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Master thesis in Agriculture

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Allometric models for above ground biomass of European hazelnut (*Corylus avellana*) in orchards, living fences and agroforestry systems in Denmark

An exploration of carbon sequestration

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Abstract

In the efforts to mitigate the altered atmospheric levels of greenhouse gasses, attention to increase the carbon sequestration of agroecosystems has gained increased interest. Agroforestry systems are praised in this matter. However, allometric biomass models are lacking for species and conditions met in the arable land, making quantifications of carbon storage in agroforestry systems difficult. One of the species relevant for agroforestry in a Danish setting is the common European hazelnut (*Corylus avellana*). In this master's thesis allometric biomass models have been developed for European hazelnut grown in light-open conditions in alley cropping systems, food forests, living fences and orchards in Denmark. Based on 32 sampled shrubs from 10 different locations in Denmark, several allometric biomass models for predicting stem, foliage, branch and total aboveground biomass of hazelnut shrubs have been produced. Biomass models including crown diameter and shrub height have been found to be the best explanatory variables for predicting the total aboveground biomass of hazelnut shrubs. This is especially relevant regarding the ability of the model to be extrapolated to external data and when considering realistic field measurements to be obtained by the end-users of the models. The circumference of the summed cross sectional area of the multiple stem diameters measured at 0.65 m above ground shows an exceptional good ability at explaining variability in shrub biomass with adjusted R^2 values above 0.99. This variable is however only applicable under circumstances of small stem numbers or a need for exceptional high accuracy. The carbon and nitrogen content of different plant parts have been analyzed. The overall average carbon content of *Corylus avellana* has been estimated to 47.79%, which is used to estimate the total carbon content of the sampled hazelnut shrubs ranging from 0.03 kg to 111.26 kg. This thesis thus contributes to the research of quantifying the carbon capture and storage of agronomic important perennial species, as an important step towards fully understanding the benefits of diverse agronomic ecosystems like agroforestry.

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Section 1: Introduction

1.1. Agriculture and climate change

The mean temperature of the world has risen 1.09°C since preindustrial times and is approaching the 1.5 °C tipping point. This is recognized to be caused by anthropogenic impact on the natural cycles of especially carbon. Combustion of fossil fuels, changes in land use, here among the reduced coverage of forest ecosystems, and a global loss of soil organic carbon, all contribute to the rise in the atmospheric concentration of the greenhouse gasses (GHGs) (IPCC, 2022a; Granata et al., 2020a; Masciandaro et al., 2018). This has led to a rise of especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) to levels not seen in at least 800,000 years (Hart et al., 2017). Climate change caused by these alleviated levels of GHGs concentrations has led to an increase in frequency and intensity of weather and climate extremes. Heavy precipitation events and related floods, hot extremes, droughts, and increased cyclones and hurricanes have already caused damages and losses in human and natural systems (IPCC, 2022a). Climate change is expected to change the relationship between crops, pests, pathogens and weeds and to decrease yields in globally important staple crops such as maize and wheat (Gordon et al., 2018; Zougmoré et al., 2021).

The global agricultural production has managed to increase with 56% from 2000 to 2022, following along the increasing demands of the growing population (FAO, 2023b). This increase has broadly been recognized to be achieved at the expense of the environment (FAO, 2023b, Giannitsopoulos et al., 2020). The success is primarily caused by an increased use of agrochemical inputs, extended use of irrigation, improved high yielding varieties and an intensification in the use of agricultural areas with a shortening of fallow periods and a decrease in temporary pasture lands and meadows (Brown et al., 2018; FAO 2023b, FAO 2023c). The agriculture sector is one of the most vulnerable sectors to the negative impacts of climate change and environmental degradation, given its direct reliance on the function of supporting and regulating ecosystem services. These ecosystem services are fundamental for the provisioning of food, fiber, fodder and energy (Ghaley et al., 2014; MEA, 2005). The agricultural sector is however also contributing to the emissions of GHGs driving the change itself.

The agricultural sector was responsible for 30% of global GHG emissions in 2021 (FAO, 2023a). Around half of the emissions stem from on-farm activities, with ruminant livestock enteric fermentation emitting methane as the biggest contributor on-farm, followed by livestock manure. Agricultural soils alone are furthermore estimated to emit 0.8-1.2*10^9 Mg carbon yearly to the atmosphere, due to agricultural practices that lead to a decrease in soil organic carbon (Masciandaro et al., 2018). One fifth of the emission is caused by changes in land use, primarily with the goal of expanding agricultural land causing deforestation and fires. The net forest conversion is the largest solo component of agricultural GHG emissions (FAO, 2023a). These trends will together with the continued degradation of ecosystem services, arable land and biodiversity cause severe damage to agricultural production systems and the food security of the world (FAO, 2017). Coinciding with a predicted rise in the world population towards 2050 the global society face a complex problem (FAO, 2023a; Smith et al., 2012)

1.2. Global mitigating efforts and the role of biomass

United Nations Framework Convention on Climate Change (UNFCCC) with the overall aim "*to stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system*." was established in 1992 (UN, 1992). World leaders and organisations have made agreements to reduce further global emission of GHGs and efforts to mitigate the current level by capturing and storing carbon from the atmosphere by committing to among other the Kyoto protocol in 1997 (COP3), the Paris agreement in 2015 (COP21) and latest the COP28 in Dubai 2023. Several of the countries adhering to the UNFCCC, annex 1 countries also referred to as industrialized countries by UN, are obligated to report on national GHG emissions. The countries have to deliberately outline areas of GHG sources and sinks, within their national context in yearly national inventory reports (UN, 1992).

As a consequence an increased interest and need emerged for the ability to accurately quantify carbon storage in woody plant biomass and forest ecosystems as a whole (Conti et al., 2019; Dutcha et al., 2020). This was further enhanced by the Kyoto Protocol in 1997, making carbon trading possible and further acknowledging the importance of preserving the carbon storage within existing vegetation and soil. The mitigating potential of sequestering atmospheric carbon through afforestation and reforestation projects was also recognized (Kumar & Nair, 2011, Granata et al., 2020a). Allometric biomass models have historically been developed for

estimating expected yields of arboricultural production systems and have come to play an important role in the quantification of carbon storage in the world vegetation. Allometric biomass models utilise the relationship between biometric measures of most commonly stem diameter and height and the above ground biomass (Piccard et al., 2012). These models are essential field level data to be used in combination with forest inventories or satellite images to estimate the carbon stock on a large spatial scale (Zianis et al., 2005).

Since crop land, permanent meadows and pastures takes up one third of the world land area, attention is given to increasing the carbon sequestration on arable land as well (FAO, 2023c, Kumar & Nair 2011). Transitioning from an annual crop to a perennial woody crop like in a fruit, nut or oil orchard will create an increased accumulation of carbon within the living biomass, whilst still producing food (Granata et al., 2020a; Kumar & Nair 2011; Pacchiarelli et al., 2022). In more mature orchards this will also lead to less soil tillage which in combination with the larger, deeper and more permanent root system from the perennial crops, can enhance the content of soil organic carbon by decreasing the rate of mineralization (Gentile et al., 2016; Granata et al., 2020b). However, there is a lack of allometric biomass models developed for perennial trees and shrubs grown in open field conditions and for the species found in agricultural systems (Schindler et al., 2023).

The Food and Agriculture Organization of the United Nations (FAO) calls for "long term sustainable production techniques" that incorporates the three equally important objectives of increasing production, mitigating negative impact on climate and environment and adapting to the already changing climate (FAO, 2017; FAO 2023b). A promising solution in this regard is found within agroforestry systems (Kay et al., 2019; Kumar & Nair, 2011; Schindler et al., 2023; Smith et al., 2012).

1.3. Agroforestry as a part of the solution

Agroforestry is the integration of woody perennials with crops and/or livestock on the same piece of land either managed simultaneously or sequentially (Brown et al., 2018). The system aims at mimicking natural woodland ecosystems, where diverse species efficiently are utilizing, sharing and cycling resources of water, nutrients and light. The aim is to optimize synergies and minimize competition, which is highly related to edaphoclimatic conditions, the combination of species, the spatial design and the management of the system (Gordon et al.,

2018; Smith et al., 2012). Given the broad definition of agroforestry, it covers a wide range of systems, which can be categorized in three overall types: Agrisilviculture which is the combination of trees and shrubs with crops. Silvopasture which is the integration of trees and shrubs in systems with livestock. Lasty is agrosilvipasture, which covers the combination of both herbaceous crops, livestock and trees on the same unit of land (Brown et al., 2018; Smith et al., 2012). Brown et al. (2018) expands the definition to also cover forest farming, forest grazing, home gardens in urban areas, entomoforestry and aqua-silvo-fishery. The forest farming and grazing differentiate from the first three categories by clearing area within an existing forest and introducing the elements of crops or animals, as opposed to the first three categories where trees and shrubs deliberately are introduced on crop or pastureland.

The productivity of agroforestry systems, in terms of marketable yields, has been studied by using the land equivalent ratio (LER). LER compares the total yield of the agroforestry system with the corresponding area needed to produce the same yield of the different commodities in monocrop systems. In temperate agroforestry systems LER values of 1.3 to 1.6 have been reported for walnut-cereal system and 1.25 to 1.4 for poplar-cereal systems in the Mediterranean climate of Europe (Gordon et al., 2018). In another study by Lehmann et al. (2020) LER values ranged from 1.36 to even 2.00 with the lowest being from a Danish food and energy system combining belts of short rotation coppice of willow, hazel and alder trees with a cereal dominated organic crop rotation. The highest LER value was found in a mixed fruit tree orchard in Poland intercropped with vegetables, followed by a traditional silvopastoral system in Romania combining trees (mainly beech and alder) established via natural succession, pasture and cows with a LER value of 1.96. All values above one is an indication that the vegetation (and partly animals) within the system are using the resources more efficiently and therefore that the synergetic effects among the diverse elements of the system are more prevalent than the competition (Gordon et al., 2018).

The trees and shrubs in agroforestry systems often serve multiple purposes by contributing with commodities such as timber, fuelwood, fencing, fruits, nuts, medicine, gums, resins and fodder, but equally important contribute with essential improvements of the supporting and regulating ecosystem services (Giannitsopoulos et al., 2020; Smith et al., 2012). Agroforestry is mentioned within the Kyoto Protocol as a “Green house gas offset activity”. It has gained attention for sequestering carbon in the woody biomass and in the soil in larger amounts and for a longer time, compared to annual herbaceous crops (Kumar & Nair 2011; Gordon et al.,

2018; Pardon et al., 2017). Besides the direct carbon sequestration within the aboveground biomass and roots of the woody perennial component, the mitigating effects of the agroforestry system are also found in the potential effective storage of carbon within the soil and the potential reduction of external inputs (Pardon et al., 2017). These can be found in the additional positive effects by introducing trees and shrubs in to the farmland (Gordon et al., 2018). Introducing trees have been shown to reduce soil erosion from wind and water by giving shelter and by its wider and deeper root systems. This is also beneficial in regards to minimizing nutrient leaching within the soil column and as surface flows, especially concerning nitrogen and phosphorous. This can furthermore avoid issues of eutrophication in aquatic ecosystems and lead to a more effectively use of applied fertilizers, potentially resulting in a reduced application (Gordon et al., 2018, Giannitsopoulos et al., 2020; Ong et al., 2015; Pardon et al., 2017). The continuous production of root exudates, the decomposition of fine roots and yearly contribution of litterfall, all contribute to an increased input of organic matter to the soil. This can in turn increase soil fertility by improved soil aggregate formation, increased amount of plant available nutrients in the top soil and enhance soil biodiversity (Kumar & Nair, 2011; Pardon et al., 2017; Smith et al., 2012). The reduced till also found in mature orchards, will also be a consequence in the agroforestry system, which can further support the more long term storing of soil organic matter within the soil.

Other positive effects of including trees are their ability to regulate the microclimate of the field by e.g. being a buffer for nearby crops and animals against overheating. Agroforestry systems have been shown to be an excellent measure against the spread of wildfires in the arable land of Southern Europe (Kumar & Nair, 2011). The areas with trees in rows or patches can moreover increase the in-field biodiversity and serve as a habitat for natural enemies and parasitoids of crop pests, improving natural regulation (Gordon et al., 2018; Jensen et al., 2019; Kumar & Nair, 2011, Rhode et al., 2019). FAO points to the ability of diverse agroecosystems such as agroforestry systems to serve as an ecological insurance for the individual farmer. Farmers are more robust against crop failures of individual elements of the system by diversifying the production (FAO, 2018). These beneficial mitigating effects combined with the high reported productivity and improved resilience, make agroforestry a promising solution to the three folded task facing the future of agriculture. The presented potential positive benefits of agroforestry systems are dependent on the ecoregion, the soil and climatic conditions, the species combined, the management and the design of the system (Jensen et al., 2019; Kumar & Nair, 2011).

1.4. Agroforestry in Europe and its carbon sequestration potential

It is estimated that 8.8% of the arable land in the European Union can be considered as agroforestry. The biggest areas is found in the Mediterranean part of Europe and with silvopasture covering the majority of the areas (den Herder et al., 2017). In a study by Kay et al. (2019) it is estimated that an additional 8.9% of the agricultural area in Europe (136,758 km^2) are facing multiple serious environmental threads that could be solved by transitioning to agroforestry practices. These so called "Priority areas" are crop land and pasture land assessed to face more than five environmental pressures affecting the agricultural production. These are water quality and availability, soil quality related to soil organic carbon content, the threat of wind and water erosion, rising temperature and the state of the biodiversity (Kay et al. 2019). If the areas were transformed to agroforestry systems, it is estimated that it could mitigate 1.4% to 43% of the European agricultural related GHG emissions of 540 million t CO2eq (Number from 2017 and including Switzerland). This is calculated only by accounting for the carbon stored in the above- and belowground biomass, hence excluding the potential gains of carbon storage in the soil (Kay et al., 2019). The large range was dependent on the type of agroforestry systems adopted, especially related to the density and types of trees introduced. The biggest amount of carbon was expected to be sequestered in systems including fast growing tall trees for timber production and the lowest in systems with smaller tree densities as for instance in hedgerow systems (Kay et al., 2019).

Pardon et al. (2017) found that the presence of mature trees in boundary planted fields increased the soil organic carbon in the plough layer up to a distance of 30 m in to the field. This contributed to a net increase in soil organic carbon of 5.3 Mg organic carbon per hectare, compared to the control field without trees. In Gordon et al. (2018), estimates of agroforestry systems' sequestering 1.5 to 4 Mg of carbon per hectare per year were reported for reasonably low tree densities of 50 to 100 trees/ha. These estimates included both above and belowground biomass and the enrichment of the soil carbon pool. The net gain of carbon stored in standing biomass and soil also depends on the former land use. The net gain of establishing an agroforestry system on pastureland is smaller than on crop land. Pastureland contains larger soil carbon stocks, which when introducing trees are reported to cause a loss of soil organic carbon within the first five to eight years. (Gordon et al., 2018; Kumar & Nair, 2011; Pacchiarelli et al., 2022). Accurate predictions of carbon sequestration and storage potential in agroforestry systems are challenging given the many complex interactions happening within

the system (Kumar & Nair, 2011). Agroforestry also covers a broad range of systems as earlier established which makes the direct comparison of studies within the overarching label of "agroforestry" more difficult to compile (Brown et al., 2018).

Another issue is that most temperate allometric biomass models are developed for forest stand trees (Zianis et al 2005). These models will not only differ in the species covered, but also in the growth patterns. Trees in agroforestry systems will often have wider spacing and less competition. These will also undergo different management practices such as pruning, which can alter the relationship between the dendrometric measurements and the total tree biomass (Schindler et al., 2023). In Gordon et al (2018) it is mentioned that an individual agroforestry tree can be expected to have a biomass three times larger than a corresponding same aged tree in a forest stand. It is furthermore highlighted that it is not adequate to simply extrapolate the carbon cycle dynamics from a forest ecosystem to the tree element in agroforestry systems. Therefore there is a need to develop allometric biomass models for agroforestry trees explicitly as a step towards more precise quantifications of the carbon storage potentials and carbon dynamics in agroforestry systems (Gordon et al., 2018; Schindler et al., 2023).

1.5. Agroforestry in Denmark

In the newest Common Agricultural Policy for the European Union (CAP) for the period 2023 to 2027, agroforestry has become an eligible land use for receiving basic areal subsidy support (ICOEL, 2023; Landbrugsstyrelsen, 2023). This could have the potential to increase the adaptation of agroforestry in the member states. Here among in Denmark.

Denmark serves as a great example in terms of land scarcity and the need to improve carbon sequestration within the arable land. Agriculture covers 66% of the Danish land area with forest only constituting 15.6% of the area (FAO, 2019). The Danish Government have presented a goal of increasing the forest cover in Denmark with 250,000 hectare to increase the carbon sequestration and improve biodiversity (Statsministeriet, 2022). This will not change the fact that agriculture will remain the number one land use in Denmark, which as a sector accounted for 26.2% of the national GHG emissions in 2021 (Nielsen et al., 2023).
In the study by Kay et al. (2019), a total of 410.500 hectare of Danish agricultural land were "Priority areas" facing more than five environmental threads with a solution of transitioning to

agroforestry systems. This is corresponding to 15.6% of the Danish crop and pasture land (FAO, 2019). Agroforestry currently represents a niche within the Danish agricultural landscape. But it has gained momentum within the last couple of years according to the Danish Innovation Center of Organic Agriculture (ICOEL) (Birk et al., 2022a).

With the new CAP, each member state are obligated to define their own definition of agroforestry to align this with existing national agricultural guidelines and regulations (Lawson, 2023). In Denmark this has been defined as fields with more than 100 trees and bushes per hectare in combination with crops or pastures, in rotation or permanently. The perennials accepted are limited to fruit, nut or berry trees and bushes. The only design allowed for the directly areal subsidy under the name "agroforestry" is an alley cropping system. The trees have to be arranged in rows with the production of crops or pasture in the alleys in between the rows. A maximum of three rows of trees established next to each other and a maximum of 40 m between the separate rows or belts of trees are permitted. It is allowed to include livestock on the area, opening the option of silvopasture and agrosilvipasture types of agroforestry. Farmers can also design the agroforestry systems to fit within other eligible areas of subsidy, here among the supplementary support for organic fruits and berries and lowland forest for trees relevant for coppice (Landbrugsstyrelsen, 2023).

1.5.1. Project ROBUST

This thesis is a contribution to the ongoing project ROBUST that studies different aspects of agroforestry under Danish conditions. The project is led by ICOEL, in collaboration with University of Copenhagen, Center for Frilandsdyr and a number of private companies and farmers. As a part of the ROBUST project, four different agroforestry systems have been designed and established for ongoing monitoring. One of the goals within the project is to document the effect of agroforestry on the carbon storage within the biomass and soil in a Danish setting. One of the means to achieve this goal, is to develop species specific allometric models for the trees and shrubs included on the four established agroforestry trials. All four sites had planted European hazelnut (*Corylus avellana)* either as a component of creating mixed patches of shrubs and trees on pasture land or as rows in alley cropping systems. The European hazelnut (*Corylus avellana*) is also one of the accepted species on the list for trees and shrubs allowed to plant within an eligible alley cropping system in Denmark under the

CAP. It is furthermore praised as being one of the best plants for a Danish nut production with a long natural and cultural history in Denmark (Birk et al., 2022b). It has not yet been quantified how much carbon dioxide European hazelnut sequesters under Danish nor similar Southern Scandinavian climatic conditions (GlobAllomeTree.org; Pacchiarelli et al., 2022; Zianis et al., 2005). This information will be important in regards to potential future carbon dioxide quotas within Danish agriculture and in terms of comparing the carbon sequestration of different agricultural systems, here among agroforestry systems. Being able to quantify the carbon storage potential of key perennial species such as hazelnut shrubs, could furthermore be relevant in future economic support for farmers transitioning to e.g. agroforestry.

1.6. European hazelnut

Corylus avellana is a deciduous shrub of the family Betulacea and the subfamily Coryloideae. It grows with a continuous basal shooting, giving it multiple stems, with altering ages, widths and lengths. It can survive a large span of soil environments, but prefers natural to acidic, fertile and well drained soils (Hicks, 2022; Westergaard & Pedersen, 2005). According to Møller and Staun (2015) the *Corylus avellana* will under Danish conditions typically reach a height of three to six meters, but in rarer cases grow up to 12 meters in height. Regarding the diameters of the multiple stems, they will typically reach an average of 15 cm, but can in some cases reach 25 cm. The individual stems of the hazelnut shrub can become 80 to 100 years old before naturally being replaced by younger stems shooting from the base (Hicks, 2022; Hansen et al., 2007). This is also making it an excellent species for coppice systems, which historically have been including wild hazelnut shrubs in mix with e.g. willow (Vildttjenesten, 2007). The options of utilising hazelnut shrubs in a coppice system are not further explored within this thesis, but are of relevance in terms of carbon sequestration and the biofuel sector.

Corylus avellana is a monoicous plant with unisexual flowers maturing at altering times to avoid self-pollination. When grown for hazelnut production there is a need to combine a different set of cultivars with matching timing of male and female blossom. The fruit of the hazelnut shrub is the hazelnut, a single seeded true nut in a pericarp surrounded by a green involucre that differs in length and appearance by cultivar (Hicks, 2022; Westergaard & Pedersen, 2005). Given the long history of hazelnut production worldwide and its wide geographic spread, there are disputes among whether the species of *Corylus avellana* should

be subdivided. A common inconsistency is whether *Corylus avellana* and *Corylus maxima* is in fact two different species. The latter is also referred to as "filberts" and is a more vigorously growing plant with more elongated nuts and involucre, generally considered to be a higher yielding plant (Mehlenbacher & Molnar, 2022; Hicks 2022). In Mehlenbacher & Molnar (2022) *Corylus maxima* is considered to fall within the species of *Corylus avellana*, accepting that the species is very poly-morphic. This view is adopted and when referring to *Corylus avellana*, European hazelnut and hazelnut shrubs within the study this covers both.

In 2022 hazelnuts were harvested on more than one million hectares worldwide. The biggest producers being Turkey followed by Italy, Azerbaijan, the United States of America and Georgia, followed by newer producing countries like China and Chile (FAOSTAT, 2023). There is globally and nationally in Denmark an increased demand of nuts, here among the hazelnut. It is estimated by ICOEL that there is a gap in the market for nationally produced Danish nuts (Birk et al., 2022b). In Denmark hazelnut is predominantly found as a wild species in lowland forest, forest successions, hedgerows, wild fences or as ornamental plants within gardens (Hansen et al., 2007; Westergaard & Pedersen, 2005). It is promoted to be a habitat for birds to nest and several native bird species, the red squirrel and hazel dormouse are feeding on the kernels (Pinborg et al., 1989). The production of hazelnuts in Denmark can be considered a niche with 133.49 hectare registered for governmental subsidy in 2022. 29.55 ha were registered as conventional orchards and 103.94 ha managed as an organic production. (Numbers stem from a list of area-subsidized farmers for nut production, made available by Hanne Lindhard Pedersen from HortiAdvice). However, Danish trials of different hazelnut cultivars for production intentions dates back to the 1940s (Groven, 1955; Groven, 1965).

