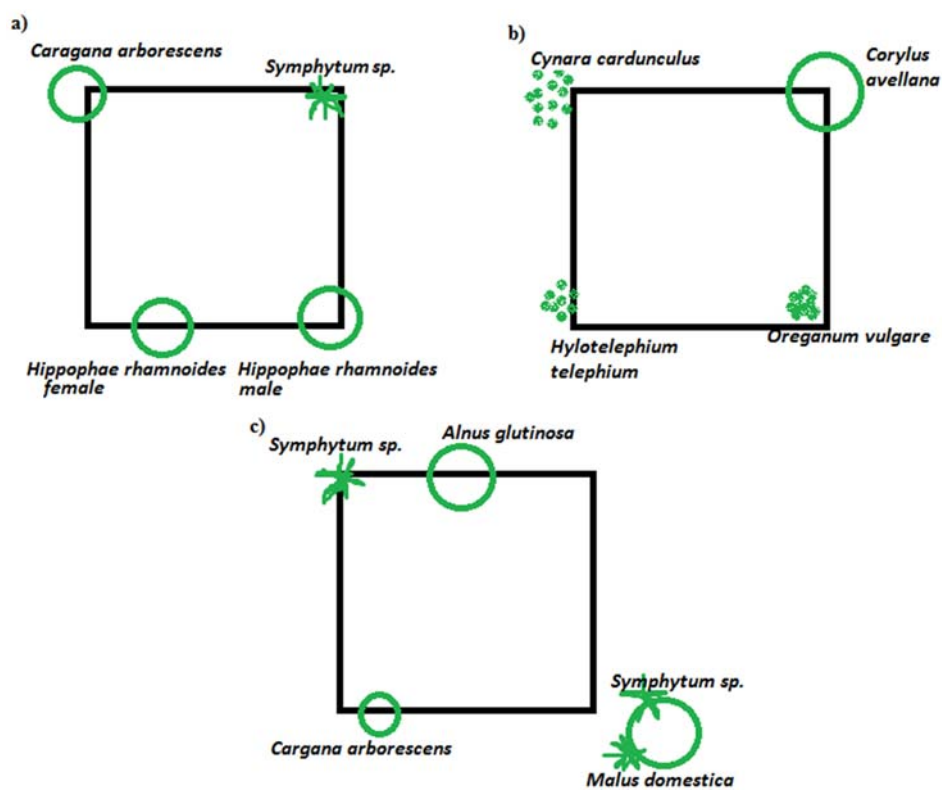
were used. Ref = reference spot.

Site and sampling square	Biomass (dry)	Weeds (dry)	Total biomass (dry)	Mean	Mean/m²
	g	g	g	g	g
Tystinge					

T. 4:2[1]					
T. 5:2[1]					
T. 8:1	43.2				
T. 9:3	47.9				
T. 10:1	12				
T. 11. 4	51.7	17.3			
T. 13:1	28.9	14.9			
T. 14:1	115.9	7.1			
T. 15:4	76.1				
T. 20:2	122.6	4.1			
Sum	**498.3**	**43.4**	**541.7**	**45.1**	**722.3**
T. Ref I					
T. Ref II	21				
T. Ref. III	25.3				
Sum	**46.3**		**46.3**	**23.2**	**370.4**
Rikkenstorp					
R. 4:2[1]					
R. 5:2	9				
R. 8:1	9.9				
R. 9:3	5.7				
R. 10:1	1.5				
R. 11:4	6.9				
R. 13:1	9.4				
R. 14:1	4.5				
R. 15:3	3.3				
R. 15:4	7.3				
Sum	**57.5**		**57.5**	**6.4**	**102.2**
R. Ref 1	7.5				
R. Ref 2	18.5				
R. Ref 3	23.6				
Sum	**49.6**		**49.6**	**16.5**	**264.5**
Hånsta Öster-gärde					
H.Ö. 4:2	23.3				
H.Ö. 5:2	66.1				
H.Ö. 8:1	25.6	5.1			
H.Ö. 9:3	26.6				
H.Ö. 10:1	10.5				
H.Ö. 11:4	6	1.5			

H.Ö. 13:1	3.2				
H.Ö. 13:1	20.2	1			
H.Ö. 14:1	14.9				
H.Ö. 15:3	55				
H.Ö. 15:4	48.2				
Sum	299.6	7.6	307.2	21.9	351.1
H.Ö. Ref. I					
H.Ö. Ref II					
H.Ö. Ref III					
Sum	10.8		10.8	3.6	57.6

[1] Vegetation was not recorded from all squares. In the empty rows there was a tree standing which in the initial idea should have been part in the estimation. This was never done due to difficulties in estimating woody biomass, and to the change in strategy to estimate vegetation.

