Food from the sky: tree-crops as an ecological alternative for the current conventional agricultural system?

Niek Pepels
970619647010
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Supervisor 1: Kees van Veluw (FSE)
Supervisor 2: Jeroen Scheper (PEN)
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Abstract

This study investigates the sustainability of a chestnut (*Castanea sativa*) based agricultural system to replace the current conventional cereal system. This conventional large-scale agricultural system produces food very efficiently and in vast quantities, but it harms the environment and is not (ecologically as well as economically) sustainable due to its reliance on energy-intensive inputs and its adverse effects on biodiversity and the environment. This research is about a specific alternative for the current conventional production of cereals as a carbohydrate source: an agroforestry tree-crop system based on the chestnut. Beetle biodiversity was compared between a temperate forest, a conventional corn system, and a chestnut agroforestry system (CAS) to find out if the CAS can support higher biodiversity than the conventional cereal system. Furthermore, carbon stocks of the conventional cereal system and the CAS were calculated to investigate if the CAS can aid in climate change mitigation. Also, net yields were calculated for the CAS and two wheat systems. Results indicate that the CAS has higher species richness (6.5 species) than the conventional cereal system (2.88 species) and a higher Shannon biodiversity score (1.514 vs 0.487). System properties likely cause the difference between the sites; the CAS is pesticide free and provides different niches while in the conventional cereal system, pesticides are applied, and only a few niches are available due to homogeneity at field scale. Mean carbon stock difference between the conventional cereal system and the CAS is 203.2 tons of carbon per hectare. The perennial biomass, together with a higher soil organic carbon content in the CAS, cause this difference. Net food yields of the CAS are higher than those of the average-yield wheat system, suggesting that the CAS can serve as a replacement for average-yield cereal systems without losing caloric production. This research shows that a CAS is an ecologically more sustainable agricultural system than the conventional staple food system and shows that a CAS can provide a way to combine the beneficial ecosystem services (like biodiversity and carbon fixation) of nature, with the high production of agriculture.

1. Introduction

Worldwide, around 48 million km^2 of land is used for the production of food [1] which includes cropland and grazing land for cattle. The land used for food production equals the surface area of the continents of Africa and South-America combined and consequently has a major impact on the planet's ecology [2]. A large part of this surface is under conventional large-scale management, mostly in developed countries. The conventional agricultural system causes several environmental problems like biodiversity decline, erosion, and greenhouse gas emissions. Currently, 62% of all species listed on the IUCN Red List are threatened by agriculture [3], and agriculture is responsible for about 24% of global anthropogenic greenhouse gas emissions [4].

The leading causes for this decrease in biodiversity are scale enlargement (removal of hedges, large fields) pesticide use, and simplification of the ecosystem by growing only one or a few different species on a large area of land [5].

Biodiversity and agriculture

Besides agro-ecosystems, nature reserves experience a sharp decline in insect and bird diversity as well. Recently, ecologists reported a decline of more than 75% in flying insect biomass over a period of 27 years in German nature reserves [6]. There is some debate about the methods used by the researchers and the exact percentage of decrease, but most ecologists agree that insect abundance has decreased sharply over the last decades in Northwest Europe. The cause of this decline is not completely clear, but it is likely due to the intensification of the agricultural landscapes instead of expansion of agriculture [7]. This intensification of agriculture goes at the expense of biodiversity and agricultural areas become 'dead zones' for insects that leave nature reserves in search for new habitat [7]. One striking finding is that 94% of the nature areas where the German research was conducted, was surrounded by agricultural land. The surrounding agro-ecosystem must have had a big effect on the health of insect populations in those nature areas [6].

Insects are an essential food source for the entire food web and declines in insect abundance will also lead to decreases of their predator populations, like bird populations. From 1980 to 2009, the number of birds in Northwest Europe decreased by 420 million [8]. This decrease is in line with the sharp decline in insect population and suggests the bird decline could be primarily due to the insect (their food) decline.

Besides their role as food for higher trophic levels, insects are important for humans because of the ecosystem functions they fulfil: pollination of crops and natural biological pest control. 84% of the different crops grown in Europe depends on pollination [9], primarily by (wild) bees. This free ecosystem service has an economic value of 22 billion euros and is of vital importance for the high yield of European agriculture [9].

Natural biological pest control is active on 55.5 billion hectares worldwide, including agro-ecosystems, and controls 95% from the approximately 100 000 potentially harmful plague arthropod species [10]. Therefore, natural biological pest control is another important ecosystem service because it protects crops from most of the arthropod species, even in large-scale conventional agro-ecosystems. However, because most of these large-scale agro-ecosystems are very species-poor and contain lots of pesticides, beneficial insects suffer, and their population numbers are smaller than in natural ecosystems [9]. Providing more resources for these beneficial insects (nectar, pollen, winter habitat, nesting possibilities) by crop diversification, reducing intensification, initiating agroforestry or permaculture practices, and introducing beetle banks and flower strips to agroecosystems, would be beneficial for them and could help to prevent certain vulnerable insects like bee species from going extinct [10, 11]. Recently, the Dutch government released the NL Bee Strategy document to promote actions to stop the bees from declining [11]. This strategy implies, among other things, increasing non-crop habitat in agricultural areas to provide floral resources to bees.

Agroforestry and climate change

The global food production system is responsible for 24% of anthropogenic global greenhouse gas emission [4] which is caused by the combination of livestock production and crop production. From a biological perspective, it is an odd situation that growing plants emits carbon because natural forests generally take more carbon out of the atmosphere than they emit. Due to this mechanism, they form an important terrestrial carbon sink [12]. The causes of the agricultural sector's emissions are plenty; tillage, production of artificial fertiliser, methane emission by cattle, and manure handling [13]. However, several practices can turn the current emitting agricultural system into a net carbon negative system. Examples are agroforestry practices, no-tillage practices, and holistic grazing management [13].
Agroforestry practices (combination of crops with woody perennial crops like trees or shrubs and/or cattle) can also increase biodiversity compared to a conventional agricultural system [14]. Furthermore, agroforestry can decrease runoff and erosion and is a promising candidate to improve the long-term ecological sustainability of agriculture [14].
Agroforestry practices can store carbon in two different stocks: in the biomass of the trees/shrubs and the soil. More than half of the carbon assimilated can end up below-ground via dead roots and root exudates, and contributes to soil organic carbon (SOC) which is a major pool of carbon storage [15]. The below-ground carbon pool is often more substantial than the above-ground carbon pool in forests. Currently, the world's forests have a significant contribution to carbon fixation as they fix about 1.1 Pg carbon per year [12].
Apart from below-ground carbon storage, carbon stored in standing biomass forms another relatively stable carbon pool as trees can live for several hundred to thousand years. Therefore, deforestation increases atmospheric carbon levels and decreases the amount of carbon stored in terrestrial ecosystems. Agriculture has caused lots of forest to disappear. 8000 years ago, before Neolithic agriculture, Europe was almost entirely covered with forests and was a considerable carbon sink [16]. These days, less than half of Europe is covered in forest, and individual countries like the Netherlands have very shallow forest cover [16]. After deforestation, most of the stored carbon is released into the atmosphere again. So, land use change *can* contribute to increased atmospheric $CO2$ levels. However, land use change can also *reduce* atmospheric carbon levels. When conventional agricultural systems are transformed into agroforestry systems (so trees and shrubs are included), carbon sequestration rates can increase, just like planting a forest would increase carbon fixation rates [14]. If we can create an agricultural system based on tree crops that can replace our current annual crops dominated agricultural system, we would be able to store much carbon and reduce atmospheric $CO2$ levels, thereby potentially mitigating climate change.

Erosion and conventional agriculture

Another major issue related to conventional agriculture is soil erosion. Currently, about 80% of the global agricultural soils are moderately to severely eroded [17]. According to a recent IPBES report, 3.2 billion people are experiencing a negative impact on their wellbeing due to land degradation caused by human activities [17]. In 2050, as much as 90% of Earth's land surface will have become degraded, and many conflicts, wars, and mass migration, will likely be a consequence of this degradation [17].
The world's lowest erosion rates occur in Europe and the US with an average soil loss of 10 tons per hectare per year (but the erosion rate differs a lot between different sites and depends on different climatic as well as geochemical factors). Although these areas have the lowest

global mean erosion rates, erosion rates are still much higher than the rates of formation of new soil from parent material under agricultural conditions, which is about 0.5-1.0 tons per hectare per year [18]. Moreover, in the last 40 years, about 30% of the agricultural land was abandoned because it has become unproductive after years of continuous erosion [18]. Experts estimate that most of the world's topsoils will be incapable of growing crops anymore within 60 years time [19] if the current erosion rates continue, indicating that soil erosion is presently already posing a major threat for food security and certainly for food security in future [18].
Erosion occurs when the soil is exposed to wind and rain. When raindrops fall and reach the bare soil, they solubilise soil particles so that soil is washed away with the water downhill. This is especially problematic in hilly and mountainous country, but erosion occurs even on land with slopes of only 2% [18]. Wind can blow soil particles away and can be a serious threat, mainly in dry climates. Permanent vegetative cover of the soil with living plants or by detritus, protects the soil from erosion and can maintains a soil's fertility. In most natural ecosystems (except deserts and high mountains), exposed soil is a rare phenomenon so that natural soil erosion rates are very low in natural ecosystems [18].
Conventional agricultural systems are characterized by ploughing, row crops, and bare soils during the winter season. These three factors make them very vulnerable to soil erosion. Currently, average conventional agriculture erosion rates are >1 mm per year, while natural ecosystems average erosion rates of <0.2 mm per year [18]. This indicates the large difference in soil erosion rates between natural ecosystems and agricultural systems.
History could and should have taught humanity that soil is of uttermost importance for stable societies as damaged soils are prone to failed harvests that can form the beginning of an insurrection and consequently the collapse of a society [20]. With the rise of the great societies that popped up in Greece, Rome, and the Middle-East several thousand years ago, soil erosion rates increased dramatically [20]. Hilly or mountainous areas characterised these areas, and when agricultural fields were created, erosion rates started to increase [20]. All the great civilisations that ever existed had a timespan of several hundred to thousand years. After this time, they collapsed. With an average erosion rate under conventional agriculture of >1 mm per year and a topsoil formation (due to geological weathering of bedrock) of <0.2 mm per year, it takes several hundred to thousand years to completely erode a topsoil ranging from a decimetre to a meter [20]. This time corresponds to the time that these civilizations existed, and provides evidence that loss of soil fertility due to erosion might be one of the principal reasons for the collapse of previous civilisations [21].
The Mediterranean area, one of the most intensively manipulated areas by humanity because of the long history of agriculture, is currently at risk of desertification and loss of soil fertility. Only a few thousand years ago, it was characterized by its high fertility and good crop harvests. However, after centuries of destructive agricultural practices (tillage causes SOC oxidation and reduces SOC levels for example), soil fertility is severely impaired. Already in the first decade AD, Roman historian Titus Livius was wondering how the lands could continue to feed the Roman empire as he observed increasing land degradation [22]. Since the start of the Roman empire, most of Italy's countryside has lost several centimetres of fertile topsoil. In combination with the dry and hot summers, agriculture has become a challenge, especially in Southern Italy [22]. Over the last 2500 years, the Mediterranean area has dried up, has lost several centimetres of topsoil, and has lost much of its fertility and potential to sustain good crop yields. It is an example of what can happen when bad agricultural practices are continued long enough.

The only form of human civilisation that existed 50 000 years ago and still exists today is the hunter-gatherer civilisation. Worldwide, hunter-gatherer tribes have declined over the last

couple of decades and/or adapted their lifestyle by starting to grow crops. However, there are still some tribal communities left that are entirely dependent on the surrounding ecosystem for food. Those tribal communities that did not (or sparingly) work the soil have continued to exist for millennia, in contrast to all the civilisations that were dependent on agriculture with lifespans of several hundred to thousand years. Those people lived from their surrounding ecosystem, just like all other animal species on this planet do. They harvested wild plant and animal foods and, because they did not work the land like agricultural people did, they did not reduce the land's potential to provide food. One could argue that growing annuals, plants that require reseeding every year, is at the base of the agricultural problems like erosion.
It is impossible to make humanity hunter-gatherers again in the traditional meaning of the word. However, it might be possible to apply the ecological benefits of this hunter-gatherer lifestyle to the modern-day conventional agricultural system to increase its ecological sustainability. How can we create a system that does not need continuous reseeding and inputs, that can provide many of the same ecosystem functions as natural ecosystems (carbon fixation, water purification, biodiversity), and that can yield enough calories to compete with the current conventional agricultural system? A system based on tree crops might be the answer.

Tree crops

Ideally, the conventional agricultural system should be replaced by a system that prevents erosion, promotes rainwater infiltration, is a carbon sink, and promotes biodiversity. One such an alternative agricultural system that was already proposed decades ago by Russel Smith [23] is a system based on tree crops; a system that mainly consists of tree crops that functions to a certain extent like a forest, but with the same production level as a conventional agricultural system. The most famous modern example of such a system is the farm of Mark Shepard. This pioneering farmer has turned a former conventionally managed agricultural system into a system based on tree crops on a reasonably large scale (42 hectares). His system consists of several species of tree crops and several livestock species. Trees and shrubs are planted in contour rows so that harvesting can be done with machines, enabling large-scale application of such a system (Fig. 1). Moreover, the fact that only relatively few species are grown as main crops (but still enough to make it biodiverse) should encourage conventional farmers to implement this kind of agricultural system because the system is not too complicated to understand for people without experience in growing tree crops. Mark Shepard started his farm about 20 years ago and currently has one of the oldest large-scale tree-crop systems in the world. According to his numbers, he can produce 14 million calories per hectare from the combination of different crops (including animals) that he grows on his farm [24]. This number of produced calories is higher than the amount of direct human-available calories from a hectare of wheat cultivated in a conventional system in the US which provides 10.7 million calories per hectare [25]. In this number, only wheat kernels (the grains) energy content is considered. Straw calories which can be used to feed livestock (although digestibility is very low), is not considered. Nonetheless, this illustrates that it is possible to produce many calories on a large scale, tree crop dominated agro-ecosystem.