The production of hazelnut gives highly fluctuating yields under the Danish climate. The pistillate inflorescence is highly sensitive to spring frost, when first flushed and pollinated. Untimely frost in March or April can ruin the entire production. The yields of hazelnuts are therefore not considered to give stable outputs (Birk et al., 2022b). This makes the hazelnut a crop well fit to include in a diverse agricultural production system such as an agroforestry system, lowering the vulnerability of the production by altering the products. The general rise in the interest of producing Danish nuts (Birk et al., 2022b) and the native origin of *Corylus avellana* makes European hazelnut a reasonable choice for farmers seeking a more climate change mitigating and biodiversity improving agricultural operation.

This applies to farmers transitioning to agroforestry systems or farmers that in other ways are diversifying their production systems towards the inclusion of more perennial crops.

1.7. Scope of the study

The main objective of this thesis is to develop allometric biomass models for aboveground biomass of European hazelnut shrubs (*Corylus avellana*) grown in light-open conditions in alley cropping systems, food forests, living fences and orchards in Denmark, to estimate the carbon sequestration in the aboveground biomass. The target population examined includes all types of hazelnut cultivars, different plant material; vegetatively propagated or grown from seeds (wild hazel) and different levels of management from intensively managed in orchards to extensively managed in forest gardens and living fences, spread across the regions of Denmark. Living fences are included in the sample, even though they are not established with intentions of contributing to food production. This is done to include older and more extensively managed hazelnut shrubs to broaden the applicability of the end models to situations potentially found in agroforestry systems in the future. Considerations to what kind of model entry variables that are possible for e.g. farmers to collect within a manageable timeframe and amount of work, is considered to make the resulting models useful in practice. Models for estimating total aboveground biomass with and without foliage, stem biomass, branch and foliage biomass are developed. The carbon and nitrogen content of different plant parts of the hazelnut shrub; leaves, branches of different sizes, catkins, green shoots, stem bark and wood are also examined. The results of the analysis of carbon content will be used together with the shrub biomass models to give an estimate of the total carbon content expected to be sequestered by hazelnut shrubs in different agronomic systems.

1.8. Literature review on sampling methods for developing allometric biomass models

A literature review was conducted on the recommended methods and measurement for producing useful allometric models that align with the historic and worldwide academia on estimating woody biomass. This was done keeping in mind the morphology of hazelnut shrubs.

1.8.1. Sampling size and sample distribution

Creating allometric biomass models requires a combination of destructive and nondestructive measurements of a sample of trees, with the end goal of being able to estimate the biomass of the rest of the tree population. As being the case for most data sampling, there is a need to balance the number of samples with an acceptable level of representation of the population sought to be described (Wu and Thompson et al., 2020). It is also important, as stated in Picard et al. (2012), to balance the cost and time related to increasing a sample size for gaining a higher accuracy and precision of the biomass predictions.

The sample size for developing allometric biomass models vary a lot within the visited literature. In Zianis et al. (2005) existing allometric biomass and volume models for common European forest species were synthesized in to a database. They found that the sample sizes to establish the allometric biomass and volume models varied between 3 and 1503 units, with most models calibrated on datasets with sample sizes of 6 to 100 trees (units). In a study by Roxburgh et al. (2015) with the objective of creating guidelines for constructing allometric biomass models, the general recommendation was 50 individuals. The study by Roxburgh et al. (2015) is based on a computer resampling experiment, examining 23 published allometric biomass models developed for common trees in Southeast Australia. The recommendation of 50 units was found by plotting the coefficient of variation of the predicted biomasses with the sample size. Here there is a steep decline in the coefficient of variation with increasing sample size, until the sample size approach 50 units, where the graph flattens and the decline is more subtle. A similar figure of total sampling number is recommended by Dutcă et al. (2018), suggesting to sample at least 5 units from at least 10 different stands/sites.

It is highlighted by several studies (Albert et al., 2014; Chen et al., 2023; Conti et al., 2019; He et al., 2016; Roxburgh et al., 2015) that trees with multiple stems and/or a shrub-like morphology will have a greater natural variability in the biomass. The relationship between biomass and biometric measurements such as height and diameters will also show greater variability than most single stemmed trees. Roxburgh et al. (2015) found that a sample size of the mallee morphology needed a sample size of approximately 55 individuals and the shrub morphology around 56, to develop a biomass model with an estimation error of +/- 10%.
The allometric biomass models and associated dataset used in the study by Roxburgh et al. (2015) is mainly covering species of eucalyptus and acacia. The morphology of the hazelnut shrubs can roughly be assumed to fall in between the group of mallee and shrubs, leading to a

recommended sample size of 55 units. The sampled units in this particular study is expected to contain a great variability extending beyond the fact that the hazelnut shrubs have a multi stemmed morphology, given differences in location, variety and management practices. As stated in Picard et al. (2012) a general rule for establishing a sampling size is that the more variety in the sampled material, the higher a sample size is required for reaching a sufficient level of precision. Based on the literature recommendations the ideal sampling size for this particular study would require to sample 50-60 hazelnut shrubs.

Besides the number of units, the distribution of the sample in regards to size in height, stem diameters and age is also important considerations when developing a sampling plan, in order to get a broad and balanced sample. It is highlighted by Picard et al. (2012) and Dutcă et al. (2020) that an allometric biomass model is most accurately predicting the biomass of trees with a diameter (or size in general) laying in the middle of the range of the diameters of the sample trees used to develop the model. According to Roxburgh et al. (2015), Dutcă et al. (2020) and Picard et al. (2012) the most optimized sample plan for developing an accurate allometric model is to ensure an equal representation of the different diameters of stems. If the model is developed based on an equal amount of sample units within each diameter strata, the model will be better at predicting the biomass of trees with diameters not necessarily laying in the middle of the diameter range of the trees sampled to create the model (Dutcă et al., 2020). The biomass of the trees or shrubs that are going to be predicted by a developed allometric biomass model, however, still have to lay within the dimensions of the sample trees used to calibrate the model (Dutcă et al., 2020; Paul et al., 2016).

1.8.2. The biometric variables

When it comes to which potential explanatory variables to measure from each sample unit (shrub or tree), there is a need to balance model accuracy and predictability, time efficiency when collecting data and the future end-users of the model. (Chen et al., 2023; Picard et al., 2012; Roxburgh et al., 2015). In the literature the most common predictor variable is centered around stem diameters. Especially the diameter of the stem at breast height (1.3 m) is often the best univariate variable at predicting the biomass of the entire aboveground biomass of a tree or a stem. (Albert et al., 2014; Dutca et al., 2020; Husch et al., 2003; Roxburgh et al., 2015; Zianis et al., 2005) The diameter at breast height (dbh) best describes trees with a single stem,

as noted by Chen et al. (2023) and Conti et al. (2019). Shrubs and multi stemmed trees often ramify below the point of 1.3 m, equally correct for common hazelnut shrubs (Møller & Staun, 2015). Hazelnut shrubs will, if not trained single stemmed, not only grow from its multiple stems in height, but also continuously grow new shoots from its underground stool, representing a totally different carbon allocation strategy (Albert et al., 2014; Hicks, 2022).

Pacchiarelli et al. (2022) found the best describing predictor variable for European hazelnut to be the stem diameter at 0.6 m. Skema et al. (2018) measured all stem diameters at 0.3 m and 1.3 m of the hazelnut shrub with the diameter at 1.3 m being the best predictor parameter together with the composite parameter D^2H. In Conti et al. (2019) the best fitting general biomass model for shrubs with a morphology like hazelnut all include the predictor variable of the diameter below 0.3 m, but above the root collar. Paul et al. (2016) recommends using the diameter at 0.1 m for multi stemmed trees and shrubs. Based on the experiences found in the literature regarding stem diameter measurement, the diameters at 1.3 m, near 0.6 m and a measurement of the lower stem section between 0.1 m and 0.3 m seem appropriate to ensure all best options available for model development.

Several studies (Chen et al. 2023; Taeroe et al. 2015; Conti et al. 2019) have found that adding an additional predictor variable to the allometric equation increases the accuracy of the model. Here the additional variables are often total tree height (H) or crown dimensions like crown diameter or crown area (Albert et al., 2014; Chen et al., 2023; Conti et al., 2019; Picard et al., 2012; Zianis et al., 2005). Conti et al. (2019) highlights the importance of including crown dimensions as a parameter additional to stem diameter(s), when developing allometric biomass models for shrubs and multi stemmed trees. A proportionally bigger part consists of the crown in multi stemmed, shrub like trees, as opposed to single stemmed forestry trees. In general it is concluded by Conti et al. (2019) that it is difficult to reach a sufficient biomass prediction accuracy if only including one parameter, when estimating shrub aboveground biomass.

1.9. Delimitations

This study only investigates the aboveground biomass of the hazelnut shrubs, leaving out the belowground biomass of living and dead roots. It was not possible to examine this part of the shrub given the time and resources available within the framework of the study. The root biomass will be included based on the commonly used root to shoot ratio of 26% for trees and

shrubs in the temperate zone (Cairns et al., 1997; Pacchiarelli et al., 2022) for the calculations of expected accumulated carbon storage. The biomass removed from the systems in form of pruning and harvested nuts were not included in the study. Partly because the information was not available for most sites and partly because this part represents biomass that in most cases leaves the systems. This part of the biomass could therefore not be estimated and included in the predictions of carbon sequestration of hazelnut shrubs.

The original aim of the sampling size of the study was at least 50 to 60 units (hazelnut shrubs) from 13 different sites, based on the recommendations found from the literature review. It turned out not to be possible within the time frame of the fieldwork, where measuring shrubs with many stems and handling of the larger stems, especially related to the process of dividing leaves and branches, took much more time than first anticipated. The number of sites and sample units were therefore downsized to 10 sites and a total of 32 sample units.

Site informations that potentially could serve as explanatory variables were collected hereunder edaphic information covering soil pH value, soil texture class, surface geology, C:N ratio and bulk density, information on management practices, topography, site climatic conditions, former land use, system design and competition from other vegetation. The big variation among the sampled hazelnut shrubs, naturally caused by the aim to represent many different management systems, sizes and ages, led to the decision that the sampled material was not homogeneous or big enough to give any convincing results on the impact of the site related factors. For this to have any statistical validity a larger number of hazelnut shrubs should have been sampled from each site and ideally with less diversity, in order to determine the effect of for instance climatic conditions, management choices or the design of the system on the development of the biomass. The only site related factor included in the regression models in this study was whether the shrubs had been pruned or not. A simple and somewhat broad variable covering both side pruning, top pruning and coppice. The other site related factors are however included in the presentation of the 10 sites and serves to explain the diversity of the sites included and the diverse conditions and circumstances where hazelnut shrubs are grown in Denmark.

Section 2A: Methods for fieldwork

The fieldwork was conducted over the course of one and a half month from the last week in July 2023 until the first week in September 2023. The season for the data collection allowed to include the fully grown leaves as a part of the data sample. 10 different sites were visited, covering most regions of Denmark, however, not the northernmost nor the southernmost parts, as seen on the map in figure 1. Even though Denmark is the smallest of the Scandinavian countries both the soil conditions and the average weather conditions vary significantly, as seen in table 1 highlighting the key mean weather values (2011-2023) and soil conditions.

2A.1. The overall sampling strategy

From each site 2 to 6 hazelnut shrubs were measured, both measuring potential explanatory variables that described the shrub as a whole and measurements that described each stem within the shrub in more detail. It was not possible to fell the entire shrubs with all the stems. Instead, a sample of two to five stems were felled from each shrub, ideally representing the different diameter strata and stem lengths represented within the given shrub.

This meant that the data collection, analysis and development of allometric biomass models had to be done on two nested, coherent levels: 1) The individual stems within the hazelnut shrub. 2) The hazelnut shrub as a whole. The felled stems with known biomasses were used to predict the biomass of the remaining stems in the shrubs that had only been measured with non-destructive methods. This called for developing allometric biomass models for stem biomass, stem volume, branch biomass, foliage biomass and total above ground biomass with and without foliage on the stem level as the very first step in the analysis. Only then could the estimated corresponding biomasses of the shrubs be determined and used for developing shrub level biomass models.

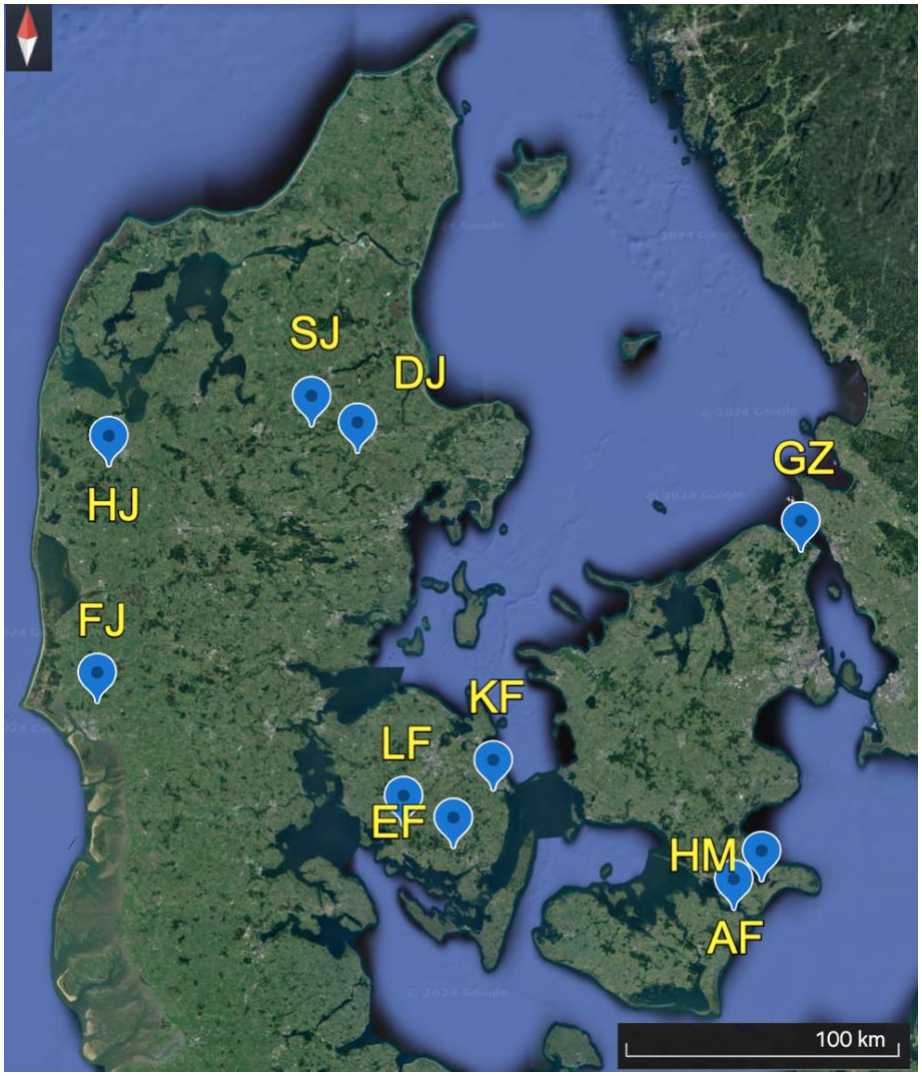


Figure 1: Satellite picture of Denmark, with the locations of the 10 sites for data collection marked. The map is created in Google Earth (2024).

2A.2. Identifying sites for data collection

Identifying the sites for the data collection required some investigation. The composition of sites needed to cover both intensive managed hazelnut orchards, different agroforestry systems, extensively managed hazelnut shrubs, as well as hazelnut shrubs out of production like in living fences. By doing so, the sample is expected to cover the range of different future management approaches applied in agroforestry systems of different types and management intensities. Additional criteria for picking the sites were that the hazelnut shrubs could not be understory vegetation, as in a forest system, and they had to be above 50 cm in height. The sites also needed to be able to offer at least three hazelnut shrubs for sampling.

Table 1: Mean annual weather data from the 10 sites visited and indicators of soil conditions. The mean annual temperature, sun hours, windspeed and precipitation for each site were derived from the weather archives of the Danish Meteorological Institute and based on the information of the commune level (DMI, n.d.). The soil texture classes were found by looking up the site addresses and identifying the fields visited on the map "MiljøGIS – Geodata fra Landbrugstyrelsen" using the map layer "Jordbundskort 2019"(Geodata fra Landbrugsstyrelsen, n.d.) and cross checked with the owners on the sites. The surface geology was found by visiting GEUS map using the "Jordartskort 1:200.000"(GEUS, n.d.). The topography was estimated by visiting the fields and actual point of data sampling on Google Earth (Google maps, 2024).

Site	Region	Temperature (°C) (2011-2023)	Precipitation (mm) (2011-2023)	Sun hours (h) (2011-2023)	Wind speed (m/s) (2011-2023)	Surface geology	Soil texture class	Topography (Meter above sea level)
AF	Falster	9.66	618.6	1885.5	5.51	Glacial till	JB6	17
DJ	Øst-jylland	8.81	757.1	1651.5	3.77	Pre-Quaternary / Glaciofluvial sand & gravel	JB7	111
EF	Sydfyn	9.64	718.3	1814.3	4.47	Glacial till	JB5	92
FJ	Vest-jylland	9.38	919.8	1698.6	5.22	Glaciofluvial sand and gravel	JB2/JB4	16
GZ	Nord-sjælland	9.32	692.1	1784.8	3.82	Glaciofluvial sand & gravel/ glacial till	JB4	41
HJ	Vest-jylland	8.95	972.6	1662.7	4.98	Glaciofluvial sand & gravel	JB4	33
HM	Møn	9.54	616.9	1859.6	5.18	Glacial till	JB7	15
KF	Sydfyn	9.64	718.3	1814.3	4.47	Glacial till	JB5	50
LF	Sydfyn	9.5	705.72	1789.25	4.31	Glaciofluvial sand & gravel/ glacial till	JB3/JB6	94/97
SJ	Øst-jylland	8.77	832.41	1628.36	4.14	Glacial till	JB1	52

Only very scarce information on hazelnut producers in Denmark is available online given the still small scale of production. The same is the case for agroforestry systems where hazelnut shrubs might only be a small part of the diverse production and not the crop promoted by the place. For the living fences with hazelnut shrubs, it is often privately owned and required that someone knew of its existence. Non-probability sampling methods were used to identify the relevant data collection sites. Non-probability is common to use in situations where the targeted population is hard to reach or not equally available/reachable, where it is not possible to acquire a good description of the population and where time and budget is limited (Emerson, 2015; Wu and Thompson, 2020). The sites have been found and chosen through a combination of purposive and convenience sampling methods, with elements of snowball-sampling:

- The element of convenience sampling were used in the manner that the data collection sites were identified in any way possible (Emerson, 2015; Wu and Thompson, 2020).

- Purposive sampling is that the researcher decides which of the available units, here sites, best represent the population sought to be described (Wu and Thompson, 2020). The elements of purposive sampling have been used in the quest to represent most parts of Denmark, as well as seeking to cover a broad range of hazelnut shrub ages and sizes, when selecting sites for data-collection.

- The snowball sampling strategy was used in the very beginning of the search for data collection sites. Here key informants covering a horticultural adviser from Hortiadvice, owners of nurseries known for their expertise in nut-trees, the project coordinator of project ROBUST from Innovation Center for Organic Agriculture and relevant networks on Facebook, were used for initiating the search for potential data sites. The key informants shared information on relevant people to contact for finding relevant data collection sites. When engaging with farmers or private persons on phone or mail, they were always asked if they knew others, who owned hazelnut shrubs with a potential interest to participate in the survey. An initial search for potential sites for data collection were posted on two networks on Facebook, one called "Skovlandbrug" (Agroforestry) with 2500 members created by the ROBUST project coordinator and another called "Skovhaver og Permakultur" (Forest gardens and Permaculture) with 5400 members. The interaction on the Facebook groups did not lead to any of the final sites chosen.

Because of the risk of bias associated with non-probability sampling, the approach and ways of identifying sites for data collection is here described in more detail as to ensure as much transparency as possible (Wu and Thompson, 2020). Five of the final data sites (AF, DJ, KF, LF, SJ) were found through a list of all farmers getting area subsidy for hazelnut production in 2022 in Denmark (based on 2021 data), covering both organic and conventional production. The list was shared by Hanne Lindhardt Pedersen from Hortiadvice. All farmers on the list were in a structured manner sought to be contacted. It was not possible to find the contact information on all and some were not interested or never returned mails or phone calls. Several inaccuracies were also encountered on this list. Some of the farmers had expanded their plantations in 2022 and some had decommissioned the production. Other potential sites were

not even registered on the list, since they were too small scale to bother registering or were viewing the hazelnut production simply as a hobby. In addition to the list of government subsidies, agroforestry sites registered by ICOEL and Praktisk Økologi on an "agroforestry map of Denmark" published in an agroforestry catalogue (Birk et al., 2022a) were also contacted. Two of the final sites, HJ and GZ, were found on the "agroforestry map". One site, FJ, were a participant in the ROBUST project, but had an alley with hazelnut shrubs that had been planted in relation to another project, InTRÆgrer, in 2019. Site EF was found directly through an online search of hazelnut producers in Denmark and the last site, HM, was a private connection, who owned an old fence with hazelnut shrubs.

2A.3. Site information

At arrival to the field a set of standardized questions were posed to the owners about their reasons behind choosing hazelnut shrubs, their current or expected outcomes, sales channels, their management plan as well as some general questions about site soil fertility. Questions about the plant material were primarily handled by phone or mail prior to arrival, since it was important information for choosing the sites in the first place. The latter covered information on whether it was seed plants (considered to be "wild" plants) or vegetatively propagated plants, growing on own roots or grafted on a rootstock, type of cultivar, the stand age and the system design, hereunder the planting distances, mix of cultivars for pollination and potentially other species neighboring the hazelnut shrubs. The questions and the site information field note template are attached in the Appendix A.1 and A.2.

The 10 different locations are presented in table 2 with descriptions of the systems, cultivars and key management information. In figure 2 five orthophotos of five of the different sites are presented to illustrate the indeed very different agricultural systems covered. Two of the sites, EF and LF, are subdivided. At site LF there was an opportunity to sample from both a newly established hazelnut orchard and from an old living fence. The samples taken in the orchard and from the living fence had a relatively big distance, as seen in figure 2. Given the distance and the diversity of the two systems, it is presented as two sites in table 2. At site EF several approaches to hazelnut orchard management were present, leading to the decision of sampling two shrubs from each field A, B and C, representing different management strategies.

As seen in figure 2, field EFA has a much more closed canopy than field B and C, since it had not been pruned in 10-15 years as opposed to the other two fields.