9.3 Appendix 3. Raw data of herbal vegetation, version 2.0

Table A3.1. Raw data of herbal estimation version 2.0, species specific biomass.

Herb	Wet weight	Dry weight	Sampling area	Biomass	Average biomass	Average C content
	g	g	m^2	kg/m^2	kg/m^2	g/m^2
Hylotelephium	357.6	122.3	0.0625	1.96		
telephium	337.4	111.3	0.0625	1.78	1.87	0.89
Mentha	132.6	30.6	0.0625	0.49		
(Chocklate*)*	106.3	30.9	0.0625	0.49		
	33.8	23.6	0.0625	0.38		
	36.1	31.3	0.0625	0.50	0.47	0.22
Origanum vul-	83.3	28.9	0.0625	0.46		
gare	155.2	55	0.0625	0.88		
	98	30.9	0.0625	0.49		
	198.9	63.8	0.0625	1.02	0.71	0.34
Fragaria vesca	32.4	9.4	0.0625	0.15		
	137.3	29	0.0625	0.46		
	146.6	67.8	0.0625	1.08		
	102.3	46.6	0.0625	0.75	0.61	0.29
Fragaria x ana-	270.4	73.2	0.0625	1.17		
nassa	104	22.9	0.0625	0.37		
	131.5	43.2	0.0625	0.69		

66

	75.8	31.2	0.0625	0.50	0.68	0.32
*Mentha (*Apple*)*	84.2	23.2	0.0625	0.37		
	164.5	48.9	0.0625	0.78		
	108.3	24.1	0.0625	0.39	0.51	0.24
*Mentha (*Moroccan*)*	146.5	40.6	0.0625	0.65		
	125.1	33.8	0.0625	0.54		
	83.5	34.8	0.0625	0.56	0.58	0.28
Symphytum	57.4	8.4	0.0625	0.13		
	292.6	23	0.0625	0.37	0.25	0.12
Blitum bonus-henricus						
Ho.u II	181.5	33.6	0.0625	0.54		
	328.5	49.1	0.0625	0.79		
	88.4	47.2	0.0625	0.76		
	349.4	125.6	0.0625	2.01	1.022	0.49
Melissa officinalis	53.5	14.6	0.0625	0.23	0.23	0.11
Malva	109.8	37.1	0.0625	0.59		
	103.7	29.7	0.0625	0.48		
	143.5	89.9	0.0625	1.44		
	61.1	43.8	0.0625	0.70	0.80	0.38
Agastache foeniculum	408.9	114.7	0.0625	1.84		
	396.2	120	0.0625	1.92		
	179.8	143.6	0.0625	2.30		
	59.7	49.3	0.0625	0.79	1.71	0.81
Rosmarinus officinalis	160.1	91.8	0.0625	1.47	1.47	0.70
Myrrhis odorata	171.6	90.6	0.0625	1.45		
	81	70.7	0.0625	1.13	1.29	0.61

Table A3.2. Biomass of the different herbs.

Herb	Biomass kg/m^2
Hylotelephium telephium	1.87
*Mentha (*Chocklate*)*	0.47
Origanum vulgare	0.71
Fragaria vesca	0.61
Fragaria x ananassa	0.68
*Mentha (*Apple*)*	0.51
*Mentha (*Moroccan*)*	0.58

Symphytum	0.25								
Blitum bonus henricus	1.02								
Melissa officinalis	0.23								
Malva	0.80								
Agastache foeniculum	1.71								
Rosmarinus officinalis	1.47								
Myrrhis odorata	1.29								

9.4 Appendix 4. Bulk density

Table A4.1. Bulk density [g/cm³], whole cylinder. Absolute values (A) and mean values (M) for each layer.