Figure 1. New Forest Farm: a savannah like landscape consisting of tree crops and grass as a permanent agricultural system is the result. The contour lines are visible, trees follow these lines.

Some research has been conducted on the environmental benefits of food forests, for example in the Netherlands. Often, those studies look at rather complex small-scale systems consisting of tens or hundreds of different species. In the most famous Dutch food forest, de Ketelbroek, more ground beetle (Carabidae) species were found than in the nearby nature reserve De Bruuk, indicating that such (plant) species-rich agroforestry system can be an important habitat for many different species [26]. However, it is quite hard and possibly even unrealistic to scale these food forests up because most farmers are withheld from starting these food forests due to the level of complexity (certainly in comparison with a monoculture) and the level of knowledge required for the maintenance of these systems. That is why agroforestry systems like alley cropping and silvopasture as practised by Mr Shepard, are more likely to be implemented by farmers at a large scale.

Current staple food production

In agriculture, the production of staple foods (potato, corn, wheat, rice, soy) has a significant ecological footprint because these crops are almost always grown in a conventional, monoculture system. Currently, a staggering > 50% of the worldwide produced calories comes from only three different plant species: corn, wheat, and rice [27]. A large part of these crops is not even directly (so the wheat grain kernel for example) consumed by people, but used as feed for cattle, biofuel, or processed into processed foods for human consumption, like pasta, bread, or noodles. For example: in the US, corn is grown on 36 million hectares and, together with soybeans, it dominates agro-ecosystems [28]. From the total corn yield, 40% is used to produce biofuels and 36% to feed livestock [28]. Only a small part of it is directly consumed by people (via processed food or corn, but not via meat).

At the same time, the conventional agricultural system has a very high demand of inputs (artificial fertiliser, herbicides, pesticides and diesel) and causes several ecological problems, like algal blooms in the Gulf of Mexico [28].

This thesis investigates if growing (part of) our staple foods using tree crops in a perennial system can provide some of the ecological benefits of a natural temperate forest. An example of what is meant by replacing these staple food crops: wheat flour is often used to produce pasta, bread, and cookies. Wheat production takes place in conventional monoculture systems that create all the before-mentioned problems. Tree crops, like the sweet chestnut (*Castanea sativa*), produce a nut that has a somewhat similar nutritional profile as grains because it

contains lots of carbohydrates and just a small amount of fat. Chestnuts can be ground into flour which can serve as a partial replacement of wheat flour in many processed foods. Increased demand for gluten-free products (like chestnut flour) stimulates these alternative flour crops. Another example is rapeseed oil that comes from rapeseed grown in vast monocultures all over the globe. Cooking oils can also be produced by tree crops, like walnuts, hazelnuts, and almonds.
To replace the current conventional staple crop system, a system is needed that is applicable and maintainable on a large scale. That is why very species-rich food forests are not a suitable candidate to produce our staple foods. A system like Mark Shepard's system, based on several tree crops grown in rows, is much more likely to be implemented on a large scale. One of the main crops in such a system would be the sweet chestnut (*Castanea sativa*).

'L'arbre à pain'

The sweet chestnut (*Castanea sativa*) is called 'l'arbre à pain' in French, meaning bread tree. In the Ardèche region of France, a mountainous region in the south of the country, chestnuts dominate the landscape. The French started to grow chestnuts here centuries ago because they could barely grow grains (the terrain was too hilly and mountainous). A large part of the Ardèche would be characterized as 'marginal land' meaning it is not suitable for agriculture defined as annual cropping systems. The chestnut has the remarkable capacity to produce food even on those marginal lands. It provided the people with a staple food product rich in carbohydrates and calories to survive the winter months. Presently, these '*châtaigneraies'* still cover large areas in the Ardèche although some orchards have severe problems with exotic insects and diseases. Traditionally, chestnuts were often dried and ground into flour to make bread, hence the name 'l'arbre à pain'. Due to their low fat and high carbohydrate content, people call chestnuts 'corn on a tree', because cereals, like corn, are also characterised by low fat and high carbohydrate content. This property makes them the ideal tree crop to replace annual cereal crops in flour-products like bread, cookies, pastry, pasta and noodles.
In Europe, chestnut yields have decreased dramatically over the last decades due to the introduction of exotic diseases and insects (like the chestnut gall wasp, *Dryocosmus kuriphilus*). In other parts of the world like Chile and New-Zealand, yields can be up to 9700 kg per hectare with average yields of 4972 kg per hectare in Chile [29]. This yield difference between Europe and other parts of the world is the absence or reduced prevalence of several of the most damaging chestnut diseases. Another difference is that other cultivars and species are used in other parts of the world. For example, Chinese chestnuts (*Castanea mollissima*) bear averages of 6700 kg per hectare with high yielding orchards, using high-yielding varieties, reporting 12 300 kg per hectare [30]. In the Ardèche region in France, farmers are subsidized when they continue to grow traditional cultivars in an attempt to conserve the natural heritage of generations of farmers. However, some farmers transitioned to growing a hybrid of *Castanea sativa* (European chestnut) and *Castanea crenata* (Korean chestnut). This hybrid is known as 'Bouche de Betizac', and it is resistant to *Dryocosmus kuriphilus* (chestnut gall wasp), that is currently the most devastating insect occurring in Europe which can reduce yields up to 100%. An orchard planted with Bouche de Betizac trees in Europe can give high yields and can be a way for chestnut growers to transform their current low-productive orchards into healthy high-yielding orchards again, but at the cost of conserving local varieties.

Aim of the thesis
As stated earlier, some research into biodiversity has been performed in complex food forest systems or alley cropping systems. However, as far as I am concerned, there has not been any study that investigated if a chestnut-based agroforestry system can be an *ecologically* as well as *economically* sustainable candidate to replace the ecologically destructive conventional grain system. Ideally, such a chestnut-based system would consist of several tree crops with the sweet chestnut as the main crop, like the system Mark Shepard has created on his farm. This mixed crop system increases field diversity and makes the system more resilient. However, for the simple reason that there yet is no mature, climax-state system as described above, this thesis investigates a mature chestnut orchard in the Ardèche, because this system approaches such a chestnut based system closest. Furthermore, as explained above, this system is in its climax state, because it is centuries old, and provides a unique opportunity to investigate the long-term ecological effects of such a tree-crop based agricultural system.
This thesis investigates whether producing carbohydrates in a perennial chestnut agroforestry system (CAS) can be an *ecologically* and *economically* sustainable alternative for the current conventional, monoculture system of annual carbohydrate crops, like corn and wheat. This research aims to find out whether this tree-crop system can (partly) provide the ecosystem services of a temperate forest by measuring and comparing Coleoptera (beetle family) biodiversity, as a proxy for system biodiversity, in a temperate forest, the CAS, and a conventional cereal system. Coleoptera (beetle family) biodiversity is chosen because it can be used as a proxy for general biodiversity. Birds are often used as indicators for ecosystem biodiversity, but research by the British Ornithologist's Union suggests birds are a rather weak indicator group [31]. Beetles, however, came out as the best indicator for general biodiversity of an ecosystem [31]. Therefore, this group is used as a proxy for biodiversity.
The CAS has a relatively high plant biodiversity, but it is not as high as the plant diversity in a natural forest. Furthermore, a CAS is managed more intensively than a natural forest, so I expect beetle diversity in the CAS to be a bit lower than in the natural forest, but higher than in the homogeneous cereal system.
Carbon stocks (biomass + soil) are calculated for the CAS and the conventional cereal system to find out if the CAS can help with climate change mitigation. Carbon stocks are expected to be higher in the CAS than in the cereal system because the woody biomass of the CAS can serve as an additional carbon sink.
To compare the economic sustainability of the CAS with the conventional grain system, yields expressed in kcal are calculated for the CAS and the conventional cereal system. All different inputs and outputs are expressed in kcal. Then, a net yield (output kcal-input kcal) is calculated to find out if the CAS can compete with the conventional cereal system concerning net calories produced.

2. Material and methods

Study area
The forest and the two chestnut sites are located in the Ardèche region of France. The Ardèche is a mountainous region characterised by chestnut forests that are already under cultivation for several centuries. The soils of the area where the forest site and chestnut site are located, mostly consist of granite. The high granite content, in combination with the steep slopes, makes conventional agriculture impossible and is the reason why chestnut cultivation was started several centuries ago. Altitude ranges from about 400 to 600 metres, the chestnut sites are located on a south-facing slope, and the forest is located on a north-facing slope. Average temperatures range from 4.9 °C in January to 22.8 °C in July and annual mean precipitation is about 800 mm.

The corn site is situated in Tilburg in the Netherlands and belongs to dairy farmer Kees Fonken. A corn site was used as a representative of the conventional cereal system, due to its accessibility (in between the rows there was enough space to walk and to sample the beetles). The area is flat, and the soil is sandy soil. On average, yearly precipitation is 750-850 mm and mean temperatures range from 3.1 °C in January to 17.9 °C in July. Altitude is about 16 metres.

Site management and characterisation

The chestnut site used for biodiversity measurements was under the organic management of Francis Pierron. It is a traditional chestnut orchard, meaning harvesting is done by hand. Most of the trees were more than 200 years old and suffered a bit from several new diseases and invasive insects such as the chestnut gall wasp. The understory was dominated by ferns which are a problem as they make chestnut harvesting impossible. Francis managed the site by removing the ferns underneath the chestnut trees. He removed them by pruning and by burning. Besides the ferns, herbaceous plants and some woody plants like common broom grew underneath and in between the chestnut trees. Furthermore, dead branches of the chestnut trees were removed and used to heat the farmer’s house. Sheep occasionally grazed the herbs underneath the trees. Its steep slopes and shallow soils characterise the site.
Another chestnut site was used for the climate mitigation measurements. This site is located next to the chestnut site where biodiversity measurements were performed and belonged to the cousin of Francis Pierron. This site was used for the carbon sequestration measurements because tree spacing was more intense (in rows, distance around eight metres) and this site represents the most common tree spacing of the chestnut system in the area. However, this site was not chosen for biodiversity measurements because the lowest branches were too high for sampling. Because of the regular spacing of the trees, it was easy to calculate the number of trees per hectare.
The forest site contained several woody species like ash, hazelnut, chestnut, wild blueberry, wild rose, pine trees, elderberry, as well as non-woody species growing in the understory. The only management that took place on this site was the harvesting of wild mushrooms and wild blueberries.
The corn site is a conventional cereal system meaning management is intense; tillage is performed, as well as herbicide and artificial fertiliser application. No other plant species were observed in the field due to the use of herbicides.

Sampling design biodiversity measurements

Each study site occupied 1 ha. Per study site, eight quadrants of 10x10 metres were selected. Selection was not randomly but was based on lowest branches height that was available for sampling. In the CAS, some trees had the lowest branches at a height that was too high to inspect the leaves. Plot selection was performed to exclude those trees as they would make a false comparison with the corn site where the *total* leaf surface could be sampled. This selection procedure was done to compare about the same quantity of leaf surface between the different sites.
Sampling occurred in the same way in the forest and the CAS sites. First, visual inspection of the leaves of the woody species was performed. Then, beetles were collected out of the trees with the use of a beating net (an umbrella served as beating net). Last, the herbaceous layer was sampled with the use of a general beetle net. All the beetles that were found were determined to family level. Beetles were determined to family level because the family level already provides much information about behaviour and habitat type but is less laborious than the determination to species level. Data are provided in Appendix A, Table A1 and A2.

In the corn site, a general beetle net could not be used because no herbaceous plants were present. Furthermore, the use of a beating net was not appropriate since corn plants are no woody species. Also, the use of a general beetle net to sample the corn plants was not possible as this would damage the corn plants. So, only visual inspection of the plants and the soil was performed in this site. Because of the structure of the monoculture and the relatively low height of the corn plants (+-70 cm), the entire leaf area could be inspected. Data are listed in Appendix A, Table A3.
Sampling was done only when weather conditions were appropriate for beetle activity (no rain, temperatures >20 degrees Celsius) and when conditions were similar during the sampling of the different study site to rule out meteorological effects on between-site differences. Temperatures during sampling the three sites ranged from 20 to 24 degrees Celsius. The weather was cloudy, and the sun occasionally appeared.