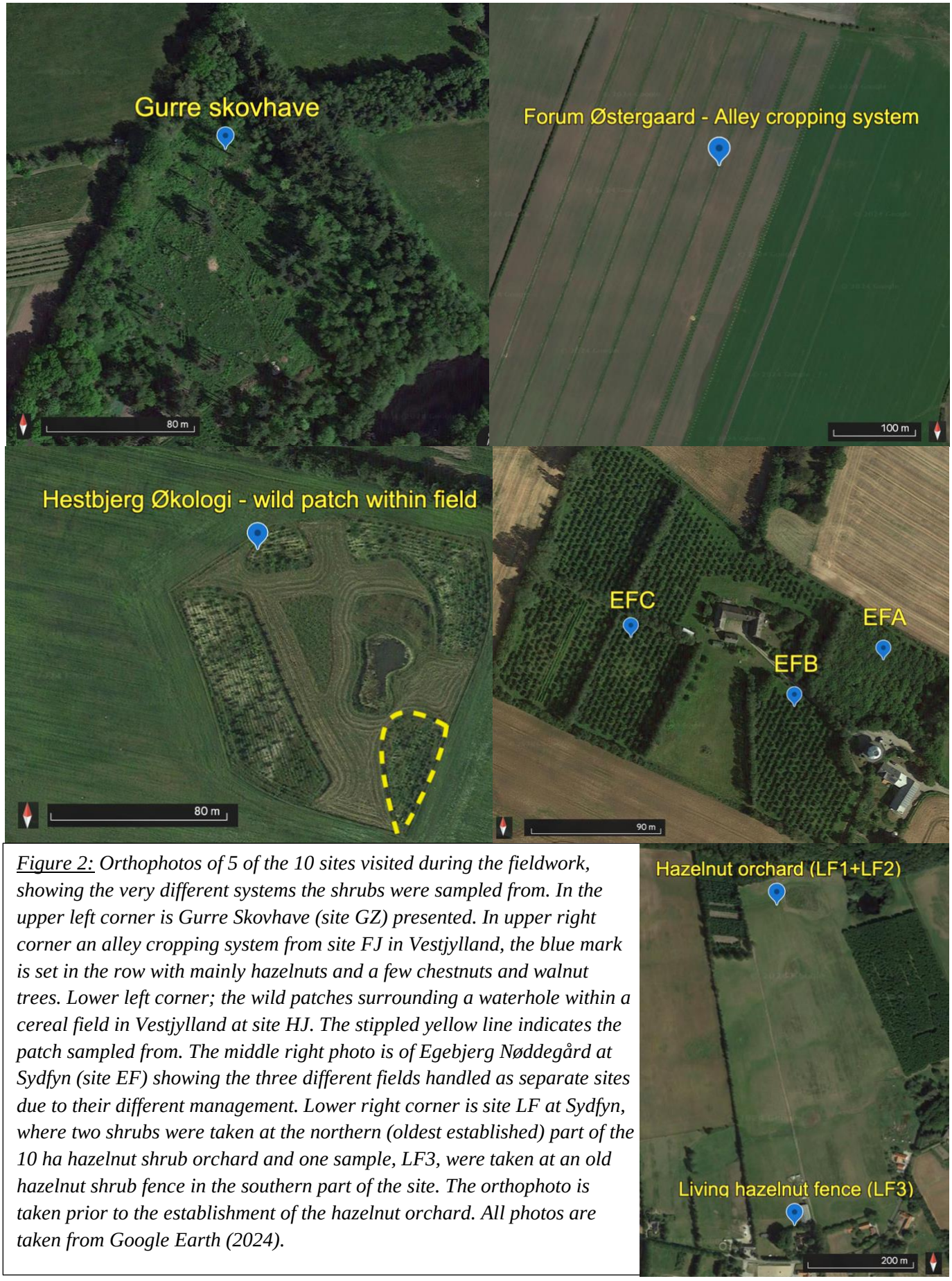
The hazelnut shrubs collected at site AF, HM, LF3 and HJ were not grown for nut production purposes. The wildlife/biodiversity patch at site HJ, as seen in figure 2, was however placed within an organic cereal field. All other sites were following organic production methods. Either they were in the process of becoming certified as organic (LF1+2) or were already certified (DJ, FJ, GZ, KF and SJ). Site EF(A-C) were not registered for areal subsidies and neither for an organic certification. The orchards had been managed using conventional methods by the former owner, but the new owners had since 2020, according to themselves, only used organic methods. At most sites the hazelnut shrubs were vegetatively propagated growing on their own root system, with an exception at site FJ. Here the cultivars were informed to be grafted on rootstocks. It was, however, difficult to confirm this in the field.
The six wild hazelnut shrubs were seed plants.

To get an insight in the soil fertility at the sites, proxy indicators of soil fertility were examined. The surface geology and texture class, see table 1, were supplemented by information on the soil bulk density and soil pH value of the upper 30 cm of soil. At the data collection sites, one to three samples of the 30 cm of the top soil were taken with a soil auger. If the sampled shrubs were placed far away from each other or the understory vegetation indicated a drastic change in soil conditions, several soil samples were taken. The point sample method is very limited and not very representable, knowing that soil pH values and soil conditions in general, can vary a lot within a small area (Plantedirektoratet, 1994). Given this was not the main focus of the study and only served as a proxy for indicating the overall soil conditions, this was accepted, bearing in mind the limitations associated with the results.

Table 2: Presentation of the different sites visited with key information on management systems and the samples taken.

Site	Region	System	Plant distances (m)*	Stand age in years	Cultivars sampled	Fertilizer	Pruned
AF	Falster	Living fence between lawn and gravel road.	0.8-0.9	6	Unknown mixed cultivars.	No	Not yet.
HM	Møn	Living fence between two properties.	1	+50	Wild	No	Stems and branches in 2-3 m height facing the garden.
GZ	Nord-sjælland	Forest garden; hazelnut shrubs both planted in rows along contours and in a double rows.	1.5 m in the contour plantings 2x3.5 in double row	6	Red Zeller, Lambert Filbert, Long Early Zeller	Composted horse manure	Not yet.
EFA	Sydfyn	Extensive hazelnut orchard.	4x4	45	Lambert Filbert	No	Not the last 10-15 years.
EFB	Sydfyn	Intensive hazelnut orchard.	4x4	45	Lambert Filbert	Not since 2020	Branches and new shoots pruned yearly.
EFC	Sydfyn	Silvopasture: Hazelnut orchard w. grazing sheep, ducks and hence.	4x4	45	Cosford	Manure from infield animals	Branches pruned yearly. New shoots taken by the sheep.
KF	Sydfyn	Young hazelnut orchard mixed with walnut trees.	1.5x6	5	Hall's Giant, Red Zeller, Cosford	No	Not yet.
LF1+2	Sydfyn	Young hazelnut orchard w. alfalfa in between rows.	2.5x5	3	Lambert Filbert, Long Early Zeller	Communal compost	Not yet.
LF3	Sydfyn	Living fence between private garden and gravel road.	0.3-1	70	Wild	No	Stems and branches in 2-3 m height. Coppiced only leaving the stool around 20 years prior to visit.
DJ	Øst-jylland	Extensive orchard w. wildflowers and potatoes between some rows.	2x3	6	Cosford and/or Lambert Filbert**	No	Not yet.
SJ	Øst-Jylland	Living fence as a part of a multiple species orchard.	1.8	16	Lambert Filbert	No	No
FJ	Vest-jylland	Alley cropping system. Two rows of hazelnut shrubs mixed with chestnut and walnut trees.	4x4 within row, 32 m alleys.	4	Emoa, Long Early Zeller, Lambert Filbert, Gustav's Zeller	Not directly, potentially spill over from annual crops in the alleys.	Some stems had to be cut down due to frost damages.
HJ	Vest-jylland	Wildlife/biodiversity patch within grain field.	NA	5	Wild	Not directly, potential runoff from surrounding field.	No

**The first number in the plant distances depicts the distance between the shrubs within the row, the second number the distance between the rows.*
***The owner could not tell which plants belonged to the different cultivars.*



<u>Figure 2:</u> Orthophotos of 5 of the 10 sites visited during the fieldwork, showing the very different systems the shrubs were sampled from. In the upper left corner is Gurre Skovhave (site GZ) presented. In upper right corner an alley cropping system from site FJ in Vestjylland, the blue mark is set in the row with mainly hazelnuts and a few chestnuts and walnut trees. Lower left corner; the wild patches surrounding a waterhole within a cereal field in Vestjylland at site HJ. The stippled yellow line indicates the patch sampled from. The middle right photo is of Egebjerg Nøddegård at Sydfyn (site EF) showing the three different fields handled as separate sites due to their different management. Lower right corner is site LF at Sydfyn, where two shrubs were taken at the northern (oldest established) part of the 10 ha hazelnut shrub orchard and one sample, LF3, were taken at an old hazelnut shrub fence in the southern part of the site. The orthophoto is taken prior to the establishment of the hazelnut orchard. All photos are taken from Google Earth (2024).

2A.4. Identifying the hazelnut shrubs to measure

Depending on agreements with the owners and time available at the site, 2 to 6 hazelnut shrubs were measured per site. An element of randomness was sought to be introduced at the step of picking out the hazelnut shrubs to measure and sample. Given the diverse systems covered within the 10 sites, it was done differently depending on the site and the degree of freedom to choose from the owners. In the orchards (KF, LF1+2, EF and DJ) with several rows of hazelnut shrubs, the rows and the number of trees per row were counted. An online random numerator (random.org, n.d.(a)) were used to pick the row and the specific shrub. At the sites with living fences (LF3, HM, AF, SJ), the total number of hazelnut shrubs were counted and the random numerator used to choose the specific shrub. The same method applied to the hazelnut shrubs planted along contour lines at the forest garden at site GZ and to the one alley of hazelnut shrubs, at the alley cropping system at site FJ. At site HJ the hazelnut shrubs were mixed with other small trees and shrubs in a non-systematic design in several patches within a cereal field. One of the patches were chosen and the dimensions measured with a 30 m metal measuring tape. Then a random number in meters of length and width of the patch were generated from the random numerator. The hazelnut shrub closest to this point were chosen. See figure 2 for the specific patch. Shrubs that were not healthy looking, or for some other reason looked like an outlier, were avoided and the random numerator was used again.

When deciding which shrubs to measure consideration as to include different cultivars and shrubs of altering dimensions were taken. In an orchard like at KF or LF where several cultivars were represented, the rows with the respectable cultivars were divided and the randomized shrub selection was done for each group of cultivar. The distribution of cultivars were sought to fit the general trend in Denmark, with the most common cultivars being the old cultivars of Lambert Filberts, Cosford and of the Zeller types (Red Zeller, Long early Zeller or Gustav's Zeller) and with a smaller representation of the newer cultivar of e.g. Emoa. The considerations of shrub size were combined with the randomized shrub selection by redoing the randomized selection, if for instance the second or third shrub chosen, had the same dimensions as the already sampled shrubs from the given site. One of the hazelnut shrubs measured, EFB1, were specifically suggested by the owners, since they wished to fell it completely. It was agreed to do so, since it covered a hole in the size distribution of the felled stems.

When the hazelnut shrubs for sampling were located, notes of the level of competition from surrounding vegetation such as understory vegetation, weeds, neighboring hazelnut shrubs or small trees were taken. The presence and distance to shelterbelts and any abnormalities were also noted. The understory of the hazelnut shrubs sampled was for most part grasses cut multiple times a year. At some sites (especially FJ and KF) there was a high weed pressure dominated by thistles and common nettles that had grown taller than the young hazelnut shrubs. At site LF(1+2) an intentional mixture of alfalfa were planted between the rows and at site DJ a mixture of grasses and flowers for promoting the biodiversity of insects and pollinators in the field were chosen. At site EF, on field EFC they had sheep grazing in between the hazelnut shrubs.

2A.5. Nondestructive field measurements

The biometric measurements collected in the field at shrub level and individual stem level were determined mainly from the literature review presented in the background section. The recommended non-destructive measurements of shrub height, crown diameter, stem length and stem diameters (over bark) at 0.1 m, 0.3 m, 0.6 m and 1.3 m points along the stems, were tested in a pilot-test prior to the actual data collection. The pilot test was conducted at the Aboretum[1] in Hørsholm, located in Nordsjælland, Denmark. The procedure of the non-destructive and destructive measurements were tested on a wild hazelnut shrub, which was not a part of the official botanic collection of the Aboretum. It was found impossible on many of the stems to measure the diameter at 0.1 m, because the stems either grew too close to another stem, or simply had not divided from the stump at that height. The 0.3 m point seemed to be significantly smaller than the 0.1 m and too close to the diameter measured at 0.6 m. A compromise of measuring the heights at 0.2 m were decided. The final diameter measurements were decided to include the diameters at 0.2 m, 0.65 m, being half way to traditional measurement of diameter at breast height and diameter at breast height (1.3 m). The crown diameter and shrub height were measured for all hazelnut shrubs. The height was measured as the shortest distance in a vertical line from the ground to the tallest leaf bearing stem. The measurements were done with a telescopic measurement pole for stems above 2 m and for stems below 2 m with a folding ruler. The crown diameter is a measure based on the average of two in-field measurements:

[1] . The Aboretum is a collection of more than 8.500 woody plants and is a part of the University of Copenhagen.(https://ign.ku.dk/arboret-hoersholm/om-arboretet/)

The diameter of the crown, where it was widest and its perpendicular diameter. The shrub height and crown diameters measurements include a degree of interpretation, even though all measurements were made by the same person. It was therefore sought to estimate the precision error of the measurements: At site SJ the height of ten hazelnut shrubs were repeated three times, with a day in between the two first measurements and some hours between the last two repetitions. Five hazelnut shrubs at site SJ also had their mean crown diameters measured twice.

All stems within each shrub had their diameters at 0.2 m, 0.65 m and 1.3 m above ground measured with a calliper. If the stem did not have a circular shape, two perpendicular diameter measures were taken and the average of these used as the final diameter value. The 0.65 m point was marked with tape and each stem were given an ID-number. The length of the stems was measured along the stem, from the ground to the tip of the stem. Small stems with the dimensions: Length below 0.5 m or stem diameter at 0.2 m below 0.8 cm, were considered as shoots rather than stems. The shoots were not measured any further, but the number of total shoots was counted. Dead stems were not included.

Difficulties similar to the once encountered in the pilot test for measuring the stem diameter at 0.1 m, were met measuring the stem diameter at 0.2 m. This was primarily an issue for the bigger shrubs. In some cases two or three otherwise "independent" stems were dividing further up than the 0.2 m point, giving them a shared lower 0.2 m diameter (see figure 3 for an example). Stems growing too close was another issue that made it impossible to measure the diameters separately. The shared diameter or circumference of the stems at 0.2 m was regarded as a shared resource by the implied stems. See under section 2C.1, how they were used to estimate the individual stem 0.2 m diameters.

To ensure that a wide and ideally equal representation of different stem sizes was included in the sample, the stems were divided in to groups of 2 cm based on their diameters at 0.65 m. The diameter groups, also referred to as diameter strata, are presented in table 3. The grouping was used together with stem length to monitor the size distribution of the stem samples, as the field work progressed, but was also practical in the field to decide which stems to fell. All stem ID numbers within each diameter group from a shrub, were listed in a random list maker at random.org (n.d. (b)). The first stem ID number on the randomized list was the one felled. This was done to include another level of probability sampling, while still ensuring that the stem sample represented the shrub in the best way possible.

If only one or two diameter groups were present, as for most young hazelnut shrubs, the second and third stem on the randomized list were chosen as well. If several diameter groups were presented within a shrub, the group less represented in the site or overall sample was prioritized.

The number of stems felled per shrub depended on the size of the shrub, the number of stems and the agreements with the owners. In average 3 stems were felled per shrub, ranging from 1 to 5 stems. At some sites it was not possible to fell the stems of the biggest diameter groups, due to the agreements.
The oldest hazelnut shrub, LF3 had 57 individual stems and a high stool, meaning that most of the stems started 30 cm above the ground. The big dimension of the stool, compared to other sampled hazelnut shrubs, were properly because LF3 had been coppiced around 20 years prior to the visit.
The stool dimensions were measured and at the half point of the stool, the shrub was divided in two parts.
Only one of the halves was measured and the biomass of the other half was assumed to be equal to the measured half.

Table 3: Stem diameter groups

Diameter groups	
A	] 0 cm ; 2 cm]
B	] 2 cm ; 4 cm]
C	] 4 cm ; 6 cm]
D	] 6 cm ; 8 cm]
E	] 8 cm ; 10 cm]
F	] 10 cm ; 12 cm]
G	] 12 cm ; 14 cm]
H	] 14 cm ; 16 cm]
I	] 16 cm ; 18 cm]
J	] 18 cm ; 20 cm]
K	] 20 cm ; 22 cm]

2A.6. Destructive field measurements

The stems were felled using a looping shear on small stems, a handheld saw for the larger stems and a chainsaw where needed and available. The stems felled were measured in greater detail by measuring the stem diameter at 2 m and every half meter until the stem top was reached. The stem lengths were measured again for a presumably more precise value. This also made it possible to determine the error of precision of the stem length measurement. All side branches and foliage were separated from the main stem. Lamina and petioles were separated from the branches. The branches were furthermore divided in to four categories based on their diameters: Small branches: ≤ 1 cm, Medium branches:]1 cm ≤ 4 cm], Large branches:]4 cm ≤ 8 cm], X-large branches: > 8 cm. Separating the leaves from the branches was time consuming and sensitive to rain or wind. Most of the weighting of leaves and branches were therefore not done in the field, but as soon as possible at an indoor/covered space. The main stems were divided in sections and weighted either directly in the field or as soon as possible after.

Figure 3:
Picture from the fieldwork, shrub EFA1. The upper part of the tape indicates the 0.65 m mark measured from the ground along the stems (not yet measured on all stems in the picture). The red marks the stem discs for determining dry weight to fresh weight ratio and basic densities. The blue disc sample is for the carbon and nitrogen analysis. The pink dashed line is showing an example of a situation, where it was not possible to measure the diameters of the two stems at 0.2 m independently.

The samples of stems, branches and foliage were kept in plastic bags, as seen in figure 4, if transported to another place for weighting. This was done to minimize evaporation.

The plant parts were weighted on two different weighting scales depending on their weight and dimensions. Smaller samples were weighted on a scale with a precision of ± 1 g. The larger stem sections and bigger amount of foliage and branches were weighted using a hanging scale with a precision of ± 6 g. Stem disc samples were taken along the stem, with the width ranging from 1 to 3 cm. These were taken at 0.2 m, 0.65 m, 1.3 m and 2 m above the ground. For stems longer than 2 m, additional stem disc samples were collected at every following half meter point.
An 8 to 10 cm long sample was taken of the smaller stems/stem sections with diameters below 2 cm.[2]
The fresh weights of the stem samples were measured using the small weighting scale with a precision of ± 1 g. The stem samples were then taken to the laboratory for determining the fresh to dry weight ratio and basic density.

Figure 4: Stem sections of shrub EFC2.2, divided in the field and transported in plastic bags for a site for weighting.

[2] During the calculations of stem dry weight, it was found that the sample for FJ3.4 at 0.65 m and FJ4.1 at 0.65 m were missing.

In addition, separate stem samples were taken for the analysis of carbon and nitrogen content. Samples for carbon and nitrogen analysis were only sampled on one shrub per site, except at site GZ, where it was done for two different cultivars. In figure 3 it is illustrated how the two stem samples were taken.

Figure 5: Example of foliage from a larger single stem. The total amount of foliage is mixed to ensure a representation of older, newer, shadowed and sun exposed leaves is included in the subsample brought to the laboratory for further analysis.

Samples corresponding to 10-100% of the stem foliage were taken by first mixing the separated leaves on a tarpaulin, or in a bowl for small stems, to ensure a representation of both older, newer, shadowed and sun exposed leaves, as done in figure 5. A couple of random handfuls of leaves, depending on the amount of foliage, were collected and weighted. Same procedure was done for the small branches. For the medium sized and large branches, small discs or pieces were cut of the branches, either from all branches within the category, or if many, from a randomly picked subsample of branches. Same procedure was applied to sampling material for the carbon and nitrogen analysis of the crown biomass. However, the samples were smaller. The stem and branch samples were kept in paper bags and the foliage in plastic bags with small air holes in a refrigerator or cooler bag, until it reached the ovens at the laboratory.

In addition to the main samples of branch, foliage and stems, fresh shoots, catkins and hazelnuts in husks were also collected from some sites. The green fresh shoot of the tip of the branches was sampled just for carbon and nitrogen analysis. The catkins were collected from the last four sites (EF(ABC), AF, DJ and SJ) also for the carbon and nitrogen analysis. Hazelnuts were registered at 27 out of the 85 felled stems, but due to the 1.5 month long period of data collection, the hazelnuts sampled and weighted were in very different states of maturity. Many of the hazelnut shrubs were young and had either not yet been bearing nuts, or were setting nuts for the very first time. It was thus decided not to include the hazelnuts in the biomass models.

Section 2B: Methods in the laboratory

2B.1. Dry weight to fresh weight ratio

All stem discs and stem pieces were placed in paper bags in an oven at 105°C until stable weight. The samples of branches and foliage were also placed in paper bags in an oven at 65°C until stable weight. The dry weight (DW) to fresh weight (FW) ratio (χ) for each sample was calculated using the expression:

$$\chi = \frac{DW}{FW} \quad [1]$$

To calculate the DW of the total foliage and branches for each stem, the total fresh weight for each category of branches and the foliage were multiplied by the χ value found for the representing aliquots. For calculating the stem DW, each stem section (i) would have two samples representing it χ_{i1} and χ_{i2}, one in each end of the section weighted. Therefore the χ value to calculate the DW of the given section, would be a mean of the two χ values:

$$DW_{stem\ section\ i} = FW_{stem\ section\ i} * \left(\frac{\chi_{i1} + \chi_{i2}}{2}\right) \quad [2]$$

The total stem DW will then be:

$$DW_{stem} = DW_{stump\ method\ b} + \sum_{i=1}^{n} DW_{stem\ section\ i} \quad [3]$$

Where n is the number of stem sections. $DW_{stump\ method\ b}$ is representing the lowest part of the stem, the stump, below the cutting point. This section of the stem has not been weighted, but is still a part of the total stem AGB. This part had to be estimated by calculating the volume and multiply it with an estimated stem basic density. Estimating the dry weight of the stem and crown by multiplying the fresh weight with the DW to FW ratios will in the coming sections be referred to as method A. The alternative method used for estimating $DW_{stump\ method\ b}$ can be applied to the rest of the stem as well. This method will be referred to as method B. The entire stem dry weight will also be estimated using method B, as to compare the two methods.

2B.2. Basic density of the stem

The basic stem densities were to be found for all 452 stem discs and pieces. The basic density is the dry weight (DW) of a piece of wood divided by its fresh volume (V_f):

$$\rho_{basic} = \frac{DW}{V_f} [4]$$

The weight of the dry wood is known from drying the samples at 105°C until stable. The fresh volume was measured using two different methods and compared:

- Method 1: Stem sample volumes were estimated from their water uptake when soaked to full saturation and the cell wall density.
- Method 2: Stem sample volumes were estimated using the water displacement method.