Samples and depth	Bulk density								
	Rikkenstorp		Hånsta Öster-gärde		Tystinge		Holma		Klockaregår-den	
1	A	M	A	M	A	M	A	M	A	M
0-10	0.74	0.76	1.27	1.21	0.52	0.60	0.77	0.95	0.83	0.89
20-30	1.10	0.97	1.01	1.16	1.08	1.14	1.38	1.23	1.10	1.13
40-50	1.08	1.01	1.10	1.23	0.92	0.94		1.88	1.28	1.18
2										
0-10	0.76		1.31		0.52		0.93		0.85	
20-30	1.09		1.10		1.11		1.63		1.18	
40-50	0.92		1.29		0.92		1.76		1.16	
3										
0-10	0.85		1.19				0.94		0.88	
20-30	0.91		1.22				1.02		1.18	
40-50	1.24		1.24				1.84		1.04	
4										
0-10	0.76		1.06		0.51		1.15			
20-30	0.89		1.24		1.11		1.10			
40-50	0.96		1.29		0.96		2.21			
5										
0-10	0.72		1.21		0.86		0.97		1.01	
20-30	0.88		1.24		1.27		1.03		1.06	
40-50	0.85		1.23		0.97		1.73		1.22	
Ref 1										
0-10	0.87	0.76	1.18	1.19			0.76	0.82	0.91	0.91
20-30	1.04	1.16	1.25	1.25			0.85	0.92	1.04	1.11
40-50	0.86	1.14	1.31	1.28			1.13	1.19	1.22	1.21
Ref 2										

Samples and depth	Rikkenstorp A	Rikkenstorp M	Hånsta Östergärde A	Hånsta Östergärde M	Tystinge A	Tystinge M	Holma A	Holma M	Klockaregården A	Klockaregården M
0-10	0.70		1.25		0.56	0.70	1.01		0.91	
20-30	1.24		1.37		1.14	1.07	1.01		1.19	
40-50	1.20		1.30		0.97	0.89	1.24		1.19	
Ref 3										
0-10	0.70		1.15		0.83		0.69		0.90	
20-30	1.20		1.13		0.99		0.89		1.09	
40-50	1.37		1.23		0.81		1.19		1.22	

Table A4.2. Bulk density [g/cm^3] fractions <2mm. Absolute values (A) and mean values (M) for each layer.

Samples and depth	Bulk density									
	Rikkenstorp		Hånsta Östergärde		Tystinge		Holma		Klockaregården	
1	A	M	A	M	A	M	A	M	A	M
0-10	0.73	0.75	1.27	1.21	0.49	0.45	0.76	0.85	0.83	0.89
20-30	0.96	0.85	1.01	1.16	0.81	0.76	1.38	1.11	1.10	1.13
40-50	0.97	0.90	1.10	1.23	0.44	0.45		1.88	1.28	1.18
2										
0-10	0.75		1.31		0.43		0.75		0.85	
20-30	0.75		1.10		1.02		1.63		1.18	
40-50	0.85		1.29		0.49		1.76		1.16	
3										
0-10	0.83		1.19				0.82		0.88	
20-30	0.85		1.22				0.84		1.18	
40-50	1.08		1.24				1.84		1.04	
4										
0-10	0.73		1.06		0.51		0.99			
20-30	0.85		1.24		1.08		0.91			
40-50	0.87		1.29		0.63		2.21			
5										
0-10	0.70		1.21		0.82		0.92		1.01	
20-30	0.84		1.24		1.16		0.79		1.06	
40-50	0.73		1.23		0.72		1.73		1.22	
Ref 1										
0-10	0.82	0.73	1.18	1.19			0.67	0.77	0.91	0.91
20-30	0.94	1.10	1.25	1.25			0.76	0.82	1.04	1.11
40-50	0.77	1.01	1.31	1.28			1.07	0.97	1.22	1.21
Ref 2										
0-10	0.70		1.25		0.52	0.65	0.99		0.91	
20-30	1.20		1.37		0.94	0.97	0.85		1.19	