Mean beetle abundance was compared for the three different sites, as well as mean plot species (family) richness to find out if the CAS site was comparable to the forest site and if there was a difference with the cereal site.
Beetle biodiversity was compared at family level and was compared between the three sites with the Shannon Biodiversity index. The Shannon Biodiversity index (H) is a tool to compare the biodiversity between different sites. It accounts for both abundance and species richness data. Often, *species* diversity is compared. However, for this thesis *families* were used instead of species. Instead of species richness, family richness was compared. So technically family richness and family biodiversity were calculated instead of species richness and species biodiversity. For simplicity, however, the terms species richness and species biodiversity are used in this thesis. Shannon's diversity index was calculated for the three different sites with the following formula:

$$H = -\sum_{i=1}^{S} p_i \ln p_i \quad (1)$$

with $P_i = n_i/N$
and n_i = individuals of species i
and N = individuals in population
and S = total number of species

To find out if a family dominated the site, the Shannon's evenness was calculated. Data are reported in Appendix A, Table A4. A high evenness, meaning all families found have similar contributions to the overall Shannon diversity, is indicated by a score of 1. A low evenness (closer to 0 than to 1) indicates there is dominance of one or a few families. It is calculated by dividing H by the natural logarithm of the total different species (here families) found and is listed in Appendix A, Table A5:

$$E_H = H / H_{max} = H / \ln S \quad (2)$$

with H = Shannon Biodiversity index
and Hmax = ln (S)
and S = total number of species

Sampling design climate mitigation
The number of trees on 2500 m^2 ($1/4^{th}$ hectare) was counted. For each of the counted trees, circumference was measured at 1.3 above soil level. Tree suckers (if present) were measured as well. With the tree circumference, the diameter at breast height (DBH) was calculated with the formula:

$$D = C / \pi \quad (3)$$

with D=diameter,

and C=circumference
and π=number of Pi (3.14159…)

Biomass equations were used to calculate the total biomass of the trees on this quarter hectare using the diameter as input variable. Colleagues [32] determined allometric relationships between DBH and biomass from trees in different chestnut plantations in Spain, Italy and France. Although sites differed in soil type, climate, height, and precipitation level, one allometric equation (per tree part) could be made that accurately predicts biomass based on DBH [32].
With the use of these allometric equations (Fig. 2), the aboveground biomass of the leaves, trunk, branches, and total biomass was calculated for the trees found on this quarter hectare.

$$\text{Trunk biomass} = 0.064\ (\text{DBH})^{2.401}$$
$$n = 42\quad r = 0.919$$
$$\text{Branch biomass} = 0.023\ (\text{DBH})^{2.307}$$
$$n = 42\quad r = 0.879$$
$$\text{Leaf biomass} = 0.004\ (\text{DBH})^{2.296}$$
$$n = 22\quad r = 0.856$$
$$\text{Total wood biomass} = 0.080\ (\text{DBH})^{2.421}$$
$$n = 49\quad r = 0.916$$

Figure 2. Biomass regression equations for *Castanea sativa* for different parts of the tree based on DBH [32].

After calculating above-ground biomass of the CAS, below ground root biomass was calculated with the root to shoot ratio (from literature), expressed as below ground biomass : above ground biomass. The root to shoot ratio of *Castanea sativa* is 0.767 [33], meaning root biomass = 0.767 * above ground biomass. After calculating the total biomass (above-ground & below-ground) of the trees in the CAS, biomass was transformed to carbon with the average hardwood tree conversion factor of 0.48 found by colleagues [34]. Data are provided in Appendix B, Table B1.
The CAS floor biomass layer consisting of (leaf) litter was neglected for the calculation of total CAS carbon storage because the management of CAS is to burn the herbaceous layer every year, leading to no long-term carbon stock of this layer. This leaf part of the CAS can be considered similar to the corn plant biomass residues which also are no long-term carbon stock since they are often fed to livestock, used as biofuel, or burned. Total calculated carbon was multiplied with four to get the amount of biomass carbon of the CAS on 1 hectare.
Estimates for carbon stored in soil (SOC) for the CAS were made by comparing different studies on chestnut systems (or close relatives such as beech forests, also a Fagaceae) and temperate forests (Table 1). These studies used different soil depths to measure the carbon stock. After analysing the different methods used and the different site characteristics, two values (in bold in Table 1) were chosen to be used in this thesis. These values came from a study on carbon stocks in Portuguese chestnut stands by colleagues [35] and are in line with the values reported by other studies (Table 1). For example, the lowest value chosen for this thesis was 84 tons C per hectare, and this value was confirmed by other studies done on beech forests in Italy [36] and chestnut forests in Bulgaria [37]. The highest chosen value (180 tons C per ha) was close to the value that other studies, like a study in Greece on chestnut stands [38] found (Table 1), and seems to be a reasonable estimation. Total carbon stocks (biomass & soil) were also mentioned by several authors (Table 1). These values were used to compare the outcomes of my calculations to find out if my findings are in line with comparable systems and are discussed in the discussion section.

Table 1. An overview of different studies done on chestnut or forest carbon storage, some measured soil carbon and some measured total carbon stock including both biomass carbon as well as soil carbon. C=carbon.

study	*total (biomass & soil) C in tons/ha*	*type of data*	*soil carbon (tons C per ha)*	*soil depth (cm)*	*species*	*region/country*
[36]	-	highest value	156	40	beech *(Fagus sylvatica)*	Italy
[36]	-	lowest value	84	40	beech *(Fagus sylvatica)*	Italy
[35]	-	**lowest value**	**84**	60	chestnut forest	Portugal
[35]	-	**highest value**	**180**	60	chestnut forest	Portugal
[38]	-	average	163	60	chestnut forest	Greece
[37]	-	average	84	50	chestnut forest	Bulgaria
[39]	123 t C/ha	average	-	100	mixed forests	Europe
[39]	171 t C/ha	average	-	100	mixed forests	United States
[40]	185 t C/ha	average	-	100	maple-beech-birch	United States
[41]	224 t C /ha	average	-	90	beech *(Fagus sylvatica)*	Germany

Data on total carbon stock of the cereal system were obtained from literature. One assumption I made was that the biomass produced (including roots) does not count as perennial carbon stock since the carbon stored in these compartments tends to get released very quickly. For example, when people or other animals consume the grains and straw, the carbon will be emitted back into the atmosphere. Most of the root carbon biomass is released quickly after harvest into the atmosphere because tillage and consequent carbon oxidation in this system is performed. So, only the soil organic carbon was used as a stable carbon stock for the cereal system. Most cropland soils in Europe have soil organic carbon levels varying between 1.5 and 3.5%, although exceptions occur of course, depending on the region, soil type, and climate. For this thesis, both a low and a high SOC level were used (as was done for the CAS SOC). I assumed an average bulk density of 1200 kg per m^3 soil and calculated the carbon stock for the top 30 cm of soil (topsoil). These are of course rough estimations and the bulk density, for example, can differ substantially between different soil types. However, for the purpose of this research, which is to get an idea of the order of difference between the conventional cereal system and the CAS, this works perfectly well. Furthermore, this was precisely the reason that both low and high values were chosen for both the CAS and the conventional cereal systems. So, the low SOC stock (1.5% SOC) used was equal to 54 tons of

C per hectare and the high SOC (3.5%) stock used was 126 tons of C per hectare. All the C stock data for the CAS and the cereal system are listed in Appendix B, Table B2.

To visualize how much extra carbon would be sequestered when a CAS would partially replace the conventional cereal system, calculations were made with the assumption that *1/3 of Europe's cereal growing area was converted to the CAS.* One-third was chosen because it represents a realistic area where the chestnut can be cultivated in Europe, and at the same time it is a realistic estimation of the proportion of wheat flour that can be replaced by chestnut flour in products without major product differences.
Europe emitted 4451.8 million tons of CO_2 in 2015 which is equal to 1213.0 million tons of carbon [42]. In total, 57 million hectares of cereals were grown in Europe in 2015 [43]. Different calculations were made to calculate the difference in C storage when this potential agricultural conversion would take place. First, averages of the low and high total C stock for the CAS, as well as for the cereal system, were calculated with the formula:

4 average total C stock (tons C/ha) = (high total C stock + low total C stock) / 2

To calculate the per hectare difference of converting a hectare of cereal system into a hectare of CAS, the following formula was used:

5 extra C stored by conversion to CAS (tons C/ha) = average total C stock CAS – average total C stock cereal system

Then, this difference in C storage was calculated for one third of the total cereal area(57 million hectares) in Europe with the following formula:

6 potential extra C storage by converting 1/3 of cereal system to CAS (kg) = 1/3 * 57 000 000 * OUTCOME FORMULA 5 * 1000

To calculate how many years of EU emission this conversion would take up, the following formula is used:

7 # years EU emission sequestered= OUTCOME FORMULA 6 / 1 213 000 000 000 (yearly European emission of C)

The extra carbon storage by this agricultural conversion (FORMULA 6 OUTCOME) was also expressed in the number of years of Europe's annual transport C emissions (2,79E+11 kg C), Europe's annual fossil fuel C emissions (6,67E+11 kg C), and Holland's annual carbon emissions (2,07E+11 kg C) with data from Eurostat [42].
Finally, the number of people's lifetime emissions that would be taken up by this agricultural conversion was calculated for three countries: the United States, the Netherlands and India. The countries differ in per capita emission rates with the United States having the highest C per capita emissions and India having the lowest per capita emissions [44]. A lifetime was assumed to be 80 years for all countries. Lifetime emissions were calculated with the following formula:

8 # people's lifetime C emissions = OUTCOME FORMULA 3 / ((data world bank / 3.67) * 80)

The data from the world bank were divided by 3.67 to convert CO_2 emissions into C emissions.

Yields of CAS and conventional system

Net yields (expressed in kilocalories) were compared between two conventional wheat systems and the CAS to find out if the CAS can be an economical alternative for the conventional cereal system. These two different wheat systems were chosen because input/output analyses have been done on them, and because they represent a high-yield system and a world-average wheat yield system. The world-average yield wheat system data came from a wheat system in Kansas, US. It produced about 2900 kg of grains per hectare, which is close to the world's mean wheat yield [25]. The other wheat system was situated in France and produced 6500 kg of grains per hectare [45]. This high-yield wheat system is characteristic for Europe, where wheat yields are very high compared to other parts of the world, with an average of around 6000 kg of grains per hectare [46]. The system in France was used as a high-yield system, while the US system was used as the world's average-yield system. I estimated the CAS yield data after reading several articles that investigated chestnut yields around the world, and after talking with the French chestnut grower Francis Pierron, the owner of the chestnut orchard where this study was done. He estimated one healthy >200-year old chestnut tree could produce 100 kg of chestnuts per year. On a typical CAS hectare in the study area, 80 trees occupied the land. In total, this would be 8000 kg of chestnuts per hectare. At this moment, his orchard produces far fewer nuts because of problems with the chestnut gall wasp. However, with healthy, high-yielding trees, he believed this was an appropriate estimation. I realized this is a high value, therefore I compared it with literature data. As described in the introduction, chestnut yield data are very different for different areas of the world and different cultivars or species. Some varieties like the Chinese chestnut (*Castanea mollissima*) can produce 6700 kg per hectare in intensively managed orchards [30]. In other parts of the world yields are also regularly higher than 4500 kg of chestnuts per hectare [29]. I believe more research into chestnuts and improved breeding could quickly make Europe's chestnut orchards productive again. One example is the hybrid 'Bouche de Betizac' which resists several of the diseases/insects that devastate traditional varieties of chestnuts in Europe. I have seen these hybrid orchards in the Ardèche that looked very healthy, and that produced huge nuts. For this research, chestnut yields of 4500 kg of chestnuts per hectare were used. I believe this is a realistic value for healthy orchards and I even think this value is a bit on the low side compared to Chinese and Chilean yields.

The inputs and outputs for the two wheat systems described earlier were calculated by [25] and [45] and were expressed in kcal/ha. All the different inputs like herbicides, fertilisers, machinery, and diesel for the machines, were calculated and expressed in kilocalories by these studies. For the CAS, I estimated the inputs with the US average-yield study on wheat [25] as a basis. I assumed the CAS does not have any fertiliser and herbicide/pesticide inputs. Furthermore, I estimated the number of hours needed for keeping bees, harvesting chestnuts, harvesting mushrooms and removing dead wood. This number was expressed in kcal. Machinery costs, diesel, and other labour expressed in kcal were estimated as well (Appendix C, Table C1).

To compare the net kilocalories produced between the three different systems, one important assumption was made: in a CAS, the leaves form a major energy stock while in the wheat systems, the straw forms a significant energy stock. Straw in the wheat systems was considered to be a similar product as leaves in the CAS; people cannot directly eat it, but it contains lots of energy (kcal). In a CAS, the leaves fall to the ground each autumn and decompose there or are being burned by farmers. The wheat straw can be used as cattle feed (although it is bad-digestible and cannot be eaten in large quantities), or as a mushroom medium, or as a biofuel. The chestnut leaves could theoretically also be used as a mushroom medium or as a biofuel, but this is not often done. Furthermore, the yearly input of organic material is vital to maintain soil organic carbon levels and therefore to sustain soil fertility.

That is why conservation tillage becomes more popular among conventional farmers. Crop residues are left on the soil and serve as a mulch. Earthworms incorporate the mulch into the soil thereby maintaining or increasing SOC levels. In my opinion, as well as the opinion of many soil-scientists, a soil's fertility can only be maintained if SOC levels are maintained. Therefore, I assumed that all the straw produced by the wheat systems was used as mulch and consequently, straw (or leaves) does not form an energy output in this thesis. It is indicated though, in the results, to visualise the magnitude of these energy pools. However, the only output from the wheat systems in this study were the wheat kernels. In the CAS, the quantity of leaves was calculated with the biomass equations mentioned before. The energy in the leaves was again not considered an output because the assumption was made that all the leaves remained in the orchard (as mulch, or burned).
The amount of straw produced by the wheat systems was calculated with the conversion factor:

9 wheat straw yield (kg/ha) = 1.3 * wheat grain yield [47].