The reason why two methods were applied is that method 1 was assessed to overestimate the basic density values. This was further investigated and most likely caused by the fact that no vacuum had been applied to the stem samples, in order to remove potential air blocking the water from entering. Another issue hampering the wood in reaching actual water saturation was that several stem samples were long and narrow pieces with bark, leaving a small area for the water to enter the wood. This combination is potentially the reason for the underestimation of the fresh volumes and thereby the overestimation of the basic densities. Method 2 was tested on 105 of the samples, to test if these volume measurements gave more realistic densities, when compared to the literature values of 0.517 g/cm^3 (Chave et al., 2009) and 0.557 g/cm^3 (Özden et al., 2017). Both bark and pith were included in this study, which would be expected to lower the basic density values in comparison with the ones from the literature presumably only measuring the density of the wood tissue. In Özden et al. (2017) they only measured the density of the xylem tissue, where it was not specified for the value informed in Chave et al. (2009). Method 2 gave lower and more realistic density values than method 1. Besides having more realistic results, the method of water displacement have more credibility as cited in Husch et al. (2003) p. 125:

"The most accurate method of measuring volume of an irregular shaped solid is by measuring the volume of water that it will displace".

Due to time constraints, only the 105 samples out of the 450[3] had their fresh volumes measured twice.

[3] Two measurements failed during the work in the laboratory.

However, this was enough to compare the different results of the two methods and develop a regression model to "correct" the rest of the method 1 densities to a fitting method 2 density value. The remaining method 1 densities were "corrected", because they had to be used to estimate the total stem dry weights (Method B), where an erroneous density value could impact the results to become invalid. The final densities used for further calculations were a combination of the 105 method 2 density values and the "corrected" 345 method 1 density values. Both method 1 and 2 are explained in further detail below, because a big share of the variation found in the density values stems from the original method 1 measurements.

2B2.1. Method one

Method 1 was used on all 452 stem samples. The intact stem samples with bark[4] were saturated in water at room temperature and under normal atmospheric pressure. The samples were submerged in water until the change in weight had stabilized. For stem samples with a dry weight above 10 g, this criteria was met when the sample had increased the weight with a maximum of +2% compared to the earlier weight measured. If the dry weight of the sample was below 10 g, it was assumed stable and fully saturated when the weight had increased with no more than +0.1 g. This value was chosen as the weighting scale used for the measurements had a precision of +/- 0.1 g. The soaking time of the stems differed from one to five weeks[5] before fulfilling the above mentioned criteria to be water saturated. The time passing between two measurements of the same sample was as a minimum of two days. Each sample was *dripped off* for 30 seconds to remove surface water before weighing.

The saturated weights of the stem samples were used to calculate the basic density, assuming that the samples had reached their maximum moisture content ($V_{max\%}$) by being completely waterlogged.

$$V_{max\%} = \frac{SW - DW}{DW}$$

Where SW is the weight of the stem disc fully saturated, DW is the dry weight of the stem disc. The basic densities were calculated using the following expression:

[4] Most lichens were removed from the bark of the stem samples before submerged in water.
[5] To avoid fungal growth, atamon was added to the water.

$$\rho_{stem\ sample\ i} = \frac{DW_i}{\left(\frac{SW_i - DW_i}{\rho_{water\ at\ 20°C}}\right) + \left(\frac{DW_i}{\rho_{cell\ wall}}\right)} \quad [5]$$

Where the DW_i refers to the dry weight of stem sample *i* after being dried in the oven at 105°C until stable weight. SW_i refers to the weight of sample *i* when water saturated, $\rho_{water\ at\ 20°C}$ is the density of tap water[6] having the temperature of 20°C, here set to 0.9982 g/cm^3. The $\rho_{cell\ wall}$ is the estimated mean hardwood cell wall substance density with the value of 1.51 g/cm^3 (Kelloggs and Wangaard, 1969; Passialis, 1998; Zauer et al., 2013)

2B2.2. Method two

Method two relies on the principles of Archimedes. An object submerged in a liquid (or gas) will displace an amount of this liquid (or gas) that is equal to the volume of the object (Encyclopaedia *Britannica*). The water displacement method was used on the lowest samples taken from each of the 85 stems and an additional 20 randomly picked samples taken at different sample heights. The samples were soaked in water for at least two weeks, until their fiber saturation points were assumed to be met, to ensure that the volume would not increase any further. A cylinder of water with a fitting width to the stem discs was filled with water. The change in water level when the wooden sample was submerged in to the water was noted. The difference in water level equals the volume of the wooden sample. The density was found using equation [4].

The four missing density values, covering the two missing samples from the field and two values missing from the work in the laboratory, were found through the development of a regression model with the explanatory variables of "distance to stem top" and the diameter of the stem sample. More details on these four values can be found in Appendix B.7

[6] This is a generalized value – the content in tap water can variate among countries and regions.

2B.3. Age of the individual stems

The ages of the individual 85 hazelnut stems were estimated by counting the growth rings of the lowest sampled stem discs (either at 0.2 m, 0.3 m or 0.65 m sample height). As noted in Husch et al. (2003) the count of growth rings in temperate tree species is the best method of determining tree age, since the early spring wood and late summer wood alters in colour, which was also the case for the wood in the hazelnut stems.

The discs were polished to ensure a flat, smooth and even surface of the stem discs. Thus making the growth rings easier to distinguish. A hand lens was used to count the rings directly from the wooden discs. The results were cross-checked by scanning all samples in 600 pixels per inches and counting the growth rings on the picture as well.

Figure 6: An example of a scanned picture of one of the stem discs, here from site LF, shrub LF3. The rulers are included to enable the scanned pictures to be used for potential future studies.

Figure 6 is an example of one of the scanned stem samples. Several stems had false growth rings, often caused by abnormal weather, making the estimation of age more complicated (Husch et al., 2003).

2B.4. Carbon and nitrogen analysis

2B.4.1. Combining the crown biomass samples

For the carbon and nitrogen analysis, the biomass samples were all dried in an oven at 55°C until stable weight. The foliage samples were pooled in samples divided by sample time (week 30+31, week 32+33, week 34+35 and week 36) and further subdivided by sample region within that time. This led to seven samples of foliage. The small branches were

combined using the same categories of sample time, but no division of the geographic origin of the samples. This led to four pooled samples of small branches. The medium branches were divided in two equally sized groups. One only containing samples from site EF and the other a mixture. The three samples of large branches were combined in one single sample. The five samples of catkins and eight samples of green shoots were also combined in to one sample of each type. See appendix A.3. for the actual sample IDs combined.

2B.4.2. Dividing stem samples in categories of diameter and sample height

The 135 stem samples were divided in to 39 categories based on 2 cm intervals of stem diameters and sample height as seen in table 4. Categories with one to three samples were combined in to one pooled sample. If a category had between four and six samples, a random list maker (Random.org, n.d.(b)) was used to choose the three samples to combine to represent the given diameter and sample height. For the categories with more than six samples, hence deselecting more than half, two times three samples were pooled instead. By doing this, the category was more correctly represented. In the 0.2 m height and stem width group A, there were included four samples in each of the two pooled samples. The first three were chosen randomly, but since samples from site FJ were not represented in any other category, these were added intentionally.

All stem samples within each category were debarked and the bark percentage of the samples were determined, based on weight. The bark and wood were analyzed separately. An equal amount of bark was pooled from each sample within the categories to form 39 bark samples. The same was done for the wood. The pooled foliage, branch, bark and wood samples were ground in two rounds to fine powder and then analyzed for the carbon and nitrogen content in a Thermo Scientific FLASH 2000 organic elemental analyser (Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA).

Table 4: The stem samples divided in to 39 categories based on stem diameter group and sample height for the carbon and nitrogen analysis. The numerated samples, are the ones where a random list maker had been used to pick the samples from a larger group of fitting samples. The first two letters of the sample ID indicate site, then the number of the shrub and lastly the individual stem number.

Height/ Diameter	A]0 cm < 2 cm]	B]2 cm < 4 cm]	C]4<6]	D]6<8]	E]8<10]	F]10<12]	H]14<16]	K]20<22]
0.2 m	1. DJ3.9, 2. AF2.10, 3. GZ4.5 4. FJ3.4 / 1. GZ3.2, 2. KF2.5, 3. LF2.2, 4. FJ3.5	1. HM1.7, 2. EFB1.2, 3. GZ4.10 / 1. HJ1.1, 2. SJ1.29 3. DJ3.2	-	-	-	-	-	EFB1.1
0.65 m	1. KF2.5, 2. DJ3.9, 3. GZ3.10, / 1. GZ4.5, 2. LF2.2, 3. SJ1.15	1. HM1.7, 2. EFB1.2, 3. GZ3.5 / 1. SJ1.29 2. AF2.7, 3. GZ4.10	AF2.4, EFA1.5	HM1.20	-	EFC2.2, EFA1.2	EFB1.1	-
1.3 m	1. HJ1.1, 2. GZ3.2, 3. SJ1.15, / 1. GZ3.10, 2. EFB1.2, 3. DJ3.2,	1. AF2.7, 2. GZ3.5, 3. GZ4.10	HM1.20, EFA1.5	EFA1.2	EFB1.1, EFC2.2	-	-	-
2 m	1. DJ3.7, 2. GZ4.10, 3. SJ1.29 / 1. EFB1.2, 2. GZ3.10, 3. HM1.7	1. EFB1.1, 2. AF2.4, 3. SJ1.13	HM1.20, EFA1.5, EFC2.2	-	-	-	-	-
3 m	1. AF2.4, 2. HM1.1, 3. GZ3.5 / 1. GZ4.10 2. AF2.7, 3. EFB1.1	EFA1.5, SJ1.13	EFC2.2, HM1.20	EFA1.2	-	-	-	-
4 m	AF2.7, SJ1.13, HM1.1	EFC2.2, HM1.20, EFA1.5	-	-	-	-	-	-
5 m	EFC2.2, HM1.1, HM1.7	HM1.20, EFA1.5	EFA1.2	-	-	-	-	-
6 m	HM1.20	EFA1.2, EFA1.5	-	-	-	-	-	-
7 m	HM1.20, EFA1.5	EFA1.2	-	-	-	-	-	-
8 m	EFA1.2, EFA1.5	-	-	-	-	-	-	-
9 m	EFA1.2, EFA1.5	-	-	-	-	-	-	-

2B.5. Analysis of soil samples

16 top soil samples in total were taken for further analysis. The samples were weighted and larger rocks were removed, before they were dried in the oven at 55°C for two days. The samples were weighted again and sieved through a 2 mm sieve. The water percentage and weight of stones were determined. 10 g of each sample were then used to create a soil slurry in a 0.1 M $CaCl_2$ solution for measuring the pH value. Another fraction of the soil samples were used for an analysis of the carbon and nitrogen content also in a Thermo Scientific FLASH 2000 organic elemental analyser (Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA).

The bulk density (BD) was estimated by first calculating the volume of the entire soil sample, based on the dimensions of the soil auger, with an inside diameter of 2.5 cm and a length of 30 cm. The soil samples were estimated to have a volume (V_{total}) of 147.3 cm^3 per sample.

This is a rough estimate, since the soil auger was a half open model, meaning that the different soil samples would not be of exact same size/volume. This would to some extent depend on the coherency of the soil (moisture content, aggregates, clay content) and the way the soil auger was pulled from the ground.

$$BD = \frac{SW_{<2\ mm}}{V_{total} - (SW_{>2mm}/2.65)} \quad [6]$$

The weight of the stones ($SW_{>2mm}$) were used to calculate the volume of the stone fraction, by dividing with the density of quartz (2.65 g/cm^3). The volume of the stone fraction was then subtracted from the total soil sample volume, to get the estimated volume of the mineral soil. Finally the bulk density was calculated by dividing the dry weight of the mineral soil ($SW_{<2mm}$) with the estimated volume of the mineral soil.

Section 2C: Calculations

2C.1. Estimating the missing stem diameters at 0.2 m

To overcome the issue of missing stem diameters at 0.2 m, the diameters of the individual stems were estimated from the measurements of the common diameter or circumference at 0.2 m, with the following procedure: The cross sectional areas (A) of each stem at point 0.65 m were calculated from their diameter ($d_{0.65}$), with the formula:

$$A_{stem\ at\ 0.65\ m} = \pi * \left(\frac{d_{0.65}}{2}\right)^2 \quad [7]$$

The share of each stem cross sectional area of the summed cross sectional area of the involved stems at 0.65 m were determined. The share was assumed to be the same at 0.2 m. The cross sectional area of the 0.2 m point (A_{common}) was calculated as for the stems at 0.65 m and divided in to the shares of each stem (i), with n being the number of stems implied:

$$A_{stem\ at\ 0.2\ m(i)} = A_{common} * \left(\frac{A_{stem\ at\ 0.65m(i)}}{\sum_{i=1}^{n} A_{stem\ at\ 0.65m\ (i)}}\right) [8]$$

From the appointed 0.2 m area of each stem, the corresponding diameters were calculated:

$$d_{0.2\ estimated} = 2 * \sqrt{\frac{A_{stem\ at\ 0.2\ m(i)}}{\pi}} \quad [9]$$

This procedure was done to estimate the diameters at 0.2 m of 7 of the 85 felled stems, especially in order to estimate the volume of the lower stem parts. A specific situation applied to the biggest and oldest shrub, LF3. Here the dimensions of the stool was measured instead of a common stem diameter. The stool was 30 cm in height and had two perpendicular diameters of 70 cm and 110 cm. The diameters at 0.2 m had to be estimated by the same principle of the stems sharing the stool as a common resource.

The diameter measured at 0.2 m turned out to be too inconsistent and difficult to measure precisely in the field. This meant that several of the measured stems, to which the stem biomass had to be predicted, did not have precise individual stem diameters at 0.2 m. They would have had to be estimated by the described method above, introducing another level of estimation. To avoid this and potential end-users of the models to deal with this troublesome field measurement, the diameter at 0.2 m was not included in any further analysis.

2C.2. Calculating the stem volume

The stem volume outside bark had to be calculated for all 85 stems from the ground and to the very tip of the stem. The stems were divided in section: From the bottom cut to the 0.65 m mark, from 0.65 m to 1.3 m, from 1.3 m to 2.0 m and then every 0.5 m until the tip of the stem. For each section information on bottom and top diameter and the length of the sections was available. This level of detailed information required the use of Smalian's formula, used in forest mensuration since 1894:

$$V = l * \frac{A_1 + A_2}{2} \qquad [10]$$

Smalian's formula estimates stem volume by multiplying log length (l) with the average cross sectional area of the two ends of the given log (A_a and A_b). The area of the cross section of the log is given by the area of a circle, here using the diameter (d):

$$A = \pi * \left(\frac{d}{2}\right)^2 = \frac{\pi}{4} * d^2 \qquad [11]$$

Expression 10 and 11 can be integrated, letting the diameters becoming the direct input to the formula, here for calculating the volume of stem section i:

$$V_i = \frac{\pi}{8} * \left({d_{1i}}^2 + {d_{2i}}^2\right) * l_i \qquad [12]$$

Tree stems have traditionally been perceived as taking the shape of either a cone, neiloid or paraboloid (Husch et al., 2003). A combination is also often applied when dealing with an entire stem and not only a commercial timber log, as seen in figure 7. In Smalian's formula a tree stem is assumed to consist of stem sections resembling the frustum of a paraboloid corresponding to segment B in figure 7. Section B will in this study cover all stem middle sections from the lowest diameter measurement and upwards. The last piece of stem, section C, will be calculated as the top of a paraboloid, following the volume of a paraboloid:

$$V_A = \frac{(A_C * l)}{2} \quad [13]$$

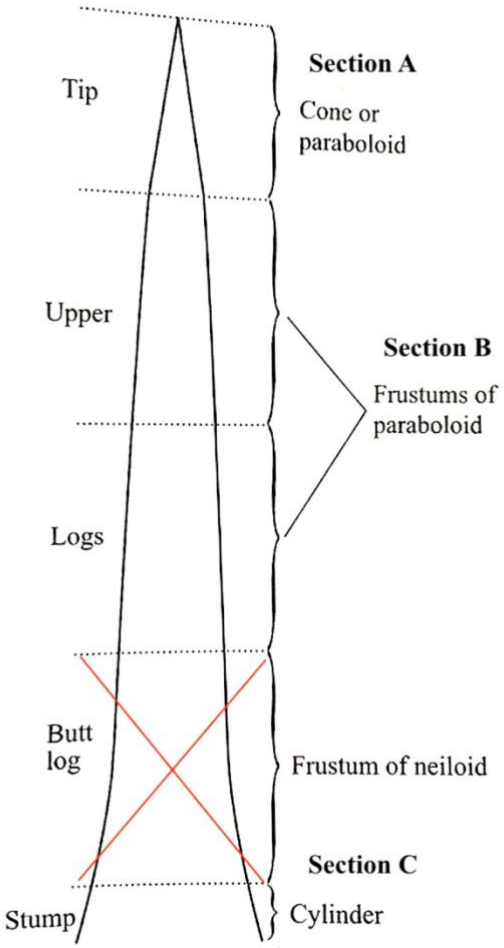


Figure 7: Overview of stem sections and their assumed solid form. Drawing modified from Husch et al. (2003) p. 121.

Hazelnut stems have relative small diameters compared to larger single stemmed forestry trees, to which these formulas originally have been developed. If the hazelnut shrubs have not been pruned, the stems become smooth and slender, without much sway as illustrated for the butt-log part at figure 7. This section is therefore not included as it does not fit the form of most hazelnut stems encountered in the data collection. The stump section is assumed to take the form of a cylinder, where the diameter is set to be the lowest stem diameter measured at 0.2 m:

$$V_A = A * l \Leftrightarrow \frac{\pi}{4} * l * d_{0.2\,m}^2 \quad [14]$$

The total volume of a given stem will then be the sum of the volume for all sections:

$$V_{stem\_total} = \sum_i V_i = V_A + V_{B1} + V_{B2} + V_{Bx} + V_C \quad [15]$$

With *x* indicating that there can more than two B sections.

2C.3. Calculating stem dry weight using method B

The dry weights of the 85 felled stems were estimated combining the above described volume estimations and the measured stem basic densities. Since this had already been done through the use of the stem fresh weights and the dry weight to fresh weight ratio (χ), the method using volumes and densities is referred to as method B. Each of the B stem sections, see figure 7, has a density value adhering to the upper (ρ_{i1}) and lower part (ρ_{i2}) of the given stem section. The mean of the two densities was applied to best describe the density of the given stem section:

$$DW_{stem\,i} = V_i * \left(\frac{\rho_{i1} + \rho_{i2}}{2}\right) \quad [16]$$

For the top A section of the stem, the uppermost estimated density value of the given stem was used. For the lower C section, the density value estimated for the lowest sampled stem disc was applied. The total stem biomass is the sum of the stem sections.

2C.4. Approach to biomass model development

Because of the sampling design of only felling two to five stems per hazelnut shrub, there are two nested levels in the biomass models: First stem-level models for predicting internal data, hence to estimate the biomass of the only measured but not felled stems, in order to estimate the total biomass of the sampled hazelnut shrubs. Stem level models for potential use on external data are also included. Secondly, shrub level biomass models are developed for extrapolation purposes to external data. The relationship between the predictor variables and the response variable in the two levels of the biomass models is treated as log-log transformed power functions. The log-log transformation is done in order to homogenize and normalize the variance of the response variable across the range of the predictor variable. By doing this, the data can fulfill the prerequisites of parametric regression analysis and allow fitting linear regression models to the dataset. This increase the statistic validity of the analysis and simplifies the calculations by allowing for ordinary least squares methods to be applied

(Baskerville 1972; Sprugel, 1983). This furthermore ensures that the error term at the original scale is multiplicative rather than additive (Mascaro et al., 2011; Xiao et al., 2011).
The log-log transformed linear model in its simplest form containing only one predictor variable:

$$\ln(y^{\wedge}) = \beta_0 + \beta_1 * \ln(x_1) + \varepsilon \quad [16]$$

*Note that some models will contain multiple variables.

- Where $y^{\wedge}$ is the model predicted value of y.
- β_0 is the model intercept to be estimated.
- β_1 is the slope coefficient to be estimated.
- ε is the error term.

Getting the predictions of biomass in the right units and not on the natural logarithmic scale, when the models have been developed in this format, will require a back transformation, by first taking the exponential function of the model:

$$y^{\wedge} = \exp(\beta_0) * x^{\beta_1} * \exp(\varepsilon)$$

Given experience in the literature, (Baskerville, 1972; Sprugel, 1983; Xiao et al., 2011) a systematic bias has been found when back transforming the error term, leading to an error of the predicted biomasses ranging from 10-20% (Baskerville, 1972). In order to correct this error, a correction factor is common to apply (Baskerville, 1972; Mascaro et al., 2011; Schindler et al., 2023; Sprugel, 1983) based on the mean square error of the regression (MSE).[7]

$$CF = \exp\left(\frac{MSE}{2}\right)$$

$$\Leftrightarrow$$

$$CF = \exp\left(\frac{\sum_{i=1}^{n}\left(\ln(y_i) - \ln\left(y_i^{\wedge}\right)\right)^2}{(n-2) * 2}\right)$$

- Where y_i is the observed value of y.
- $y_i^{\wedge}$ is the corresponding model predicted value of y.
- n is the number of observations.

[7] Originally presented by Baskerville, 1972, therefore also often referred to as the "Baskerville correction factor".

- The “(n-2)” in the expression corrects the squared residuals to the degrees of freedom. The number subtracted from n depends on the number of parameters estimated. So in a model where there is more predictor variables and therefore parameters (β_k) to estimate, the number will increase.

So when having back transformed the log-log linear model, the "exp (ε)" part of the power function will be replaced by the correction factor (CF) to minimize the bias associated with the back transformation. For the stem level models the following explanatory/predictor variables were tested: Stem diameter at 0.65 m (D0.65) and 1.3 m (DBH), stem length, a composite variable of length times the squared diameter at 0.65 m (LD^2) and the binary variable called “pruned” indicating with a “1” for stems that have been pruned, and “0” for stems that have not been pruned. The estimated stem ages were also tested as an explanatory variable. For the shrub level the main strategy was to use the shrub height and crown diameter, as well as exploring different opportunities of composite variables based on stem diameters. The variable “pruned” was also tested.

Based on the estimated biomass of total above ground biomass and stem, branch and foliage biomass separately, a biomass expansion factor was determined for all individually felled stems and for the entire shrubs. The biomass expansion factor (BEF) was calculated as the relation between the total aboveground biomass and the *stem biomass* (as the biomass of the stems excluding the crown biomass):

$$BEF = \frac{Total\ above\ ground\ biomass\ (incl.\ foliage)}{Stem\ biomass\ excluding\ branches\ and\ foliage}$$

Furthermore the branch to stem ratio and foliage to total above ground biomass (including foliage) were also determined.

2C.5. Estimating the total shrub carbon and nitrogen content

The results of the nitrogen and carbon analysis were used to estimate the total carbon content and nitrogen content of the sampled 32 shrubs. This was done for the different plant parts of foliage, branches and stems separately, as to use the different content of carbon and nitrogen found in the different plant parts. The value of carbon and nitrogen content used for the foliage was determined by the sample time and place of the shrub, since the foliage had been analyzed

grouped by sample periods of two weeks and the sample place. The shrub branch biomass was divided in to categories of small, medium and large branches, based on the average distribution found in the stems sampled from the given shrub. By doing this the information from the carbon and nitrogen analysis of the content in the different branch sizes of small, medium and large could be utilized, even though still being an estimate.