40-50	1.02	1.30	0.48	0.43	0.93	1.19
Ref 3						
0-10		1.15	0.78		0.65	0.90
20-30		1.13	0.99		0.85	1.09
40-50		1.23	0.39		0.91	1.22

9.5   Appendix 5. Raw data of trees and shrubs

Table A5. Raw data of trees and shrubs at Hånsta Östergärde, Holma and Klocka-regården

Species and site	Height [cm]	Diameter [cm], crown	Diameter [cm], stem
Hånsta Östergärde			
*Malus domestica (*Amorosa*)*	200	142.5	3.50
Elaeagnis umbellata	165	100	2.36
*Malus domestica (*Astrakan*)*	215	120	3.25
Alnus glutinosa	200	115	3.57
Corylus avellana	140	65	1.80
Cargana arboreacens	150	145	2.50
*Hippophaë rhamnoides (*male*)*	125	100	2.55
*Hippophaë rhamnoides (*female*)*	150	90	2.58
*Malus domestica (*Alice*)*	200	130	3.79
Holma			
*Malus domestica (*Amorosa*)*	215	176.5	5.03
Elaeagnis umbellata	160	200	2.48
*Malus domestica (*Astrakan*)*	145	141	4.30
Alnus glutinosa	312	165	4.20
Corylus avellana	115	141	2.42
*Hippophaë rhamnoides (*male*)*	88	80	1.15
*Hippophaë rhamnoides (*female*)*	257	200	3.18
*Malus domestica (*Alice*)*	200	103.5	2.74
Klockaregården			
*Malus domestica(*Alice*)*	219	65	2.42
Elaeagnis umbellata	92	34	0.96
Malus domestica (?)	177	65	2.80

Corylus avellana	178	75	1.37
*Hippophaë rhamnoides (*male*)*	43	37	1.11
*Hippophaë rhamnoides (*female*)*	89	42	1.21
Malus domestica (?)	185	50	2.71
Rubus subg. Rubus	167		2.71

9.6   Appendix 6. Table of components to biomass figure 7

Table A6. Biomass in kg DW.

Species and site	Biomass kg DW
Hånsta Östergärde	
Malus domestica (Amorosa)	64.70
Malus domestica (Astrakan)	59.61
Malus domestica (Alice)	76.21
Alnus glutinosa	67.17
Sum trees	**267.69**
Elaeagnis umbellata	16.90
Corylus avellana	8.57
Cargana arboreacens	17.17
Hippophaë rhamnoides (male)	15.32
(female)	18.46
Sum shrubs	**76.42**
Herbal biomass	**25.23**
Holma	
Malus domestica (Amorosa)	148.31
Malus domestica (Astrakan)	70.91
Malus domestica (Alice)	38.75
Alnus glutinosa	150.29
Sum trees	**408.25**
Elaeagnis umbellata	18.19
Corylus avellana	12.90
Hippophaë rhamnoides (male)	44.61
(female)	2.43
Sum shrubs	**78.13**
Herbal biomass	**2.94**

Klockaregården	
Malus domestica (Alice)	32.92
Malus domestica (?)	35.79
Malus domestica (?)	34.87
Sum trees	103.58
Elaeagnis umbellata	1.79
Corylus avellana	6.40
Hippophaë rhamnoides (male)	1.22
(female)	2.73
Rubus subg. *Rubus*	22.27
Sum shrubs	**34.41**
Herbal biomass	**36.19**

9.7 Appendix 7. Yearly production of leaves and herbal biomass

Table A7. Yearly production of leaves from trees and shrubs and herbal biomass, [g].

Vegetation components	Site		
	H.Ö.	H.o.	K
Tree leaves	0.028	0.033	0.015
Shrub leaves	0.021	0.017	0.013
Herbs	25000	2900	36000
Total biomass	25000	2900	36000

9.8 Appendix 8. Raw data roots.

Rikkenstorp

Table A8.1. Raw data of wet weight and root biomass from the soil samples, and the corresponding amount of roots in gram per gram soil or per m³.