The calorific value of wheat straw used was 4349.8 kcal per kg straw [48]. Wheat straw energy content was calculated by:

10 straw energy (kcal/ha) = OUTCOME 9 * 4349,8 kcal per kg straw

For the CAS, the total leaf biomass yield per hectare was calculated by allometric equations described earlier in the material and methods chapter. The calorific value of leaves used in this study was 4411.5 [49]. Total energy content of the leaves for 1 hectare was calculated as follows:

11 leaves energy (kcal/ha) = leaves biomass for 1 ha * 4411,483711 kcal per kg leaves

Wood formed another output for the CAS. This wood consists of dead branches, tree suckers, and pruned branches. Wood outputs per hectare were estimated by data provided by Francis Pierron. The calorific value used here was 15.8 MJ per kg [50]. This is equal to 3704.59 kcal per kg wood. Dried weight of chestnut wood value used here was 580 kg per m^3. First, total wood in kg per ha was calculated. Then total energy in harvested wood was calculated as follows:

12 wood energy (kcal/ha) = wood weight harvested per ha (kg) * 3704,59 kcal per kg wood

Honey can be another output product of a CAS, as bee hives are popular in chestnut orchards in France. Estimations of the total possible honey yield per hectare and consequently the total energy output in this honey was calculated with data provided by Mark Shepard [24] who has experience with a CAS like system. Furthermore, wild mushrooms can be another output of the CAS. According to Francis Pierron, yields vary a lot between years. Therefore, I used a low fresh-weight estimation of 10 kg fresh mushrooms per hectare. All the outputs are listed in Appendix C, table C2.
Finally, inputs and outputs, net yield (output calories – input calories), and gross yield were calculated for the CAS and compared with the values reported for the two wheat systems.

Statistical analysis

SPSS software was used to find out if there were significant differences between the different sites. All comparisons were conducted at a significance level of 0.05.
To compare the beetle abundance data and beetle family data between the three different study sites (count data), the Kruskal-Wallis non-parametric test was used. Between group differences were investigated with separate Mann-Whitney U tests.

Species richness data and Shannon diversity data were analysed with a one-way ANOVA and a Tukey post-hoc test. Shannon' evenness was analysed with a Kruskal-Wallis non-parametric test.

3. Results

Beetle abundance

There was a significant difference in overall beetle abundance between the three study sites (H(2)=16.176, p<0.001). Follow-up analyses showed that CAS does not significantly differ from the forest site (U=43.5, P=0.234) indicating the beetle abundance in CAS is similar to the abundance in the forest. However, beetle abundance in the corn system does differ significantly from the CAS system (U<0.001, P<0.001) as well as from the forest (U<0.001, P<0.001). The mean abundance in the cornfield was very low (3.13 beetles per plot) compared to the CAS (28.3 beetles per plot) and the forest (21.9 beetles per plot), (Fig. 3).

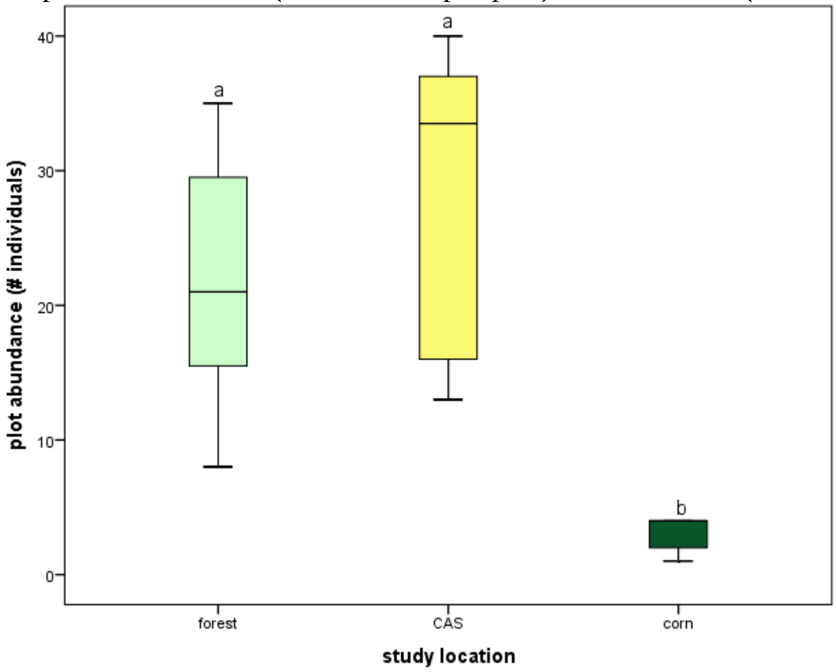

Figure 3. Mean beetle plot abundance for the three different study sites. CAS=chestnut agroforestry system.

Species richness

Species richness was clearly significantly different between the three study sites ($F(2,21) = 15.017$, $p<0.001$). A Tukey post-hoc test revealed that the species richness was significantly higher in the forest (6.63 species ± 1.847, p<0.001) and in the CAS (6.5 species ± 1.773, p<0.001) in comparison with the corn field (2.88 species ±0.835), (Fig. 4). There was no significant difference in species richness between the CAS and forest site (p=0.986). In total, 15 different families were found over all the plots in the forest, 11 different families in the CAS, and 5 in the cornfield.

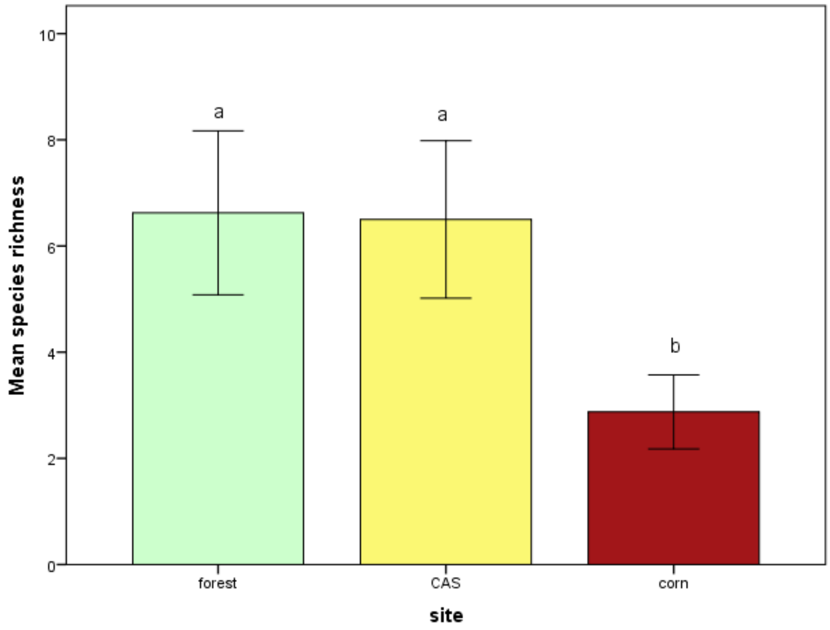

Figure 4. Mean beetle species richness for the three different study sites. CAS=chestnut agroforestry system.

Shannon biodiversity

Shannon's biodiversity index combines species richness data with species abundance data. There were significant differences in the Shannon indices between the study sites ($F(2,21) = 20.312$, $p<0.001$). Follow-up analyses showed that the CAS and forest had the highest biodiversity indices with 1.514 and 1.558, respectively (Fig. 5). These two sites did not significantly differ from each other (p=0.970). However, a Tukey post hoc test revealed that the Shannon diversity was significantly higher in these two sites in comparison with the corn site (H=0.487, P<0.001) indicating that the Shannon biodiversity of the corn site was lower than the biodiversity in both the forest and the CAS.

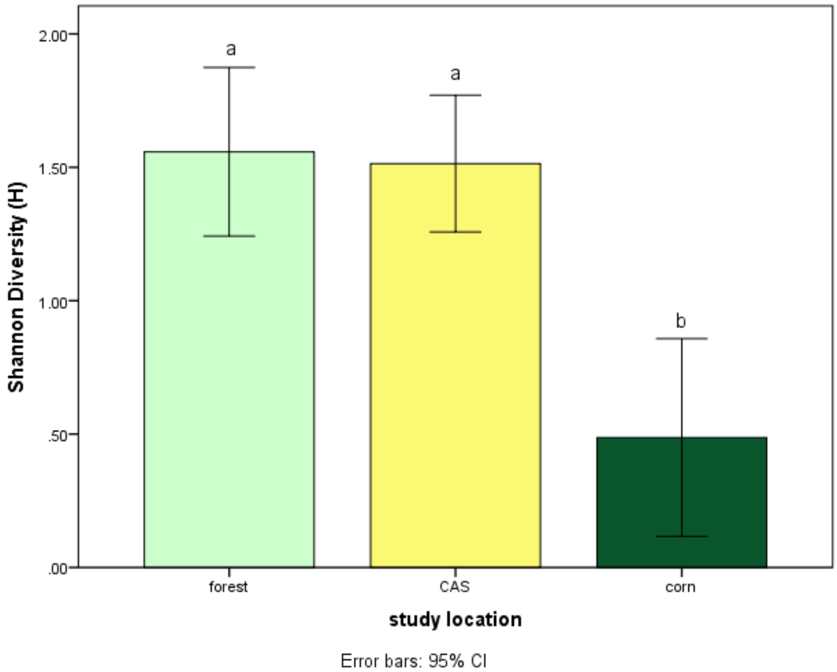

Figure 5. Shannon's biodiversity index (H) for the different study sites. CAS=chestnut agroforestry system.

Shannon evenness

To understand the outcome of the Shannon's diversity index, the Shannon evenness is often used as it shows whether one species dominates the total species list. This study found no significant difference between the three sites as determined by an independent samples Kruskal-Wallis test ($H(2)=2.274$, $p=0.321$), (Fig. 6).

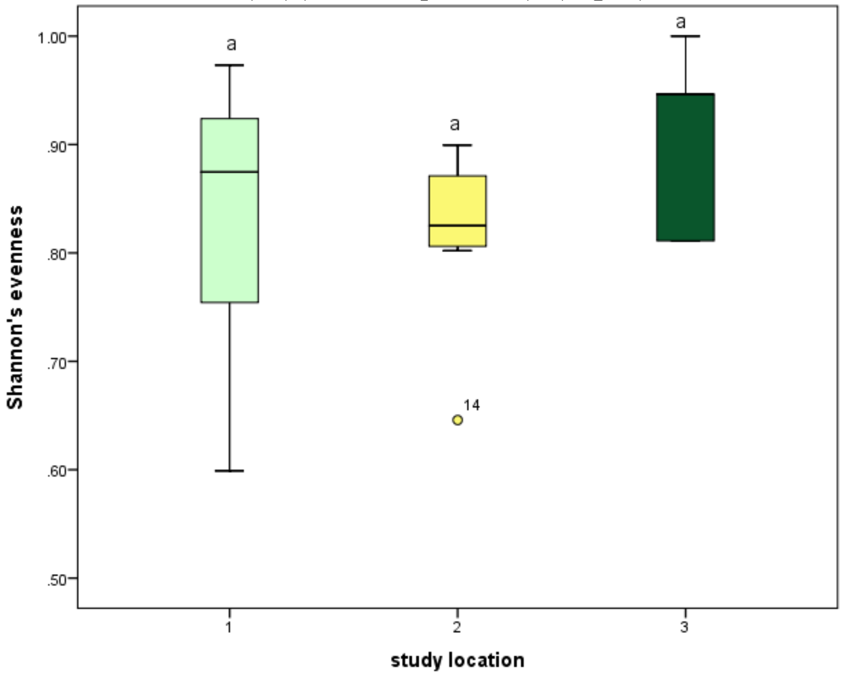

Figure 6. Shannon's evenness for the three different study sites (1=forest, 2=CAS, 3=corn field).

Carbon stocks

Carbon stocks in the CAS system were estimated with the use of allometric equations based on the measured DBH. The roots were a major carbon stock for the CAS and stored 71.2 tons C per ha, slightly less than the above-ground biomass (excluding the leaves) that stored 90.0 tons C per ha. For soil organic carbon, both a high and a low value was used (indicated by HIGH and LOW in Fig. 7**)** because there is quite some variation between different chestnut stands as reported in the literature (Table 1). On average, SOC in the cereal system was 90 tons C per hectare. In the CAS, soil C stock ranged from 84 to 180 tons C per hectare with a mean value of 132 tons C per hectare. Mean SOC difference between the two systems was 42 tons C per hectare. Total carbon stock (biomass & soil) of the CAS ranged between 245 tons C per hectare (LOW) and 341 tons C per hectare (HIGH). Mean carbon stock was 293.2 tons C per hectare.

Carbon stocks of the cereal system were lower, mainly due to absence of perennial above and below-ground biomass carbon pools. Furthermore, the SOC stock was also smaller than the SOC stock of the CAS, with values ranging between 54 (1.5% OC) and 126 (3.5% OC) tons of C per hectare (Fig. 7). Since the SOC was the only relatively stable carbon pool in the cereal system, the total carbon stock for the cereal system also ranged between 54 (LOW) and 126 (HIGH) tons C per hectare (Fig. 7). Mean carbon stock for the cereal system was 90 tons C per hectare.