For estimating the carbon and nitrogen content of the shrub stems, the amount of bark had to be estimated. The diameter groups (A to K) represented by the stems in the shrub were noted (See table 3 for the diameter groups). A simple average of the bark percentage of the represented diameter groups was then used to estimate the amount of bark in the given shrub. Same procedure of taking the average of the diameter groups represented applied to estimating the nitrogen and carbon content of the wood and bark. The total carbon and nitrogen contents of the shrubs were then the sum of the estimated weight of wood, bark, branch and foliage carbon and nitrogen. This method is referred to as the "detailed estimate" as opposed to multiplying the total aboveground biomass of the shrubs with the overall average of carbon or nitrogen content analyzed across the different plant parts.

2C.6. The statistical analysis

The statistical software R-studio [Version 4.2.3 (2023-03-15) for Macbook] and Microsoft Excel [Version: 16.81] are used throughout the statistical analysis. The fit of the different tested regression models will be evaluated by visually examining the homogeneity and normality of the residuals and by comparing the three goodness of fit statistics: The adjusted coefficient of determination (Adj. R^2), the standard error of the regression (SER) and the Akaike information criterion (AIC). For the normality inspection both qq-plots and histograms of the residuals are used together with a Shapiro Wilks test for normality of the residuals. When handling multiple linear regression models, the predictor variables are checked for correlation by calculating the Spearman correlation coefficient, to check for multicollinearity. Many of the biometric parameters are however expected to correlate. The issue of multicollinearity is highly regarded when choosing the best biomass models, together with common sense as to which field measurements logically make sense to include for the models to best be able to predict the biomass of external data. Thought is also put in to the accessibility of the explanatory variables

chosen, since the potential end-users needs to be able to relatively easy acquire the needed field information.

A Chi-squared test is applied to check the significance of introducing additional variables to the regression models. For the most promising regression models a k-fold, repeated cross validation is made and their ability to predict is quantified by the RMSE output of the test. For the stem level data set a 10-fold, 5 times repeated cross validation is performed and on the shrub level a 3-fold, 3 times repeated cross validation, given the smaller sample size. In the study the CF will be calculated from the Root Mean Standard Error (RMSE) estimated by the cross validation.

Section 2D: Literature review

An initial literature review was conducted to get an insight in allometric biomass model development in general and for hazelnut shrubs specifically. Information on hazelnut shrubs botanically, as a crop and its carbon storage potential was also sought. The main databases used for searching articles were: Web of Science, Elsevier and the Library of Copenhagen University all including peer reviewed articles and for the latter relevant books in addition. The very first initial search were on Web of Science, using the query of words:

"Corylus avellana OR European hazelnut AND growth OR biomass OR sequestration OR carbon OR morpholog* "

This gave 576 matches that, as shown in figure 8, primarily fitted the themes of this thesis. The first half of the articles was looked through thoroughly, but as the relevance decreased from there, only the titles were scanned briefly. The words "model*" and/or "allometr*" were added in a later search, as well as a broader search on allometric biomass model development. Most of the additional relevant literature were found within the list of references from the articles found in the initial rounds of search for literature. A few articles were also recommended by the thesis supervisors.

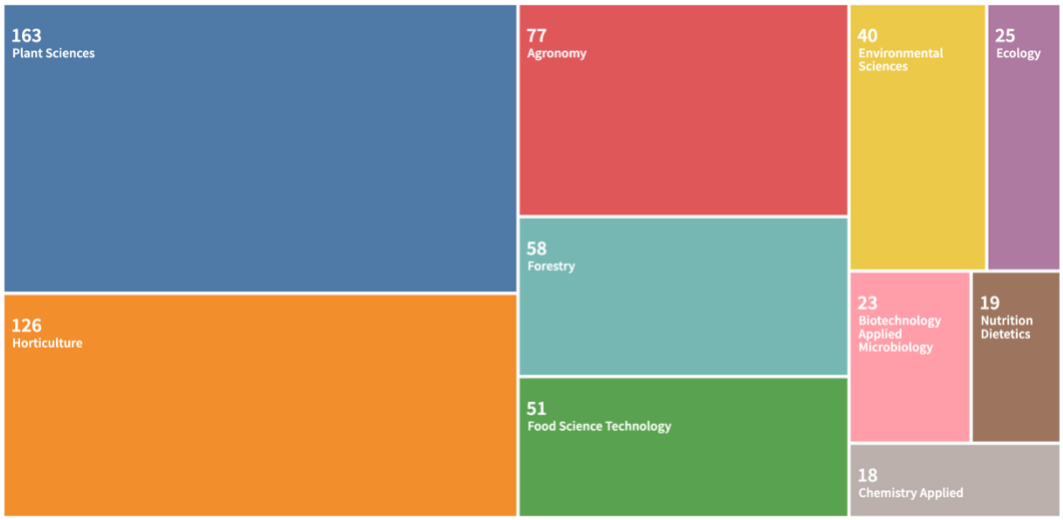


Figure 8: The result of the initial search on Web of Science divided in to themes.

For the section on agroforestry more broadly and in Europe, a literature search on the above mentioned databases was initiated using the following key words: Agroforestry AND carbon OR storage OR sequestration OR ecosystem service* (AND temperate OR Europe). Specific facts on land use coverage or GHG emissions were sought specifically, favoring data from the Food and Agriculture Organisation of the United Nations, since it is a reliable source and openly available to all.

Section 3: Results

A total of 32 hazelnut shrubs consisting of 455 stems were measured at 10 different sites around Denmark. The mean number of stems per tree were 14.2 ranging from 2 to 57 stems per individual hazelnut shrub and with the average number of shoots of 7.33 per shrub varying from 0-58 shoots. Data were collected on a total of 423 individual hazelnut stems of which 85 of them were felled and used for further analysis. In table 5 the distribution of shrubs and stems per site is presented. In average 29% of the stems within the shrubs were felled, varying from 9-67%, depending on size, total number of stems and agreements with the owners at the sites. From the 85 felled stems a total of 452 wooden discs/ stem samples were taken for further analysis to the laboratory for determining the fresh to dry weight ratio and to estimate the basic stem density.[8] The crown biomass samples totalised in: 85 samples of foliage, 119 samples of branches consisting of 79 samples in the small branch category, 32 in medium, 7 in large and 1 in x-large. The sites include a broad range of management systems (see table 2). Within these different systems, altering intentions and outputs related to the hazelnut shrubs are represented: From mainly focussing on the production of hazelnuts, through perceiving the hazelnut shrubs as a mean to increase site biodiversity and storage of carbon, to the usage of the hazelnut shrubs in fences sheltering other crops or simply dividing areas of different purposes. The responses from the owners as to what their intentions and main considerations for planting hazelnut shrubs were, is summarized in table 5.

The pH values of the sites ranged from 3.81 to 7.41 (measured in 0.1M $CaCl_2$). The lowest two values (3.81 and 4.18) were found at the 6 year old forest garden, site GZ, established in the Nordsjælland on a 50 years old noble fir *(Abies procera)* plantation. The highest pH value of 7.41 was found on site KF on a 5 year old hazelnut orchard, established on a field formerly used for Christmas trees. The field had undergone two cycles of cereal production before the hazelnut orchard was established. The second highest pH value of 7.25 was found at the old hazelnut fence at Møn, site HM. The pH sample at HM was taken behind the hazelnut shrubs leading up to a small belt with mixed, wild trees, indicating a fairly undisturbed soil, opposite of the soil at site KF. In table 5 the active pH-values are presented as site averages, as opposed to the here described potential pH values.

[8] During the calculations of stem dry weight, it was found that the sample for FJ3.4 at 0.65 m and FJ4.1 at 0.65 m were missing.

Table 5: Overview the of hazelnut shrubs sampled per site, results of the soil tests and summarized answers from the site owners on the intentions and purpose of the hazelnut shrubs within their systems. The bulk density, C:N ratio and pH values is presented as the site averages and the pH in the format of the Danish "reaktionstal", where the pH-value measured at 0.1 M $CaCl_2$ is increased with 0.5 to get the active pH value instead of the potential. At site LF only 25 out of the total 57 stems constituting the shrub LF3 were measured.

Site	No. shrubs	No. measured stems	No. felled stems	Period of data collection	Soil pH (Reaktions tallet)	Bulk Density	C:N ratio of soil	Intensions and expected outputs
AF	2	30	6	2nd half of Aug.	7.42	0.87	12.8	Sheltering, aesthetics, testing of different hazel cultivars prior to the establishment of a + 25 ha hazelnut orchard.
DJ	3	33	8	Start Sept.	4.78	0.94	11.5	Planted with the intention of improving the near field biodiversity as well as hazelnut yields.
EFA	2	38	7	2nd half of Aug.	5.9	1.04	11.5	Originally planted and managed as an intensive conventional hazelnut orchard, but have been abandoned for the last 10-15 years and left as a "wild" area. Some small harvest for own consumption and open for strangers passing by.
EFB	2	38	7	2nd half of Aug.	5.44	1.14	11.5	Intensively managed hazelnut orchard with the primary goal of selling hazelnut yields as fresh nuts to customers, who come an pick the nuts themselves.
EFC	2	7	2	2nd half of Aug.	5.36	1.07	11.5	Testing the combination of sheep grazing as well as keeping ducks within the same area as the hazelnut orchard for a multipurpose use of the area.
FJ	4	16	7	End July	5.19	1.13	14.4	Biodiversity and carbon sequestration as the main objectives followed by the hazelnut yields for costumers to "pick their-own nuts".
GZ	4	61	11	1st half of Aug.	4.78	0.84	16.3	Hazelnut yields, increasing biodiversity, minimizing soil erosion by planted along contours. The Red Zeller cultivar is added for aesthetics.
HJ	3	30	8	End July	5.42	1.20	14.1	Improving biodiversity, including hazelnut since it is a native species.
HM	2	47	6	1st half of Aug.	7.75	1.04	11.9	Sheltering, dividing two properties.
KF	3	13	5	1st half of Aug.	7.91	1.18	21.1	Hazelnut yields as a start, but later the focus will be on the walnut trees and their potential yields. The orchard is established for improving local biodiversity and sequestrating carbon. With time it is also indented to replace the sheltering function of an old shelterbelt nearby.
LF1+2	2	16	5	1st half of Aug.	5.96	1.01	12.1	Hazelnut yields, improved biodiversity especially creating habitats for the hazel dormouse (*Muscardinus avellanarius*) and carbon sequestration.
LF3	1	25 / 57	5					Sheltering, aesthetics.
SJ	2	69	8	Start Sept.	5.37	1.33	12.2	Sheltering effect of other fruit trees and berry bushes. Initially also planted for harvesting hazelnuts, but the owner has given up due to low outputs and too high amount of manual labour.
Total	32	423 / 455	85					

The different types of systems, the age of the stands and the variation of the soil conditions, testify that the sampled hazelnut shrubs in this study represents a broad range of the different management situations and site conditions, to which hazelnut shrubs exists in Denmark.

3.1. Distribution of the biometric values of the dataset

3.1.1. Shrub level

The crown diameter of the 32 hazelnut shrubs ranged from 56 cm to 650 cm. The smallest crown diameters were found in the only 4 years old alley cropping system in Western Jutland at site FJ. The biggest diameters were found among wild hazelnut shrubs in living fences at site LF and HM. The two sites also have the oldest stand ages of 70 and +50 years for LF and HM respectively. The average crown diameter of the sampled hazelnut shrubs was 261.9 cm with a standard error of the mean (SE) equal to 29.9 cm and with a median at 207.2 cm. The error of precision of the crown diameter measurement (CD) was estimated to ± 5.75%. The mean shrub height was 338 cm with SE of 39.3 cm and a median of 279 cm. The shrub height varied from 96 cm at site FJ to 855 cm at site EFA. Site EFA is a formerly intensive hazelnut orchard, which had not been pruned in 10-15 years. The neighbouring hazelnut shrubs in EFA were in high competition, creating a closed canopy environment. The shrub height was measured with an estimated error of precision of ± 2.55 %.

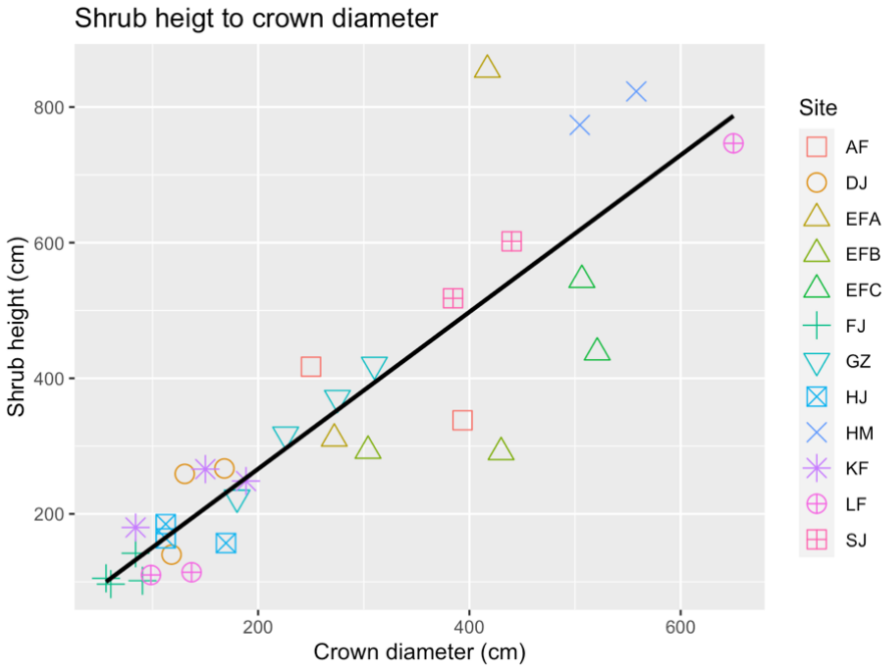


Figure 9: Scatter plot of the non-log transformed crown diameter and shrub height with a regression line. Crown diameter is able to explain 77.8% of the variation found in shrub height. The residual plot of the linear model of the trendline shows heteroscedasticity (see appendix B.1).

The CD and shrub height have a positive linear correlation, as indicated on figure 9, with a Spearman's correlation coefficient of 0.9153. The distances of the data points to the trendline in figure 9 tend to increase as the dimensions of the shrubs increase, revealing the heteroscedastic nature of the morphometric relations of the shrub. Figure 9 also indicates that the sampled hazelnut shrubs reflect a wide range of sizes, which is important in regards to fitting regression models to the data.

3.1.2. Stem level

The distribution of the measured stem lengths and diameters at 0.65 m (D0.65) are presented in the frequency histograms in figure 10 and their relation in figure 11. The stem D0.65 ranged from 0.2 cm at site FJ to 16 cm at site EFC with an overall average of 2.56 cm (SE = 0.126 cm). The stem D0.65 median is 1.6 cm and the third quantile 3 cm, confirming the skewed distribution visually expressed by the frequency histogram in figure 10. The majority of the stems belong to the smaller diameter groups of A and B and the fewer much bigger values influence the mean value quite a lot.

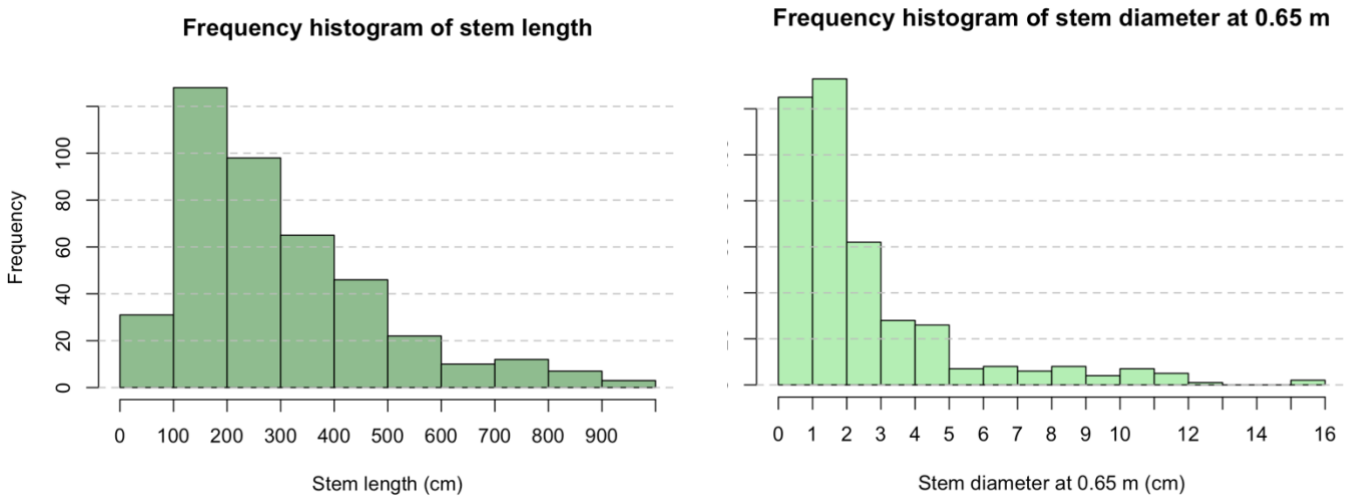


Figure 10: Frequency histograms showing the distribution of the morphometric measurements of individual stem length and stem diameter at 0.65 m. This is including all measured 423 stems. When visually presenting the distribution of the stems, the D0.65 is favoured to the DBH, since 74 stems are lower than 1.3 m and otherwise would be excluded.

As seen on figure 11 most of the higher diameter values stem from the EF sites at Fyn, especially field EFB and EFC, which were heavily pruned hazelnut shrubs in a 45 year old orchard. The stem lengths range from 55 cm to 938.5 cm, with a mean value of 297 cm (SE = 9.020 cm) and with a lower median of 253 cm. The stem length measurement had an estimated

error of precision of ± 3.59%. Interestingly the maximum value of stem length is larger than the maximum value of the shrub height, measured to be 855 cm. Both maximum values however stem from the same shrub. The difference of 83.5 cm might be due to the different ways of measuring stem length and shrub height: The shrub height was measured as the straight vertical distance from the ground to the highest leaf-bearing branch and the stem length was measured along the stem until the very tip, trying to including its bends.

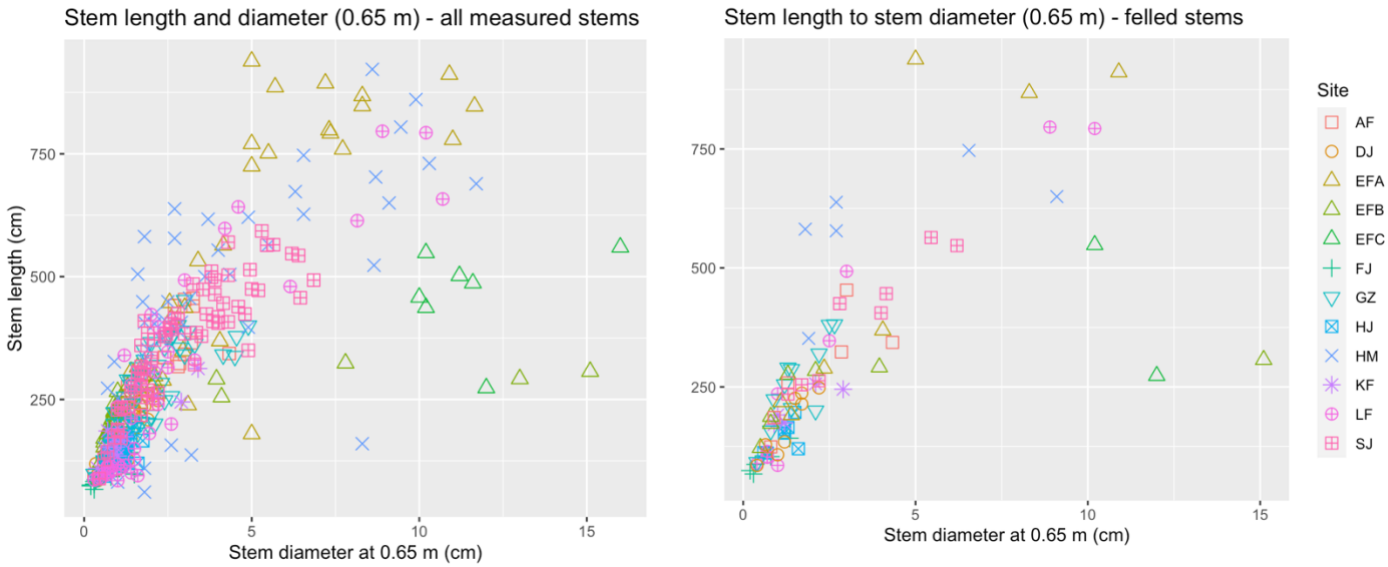


Figure 11: The non-log transformed distributions of D0.65 to stem lengths. To the left all 423 measured stems have been plotted, except one stem from site FJ that had a stem length below 65 cm. The scatter plot to the right shows the distribution of the 85 felled stems, once again excluding the one stem below 65 cm.

Comparing the two scatter plots of the D0.65 to stem length in figure 11, it seems like most trends and variation of the hazelnut stems measured (left) have been caught by the felled 85 stems (right). This is important since the felled stems create the basis of predicting the biomass of the remaining 338 stems. However, among the felled stems there are a lack of representation of the stems with a D0.65 value of 5-10 cm and stem lengths below 500 cm.

3.2. Stem age

Figure 12 shows the total stem above ground biomass including foliage (AGBF) in dry weight stated in grams to the estimated individual stem ages in years. The total AGBF ranged from 12.9 g to 33984.3 g among the stems felled and the age from 1 to 40 years, with a mean of 6.5 years and a median of 4 years. The low stem age is not surprising since more than half

the sites visited had stand ages of 6 years and below and since it was easier to get allowance to fell the smaller stems than the large ones. The AGBF increases with increasing stem age and the age variable is able to explain 81.43% of the variation found in the AGBF. Figure 12 also shows the coincident that most of the bigger stems sampled have been pruned.