Sample	Depth	Wet weight	Root biomass [g]	Roots [g/g soil]	Roots [g/m³]
1	0-10	441.67	0.10	0.00032	23.25
	20-30	573.29	0.15	0.00031	33.54
	40-50	596.44	0.15	0.00096	103.88
2	0-10	414.36	1.90	0.0067	507.11
	20-30	545.2	0.44	0.00096	104.54
	40-50	491.26	0.079	0.00020	18.34
3	0-10	468.82	0.44	0.0012	106.20
	20-30	464.63	0.21	0.00055	50.04
	40-50	492.1	0.008	$1.957E-05$	2.43
4	0-10	471.27	1.10	0.0033	246.33
	20-30	508.17	0.48	0.0011	100.30
	40-50	481.38	0.60	0.0015	146.95
5	0-10	432.67	0.30	0.00096	69.50
	20-30	447.83	0.38	0.0011	95.77
	40-50	467.59	0.11	0.00030	25.70
Ref 1	0-10	437.31	0.88	0.0027	240.20
	20-30	454.47	0.14	0.00038	39.34
	40-50	496.9	0.31	0.00079	68.05
Ref 2	0-10	362.33	1.98	0.0080	558.56
	20-30	585.62	0.19	0.00038	46.60
	40-50	628.4	0.053	$9.54302E-05$	11.46
Ref3	0-10	409.33	1.68	0.0057	397.42
	20-30	559.6	0.072	0.00015	18.17
	40-50	623.94	0.019	$3.44209E-05$	4.71

Table A8.2. Absolute root biomass [g/m³], weighted values for root biomass and mean of weighted values for root biomass. Area is the percental area of the forest garden that each sample corresponds to. Used to make Figure 8.

Sample	Absolute biomass			Area	Weighted biomass			Weighted mean		
	0-10	20-30	40-50		0-10	20-30	40-50	0-10	20-30	40-50
1	23.25	33.54	103.88	0.14	3.25	4.70	14.54			
2	507.11	104.54	18.34	0.055	27.89	5.75	1.01			
3	106.20	50.04	2.43	0.09	9.56	4.50	0.22			

4	246.33	100.30	146.95	0.05	12.32	5.01	7.35			
5	69.50	95.77	25.70	0.095	6.60	9.10	2.44	138.66	67.59	59.4
Ref 1	240.20	39.34	68.05	1	240.20	39.34	68.05			
Ref 2	558.56	46.60	11.46	1	558.56	46.60	11.46			
Ref 3	397.42	18.17	4.71	1	397.42	18.17	4.71	398.73	34.70	28.0

Hånsta Östergärde

Table A8.3. Raw data of wet weight and root biomass from the soil samples, and
the corresponding amount of roots in gram per gram soil or per m^3.

Sample	Depth	Wet weight	Root biomass [g]	Roots [g/g soil]	Roots [g/m^3]
1	0-10	502.03	0.12	0.00030	37.80
	20-30	537.45	0.86	0.00033	32.89
	40-50	488.5	0.093	0.00022	23.97
2	0-10	661.86	0.11	0.00020	25.79
	20-30	435.26	0.029	8.10215E-05	8.89
	40-50	459.4	0.006	1.55219E-05	2.01
3	0-10	559.16	0.34	0.00076	90.69
	20-30	502.82	0.031	7.24134E-05	8.84
	40-50	551.58	0.009	1.90508E-05	2.37
4	0-10	506.11	0.15	0.00035	37.00
	20-30	499.28	0.058	0.00014	16.91
	40-50	493.22	0.012	2.79212E-05	3.61
5	0-10	531.22	0.22	0.00050	60.77
	20-30	604.34	0.018	3.5091E-05	4.37
	40-50	615.54	0.006	1.14339E-05	1.40
Ref 1	0-10	521.79	0.087	0.00020	23.47
	20-30	611.06	0.016	3.11386E-05	3.91
	40-50	641.33	0.010	1.82783E-05	2.40
Ref 2	0-10	703.97	0.062	0.00011	13.12
	20-30	591.64	0.033	6.63951E-05	9.09
	40-50	661.8	0.024	4.27657E-05	5.58
Ref 3	0-10		0.051	9.96119E-05	11.47
	20-30		0.028	5.53986E-05	6.26
	40-50		0.007	1.2632E-05	1.55

Table A8.4. Absolute root biomass [g/m³], weighted values for root biomass and mean of weighted values for root biomass. v is the percental area of the forest garden that each sample corresponds to. Used to make Figure 8.