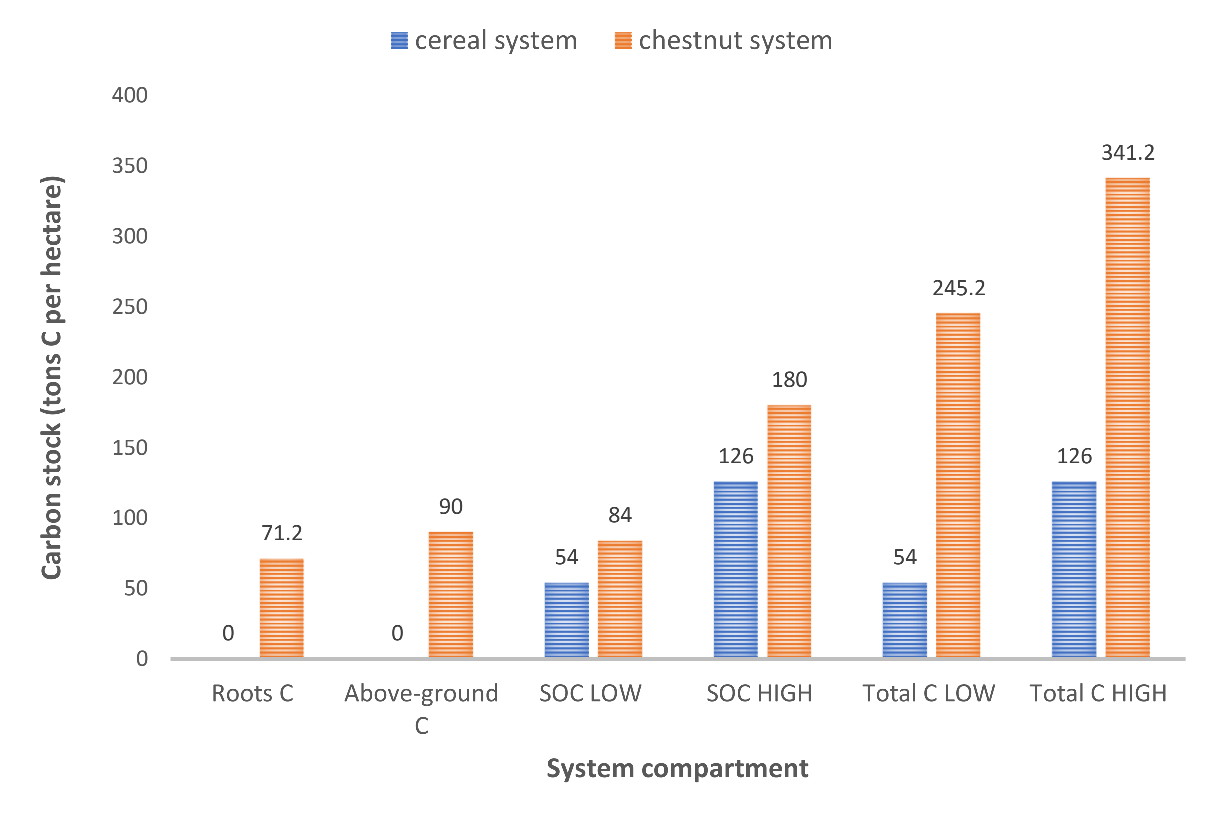

Figure 7. Carbon stocks partitioned over different compartments for both the conventional cereal system and the chestnut agroforestry system for both a low and a high SOC estimation. SOC=soil organic matter, C=carbon.

Additional carbon sequestration if one-third of Europe's cereal growing area (19 million hectares) was converted to a CAS, was calculated. When total carbon stock in the cereal system as well as in the CAS is assumed to be the average of the low and high data found, average carbon stocks for the cereal system and the CAS were 90 tons C per ha and 293.2 tons C per ha, respectively. Per hectare, 203.2 tons of C would thus be stored additionally when the CAS would replace 1 ha of cereal system in Europe. In total, 3860.8 million tons of C would be stored in the EU when 1/3 of the cereal system area in Europe would be replaced by the CAS. This 3860.8 million tons of C is equal to 3.18 years of annual EU CO2 emissions (Fig. 8). Moreover, it is equal to 13.8 years of emissions of the entire European transport sector, and it is equal to 69 years of annual Dutch C emissions (Fig. 8). Expressing this additional 3860.8 million tons of C stored in people's lifetime C emission, resulted in the following outcomes: 17.9 million Dutch people lifetime emissions of C would be stored in the CAS and as much as 104 million Indian people lifetime emissions of C would be stored in the CAS (Fig. 8).

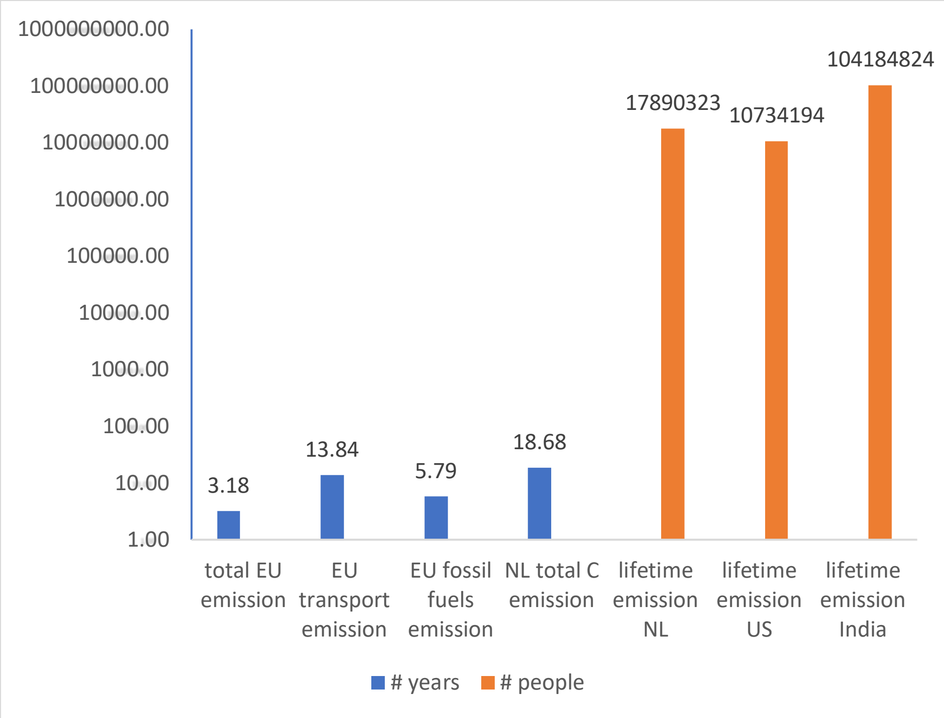

Figure 8. The number of years of emissions (blue) or number of people's lifetime emissions (orange) of carbon that would be sequestered if 1/3 of the current EU cereal growing area would be converted to CAS. CAS=chestnut agroforestry system, C=carbon, EU=European Union, NL=the Netherlands, US=United States of America.

Economic comparison conventional system and CAS

The food yield (expressed in kcal) of the CAS almost exclusively consisted of chestnuts, with honey forming a small food yield (3% of total, Fig. 9). Mushroom yield in kcal was so small that it is noted as 0% in Fig. 9. Wood yield made up most of the total yield (64%) as it has a very high calorific value. Food yield of the two different wheat systems exclusively consisted of wheat kernels.

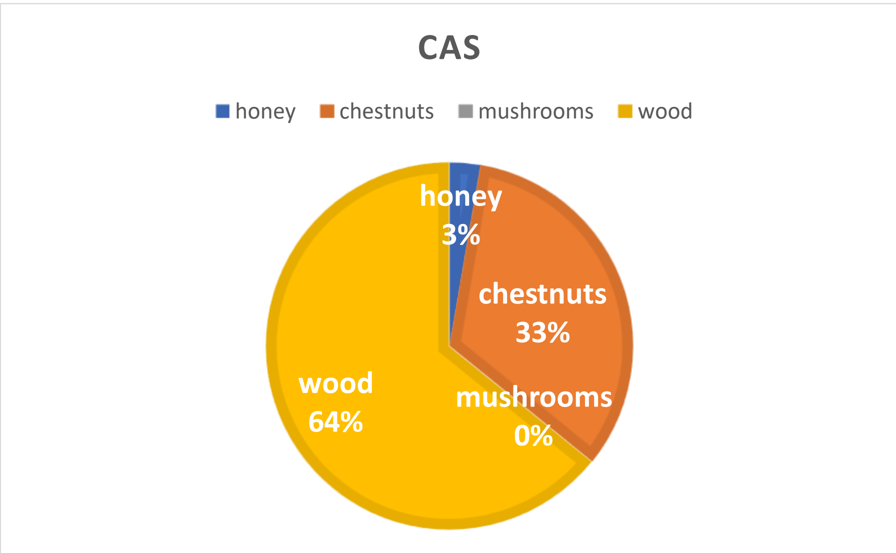

Figure 9. Partitioning of yield energy content (in kcal) over the four different outputs/yields of the CAS. Wood harvest forms the largest system energy yield, while chestnuts form the highest food energy yield of the CAS. CAS=chestnut agroforestry system.

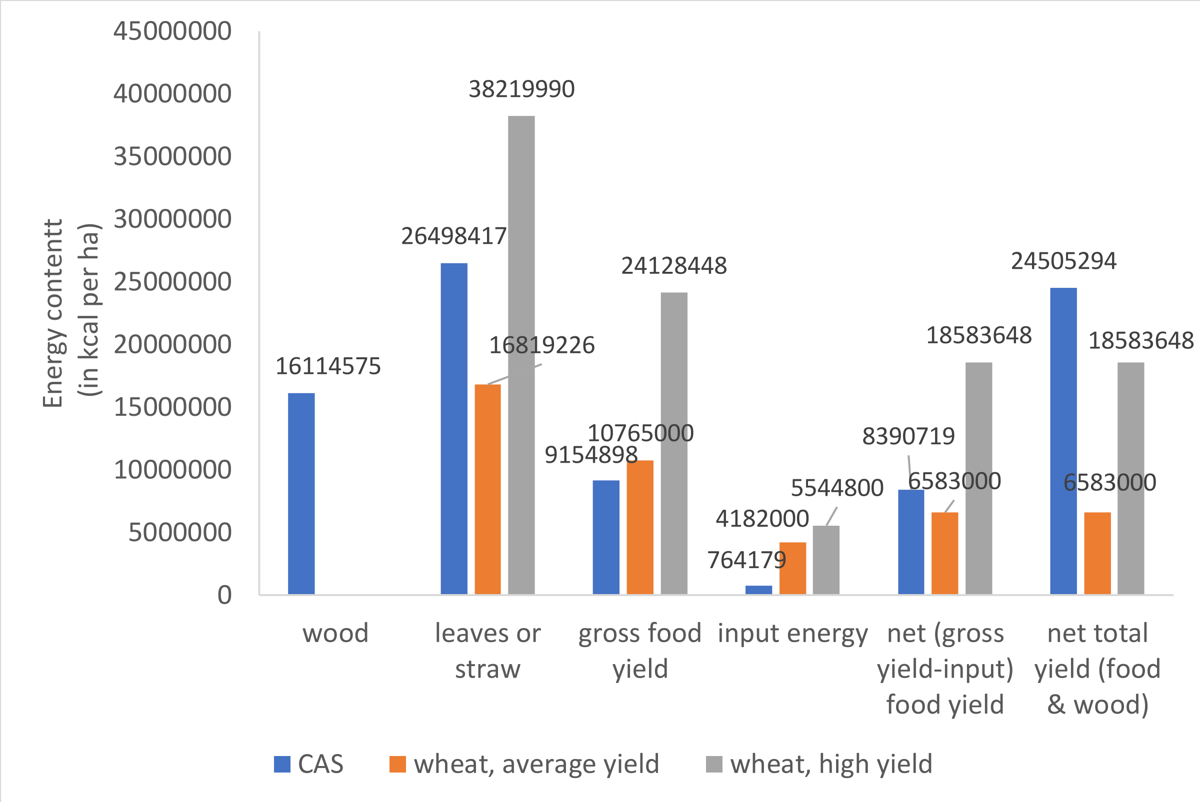

Figure 10. Inputs and outputs expressed in kilocalories (kcal) per hectare for the CAS, an average-yield American wheat system, and a high-yielding European wheat system. Leaves or straw do not count as an output (they remain on site), that is why they are not included in the net total yield. The CAS has higher net food yield than the average-yield wheat system, but lower net food yield than the high-yield wheat system. CAS=chestnut agroforestry system**.**

Leaves in the CAS and straw in the wheat systems formed the largest energy stock of the three systems with values ranging from 16 819 226 kcal per ha to 38 219 990 kcal per ha (Fig. 10). However, because these elements were assumed to remain on site, they did not form an output.
Gross yield of energy in food products only (so chestnuts & honey & mushrooms in the CAS or wheat kernels in the wheat systems) was highest for the high-yield wheat system (24 128 448 kcal per ha) and lowest for the CAS (9 154 898 kcal per ha) (Fig. 10). Input energy (for fertilisers, diesel, and pesticides) was lowest for the CAS (764 179 kcal per ha) and highest for the high-yield wheat system (5 544 800 kcal per ha) (Fig. 10). Subtracting input energy from gross food yield, resulted in the net food yield energy. Net food yield energy was highest for the high-yield wheat system (18 583 648 kcal per ha), and lowest for the average-yield wheat system (6 583 000 kcal per ha) (Fig. 10). When total net output was calculated (so food products and wood in the case of the CAS), the CAS had the highest net output (24 505 294 kcal per ha) and the average-yield wheat system had the lowest net output (6 583 000 kcal per ha) which is the same value as the net food yield energy because there is no other output for the wheat system (Fig.10).