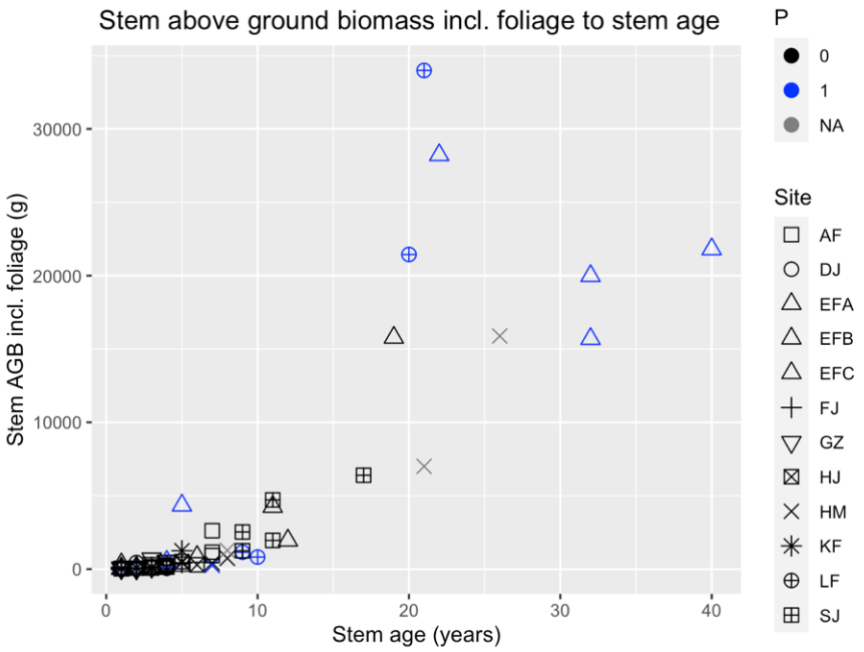


Figure 12: Scatter plot of above ground biomass including foliage to the estimated stem age. The majority of the stems are below 10 years. A scatter plot of the 1-10 year old stems is available in appendix B.2. Three stems HM1.20, HM2.1 and HM2.8 are missing the information about whether they were pruned or not. They do come from hazelnut shrubs that have been pruned, but information on whether the specific stems have been pruned are unfortunately missing.

Table 6: The two best linear regression models for predicting the stem age of individual stems in a hazelnut shrub. The variables have been loglog-transformed as to overcome the issue of heteroscedasticity. See appendix B.4 for the other tested stem age regression models.

Predictor Variables	**Estimated coefficients (SE)**	**P**	**Adj. R^2**	**SER**	**AIC**	**RMSE**	**CF**
Intercept	0.9152 (0.065)	***	0.7142	0.5146	130.7	0.5122	1.140
ln(D0.65)	0.888 (0.062)	***					
Intercept	-0.7878 (0.166)	***	0.7019	0.5256	134.3	0.5238	1.147
ln(L*D^2)	0.3330 (0.024)	***					

*"P " is codes of t-test p-value results indicating significance of the estimated regression coefficients: '***' 0.001 '**' 0.01 '*' 0.05. CF is the correction factor, RMSE the root mean standard error, AIC is the Akaike information criterion, SER the standard error of the regression, Adj. R^2 is the adjusted coefficient of determination.*

The stem age is not a common information to have and it requires destructive methods for counting the growth rings. This can be done either by inspecting the cross section of the stem, as in this study, or alternatively by an increment borer. A model to predict the stem age from non-destructive measurements was therefore developed.

Figure 13: Scatterplot of estimated stem age to the stem diameter at 0.65 m.

The two best models is presented in table 6. As seen in figure 13, D0.65 have a positive linear relation with stem age and D0.65 and age have a Spearman's correlation coefficient of 0.8365. The scatterplots of length and LxD^2 as predictor variables for stem age can be found in appendix B.3. The regression model using D0.65 as explanatory variable turned out to be the best model according to the goodness of fit statistics and the cross validation. Adding the stem length information in the format of the composite variable LD^2 did not seem to improve the fit.

The biomass expansion factor (BEF), branch to stem ratio and foliage to AGBF ratio tended to stabilize with increasing age of the stems, as seen in figure 14. The biggest variation of the expansion factors were found in the younger stems, especially below 7 years, being clearest in the foliage to AGBF ratio. Here the mean value were 0.215 for the stems 7 years old and below with a standard deviation of 0.096 and the mean value for the stems older than 7 years were 0.057 with a standard deviation of 0.033. For the BEF the mean values were 1.70 for stems 7 years and below and 1.35 for stems above 7 years. As seen on figure 14 the trend were not as clear for the branch to stem ratio, with the mean ratios of 0.303 and 0.278. All three ratios do indicate that as the stems becomes older a bigger part of the biomass is found in the wood of the stems rather than in the crown.

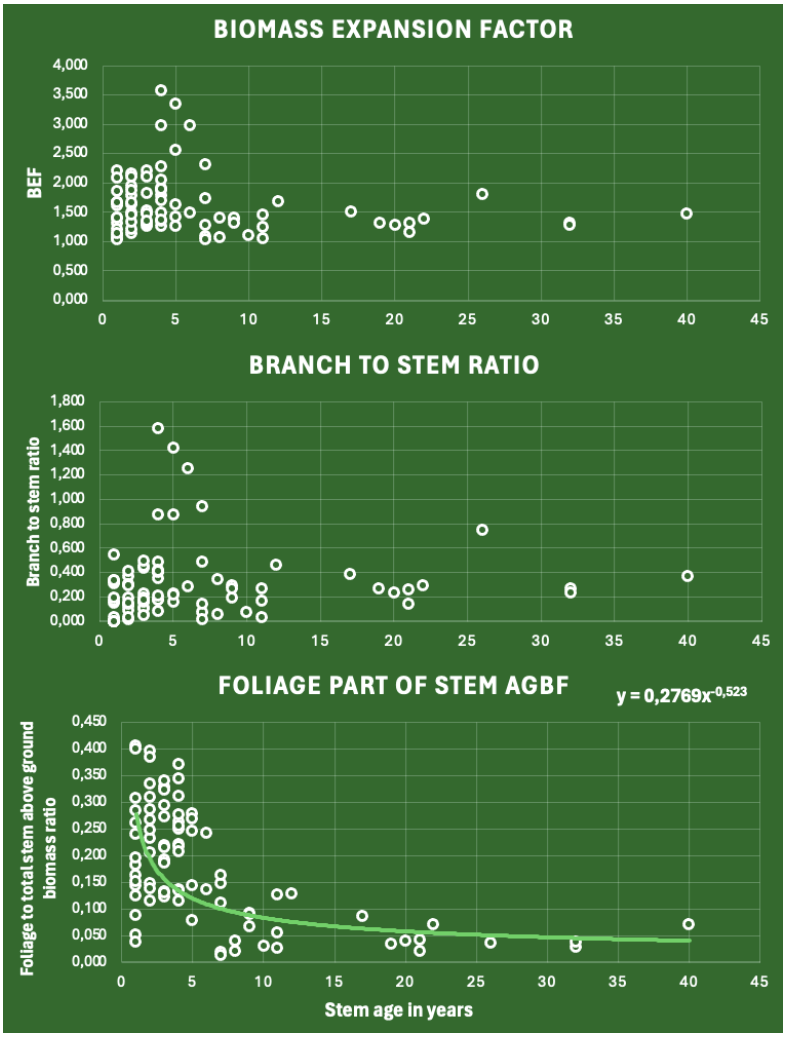
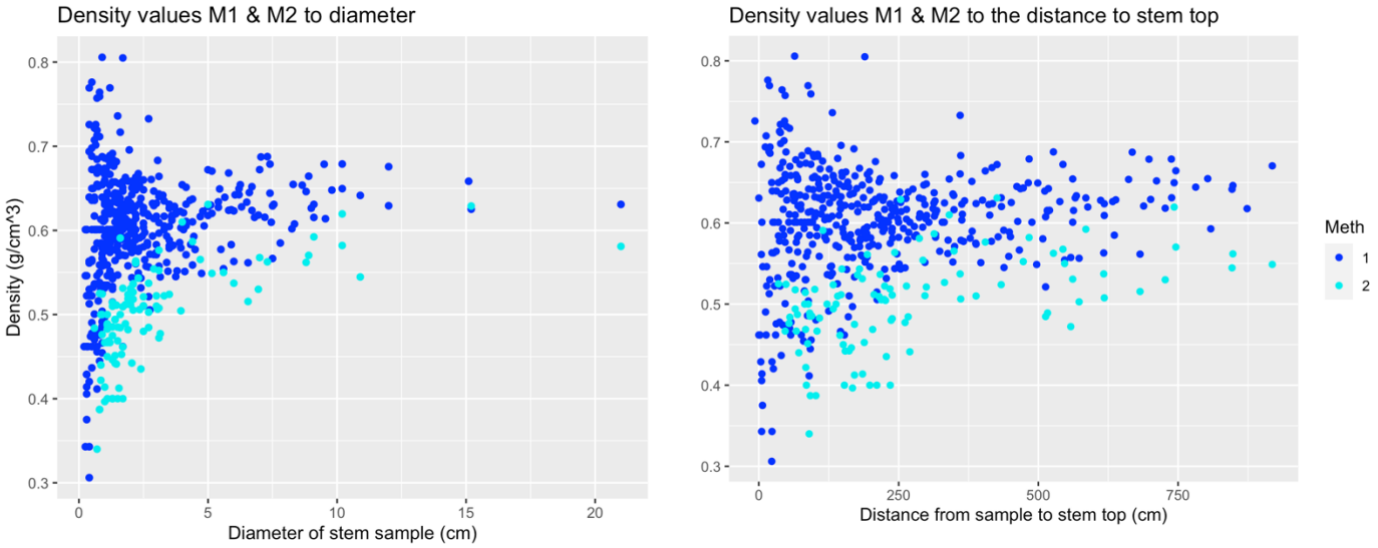


Figure 14: Biomass expansion factor, branch to stem ratio and percentage of foliage to total stem AGBF to the estimated stem age. It was only possible to plot a meaningful smooth regression (power function) for the foliage to AGBF percentage.

3.3. Stem basic densities

Method one (M1) density values measured on 450 stem samples gave an overall mean basic density of the hazelnut stems at 0.603 g/cm^3 (SE = 0.003) with at standard deviation of 0.067. The densities found by using the saturated weight of the stem samples to determine the volume, M1, was realized to give inaccurate results. The second method (M2), using the water displacement method to measure the stem volumes, was tested on 105 of the stem samples. This gave an overall mean density of 0.502 g/cm^3 (SE =0.006) with a standard deviation of 0.057. The two means are significantly different from each other, according to a two sample t-test assuming unequal variance. The same is true when comparing the 105 paired samples. This indicate that the two methods gives significantly different results. In figure 15 the M2 density

values (light blue) generally lies below the M1 values (blue). When visually inspecting the distribution of the densities to the diameter of the stem samples (figure 15, left) the variance is clearly biggest among the small diameters, true for both the M1 and M2 densities. The same tendency is present among the samples taken closest to the stem top (figure 15, right). The variance seems to be, at least partly, related to the sampled material rather than just the method of measurements. A F-test for variance concluded that there is a significant difference in the variance of the two 105 parried samples. It does however not seem big given neither the range of 0.321 (M1) and 0.291 (M2) nor the standard deviations of 0.0541 (M1) and 0.0569 (M2) seem far from each other.



<u>Figure 15:</u> Scatterplots of the 450 M1 density values (blue) and the 150 M2 density values (light blue) plotted against the stem sample diameter (right) and the distance from the height on the stem, at which the sample was taken, to the tip of the given stem (left).

Based on these findings the remaining 345 samples only measured with M1 were transformed to M2 values given the regression line showed in figure 16. The slope coefficient is 0.8288 with a 95% confidence interval of [0.816 ; 0.841]. The intercept was forced through (0,0) since the first regression line had an insignificant intercept. All 345 samples were multiplied by 0.8288 to get their corresponding "M2 density values". Because of the relative big variance in the material, which seems to be consistent among both methods, the boundaries for being considered an acceptable density value were set as [0.300;0.700][9].

[9] The density values were needed in the calculation of stem biomass. It was therefore necessary to have values that seemed realistic. The interval was assessed to be wide enough to contain all natural variance and only exclude values that most likely was caused by measurement errors.

Estimated density values had to be assigned to a total of 8 values;
4 outliers and 4 missing values
(see appendix B.7 for the specific samples and values). The final overall mean of the basic stem densities is 0.502 g/cm^3 (SE = 0.003) based on all 454 samples. The mean density values of the different stem diameter groups are shown in table 7. The basic stem densities seem to increase with increasing diameter.

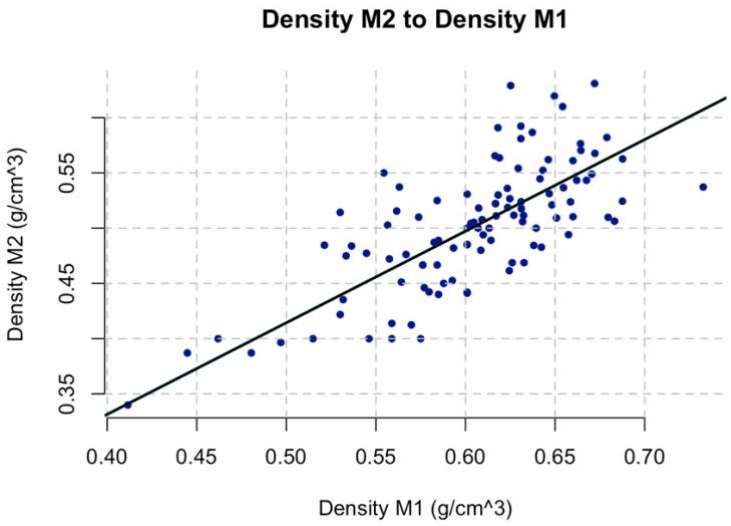


Figure 16: The 150 parried measurements of density, with a regression line with the slope of 0.8288 and an intercept at 0.

The diameter of the stem sample was the best single predictor variable at predicting the densities (table 8). The loglog transformed variables gave a more reasonable residual plot, however still showing a funnel shape across the horizontal axis (see appendix B.6 for the residual plots). Model 2 is evaluated to be the best model to predict the stem basic density, given the lower AIC values and adjusted R^2 values. Model 2 is used to predict the density values of the 4 missing values and 4 outliers. The R^2 values are however low for both model 1 and 2 with the multivariable model 2 including diameter and distance to stem top, only being able to explain 12.8% of the variance found in the density values.

Table 7: First is the mean dry weight to fresh weight ratios of the eight diameter strata and the crown parts presented with the number of samples within each category. Second is the mean stem basic density of the eight diameter strata and the number of samples within each strata. Both the DW to FW % and basic density increase with increasing diameters.

Diameter group		**DW to FW ratio (χ)**	**No. of samples**	**Basic stem density (ρ)**	**No. of samples**
A	] 0 cm ; 2 cm]	48.49%	252	*0.492*	*262*
B	] 2 cm ; 4 cm]	55.59%	108	*0.503*	*109*
C	] 4 cm ; 6 cm]	59.16 %	37	*0.517*	*39*
D	] 6 cm ; 8 cm]	57.62 %	22	*0.528*	*23*
E	] 8 cm ; 10 cm]	59.04 %	12	*0.538*	*13*
F	] 10 cm ; 12 cm]	60.68 %	3	*0.566*	*5*
H	] 14 cm ; 16 cm]	48.49 %	*2*	*0.587*	*2*
K	] 20 cm ; 22 cm]	55.59 %	*1*	*0.581*	*1*
Leaves		*38.95 %*	*80*	-	-
Small branches		*45.94 %*	*78*	-	-
Medium branches		*54.39 %*	*32*	-	-
Large branches		*57.49 %*	*7*	-	-

*Table 8: The two best fitted models for predicting the stem densities. See appendix B.5. for the other tested regression models. "P " is codes of t-test p-value results indicating significance of the estimated regression coefficients: '***' 0.001 '**' 0.01 '*' 0.05.*

Predictor variables	Estimated coefficients (SE)	P	Adj. R^2	SER	AIC	RMSE
Model 1						
Intercept	-0.7211 (0.006)	***	0.1193	0.1074	-720.5	0.1068
ln(Diameter)	0.0458 (0.006)	***				
Model 2						
Intercept	-0.6365 (0.037)	***	0.1281	0.1069	-723.9	0.1066
ln(Diameter)	0.0669 (0.011)	***				
ln(Dist. top)	-0.0195 (0.008)	*				

3.4. Comparing two methods of estimating stem dry weight

The stem dry weights (excluding the crown biomass) were estimated using two different approaches:

- Method A (MA) that used fresh weight of the stem sections measured in the field with the DW to FW ratios found from the samples in the laboratory. See table 7 for the average dry weight to fresh weight ratios. MA is assumed to be closest to the true stem dry weight.
- Method B (MB) using the calculated stem volume together with the estimated basic densities.

The mean value of MA is 1.956 kg (SE = 0.526 kg) and 1.910 kg (SE = 0.509 kg) for MB. MB tends to overestimate the stem dry weight with 7.34% compared to MA. The results of the two methods were tested for difference in a paired samples Wilcoxon test (p-value = 0.03987), which concluded that the two methods give significantly different stem dry weights. The two methods, as shown in figure 17, do reach similar values of stem dry weight. The slope of the regression line in figure 17 is 0.967 (0.005) with a 95% confidence interval of [0.957 ; 0.978], hence not including 1, which otherwise would indicate that the results of the two methods were indifferent. Stems below 1000 g were plotted and a regression line fitted, to test whether the bigger stems is the main reason to variance. The slope of the regression line fitted to the smaller stems was 1.00002 (0.011) with a 95% confidence interval of [0.978; 1.022], hence including 1. This confirmed the preliminary hypothesis that the main difference between the two methods was found among the bigger stems. (See appendix B.8 for the graph). It does also point to the possibility that the overall difference found between the two methods is a random coincidence.

This decrease the validity of the first stated difference between the two methods. The MA stem dry weights were the ones used for further analysis and for fitting stem biomass models.

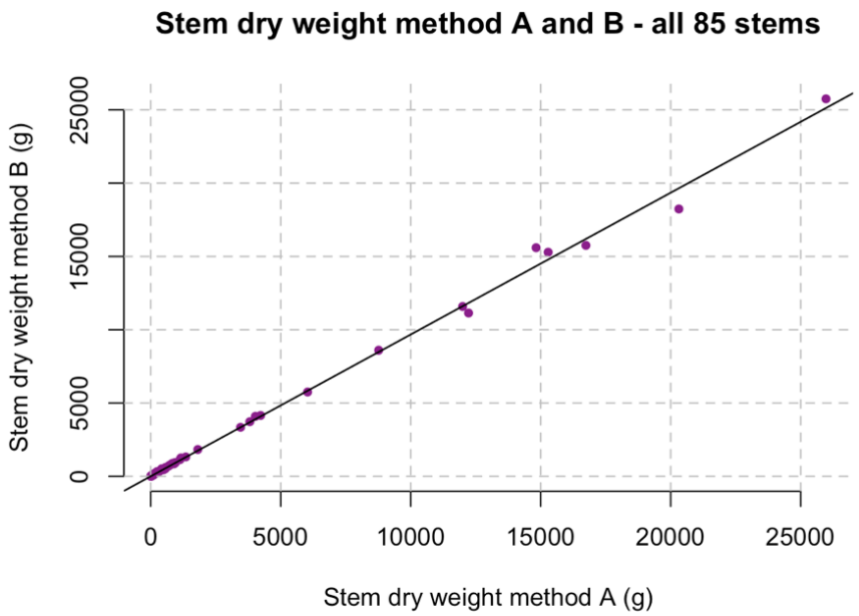


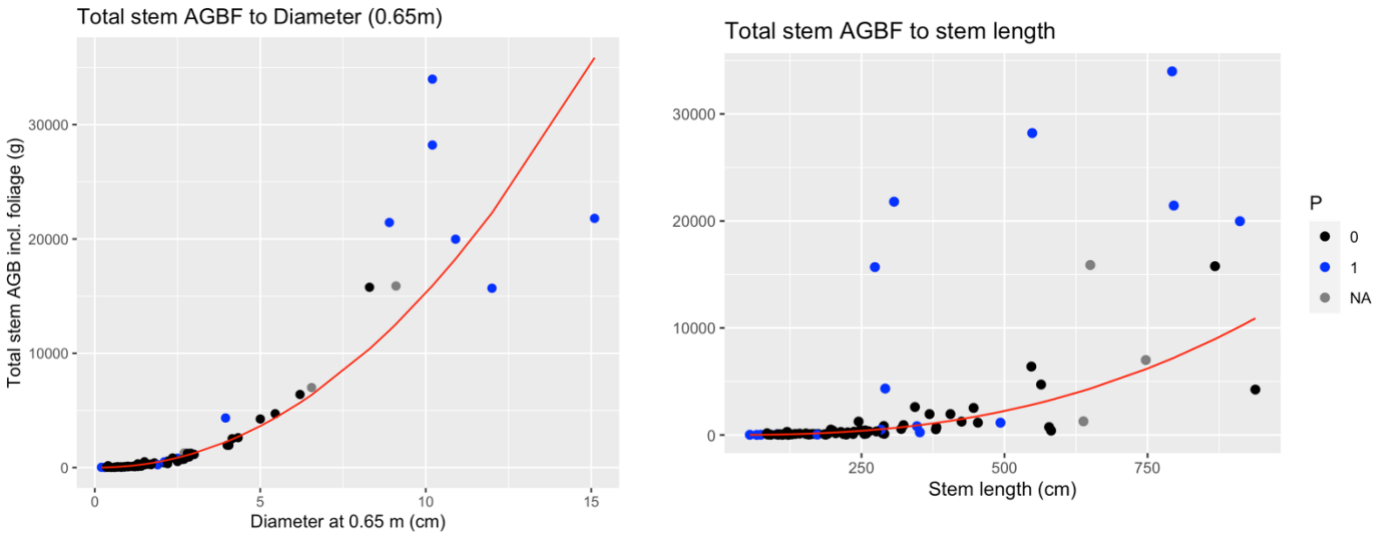
Figure 17: Comparison of method A and method B at their estimations of the stem dry weights. The regression line have the slope: 0.967 and a forced intercept in (0,0), because the intercept was deemed insignificant.

3.5. Stem level aboveground biomass regression models

19 stem level biomass regression models are presented in table 9: Seven models for predicting total stem above ground biomass including foliage (AGBF), three models for predicting the total stem above ground biomass excluding foliage (AGB), two models for stem biomass excluding the crown biomass of foliage and branches, one model for the stem volume and three models for foliage and for branch biomass. The linear regression models are presented with the estimated coefficients, significance of the estimated coefficients and with the relevant goodness of fit statistics. More models are presented for the stem AGBF than the others, in order to highlight some tendencies in the data set that also applies to the other predicted biomass variables. This will be explored further in the coming sections. The predictor variables included are D0.65, stem length, the "pruned/not pruned" binary variable and the composite variable of stem length multiplied by the squared diameter at 0.65 m (LD^2).

3.5.1. Exploring the single explanatory variables

For all response variables D0.65 was the best single *measurement*[10] at explaining the variance found in the biomass. Explaining 92.46% and 93.14% of the variance of the stem AGBF and AGB respectively, see figure 18 (left) for the AGBF model 1. Even though the D0.65 variable performed better than the composite variable for e.g. stem AGBF and stem foliage biomass (see table 9), it is too simple a model to safely use for extrapolation on other unknown data, without expecting a high error of prediction. Only having the one dimension of the diameter makes the models miss important information of the rest of the stem growth and potential indicators of management or site effects.



<u>Figure 18:</u> The total stem above ground biomass including foliage to the stem diameter (left) and stem length (right). The color indicate whether the stems have been pruned (blue) or not (black). The red power functions are the back transformed AGBF model 1 (left) and the right is the back transformed AGBF model 0 from table R5.