Sample	Absolute biomass			Area	Weighted biomass			Weighted mean		
	0-10	20-30	40-50		0-10	20-30	40-50	0-10	20-30	40-50
1	37.80	32.89	23.97	0.14	5.29	4.61	3.36			
2	25.79	8.89	2.01	0.055	1.81	0.49	0.11			
3	90.69	8.84	2.37	0.09	2.16	0.80	0.21			
4	37.00	16.91	3.61	0.05	0.10	0.85	0.18			
5	60.77	4.37	1.40	0.095	0.23	0.41	0.13	22.29	16.63	9.29
Ref 1	23.47	3.91	2.40	1	3.61	3.91	2.40			
Ref 2	13.12	9.09	5.58	1	1.40	9.09	5.58			
Ref 3	11.47	6.26	1.55	1	2.40	6.26	1.55	16.02	6.42	3.18

Tystinge

Table A8.5. Raw data of wet weight and root biomass from the soil samples, and the corresponding amount of roots in gram per gram soil or per m³.

Sample	Depth	Wet weight	Root biomass [g]	Roots [g/g soil]	Roots [g/m³]
T	0-10	464.07	0.26	0.00076	29.54
	20-30	701.136	0.050	0.000079	7.69
	40-50	725.7992	0.058	0.000092	7.39
T	0-10	298.69	0.30	0.00087	51.53
	20-30	468.74	0.068	0.00013	16.12
	40-50	502.21	0.042	0.0001	7.67
T	0-10	382.9	1.29	0.0027	202.82
	20-30	486.23	0.094	0.00022	22.10
	40-50	836.43	0.021	0.000029	2.37
T	0-10	274.54	0.54	0.0025	99.26
	20-30	576.26	0.37	0.00073	70.84
	40-50	576.6	0.29	0.00057	47.79
T	0-10	446.85	0.13	0.00036	24.01
	20-30	551.62	0.021	0.000044	4.84
	40-50	475.96	0.010	0.000025	2.03
Ref 1	0-10	606.29	1.30	0.0017	149.64
	15-25	877.79	0.15	0.00020	18.10
	40-50	706.686	0.034	0.000039	4.26
Ref 2	0-10	311.08	0.31	0.0013	55.99
	20-30	545.04	0.13	0.00026	26.41
	40-50	531.11	0.12	0.00026	21.63

Ref 3	0-10	464.07	1.82	0.0051	325.54
	20-30	701.136	0.066	0.00011	9.32
	40-50	725.7992	0.044	0.000072	4.89

Table A8.6. Absolute root biomass [g/m³], weighted values for root biomass and mean of weighted values for root biomass. v is the percental area of the forest garden that each sample corresponds to. Used to make Figure 8.

Sample	Absolute biomass			Area	Weighted biomass			Weighted mean		
	0-10	20-30	40-50		0-10	20-30	40-50	0-10	20-30	40-50
1	3.92	0.85	0.85	0.14	0.55	0.12	0.12			
2	4.51	1.46	0.91	0.055	0.25	0.08	0.05			
3	16.29	2.52	0.28	0.09	1.47	0.23	0.02			
4	12.67	8.09	5.46	0.05	0.63	0.40	0.27			
5	3.07	0.56	0.24	0.095	0.29	0.05	0.02	7.41	2.06	1.14
Ref 1	11.53	2.11	0.35	1	11.53	2.11	0.35			
Ref 2	7.20	3.02	2.47	1	7.20	3.02	2.47			
Ref 3	42.02	1.11	0.58	1	42.02	1.11	0.58	20.25	2.08	1.13

9.9 Appendix 9. Conversion of g roots/1m² to g roots/60m²

Table A9. Root biomass per m² and for the whole forest garden.

Site	Root biomass	
	g/m²	g/60m²
Tystinge	106.092	6365.54
Hånsta	48.20	2892.16
Rikkenstorp	265.69	15941.13