4. Discussion

Species richness, abundance and biodiversity
Significant differences were found in the species richness and mean abundance data. Mean beetle abundance was lower in the corn system compared with the CAS and forest. The mean

beetle abundance in the cornfield was very low (3.13 beetles per plot) in comparison with the CAS (28.3 beetles per plot) and the forest (21.88 beetles per plot (Fig. 3). It is likely that the low beetle abundance in the corn monoculture is caused by the unfavourable characteristics of this system: pesticide application, single crop, and few floral resources. These issues all reduce beetle activity and survival and could explain the low abundance of beetles in the cornfield. In the CAS and the forest, several plants could provide floral resources to beetles. Furthermore, no pesticides were applied, and there was a relatively high diversity of plant species. Plant diversity at field scale is highly beneficial to attract different beetle species because multiple niches can be occupied by different species of beetles.
One other issue that might explain these outcomes is the downward trend in insect abundance over the last decennia in North-West Europe. In German nature reserves, a decline in flying insect abundance of around 75% was found in only 27 years [6]. This effect is likely to be observed in the Netherlands as well. This decline is not observed in the region where the forest and CAS were sampled and could be a reason for the substantial difference between the three sites. However, even after correcting for this decline, the difference is still significant, and it is highly unlikely that this issue is responsible for the large difference found. It might contribute to it, but it is not fully responsible for the difference. It is much more plausible that system properties cause the difference.
Large-scale conventional agriculture is harmful to beetles as insecticides are used, few floral resources can be found in the field due to herbicide application, and monoculture cropping reduces field-scale biodiversity. One could argue that the corn site should be in the same environment as the other two study sites to rule out landscape effects, but this was not possible because there were no monocultures with corn close to the two other study sites. The sole reason that the people started these chestnut orchards in the Ardèche region, is the fact that the landscape is too mountainous to grow these cereal crops; there are almost no flat areas in the valleys surrounding the forest and CAS sites. That is why no corn site could be sampled in the proximity of the other two sites; the chestnut site goes hand in hand with a mountainous environment, while the corn monoculture conventional system can only exist in regions with relatively flat land. Ideally, the three sites should have been close to each other. However, I do not believe that the results would have been very different if a corn site in France would have been sampled, because the conventional corn system is very similar, no matter if it is in the Netherlands, or in Southern France. Maybe some other species would have been found, but overall, due to the system properties of this system, I would still expect low beetle biodiversity. However, this is an important drawback of this thesis and further research could tackle this issue by studying a corn site that is close to a chestnut site to investigate if there is indeed still a difference in biodiversity.

The other part that makes up biodiversity, species richness, was also lower for the cornfield compared with the forest and the CAS (Fig. 4). This finding is in line with the hypothesis and is likely due to the homogeneity of the cropping system, as only one species is grown in a large field. In the CAS, several understory species diversified the system at field scale, even though the main crop (chestnuts) was one species as well. Several flowering plant species and herbaceous plant species covered the orchard floor, and these species were very important for beetle species richness since they provided new niches to be occupied by different beetle families that were not available in the corn system. Following Darwin's idea that different niches in an ecosystem allow different species to co-exist in the same system, it is clear that this phenomenon contributes to the higher species richness in the CAS system in comparison with the corn system; some families, like the Oedemeridae (false blister beetles), were exclusively found on flowering plants in the herbaceous layer below the chestnut trees. This also indicates the importance of plant diversity on a field scale and explains the difference

between the CAS and the corn system; in the CAS system, several understory plants exist without influencing the chestnut yield, while in the conventional corn system no understory plants can exist without reducing the corn yield (which is the reason that herbicides are used, and consequently no or few flowering plants are present in the corn system).
Species diversity as expressed by the Shannon diversity index is a combination of species richness and species abundance. It aims at reducing the influence that a family with only one or a few individuals can have on overall biodiversity (called dominance). The forest site had the highest biodiversity, slightly higher than the biodiversity of the CAS site, although not significantly. In total, 15 different families of beetles were found in the forest site, 11 in the CAS and 5 in the corn system. At first, one might expect the biodiversity of the forest to be significantly higher than the biodiversity of the CAS when confronted with these numbers. However, in the forest site, some families were encountered only very rarely. For example, only two individuals of the Cantharidae were found, and only one individual of the Scarabaeidae was found. The Shannon biodiversity index gives little weight to these findings as their abundance is so low. This explains the rather similar Shannon biodiversity score for the forest and the CAS. One way to get a glance of the evenness of the different families found, and to find out if there are differences between the study sites, is to look at the Shannon's evenness. No significant difference in Shannon's evenness was found between the forest and the CAS sites indicating there was no significant difference between the sites in evenness. Based on this finding, it would again make sense that the forest site should have higher biodiversity (15 families founds vs 11 in the CAS). Even after removing the outlier in the data of the CAS, there is no significant difference in evenness between the CAS and the forest. Thus, the Shannon evenness shows that the similar Shannon biodiversity score for the forest and the CAS is indeed caused by the combination of species richness and abundance data; the CAS site has higher beetle abundance, although not significantly, than the forest site (28.3 vs 21.9 beetles per plot), but it has a lower species richness than the forest site (15 vs 11 species). This lower species richness balances out the higher beetle abundance and results in similar Shannon biodiversity scores.
This finding of equal biodiversity scores provides evidence that the CAS can support a high beetle biodiversity, like a natural forest, and is in line with the hypothesis. Other studies that investigated beetle biodiversity in agroforestry systems in Costa Rica found that the agroforests scored in between forests and monocultures; dung beetle species diversity was highest in forest and lowest in monocultures [51]. The diversity of the agroforestry system was significantly higher than the diversity in the monoculture, but also significantly lower than in the forest [51]. This study suggests that beetle biodiversity (at family level) in the chestnut agroforestry system is similar to the biodiversity in the forest. The difference with the Costa Rica study could be that that study looked at beetle at species level and this study looked at beetles at family level. Maybe the CAS comes in between the forest and the corn monoculture when beetles at species level were determined. Therefore, it would be interesting to determine the diversity at species level to see if this is indeed the case. Future research is needed to investigate this.
One interesting and often overlooked view of agroforestry systems is that they can function as corridors between nature reserves. It is crucial that small nature reserves are interconnected to prevent inbreeding and to maintain a heterogeneous gene pool within populations. Nowadays, most largescale agricultural ecosystems function as a no-go area for many migrating animals because these agro-ecosystems lack resources needed for many animals (shelter, floral resources) to migrate. Agroforestry farms that are next to each other can function as small corridors for many low-disturbance tolerating animals (Fig. 11). Animals can migrate to the next nature reserve by using these agroforests as corridors. This connection is important in the long-term survival of a population; when a specific disease

outbreak occurs, some animals in a heterogeneous population might die, while others (with a genetic makeup that protects them from the disease) will survive and reproduce. In the Netherlands, nature is very fragmented. Therefore, corridors between core areas have been created. This system that connects nature reserves (core areas) with each other is called 'Ecologische HoofdStructuur' (EHS). Often, areas of land are bought by nature organisations in between the core areas to establish the corridor. When farmers (as farmland often separates nature reserves from each other) apply agroforestry systems to their fields, agriculture can be transformed from a no-go area into a corridor which might reduce the amount of land that nature organisations must buy and manage, and could promote viable animal populations in nature.

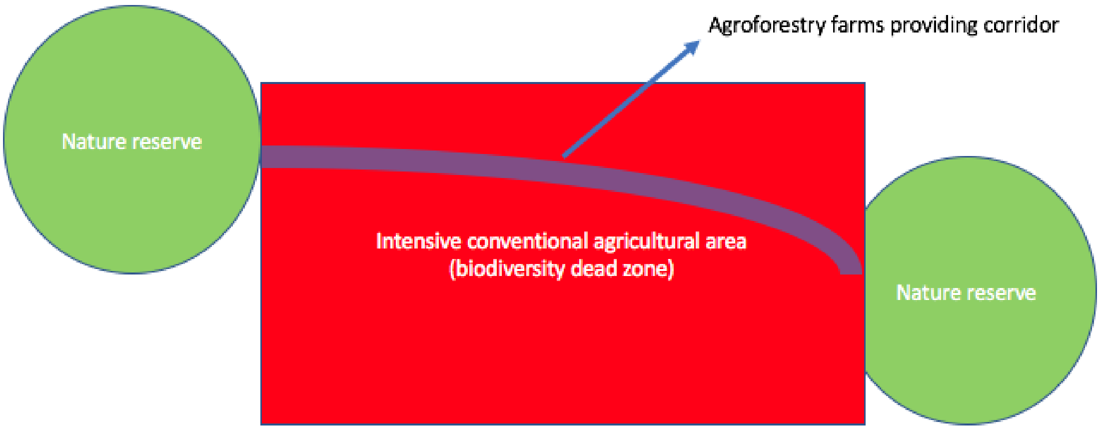

Figure 11. Schematic overview of how agroforestry farms can connect two nature reserves by providing corridor habitat.

One factor that influenced the beetle data was the difference in plant surface that could be sampled between the three sites. In the corn site, all the plant material could be observed while in the chestnut site and the forest site, only the lowest branches and leaves could be observed. Moreover, many (phytophagous) beetles live high in the canopy of the trees, which could not be sampled. This means some beetles were not observed during the sampling implying that the biomass of beetles, and likely also the diversity of beetles, will be higher than measured in the forest and the CAS. However, this is not a major issue, because the difference found in this study is already a significant difference.
Another issue that influenced the outcomes of the measurements was the choice of the sites. One of the most important differences between the sites is the management. The corn system is under conventional management, meaning that the soil is ploughed and pesticides are used. In the natural forest and the CAS, no pesticides are used. One could argue that this could explain potential differences between these systems and suggest that the CAS and forest should be compared with organically grown corn. However, I purposely decided to use a conventional corn agricultural system in this research, because worldwide most of the corn is produced in this conventional system, not in an organic system. Most the ecological harm is caused by this conventional cereal system, not by the organic system. I do expect beetle biodiversity to be higher in an organically grown corn field in comparison with the conventional corn field. However, I do not expect it to be as high as the diversity of the CAS because field scale diversity is still rather low if the corn is still grown in a monoculture. Also, this homogeneous landscape would not provide much more floral resources than the conventional system, although more weeds and thus flowering plants are expected to be present. It would be interesting for further research to include an organic corn system and a

non-organic chestnut system to find out if the management plays a considerable role in determining beetle biodiversity.

Climate mitigation

Total carbon stock differed substantially between the conventional cereal system and the CAS. Depending on the low or high SOC scenario for both the cereal system and the CAS, 2 to 6 times as much carbon can be stored in the CAS as in the cereal system (Fig. 7). This is explained by the perennial biomass, that functions as a carbon stock in the CAS, and by the higher soil organic carbon levels of the CAS (Fig. 7). Because the cereal system lacks a perennial biomass carbon stock, the chestnut system can already store 161.2 tons of C per hectare more than the cereal system, without considering the overall higher SOC stock in a chestnut system. The mean difference in SOC between the CAS and the conventional cereal system was 42 tons C per hectare. This difference is line with findings from colleagues who showed that the conversion of temperate forest to agricultural land causes the loss of on average 63 tons of C per hectare [52]. However, this thesis calculated a low and a high soil carbon stock value for the cereal system, based on the top 30 centimetres of a field, generally referred to as the topsoil. All the studies on carbon stock in agricultural land that I reviewed, only studied the top 30 centimetres. Therefore, I could only compare the values I calculated with data found in literature if I also used the top 30 centimetres. That is the reason that I chose to calculate the carbon content in the top 30 centimetres of soil. For the CAS, the soil carbon stock values were determined for the top 60 centimetres of soil by [35]. These values were used in this thesis for the CAS. So, the cereal system will have slightly higher soil carbon stock values than calculated in this thesis, because some carbon is stored in the subsoil (>30 cm depth). However, because most annual crops do not root much lower than 30 centimetres due to the presence of a compaction layer, and because chestnut trees generally root much deeper than cereals (and deeper than the 60-cm used in this thesis), I believe this inequality in soil depth between the sites is no big issue. Furthermore, there is relatively little carbon stored in the subsoil; most of the carbon is stored in the first 30 centimetres.

This thesis found a total carbon stock of 293.2 tons C per hectare for the CAS. This value is much higher than most other studies (Table 1) reported, except the study of German colleagues [41]. This study was done on beech forests in Germany and found carbon stocks of 224 tons C per hectare. The reason that the mean carbon stock value of 293 tons C per hectare was found, is probably due to the age of the system. All the trees in the CAS were >200 years old, many more than 250 years old which resulted in very large tree circumferences, and consequently high carbon stocks. Furthermore, the root : shoot ratio of chestnuts is much higher (0.767) than that for most other species, including beech (0.163) [33]. This means chestnuts have high below ground biomass/carbon and explains the higher values than reported by colleagues [41] who studied beech forests.

Still, the reported mean carbon stock value is higher than found by other authors on chestnut stands (Table 1). The difference in age can explain this; Greek chestnut stands studied by colleagues [38] were up to age 40, which is a very young age for a chestnut tree. Therefore, they found highest total carbon stock values of 163 tons C per hectare [38]. Bulgarian colleagues studied trees >80 years old and still reported relatively low total carbon stock values of 163 tons C per hectare [37]. The substantial difference between this study and their results is that they did not take the below-ground biomass into account [37] while the below-ground biomass forms an integral part of the total carbon stock as the below ground biomass : above ground biomass ratio is 0.767 for chestnuts [33]. This study finds a value of 161.2 tons of C per hectare stored only in the tree biomass (roots & above-ground part). This value is very close to the 163 reported for chestnut stands in Bulgaria [37] which shows that the results found by this study correspond with other literature data on chestnut systems.