The stem length was the worst single predictor variable compared to D0.65, DBH and stem age. An example of a model only including the stem length is included in table 9 as the AGBF model 0, where the adjusted R^2 value is only 0.7154. This is also illustrated in relation to AGBF in figure 18 (right), where the single regression model (red) only including the length variable, clearly are not able to explain a significant part of the variance within the AGBF. To include the variable "pruned" improved the fit of the AGB, AGBF, stem dry weight and stem volume models significantly. To judge from figure 18 it seems like the stems that have been pruned are some of the stems varying the most from the regression curves, coinciding with also being

[10] Single measurement is referring to a single variable that only require one field measurement of the stem as opposed to the LD^2 variable, also functioning as a single variable, but requires two field measurements.

some of the largest stems sampled. Figure 18 also displays that the management practice of pruning seem to effect the relation between stem length and AGBF the most. The variable "pruned" have a larger regression coefficient of 1.0129 (0.278) when combined with stem length as in AGBF model 4, than when combined with D0.65 as in AGBF model 3, with the coefficient of 0.3999 (0.160). This confirms the tendency seen in figure 18. The stem diameter at D0.65 supposedly explains a greater part of the variance potentially caused by the pruning practice. This fits with the observed tendencies in the field of heavily pruned stems, like at the site EFB and EFC, with much wider diameters than any other sampled stems, indicating that when pruned routinely the shrub thicken the stems.

One model, the branch biomass model 0, had stem volume as the predictor variable, since this was the second best fit for branch biomass, only surpassed by stem dry weight (see appendix B.14)[11].

3.5.2. Models for use on future external data and models for use in-study on measured stems

In the presentation of the stem level models, a distinction is made between models that are evaluated best for predicting the remaining 338 stems of the studied shrubs (coloured yellow and noted with a § in table 9) and the models best suited for extrapolation to external data outside this study (coloured green in table 9). The main difference revolves around the use of the predictor variables of stem length and D0.65 as two separate variables or as a combined variable (LD^2). The latter variable is included instead of the separate D0.65 and stem length variable, when it gave a better or equally good fit as to avoid multicollinearity and reduce the number of parameters where possible. The D0.65 and stem length variables are strongly correlated with a Spearman's correlation coefficient of 0.8992. The issue of multicollinearity negatively affects reliability of the estimated regression coefficients and the ability of the regression analysis to test the significance of the individual regression coefficients. The composite variable is therefore preferred for models used for extrapolation to get a higher validity of the parameters estimated. The need for a distinguishment arises because in several cases, the composite variable got a lower fit according to the goodness of fit statistics of adjusted R^2, SER, AIC and RSME than models using the separated D0.65 and stem length.

[11] Models with the stem volume or stem dry weight as input variables are not very useful, since they themselves often will be an estimate. It is better with an input variable that can be measured more or less directly in the field.

Table 9: Stem level biomass models. All variables are log transformed. See appendix B.10 to B.15 for all the relevant tested regression models and appendix B.9 for the 11 residual plots. The ´§´sign and yellow colour are marking the models used for predicting the biomass of the remaining 338 measured stems making the further analysis on shrub level possible. The green coloured models are the models assessed to be best for prediction purposes on future external data.

Response Variable	Predictor variables	Regression coefficients (SE)	P	Adj. R^2	SER	AIC	RMSE
Stem AGB including foliage (0)	*Intercept*	-7.9052 (0.948)	***	0.7154	1.0610	255.2	1.0266
	ln(Length)	2.5134 (0.173)	***				
Stem AGB including foliage (1)	*Intercept*	4.7288 (0.069)	***	0.9246	0.5432	139.8	0.5248
	ln(D0.65)	2.0714 (0.065)	***				
Stem AGB including foliage (2)	*Intercept*	0.7451 (0.184)	***	0.9128	0.5841	152.0	0.5774
	*ln(L*D²)*	0.7784 (0.026)	***				
Stem AGB including foliage (3)	*Intercept*	4.6769 (0.070)	***	0.9241	0.5318	132.5	0.5754
	ln(D0.65)	2.0017 (0.069)	***				
	Pruned	0.3999 (0.160)	*				
Stem AGB including foliage (4)	*Intercept*	-7.6183 (0.924)	***	0.7402	0.9893	235.9	0.9999
	ln(Length)	2.4233 (0.171)	***				
	Pruned	1.0129 (0.278)	***				
Stem AGB including foliage (5)	*Intercept*	0.8230 (0.183)	***	0.9145	0.5643	142.1	0.5523
	*ln(L*D²)*	0.7510 (0.028)	***				
	Pruned	0.5074 (0.168)	**				
Stem AGB including foliage (6) §	*Intercept*	3.9148 (0.974)	***	0.9237	0.5331	133.9	0.5229
	ln(D0.65)	1.9093 (0.137)	***				
	ln(Length)	0.1481 (0.189)	#				
	Pruned	0.4169 (0.161)	*				
Stem AGB excluding foliage (1)	*Intercept*	0.2833 (0.177)	#	0.9262	0.5608	145.2	0.5457
	ln(LD²)	0.8183 (0.025)	***				
Stem AGB excluding foliage (2)	*Intercept*	0.3656 (0.173)	*	0.9290	0.5365	133.9	0.5167
	ln(LD²)	0.7894 (0.026)	***				
	Pruned	0.5268 (0.160)	**				
Stem AGB excluding foliage (3) §	*Intercept*	2.7549 (0.947)	**	0.9337	0.5183	129.3	0.5004
	ln(D0.65)	1.8936 (0.133)	***				
	ln(Length)	0.3235 (0.184)	#				
	Pruned	0.4569 (0.157)	**				
Stem AGB excluding branch and foliage(1)	*Intercept*	0.0290 (0.151)	#	0.9454	0.4789	118.7	0.4679
	ln(LD²)	0.8209 (0.022)	***				
§ Stem AGB excluding branch and foliage (2)	*Intercept*	0.1032 (0.142)	#	0.9522	0.4382	101.2	0.4261
	ln(LD²)	0.7923 (0.022)	***				
	Pruned	0.5784 (0.131)	***				
§ Stem volume (1)	*Intercept*	1.0665 (0.128)	***	0.9577	0.3948	84.3	0.3805
	ln(LD²)	0.7583 (0.019)	***				
	Pruned	0.6056 (0.118)	***				
Branch biomass (0)	*Intercept*	-2.3257 (0.355)	***	0.8164	0.9625	222.1	0.9387
	ln(Stem vol.)	1.0157 (0.055)	***				
Branch biomass (1)	*Intercept*	-1.2805 (0.393)	**	0.7253	1.1720	250.1	1.1340
	ln(LD²)	0.7905 (0.055)	***				
§ Branch biomass (2)	*Intercept*	6.8989 (1.860)	***	0.7804	1.0480	233.6	1.0195
	ln(D0.65)	2.6607 (0.261)	***				
	ln(Length)	-0.8138 (0.362)	*				
Foliage biomass (1)	*Intercept*	3.0367 (0.103)	***	0.7294	0.8181	208.6	0.7928
	ln(D0.65)	1.4659 (0.098)	***				
§ Foliage biomass (2)	*Intercept*	8.5172 (1.299)	***	0.7756	0.7450	193.9	0.7416
	ln(D0.65)	2.1276 (0.180)	***				
	ln(Length)	-1.0664 (0.252)	***				
Foliage biomass (3)	*Intercept*	0.3514 (0.286)	#	0.6666	0.9081	226.2	0.8855
	ln(LD²)	0.5304 (0.041)	***				

*"P " is codes of t-test p-value results indicating significance of the estimated regression coefficients: '***' 0.001, '**' 0.01, '*' 0.05, '#'insignificant. D0.65 = Stem diameter at 0.65 m, LD^2 = Composite variable of the stem length multiplied with the squared diameter at 0.65 m.*

As explored earlier the 85 felled stems are representing the distribution of the remaining 338 measured stems in an acceptable way, see figure 11. Given that they are stems taken from the same group of shrubs, the models that are the best fit on the internal data (the 85 felled stems), are also assumed to be the best to predict the stem biomasses of the remaining 338 stems. This means that in cases where the goodness of fit statistics were better for models using the separated D0.65 and stem length than the combined, these models were chosen for the prediction of the 338 stem biomasses. Multicollinearity do not hamper the predictive power of a model. If the models with the composite variable however were reasonably close in fit, these were chosen as the best models for extrapolation to other data.

This can be exemplified by comparing AGBF model 6 and 7: Model 6 have three parameters and use the combined variable, LD^2 together with the variable "pruned". Model 7 have four parameters, using the stem length and D0.65 as independent variables together with the "pruned" variable. As seen in table 9, the goodness of fit statistics indicate a better fit of model 7 than model 6. Whether this is solely caused by wrongly estimated regression coefficient, is not clear. The fact that the length variable is deemed insignificant as a variable within the regression do indicate the issue of multicollinearity, since the length variable itself is able to explain 71.5% of the variation found in the stem AGBF. Given that all relevant information was included in model 7 and since it had the best goodness of fit statistics, model 7 were used to predict the total stem AGBF of the remaining 338 measured stems. Model 6 is however assessed to be the best model for predicting the stem AGBF on external data.

The findings were similar for the total stem AGB (excluding foliage) model 2 and 3 as well as for the branch biomass model 1 and 2. For the stem biomass excluding branches and foliage and the stem volume, the models including the composite variable and the variable "pruned" were the best fit according to the goodness of fit statistics, making them both the models used for stem biomass predications within the study and the best recommended for use outside the study. Regarding the stem foliage biomass, the best model seemed to be the two variable model 2, using length and D0.65 as individual variables. Model 3 using the composite variable, seem to have a considerably worse fit, than model 2.

3.5.3. Stem biomass predictions

When predicting the biomass of the 338 remaining stems, AGB and AGBF did not give the same results when predicted directly by the AGB and AGBF model 2 and when predicted by

merging the separately predicted plant parts; stem, branches and foliage. The average absolute difference of the two estimates of AGBF was 3.91% and 5.08% for AGB, after being back transformed and corrected for logarithmic bias. The summed estimates of the AGB and AGBF tend to give higher predicted values than the directly estimated AGB and AGBF, as seen in table 10. A paired Wilcoxon signed rank test assessed both the two results of AGBs and AGBFs to be significantly different from each other. The direct estimates of the total above ground stem biomass will be the values used when calculating the shrub level total biomass. The overall error of prediction is smaller when using the direct estimates, especially since the merged values contain the branch biomass model with the highest RSME of 1.0195. The individual foliage, branch and stem models will be used separately. The merged total above ground biomass will only be used when calculating the BEF and the percentage of foliage to the total aboveground biomass.

Table 10: Key descriptive statistics of the predicted stem biomasses using the models predicting the AGB and AGBF directly and when merging the separately predicted biomass of foliage, branch biomass and stem biomass. CV = Coefficient of variation.

Estimate	Mean in g (SE)	Min (g)	Median (g)	Max (g)	CV
AGB directly	1743.0 (242.4)	3.4	285.8	41534.7	2.55
AGB summed	1825.7 (250.6)	3.6	298.3	41823.8	2.52
AGBF directly	1896.2 (257.2)	5.1	356.1	44327.7	2.49
AGBF summed	1981.7 (267.5)	5.7	370.4	44639.4	2.48

3.6. Shrub level aboveground biomass

The total shrub aboveground biomass including foliage (AGBF) of the 32 sampled shrubs ranged from 0.068 kg at site FJ to 232.82 kg of the oldest shrub LF3[12]. EFA1 was the second biggest shrub with an AGBF of 163.87 kg, coinciding with also being the tallest hazelnut shrub in the dataset. The average of the AGBF of the measured hazelnut shrubs is 31.06 kg. The median value is 3.81 kg and 3 quarters of the shrubs are 42.60 kg and below, once again highlighting the overrepresentation of the smaller hazelnut shrubs in the dataset. A full overview of the biomass values of each of the 32 sampled hazelnut shrubs is available in the appendix B.17. The branch biomass varied from 0.01 kg to 43.95 kg and the foliage from 0.02

[12] The abovegroundbiomass of LF3 is estimated from only measuring half of the stems, meaning that the second half of the shrub is an estimate based on the measured half.

kg to 11.91 kg, with the smallest values stemming from site FJ and the biggest from LF3 followed by EFA1, as for the AGBF. The mean BEF value of the 32 hazelnut shrubs was 1.81, ranging from 1.28 to 2.83.

The potential underestimation of aboveground biomass by not including the small shoots was examined. Based on the smallest 31 felled stems, two biomass models for predicting shoot "stem" biomass and shoot "leaves" biomass were developed. The two models is presented in table 11. The "average shoot" with a diameter at 0.2 m of 0.7 cm and a length of 50 cm had an estimated biomass of 10.3 grams. Excluding the shoots led to a potential underestimation of the total AGBF of -10 to -37% for four of the smallest shrubs (FJ4, LF1, FJ1 & HJ3). This is a very high underestimation, but the "average" shoot is based on the dimensions of some of the bigger shoots. The error for the smaller shrubs, therefore might be less dramatic than estimated here. For the remaining 23 shrubs the potential underestimation of leaving the shoots had the average of -1.06% ranging from -0.03% to -5.05%, which correlated with shrub size, having a bigger influence on the smaller shrubs than larger shrubs.

Table 11: The two "shoot" models for estimating the missing shoot biomass of the shrubs. The shoot models are fitted to the 31 of the smallest stems with diameter values at 0.2m of 1.5 cm and below. "P " is codes of t-test p-value results indicating significance of the estimated regression coefficients: '***' 0.001, '**' 0.01, '*' 0.05, '#'insignificant.

Response variable	Predictor variables	Regression coefficients (SE)		P	Adj. R^2	SER	AIC	RMSE	CF
Shoot stem	Intercept	-0.9697	(0.572)	#					
	ln(D0.2)	1.9573	(0.257)	***	0.8763	0.2395	4.2	0.2419	1.0297
	ln(length)	0.8535	(0.121)	***					
Shoots leaves	Intercept	3.5742	(1.249)	**					
	ln(D0.2)	2.5483	(0.561)	***	0.4027	0.523	51.9	0.5126	1.1404
	ln(length)	-0.2836	(0.263)	#					

3.7. Shrub level biomass models

Models have been developed for predicting the AGB including and excluding foliage, stem biomass excluding the crown, branch biomass and foliage biomass. The best 16 different shrub biomass models are presented in table 12, with the regression coefficients and relevant goodness of fit statistics. The reason for including all 16 models is to present different options for input variables bearing in mind the different potential end-users and to clearly lay out the

pros and cons of the different models. There is presented more models for predicting the AGBF than for the other response variables. This is done in order to highlight some findings and model alternatives that also adheres to some of the other response variables, especially AGB. All tested models with variables of significant ability to explain variance of the respective response variable of biomass, can be found in the appendix table B.19 to B.23.

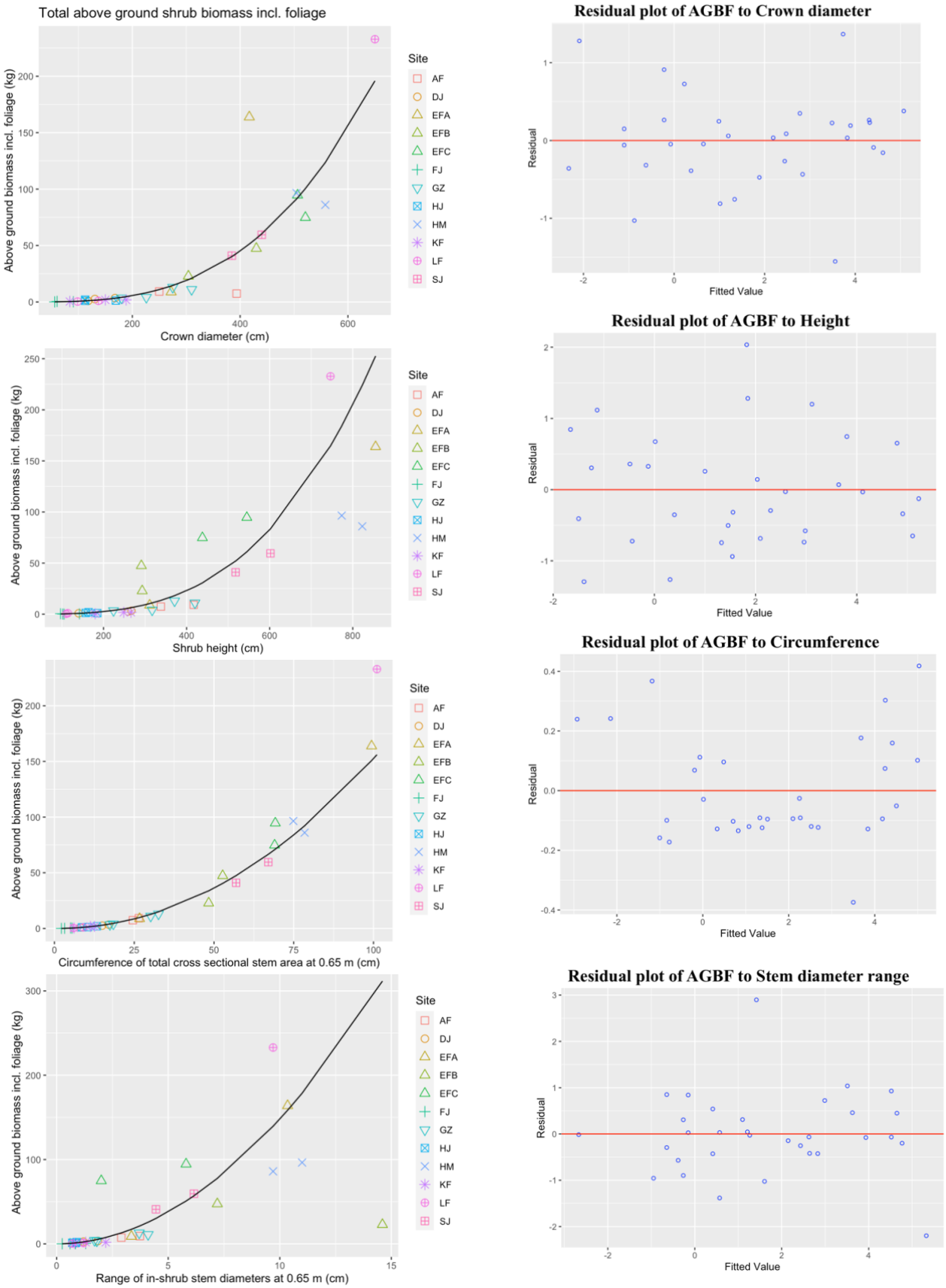
The relevant predictor variables were the directly in-field measured crown diameter and shrub height and the pruned binary variable. (1 = if any of the stems in the shrub have been pruned and 0 = if no stems in the shrub have been pruned). The crown diameter were the best solo *measurement* at explaining the variance found in the dependent biomass variables of the hazelnut shrubs. Being the best explanatory variable only requiring one single field measurement. The R^2 values are ranging from 0.9102 for the foliage biomass to 0.9241 for the AGBF. The shrub height could explain between 81.18% and 89.13% of the variance found in the biomass, being best at explaining the shrub stem biomass excluding the crown (from here just referred to as the "stem biomass", not to be confused with the stem level biomass mentioned in the previous sections) and worst at explaining the foliage. In general the R^2 values were highest and AIC and RSME values lowest for the models fitted to stem biomass, followed by the total aboveground biomass models (with and without foliage) and lastly the branch and foliage biomass models.

A number of composite variables created from the diameters of the stems at 0.65 m within each shrub, were also tested: The overall mean D0.65 of the in-shrub stems , the range of the D0.65 within the shrub (the maximum D0.65 – the minimum D0.65), the total cross sectional area of the shrubs stems at 0.65 m and the circumference calculated from the total cross sectional area. The two latter is an estimate of the same and gave the exact same goodness of fit statistics when tested with AGBF (see appendix B.19.). It was decided to only continue with the circumference measure, as this is an easier number to interpret, even though it requires an additional calculation from area to circumference.

The circumference variable turned out to be the best single predictor variable of all the variables tested, with the highest R^2-values of 0.9932 to 0.9774 and corresponding lowest AIC, SER and RSME values. (see table 12 for the exact numbers for the respective models). For all shrub models the single variable regression model with circumference as the predictor variable were included in the final model selection in table 12, due to its convincing goodness of fit statistics. The residual plots of the models including the circumference variable is not as homogeneous

as for the models including CD or height (see appendix B.18). It is however assessed to be acceptable. In figure 19 the four best single variable models for predicting AGBF is presented, including the circumference model, with their respective back transformed regression models plotted and the responding residual plots. In general the models including stem diameter related variables had less homogeneous residual plots, being true for both stem and shrub level models. The shrub level biomass regression models had generally more homogeneous residual plots than the stem level biomass regression models. As pointed for the stem level models, it is not preferable to have single variable models only covering one dimension of the shrub size, e.g. stem diameters, when planning on utilizing the models for extrapolation to external data.

Another composite D0.65 variable that showed useful results were the range of the stem D0.65. This alone explained between 81.02% and 83.93% of the variance found in the biomass response variables, being a more or less equally good fit for the stem biomass, AGB and AGBF. It is still not able to compete with the other variables in a single predictor model, but showed some good results when combined in the two or three variable regression models, see table 12. Opposite the circumference variable, the diameter range variable offers a way of including information of the stem biomass in addition to e.g. shrub height and CD, without the need to measure each and every stem. The models including the diameter range do have higher RSME values, related to the predictive ability of the model, than the chosen models including circumference. This is not surprising since the circumference measure is based on a much more detailed measure of the given shrub. The same is the case when comparing the two-variable models: AGBF model 3 and 4 based on the shrub height and CD and the CD and diameter. The two models have very similar goodness of fit statistics, with model 4 having a AIC value only -1.9 lower than model 3. The RSME value is however higher for model 3 than 4. Model 3 is assessed to be the best two variable regression model for predicting the total AGBF of hazelnut shrubs. This was also true for AGB and stem biomass. Including the dimension of the height of the shrub is important, but the diameter range serves as an alternative if the height is not possible to measure. For the stem biomass, and total AGB with and without foliage, the three input variable regression models including both CD, shrub height and diameter, had significantly better R^2, SER and AIC values.



<u>Figure 19:</u> Non-log transformed plots of the shrub AGBF to crown diameter, shrub height, circumference and diameter range, including the regression curves of the back transformed single variable regression models. To the right the corresponding residual plots to the regression models.

Table 12: Shrub level biomass regression models. All variables are log transformed. The green models are the ones assessed to be the best models. The grey coloured area is showing two models comparing the use of the "pruned" variable and the "age group" variable that are not considered suitable for extrapolation purposes. See appendix B.19 to B.23 for all the relevant tested regression models and appendix B.18 for the 16 residual plots.