On average, the chestnut system seems to have higher SOC levels than cereal systems (132 tons C per ha vs 90 tons C per ha). SOC is crucial for water holding capacity, nutrient mineralisation and soil structure. One of the most significant problems of conventional cereal systems is the decline in SOC levels. Large areas of land are losing fertility and the ability to support crops due to low SOC levels. In Southern Europe, countries like Spain, Italy, and France have vast land areas with SOC levels lower than 2% (Fig. 12) [53]**.** In combination with a Mediterranean climate characterised by dry and hot summers, a low SOC content can be fatal for crops. In Servia, around 60% of the corn yield was demolished in 2017 due to drought [54].

In Spain and Italy, large areas of cereals died in 2017 due to drought while perennial plants like olives and almonds had reduced yields. The Mediterranean lands are some of the most intensively used areas worldwide regarding food production. Thousands of years ago, the Romans and Greeks started degrading the soils when they performed agriculture. Erosion rates increased and soil carbon levels [22]. Now, a few millennia's later, much of these soils are severely degraded with SOC levels lower than 2% and the current cereal system is just not sustainable on most of the lands. Soils with low SOC levels cannot hold much water so that less biomass can be produced. Continuing with the conventional system reduces SOC even further, and a vicious cycle begins. It is of critical importance to stop the decline in SOC levels and preferably increase SOC to prevent Southern Europe turning into a desert within a few decades. The CAS system could maintain higher SOC levels than the conventional cereal system and permanently protects the soil against evapotranspiration by its canopy and by the leaves covering the soil. Higher SOC content holds more water and can contribute to higher yields. Another advantage of the CAS is that the trees can access water that is not available to cereals grown in the conventional cereal system because the trees root more profound than the cereal plants. In combination with the higher soil organic carbon levels in the CAS compared with the cereal system, water access is higher in the CAS. Especially in drought-sensitive areas with shallow soils like Southern Europe, converting the cereal system to a CAS could provide advantages concerning crop resilience. Higher access to water because of deeper rooting plants (trees) and higher SOC levels could provide opportunities to continue agriculture in areas were cereals fail in dry years while increasing SOC levels and preventing erosion.

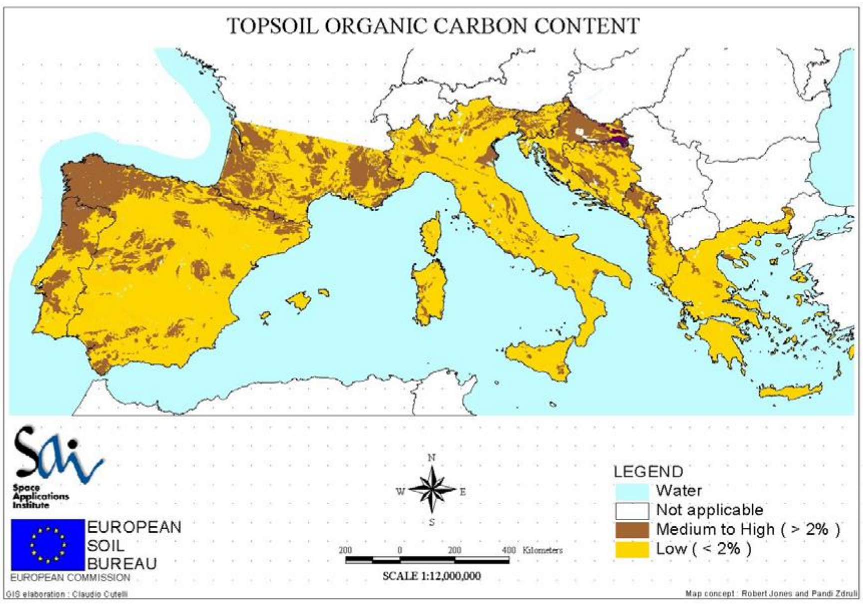

Figure 12. Soil organic carbon levels in Southern Europe as determined by colleagues [53].

Conversion of cereal agriculture to CAS

Converting one-third of the current European land surface dedicated to cereal production to CAS would sequester 3860.8 million tons of carbon. This is a notable amount of carbon that could get sequestered, but because the fossil fuel emissions are high, this potential transformation is not able to significantly help with climate mitigation (only 5.8 years of EU fossil fuel emission would be fixed (Fig. 8**)**. However, when fossil fuels are replaced by renewable energy sources like solar and wind energy, European emissions would be drastically reduced. Then, this agricultural conversion could realistically help to slow global warming. Now already, it would take up all the lifetime emissions of the entire Dutch population (17.9 million people, Fig. 8), and when in future times the per capita emission of carbon in Holland decreases due to transition to renewable energy sources, it would take up even more. Moreover, this transition would already take up the emission of more than 100 million Indian people's lifetime emissions. The difference with the number of Dutch per capita lifetime emissions is because per capita emissions in India are more than five times smaller, compared to Dutch per capita emissions.

So, transforming one-third of the conventional cereal system into a CAS could sequester 3860.8 million tons of carbon over a period of a few centuries. Fossil fuel combustions are so high (55% of total EU CO_2 emissions) [42], that this agricultural transformation would only buy some time in the attempt to slow global warming (about 3.18 years for Europe over a period of a few centuries). This indicates the importance of reducing fossil fuel emissions and shows that carbon farming alone is insufficient in combatting the global warming. Only in a world with reduced fossil fuel emissions, this agricultural conversion might provide opportunities to help slow down global warming.

Economic sustainability assessment

The CAS had the lowest gross food yield compared to the two wheat systems. However, after correcting for the input energy, the average-yield wheat system was the system with the lowest *net* energy output, and the CAS ranked intermediate between the average and the high-yield wheat system. The difference in ranking between the gross and the net food yield is due to the higher inputs of the wheat systems. The average-yield wheat system that had the lowest net food yield had four times the input energy than the CAS (Fig. 10**)**. The low inputs in the CAS is mainly due to the lack of fertiliser input in the CAS, which forms a large input energy source, as well as the reduced diesel use in the CAS due to the lower machine use. As mentioned in the material and methods, the leaves and the straw were not considered outputs (meaning they were not harvested). They were considered to remain on site or to be burned. From Fig. 10 it can be noted that they form a considerable energy sink in the systems and contain more energy than the energy of the food yield. The CAS had a higher net food yield than the average-yield wheat system, but a much lower food yield than the high-yield wheat system. This suggests that, from the classical and outdated economic view (that does not consider long-term issues such as air quality, ocean acidification, climate change) and that uses infinite economic growth models, while the planet has planetary boundaries [55], the CAS could be a suitable candidate to replace the wheat systems in regions with average (or low)-yield wheat systems. Of course, this economic view is outdated, and new views, like the doughnut-economy view introduced by Kate Raworth, that consider social, economic, and ecological factors, emphasise not to look at yields only [55]. Environmental pollution should also be considered and should be valued. An agricultural system with a relatively low yield, but low environmental pollution or even the ability to increase air quality, to create clean drinking water, and to fix carbon, could have a higher economic value as a conventional agricultural system. This higher economic value can be explained by the problems the conventional systems create; these problems do have economic value as they reduce future generation's soil fertility, increase the costs to filter drinking water and increase the costs to combat climate change in comparison with a more sustainable system. This thesis did not want to come up with one value for the different systems that considered all these problems and the yields, but I think it is vital to emphasise that yield only data are not sufficient in determining whether a system is also economically viable. However, I do acknowledge that yield data are still important when alternative, more ecological agricultural systems are investigated, because the world must be fed sufficient food. Alternative carbohydrate systems that score low concerning net calories produced are not a suitable candidate to replace conventional carbohydrate systems, no matter how ecologically sound they might be. Working with such systems would mean more land surface is needed and, because we currently already use almost all the potentially suitable agricultural land, this would mean that the last remaining nature reserves like the Amazon would have to be destroyed to create additional agricultural land. Of course, this is not a sustainable thing to do, and therefore I still consider yield data to be valuable.

The CAS would thus be a suitable candidate (regarding net yields) to replace the average-yield wheat system which means large areas in the US (where this average-yield system is common) could be transformed to systems like CAS without a reduction in net food yield. There would be even an increase in total net yield as the wood harvest of this CAS is another major energy output. Considering total net yield (food products and wood) shows that the CAS scores even higher than the high-yield wheat system (Fig. 10). The wood could be used as a renewable energy source (biomass), and therefore the CAS can indeed have higher total net energy yields than the two wheat systems. When this wood is used as a renewable energy source, less land would have to be used to grow biomass crops. This land could then be used to grow food for people, and therefore, even though the net food yield of the CAS is lower than the high-yield wheat system, the CAS might even be a likely replacement of the conventional cereal systems on high-yielding soils.

Furthermore, the wood could be used as a mushroom medium. 1000 kg wood biomass can result in 1.25 tons mushrooms [24]. A yield of 4350 kg per ha (7.5 m^3) was used for the calculations of the wood energy which equals 5437.5 kg of mushrooms (fresh weight) containing 1 576 687 kcal of energy as another food output in the case oyster mushrooms are grown on the wood [24]. Because mushrooms are very low in calories (29 kcal per 100 grams for oyster mushrooms), they do not increase the total food yield of the CAS a lot, but they have a high nutritional value [24]. This is another example of the drawbacks of working with yields in kcal only; a perennial agroforestry system can produce different kinds of products, like nuts, fruits, mushrooms and vegetables. Only nuts have high caloric value. However, if such a system can also produce lots of vegetables, less land for conventional monoculture system vegetable production is needed. Therefore, it is problematic to only compare the caloric yield of an agroforestry system with the caloric yield of a conventional agricultural system; if the yield of the conventional system is higher, there is still demand for vegetables. Then, other areas of land need to be used for vegetable production and, because vegetables have low caloric values, the average caloric yield of both the high-caloric yield system and the vegetable system will be much lower than the high-caloric yield system only. While in the agroforestry systems, vegetables can be produced in the same system where high-caloric products like nuts are also produced.

For this thesis, however, I worked with a simplified agroforestry system (monoculture of chestnut trees), and there was no room for growing vegetables in this system because of the lack of light reaching the orchard's floor. Furthermore, this thesis specifically investigated the use of an alternative carbohydrate-producing system and was not focussed on different products such as vegetable or fruit production. This thesis wanted to find out if, when the focus would mainly be on yield, a CAS could compete with the current agricultural system.

As shown earlier, it can compete with an average-yield wheat system (concerning net food kcal) and even with a high-wheat system where wood calories are considered as well.
In high-yielding wheat regions like Europe, the CAS can particularly be a suitable candidate to replace the wheat systems on the least productive soils as the chestnut trees are characterised by their ability to grow on marginal and steep land with shallow soils (like in mountainous areas in Europe). Of course, wheat still needs to be produced and I argue it would be best to limit the production of wheat to the highest-yielding lands, often found in valley bottoms where centuries of hillside erosion have created a thick and fertile layer of topsoil. Here, wheat yields can be very high, and because valley bottom lands often do not have steep slopes, erosion will not be a severe problem. The CAS would preferably be located on less fertile lands often located higher up the hills or mountains. This land is particularly vulnerable to erosion and often has already lost centimetres of topsoil due to poor agricultural practices (not terracing, tillage) [22]. Chestnuts, however, can perform very well on such land and can protect the soil from erosion, just like natural forests protect these steep soils from erosion. In regions with average or low-yielding wheat crops (like the United States), the CAS could be implemented everywhere where the chestnuts can grow.

5. Conclusion

This thesis investigated the ecological and economical aspects of an alternative agricultural system, a perennial chestnut based agroforestry system (CAS), to find out if it could be a suitable candidate to replace the ecologically harmful conventional cereal system that currently dominates staple food production. These aspects were evaluated by comparing beetle biodiversity, carbon stocks, and net yields of the two systems.
The results illustrated that biodiversity of beetles at family level was equal in the forest and the CAS sites, indicating that the CAS can provide the same biodiversity ecosystem function as a natural forest. Moreover, biodiversity in the CAS was higher than in the conventional cereal system, where only a few families were found. Also, large differences in beetle abundance were observed between the CAS and the corn site. The CAS had high mean beetle abundance, while the corn site had very low mean beetle abundance. Differences in biodiversity between the CAS and the corn site may be explained by:

(1) the homogeneity at field scale in the corn site (only one plant species present), and the heterogeneity at field scale in the CAS (several plant species of both herbaceous and woody plants were present in the understory, below the trees).
(2) the absence of floral resources in the corn system and the presence of several flowering plant species in the CAS, attracting several families that feed on nectar.

Carbon stocks were largest for the CAS and smallest for the cereal system. The presence of perennial biomass (stem & roots & branches) in the CAS was largely responsible for the greater carbon stock in the CAS. A scenario where one-third of the current European land area used for cereal production was converted to the CAS, showed that 3860.8 million tons of carbon would be stored additionally. However, expressed as the number of years of European C emissions, this resulted in only 3.18 years of EU C emission that would be sequestered, indicating that such a conversion alone, cannot be enough to mitigate climate change.
Finally, net yields were calculated for the CAS and two different yielding wheat systems. Results showed that the CAS has a higher net food energy yield than an average-yield wheat system, but a lower net food energy yield than a high-yield wheat system, indicating that conversion of average-yield wheat fields will not decrease net food yield. Therefore, these

results strongly recommend the conversion of average-yielding regions to a CAS (if conditions are appropriate for the chestnut), because this conversion increases the region's ecological sustainability (higher biodiversity, higher carbon stock), and at the same time the CAS produces approximately the same amount of net food calories.
Altogether, this thesis presented the first data on the quantitative aspects of carbon stocks, beetle biodiversity, and net yields, for the conversion of a conventional cereal system to a CAS and showed that the CAS is a promising system to combine the ecological advantages of natural ecosystems (biodiversity, carbon sequestration) with the high production of conventional agriculture.

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8. Appendix

Appendix A

Beetle biodiversity raw data for the three different study sites.

Appendix A provides the raw data considering beetle observations that were created during the fieldwork. Species richness, beetle abundance, biodiversity, and evenness are all covered.

Table A1. Beetle measurements in the chestnut agroforestry system (CAS). 8 plots were sampled, in total 11 different families were found. Number of observed individuals from a certain family is noted per plot.

	Staphylinidae	*Elateridae*	*Oedemeridae*	*Coccinellidae*	*Cerambycidae*	*Chrysomelidae*
1	1	4	0	14	2	4
2	0	2	1	7	0	0
3	0	8	0	11	1	1
4	0	3	0	8	5	1
5	0	0	0	5	5	0
6	0	10	0	1	1	0
7	0	2	1	7	2	7
8	0	2	2	1	3	7
	Attelabidae	**Malachiidae**	**Mordellidae**	**Cantharidae**	**Curculionidae**	
1	1	0	0	1	8	
2	0	0	0	2	1	
3	1	0	0	4	6	
4	0	0	0	11	8	
5	1	0	0	1	6	
6	0	0	0	0	2	
7	2	5	0	0	12	
8	0	7	2	15	1	

Table A2. Beetle measurements in the temperate forest site. 8 plots were sampled, in total 15 different families were found. Number of observed individuals from a certain family is noted per plot.

	Staphylinidae	*Elateridae*	*Oedemeridae*	*Coccinellidae*	*Cerambycidae*	*Chrysomelidae*	*Melyridae*	*Lagriidae*
1	0	2	0	7	6	1	0	0
2	0	1	1	1	2	2	0	1
3	0	5	0	12	2	0	0	1
4	0	25	0	3	4	0	0	0
5	0	1	0	2	1	2	0	1
6	3	5	0	6	2	7	1	1
7	0	7	0	14	4	2	1	2
8	0	8	0	6	4	0	0	0
	Attelabidae	**Malachiidae**	**Anthribidae**	**Cantharidae**	**Curculionidae**	**Scarabeidae**	**Geotrupidae**	
1	0	0	0	2	2	0	0	
2	1	0	0	0	1	0	2	
3	0	1	0	0	0	0	1	
4	0	1	0	0	2	0	0	
5	0	0	1	0	0	0	0	
6	0	0	0	0	0	1	0	

7	1	1	1	0	0	0	0
8	0	0	0	0	0	0	1

Table A3. Beetle measurements in the corn site. 8 plots were sampled, in total 4 different families were found. Number of observed individuals from a certain family is noted per plot.

Plot	*Staphylinidae*	*Chrysomelidae*	*Carabidae*	*Coccinellidae*
1	3	0	0	1
2	3	0	0	1
3	2	0	2	0
4	2	0	1	1
5	1	0	0	1
6	0	0	0	2
7	0	1	1	2
8	0	0	0	2

Only 4 different families are noted but in fact 5 different families were observed. Individuals of one family, the Elateridae, were not recognized in time. The same species that I could not determine to family in the corn field, was also observed in the CAS and the forest. Therefore, in all the sites, this species was not noted. In the CAS and forest, other species from the Elateridae were recognized so here the Elateridae family was noted. Because approximately the same number of individuals of this species was observed in the three different sites, I did not consider it as a big issue that I did not note the individuals from the Elateridae in the corn site. However, in the calculations of mean plot species richness, this family was consistently added to the number of families found per plot. So, if three different families were observed according to table A2, a plot species richness of four families was noted. In the calculations of the Shannon biodiversity and mean plot abundance this could not be taken into account. Therefore, the calculated H and mean plot abundance should be higher for the corn field. However, because the difference with the CAS and forest system was so large, it does not matter that the Elateridae were ignored in the corn system. Furthermore, approximately the same number of Elateridae individuals were not recognized in the CAS and forest as well. So, these sites would also have higher Elateridae scores, and this fact should balance the lack of noted Elateridae individuals in the corn site.
In table A4, the Elateridae are added to each plot therefore table 4 shows a plot spp richness that is one number higher than one might expect based on table A3.

Table A4. Overview of the three study sites. Species richness, mean abundance, and averages are displayed per plot. Spp=species, CAS=chestnut agroforestry system.

Plot	*CAS mean abundance*	*Forest mean abundance*	*Corn field mean abundance*	*CAS spp richness*	*Forest spp richness*	*Corn field spp richness*
1	35	20	4	8	6	3
2	13	12	4	5	9	3
3	32	22	4	7	6	3
4	36	35	4	6	5	4
5	18	8	1	5	6	2
6	14	26	2	4	8	2
7	38	33	4	8	9	4
8	40	19	2	9	4	2
Average	**28.25**	**21.875**	**3.125**	**6.5**	**6.625**	**2.875**

Table A5. Shannon's evenness scores for the three different study sites per plot. CAS=chestnut agroforestry system.

Plot		***Shannon's evenness***
Forest		
	1	0,875782578
	2	0,973197315
	3	0,729363581
	4	0,598930979
	5	0,967132018
	6	0,880585195
	7	0,779203528
	8	0,87370652
CAS		
	1	0,802113683
	2	0,810143417
	3	0,828587755
	4	0,899422292
	5	0,869239141
	6	0,645845999
	7	0,872711282
	8	0,821911468
corn		
	1	0,811278124
	2	0,811278124
	3	1
	4	0,94639463
	5	0
	6	0
	7	0,94639463
	8	0

Table A5 shows three 0 values for the evenness in the corn site. This is due to the fact that only one family was observed in these plots. See table A3. Here, the Elateridae were again not taken into account for the corn site. That is why in the case of plot 5, 6 and 8, only one family was observed. For 1 species only, the evenness is automatically 0. Even after ignoring these three values, there was still no significant difference between the three sites. The 1 displayed in table A5 for plot 3 in the corn site is due to the fact that two families occur with in the same abundance.

Appendix B

Carbon stocks for the different compartments of the CAS and the cereal system.

Table B1. Measured circumference of the 20 trees on ¼ hectare of CAS. Biomass of different tree compartments (roots, branches etc.) were calculated with biomass equations based on DBH as described in material and methods. DBH=diameter at breast height. 7.2 and 14.2-14.7 are tree suckers, relatively small branches that grow from the bottom of the main stem. 20.1-20.2 form one tree that separates at ground level.

Tree	*Circumference (cm)*	*DBH (cm)*	*Trunk biomass (kg)*	*Branch biomass (kg)*	*Leaf biomass (kg)*	*Total wood biomass (kg)*	*Total above ground biomass (kg)*	*Below ground biomass (kg)*
1	371	118,1	6047,7	1387,9	229,0	7435,6	7664,6	5878,7
2	230	73,2	1918,8	460,6	76,4	2379,4	2455,8	1883,6
3	226	71,9	1839,7	442,3	73,4	2282,0	2355,4	1806,6
4	269	85,6	2794,8	661,1	109,5	3455,9	3565,4	2734,7
5	248	78,9	2299,3	548,0	90,8	2847,4	2938,2	2253,6
6	179	57,0	1051,0	258,3	43,0	1309,4	1352,3	1037,2
7.1	233	74,2	1979,5	474,6	78,7	2454,0	2532,7	1942,6
7.2	68	21,6	102,9	27,7	4,7	130,6	135,2	103,7
8	241	76,7	2146,6	513,0	85,1	2659,6	2744,6	2105,1
9	181	57,6	1079,5	265,0	44,1	1344,5	1388,6	1065,0
10	224	71,3	1800,8	433,3	71,9	2234,1	2306,1	1768,7
11	188	59,8	1182,4	289,3	48,1	1471,7	1519,8	1165,7
12	184	58,6	1122,9	275,3	45,8	1398,2	1444,0	1107,5
13	239	76,1	2104,1	503,2	83,4	2607,3	2690,7	2063,8
14.1	139	44,2	572,7	144,1	24,0	716,8	740,8	568,2
14.2	60	19,1	76,2	20,7	3,5	96,9	100,4	77,0
14.3	40	12,7	28,8	8,1	1,4	36,9	38,3	29,4
14.4	34	10,8	19,5	5,6	0,9	25,1	26,0	20,0
14.5	30	9,5	14,4	4,2	0,7	18,6	19,3	14,8
14.6	28	8,9	12,2	3,6	0,6	15,8	16,4	12,6
14.7	26	8,3	10,2	3,0	0,5	13,2	13,8	10,6
15	232	73,8	1959,1	469,9	77,9	2429,0	2506,9	1922,8
16	188	59,8	1182,4	289,3	48,1	1471,7	1519,8	1165,7
17	260	82,8	2575,6	611,1	101,2	3186,7	3288,0	2521,9
18	179	57,0	1051,0	258,3	43,0	1309,4	1352,3	1037,2
19	195	62,1	1290,9	314,7	52,3	1605,6	1657,9	1271,6
20.1	156	49,7	755,5	188,1	31,3	943,5	974,9	747,7
20.2	158	50,3	778,9	193,7	32,3	972,6	1004,9	770,7
Total biomass (kg per ¼ hectare)			37797,5	9054,0	1501,7	46851,4	48353,1	37086,8
Total biomass (kg per hectare)			151189,9	36215,9	6006,7	187405,8	193412,5	148347,4
Total carbon (kg per hectare)						89954,8	92838,0	71206,7

Table B2. Overview of biomass carbon and soil carbon in cereal system and CAS for a high SOC situation and a low SOC situation. CAS=chestnut agroforestry system, SOC=soil organic carbon.

System compartment	***Cereal system***	***CAS***
Roots carbon (kg per ha)	0	71,2
Above-ground carbon (kg per ha)	0	90
SOC LOW (kg per ha)	54	84
SOC HIGH (kg per ha)	126	180
Total carbon LOW (kg per ha)	54	245,2
Total carbon HIGH (kg per ha)	126	341,2

Appendix C

Evaluation of the different inputs and outputs of a CAS, and two wheat systems.

Table C1. Inputs expressed in kilocalories (kcal) per ha per year for the three different agricultural systems. Wheat, average yield US data come from Pimentel [25] and wheat, high-yield data France come from Bonny [45] while the CAS inputs were estimated by me. CAS=chestnut agroforestry system.

input (per ha)	*amount of input/year*	*E content (kcal per ha per year)*
CAS		
mowing herbaceous layer (hours/ha)	3	306
harvesting nuts with machine (hours/ha)	10	1020
harvesting mushrooms with hand (hours/ha)	30	4080
beekeeping (hours/ha)	92	13800
remove branches/dead wood (hours/ha)	30	7140
other labour (hours/ha)	100	20000
diesel used for machines (L/ha)	33,3	333000
transport (kg/ha)	99	33500
machinery (kg/ha)	18,3	339333,33
electricity (kWh/ha)	14	12000
total (kcal/ha)		**764179**
wheat, average yield US		
labor (hours/ha)	7,8	312000
machinery (kg/ha)	50	925000
diesel (L/ha)	100	1000000
Nitrogen (kg/ha)	68,4	1094000
Phosphorus (kg/ha)	33,7	143000
Potassium (kg/ha)	2,1	6000
seeds (kg/ha)	60	218000
herbicides (kg/ha)	4	400000
insecticides (kg/ha)	0,5	5000
electricity (kWh/ha)	14	12000
transport (kg/ha)	198	67000
total (kcal/ha)		**4182000**
wheat, high-yield France		
diesel+tyres+lubricants (L per ha)	95	1242800
Nitrogen (kg/ha)	160	2879472
Phosphorus (kg/ha)	70	230874
Potassium (kg/ha)	70	140532
seeds (kg/ha)	150	268905
pesticides (kg/ha)	5	249755

machinery	549700
total, rounded number (kcal/ha)	**5544800**

Table C2. Outputs expressed in kilocalories (kcal) per ha per year for the three different agricultural systems. Wheat, average yield US data come from Pimentel [25] and wheat, high-yield data France come from Bonny [45] while I estimated the CAS inputs. CAS=chestnut agroforestry system.

output	*Production (kg/ha)*	*Energy content (kcal/kg)*	*Energy (kcal/ha)*
CAS			
honey	227,3	3048,0	692898,0
chestnuts	4500,0	1880,0	8460000,0
mushrooms	10,0	200,0	2000,0
wood	4350,0	3704,5	16114575,0
leaves	6006,7	4411,5	26498416,5
total			51767889,5
gross food (no wood)			9154898,0
net kcal produced			**51003710,2**
net food only kcal produced			**8390718,7**
wheat, average yield US			
grains	2900,0	3712,1	10765000,0
straw	3866,7	4349,8	16819226,4
total			27584226,4
gross food (no straw)			10765000,0
net kcal			**23402226,4**
net food			**6583000,0**
wheat, high-yield France			
grains	6500,0	3712,1	24128448,3
straw	8666,7	4410,0	38219990,4
total			62348438,7
gross food (no straw)			24128448,3
net total energy			**56803638,7**
net food			**18583648,3**

4 beehives on 4000 m^2 with a production of a bit more than 23 kg honey per hive was assumed based on experience of Shepard [24]. In total, 230 kg of honey per hectare was used. This was equal to 692 898 kcal per ha according to Shepard's data [24].