Response Variable	Predictor variables	Regression coefficients (SE)		P	Adj. R^2	SER	AIC	RMSE
Shrub AGB incl. foliage (1)	Intercept	-14.4711	(0.836)	***	0.9241	0.6084	62.9	0.6399
	ln(CD)	3.0174	(0.155)	***				
Shrub AGB incl. foliage (2)	Intercept	-4.5419	(0.097)	***	0.9932	0.1816	-14.4	0.1893
	ln(Circumference)	2.0742	(0.031)	***				
Shrub AGB incl. foliage (3)	Intercept	-15.6917	(0.834)	***	0.9412	0.5355	55.7	0.5465
	ln(CD)	2.0529	(0.338)	***				
	ln(Height)	1.1344	(0.364)	**				
Shrub AGB incl. foliage (4)	Intercept	-10.4126	(1.366)	***	0.9446	0.5196	53.8	0.5876
	ln(CD)	2.1564	(0.280)	***				
	ln(Diameter Range)	0.6674	(0.192)	**				
Shrub AGB incl. foliage (5)	Intercept	-12.1505	(1.444)	***	0.9529	0.4792	49.5	0.6202
	ln(CD)	1.6172	(0.339)	***				
	ln(Height)	0.8419	(0.341)	*				
	ln(Diameter range)	0.5306	(0.185)	**				
Shrub AGB incl. foliage	Intercept	-15.5485	(0.789)	***	0.9476	0.5052	52.8	0.5717
	ln(CD)	1.8939	(0.327)	***				
	ln(Height)	1.2327	(0.346)	**				
	Pruned	0.4125	(0.193)	*				
Shrub AGB incl. foliage	Intercept	-13.5469	(1.024)	***	0.954	0.4734	48.7	0.4812
	ln(CD)	1.6342	(0.329)	***				
	ln(Height)	1.0994	(0.322)	**				
	Stand age group	0.8436	(0.280)	**				
Shrub AGB excl. Foliage (1)	Intercept	-5.0541	(0.103)	***	0.9932	0.1914	-11.1	0.1929
	ln(Circumference)	2.1744	(0.032)	***				
Shrub AGB excl. Foliage (2)	Intercept	-16.8059	(0.861)	***	0.9429	0.5533	57.8	0.5977
	ln(Crown diameter)	2.0991	(0.349)	***				
	ln(Height)	1.2509	(0.376)	**				
Shrub stem biomass excluding crown biomass (1)	Intercept	-5.4783	(0.113)	***	0.9919	0.2108	-4.9	0.2266
	ln(Circumference)	2.2051	(0.036)	***				
Shrub stem biomass excluding crown biomass (2)	Intercept	-7.4064	(0.515)	***	0.9952	0.1619	-19.97	0.1812
	ln(Circumference)	1.8872	(0.082)	***				
	ln(Height)	0.4965	(0.130)	***				
	Pruned	0.2349	(0.064)	***				
Shrub stem biomass excluding crown biomass (3)	Intercept	-13.9915	(1.428)	***	0.9593	0.4741	48.8	0.5502
	ln(CD)	1.5271	(0.335)	***				
	ln(Diameter range)	0.5400	(0.183)	**				
	ln(Height)	1.1568	(0.337)	**				
Shrub branch biomass (1)	Intercept	-6.1073	(0.161)	***	0.9826	0.2995	17.6	0.290
	ln(Circumference)	2.1242	(0.051)	***				
Shrub branch biomass (2)	Intercept	-4.2897	(0.877)	***	0.9844	0.2838	15.0	0.3111
	ln(Circumference)	2.3939	(0.137)	***				
	ln(Height)	-0.4669	(0.222)	*				
Shrub branch biomass (3)	Intercept	-12.1666	(1.526)	***	0.9348	0.5802	60.8	0.646
	ln(CD)	2.2181	(0.313)	***				
	ln(Diameter range)	0.6773	(0.214)	**				
Shrub foliage biomass (1)	Intercept	-4.69834	(0.130)	***	0.9774	0.2433	4.3	0.2500
	ln(Circumference)	1.50938	(0.041)	***				
Shrub foliage biomass (2)	Intercept	-2.9938	(0.694)	***	0.9808	0.2246	0.1	0.2961
	ln(Circumference)	1.7623	(0.108)	***				
	ln(Height)	-0.4378	(0.176)	*				
Shrub foliage biomass (3)	Intercept	-9.3066	(1.165)	***	0.9252	0.443	43.5	0.6343
	ln(CD)	1.6404	(0.239)	***				
	ln(Diameter range)	0.4314	(0.163)	*				

The opposite results were found for models predicting the crown biomass of branch and foliage. Here the height was insignificant in combination with CD, whereas the diameter range improved the fit. See model 3 for branch biomass and foliage biomass in table 12.
The height regression coefficients becomes negative in combination with circumference in the foliage model 2 and branch model 2. An increase in height therefore only increases the foliage biomass very little, with a power -0.4378 for foliage and -0.4669 for branches.
The height is however as a single predictor variable able to explain 81.18% of the variation in foliage biomass and 82.61% in the branch biomass. There must therefore be an overlap in the variance explained of height, CD and Circumference.

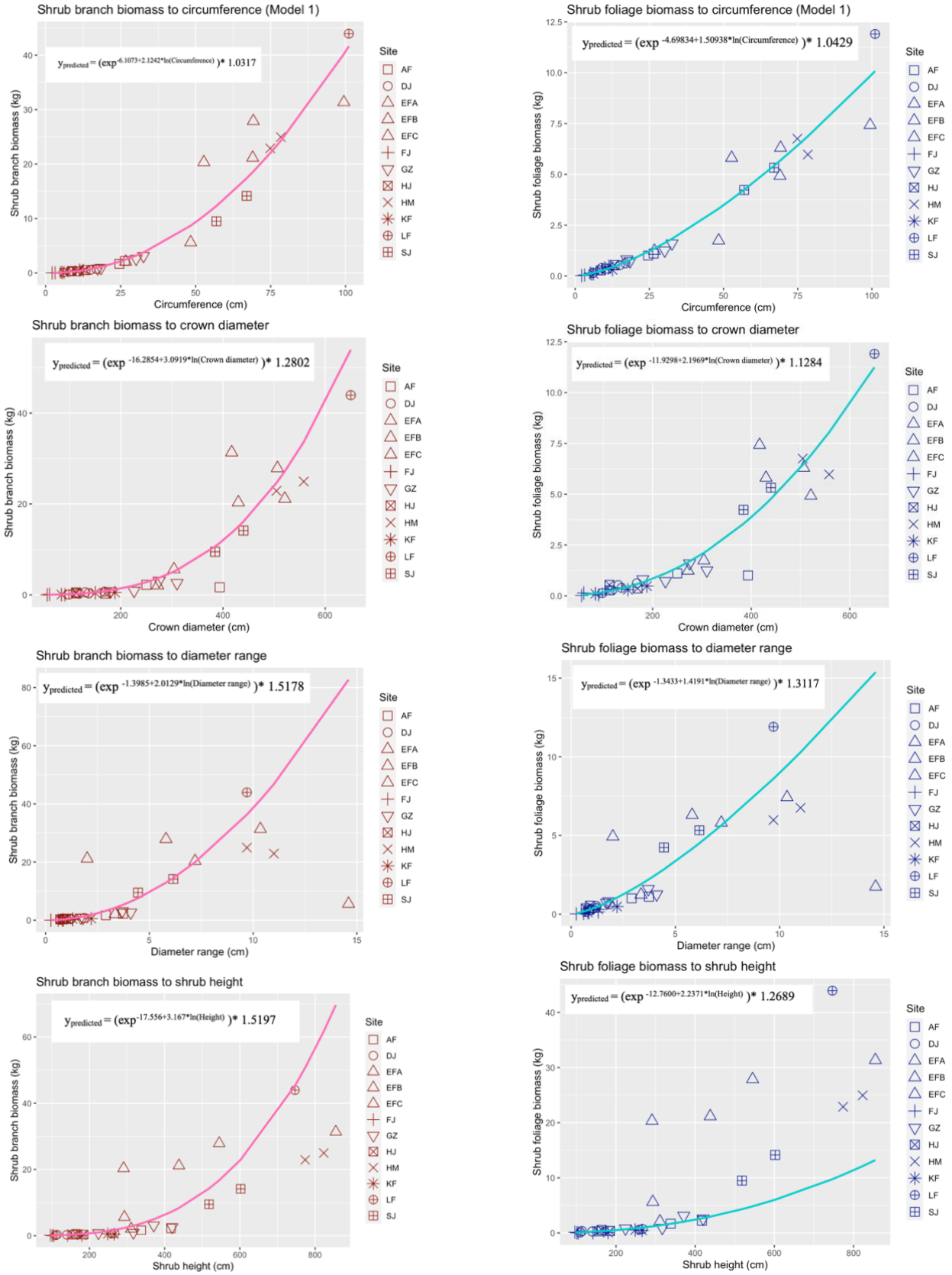
This is most likely coursed by multicollinearity since both CD, Diameter range, shrub height and Circumference are correlated, as seen in table 13. As highlighted in the stem level section, this will influence the accuracy and validity of the estimated regression coefficients presented. However, it is difficult to develop a shrub level model with a satisfying number of variables to explain the shrub dimensions, without encountering issues of multicollinearity. This could argue for choosing the two variable models combining CD and shrub height or CD or diameter range, like model AGBF 3 and 4, over the three variable model AGBF 5.

The corresponding three variable model are available in appendix B.20 for shrub AGB excluding foliage. A model combining the strong variable of circumference and shrub height would assumingly be a good fit when predicting shrub AGB including and excluding foliage, but the height variable were, properly caused by the very high correlation seen in table 13, deemed to have an insignificant regression coefficient. The residual plots were also inacceptable and not homogeneous.

Table 13: The correlation coefficients of the predictor variables used together in the shrub level biomass models.

Variables	Spearman's correlation coefficient
Crown diameter and shrub height	0.9153
Crown diameter and diameter range	0.8739
Diameter range and shrub height	0.8644
Circumference and shrub height.	0.9542

In figure 20 the four single variable plots of shrub branch biomass (left) and foliage biomass (right) is shown, with the regression curve of back transformed and corrected single variable regression models. This show how the circumference variable seems to be best at explaining the data, followed by the CD, the diameter range and lastly the shrub height.



<u>Figure 20:</u> Non-log transformed scatter plots of the shrub branch biomass to the left and shrub foliage biomass to the right, with the predictor variables: Circumference, crown diameter, diameter range and shrub height. For each plot the back transformed single variable regression model is plotted and the equations are included. The back transformed regression models are multiplied by the correction factor, calculated from the RMSE.

Including the count of stems in the models were also tested but it did not improve any of the fits. The number of stems alone could explain 43.24 % of the variance found in the AGBF, hence not very high compared to the other predictor variables available.

During the visual exploration of the data, it was found that there is a big overlap between the shrubs that had been pruned and the largest and oldest shrubs. To investigate this further on the shrub level, a binary variable dividing the shrubs in two groups of stand ages: Below and above 10 years, was created. This variable was used to color the datapoints in figure 21 (right), indicating the big overlap of the two categories. The age group variable was tested concurrently with the variable "pruned" under the development of the AGB and AGBF regression models.

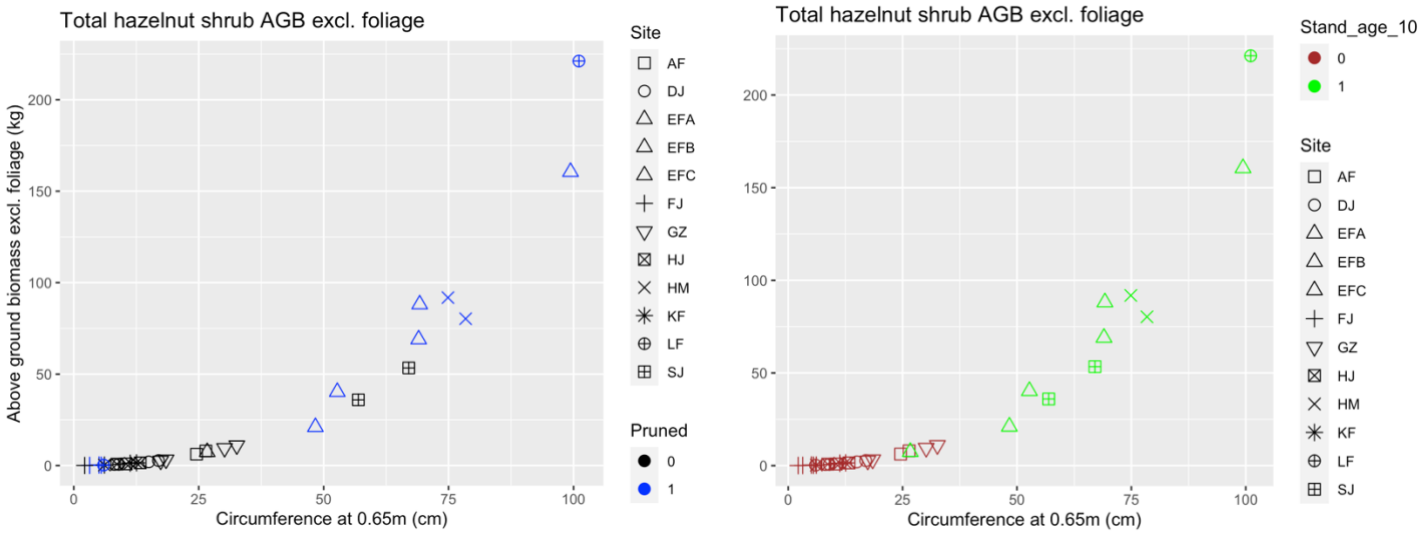


Figure 21: Scatter plot of the total shrub aboveground biomass excluding foliage to the circumference of the total cross sectional area of the stems at 0.65 m. To the left the blue data points denote the ones that have been pruned and the black the ones that have not been pruned. To the right the green color represents the shrubs with stand ages above 10 years and the brown color the shrubs with stand ages below 10 years.

When combined with shrub height and CD the age variable was a stronger fit than the variable "pruned", as seen in table 12 (grey colored models). The age variable had a higher coefficient of determination of 0.954 against 0.948 for including the "pruned" variable, an AIC value of 48.7 against 52.8 and a RSME of 0.4812 to 0.5717. When combined with CD alone, only the stand age group was significant (see appendix B19 and B20). When combined with the circumference the variable "pruned" was significantly improving the fit, where the age group was insignificant (for AGB and AGBF). This indicates that there is not a complete overlap between the two variables, but it is notable.

Another noteworthy issue associated with the variable "pruned" is its positive estimated coefficient, true for all the models where it was judged significant. This was also true for the stem level models, which actually did align with the experience found in the field. These findings however leads to a compromised confidence in the role of the variable "pruned" in regards to the shrub level. It might be a good explanatory variable for this particular dataset, but its ability to correctly predict other hazelnut shrubs is not clear. The values of the estimated regression coefficients could be highly influenced by simply having more of the larger and older shrubs included in the category of shrubs that had been pruned. The variable "pruned" is therefore not included in most of the biomass models presented in table 12. The pruned variable is nonetheless included in the shrub stem biomass model 2, partly because it seemed to improve the fit, but mainly because including the pruned variable in a model with circumference and height improved the residual plot significantly (See appendix B.18).

3.8. Carbon and nitrogen content of hazelnut shrubs

3.8.1. Bark percentages

The weight of bark constituted in average 20.3% of the stem sample weights. However, the range is large with values from 4.6% to 44.4%. The share of bark in the stem samples were related to stem diameter and the distance to stem top, as seen in figure 22.

The high percentage of bark were found among the small diameters and shortest distances to stem top. The regression model for predicting the bark share by stem diameter and distance to stem top is presented below. The last part is the correction factor (CF).

See appendix B.24 for the two single variable models.

$$y_{est.\ bark\%} = \left(exp^{3.81970 - 0.35146 * \ln(\text{Diameter}) - 0.13023 * \ln(\text{Dist. stem top})}\right) * 1.0234$$

3.8.2. Carbon content

The overall simple average of carbon content in all of the tested biomass was 47.79% (0.073) of the dry weight with a standard deviation of 0.704%. Excluding the seven samples of foliage the number was 47.85% (0.072). The stem samples were divided in bark and wood with the average carbon content of 47.78% (0.159) and 47.82% (0.054) respectively, ranging from 45.91% to 49.74% for the bark and 47.04% to 48.38% for the wood. As seen in table 15, the carbon content of the wood show a tendency to increase slightly with increased diameter, where

it decreases for the bark. The diameter groups of H and K are not following the trend, but are also only estimated based on one single sample each.

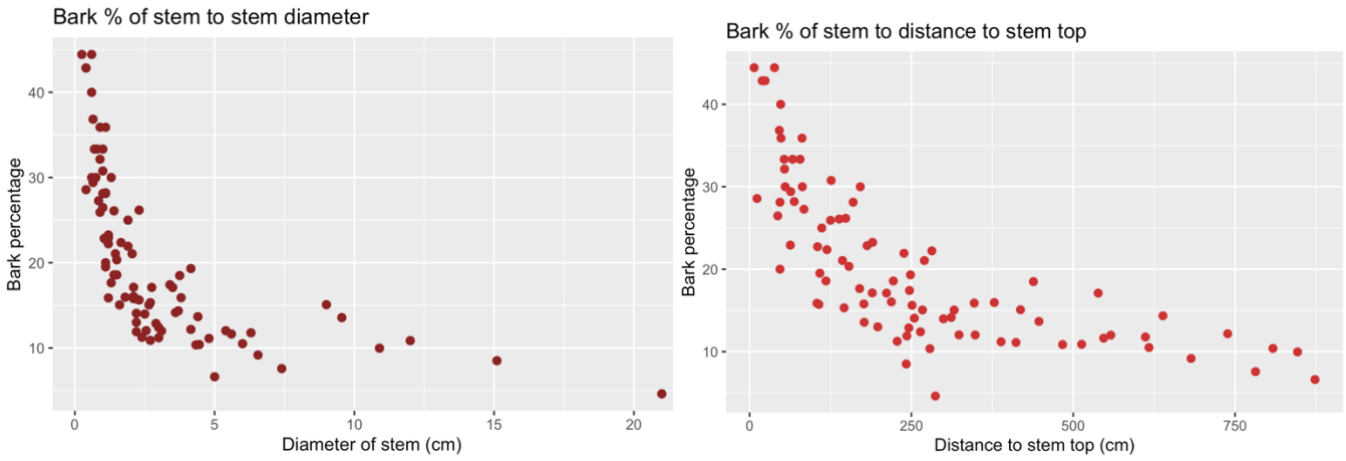


Figure 22: Percentage of bark in the analyzed stem samples to the stem sample diameter (left) and distance from sample height to the top of the given stem (right).

As for the rest of the dataset there was an overrepresentation of the stems in the smaller diameter groups. A detailed overview of carbon (and nitrogen) content of the stem samples grouped by diameter and sample height can be found in appendix B.25. For the crown biomass, the mean carbon content of the foliage was 47.05% (0.039) and for branches it was 48.07% (0.175) across all sites and sample periods. As seen in table 16, the foliage were tested in groupings of sample time and place. There is a slight tendency of a higher percentages of carbon in the foliage in the first half of the sample period from end July to start August than in the second half of the sample period from the end of August to start September.

Table 14: Results of the carbon and nitrogen analysis of branches in different size categories. The small branches are divided by sample period. Green shoots and catkins are presented as well. Small branches are branches with diameters of 1 cm and below. Medium branches have diameters above 1 cm and below or equal to 4 cm. Large branches have diameters above 4 cm and below or equal to 8 cm.

Sample period	Branch size	Nitrogen %	Carbon %	Number of samples
July-September	Green shoots	1.499	46.596	8
End July	Small	0.919	47.923	9
First half of August	Small	0.838	47.979	7
Second half of August	Small	0.778	47.926	8
Start September	Small	0.775	48.055	6
July-September	Medium	0.453	47.958	4
Second half of August	Medium	0.387	49.069	4
Second half of August	Large	0.232	47.592	3

August to September	Catkins	2.168	49.177	5

*Table 15: Table with the results of the carbon and nitrogen analysis of the stem samples presented as the mean percentage of the 2 cm diameter groups for bark and wood separately. The second column "Bark %" is the estimated bark weight of the stem samples to the total sample weight in percentage, also presented as the average of the diameter groups. The * denotes that given the small amount of samples it was not possible to calculate the standard deviation and therefore neither the standard error of the mean (SE). The last column informs about: First the number of "merged samples" analysed and therefore the number of different C and N results within each diameter group. Secondly the total number of individual stem samples merged. They have been summed in the last row.*

Carbon and nitrogen content in stem samples divided in bark and wood							
Diameter group (over bark)	**Bark % (SE)**	**Bark C% (SE)**	**Wood C% (SE)**	**Bark N% (SE)**	**Wood N% (SE)**	**Count of total samples**	
A]0;2] cm	27.7 (1.21)	48.559 (0.148)	47.607 (0.067)	0.882 (0.017)	0.365 (0.022)	16	45
B]2:4] cm	15.1 (0.64)	47.876 (0.169)	47.732 (0.059)	0.764 (0.023)	0.196 (0.007)	11	28
C]4;6] cm	11.8 (1.02)	47.007 (0.222)	47.865 (0.049)	0.740 (0.024)	0.156 (0.009)	5	10
D]6;8] cm	9.5 (1.22)	46.863 (0.531)	48.267 (0.069)	0.679 (0.004)	0.120 (0.005)	3	3
E]8;10] cm	14.4 (0.75)	46.262 *	48.216	0.678 *	0.162 *	1	2
F]10;12] cm	10.5 (0.45)	46.706 *	48.291	0.811 *	0.162 *	1	2
H]14;16] cm	8.5 *	47.175 *	47.839	0.782 *	0.197 *	1	1
K]20; 22] cm	4.6 *	48.189 *	48.344	0.862 *	0.138 *	1	1
Overall mean	20.3 (1.00)	47.781 (0.159)	47.815 (0.054)	0.795 (0.016)	0.237 (0.019)	39	92

The total amount of carbon sequestered in each of the 32 sampled hazelnut shrubs were estimated first by simply multiplying the total aboveground biomass including foliage with the simple average of 47.79% (0.073) of the carbon content in all of the analysed samples of biomass (excluding catkins). The sampled shrubs had a total amount of stored carbon ranging from 0.03 kg in the smallest shrub of FJ4 to 111.26 kg in the largest shrub LF3, with an overall average of 14.85 kg and a median of 1.82 kg. See the carbon sequestered in all 32 shrubs in appendix B.26. The carbon sequestered in the aboveground biomass of each shrub were also sought to be estimated more precisely, by estimating the carbon in each plant part separately and using the altering carbon contents found based on stem diameters, period of sampling and the expected distribution of small, medium and large branches (see in the method section 2C.5. for details). When comparing the simple estimate with the more detailed estimate, it only differs with an average absolute percentage of 0.208% and when compared in a Wilcoxon signed rank test there is no significant difference. See the similar estimate in appendix B.27.

This means that the simple average of the carbon content across different plant parts; foliage, bark, stem and branches, can be used with good confidence together with the aboveground biomass models presented earlier in table 12 for estimating the carbon sequestered on shrub level.

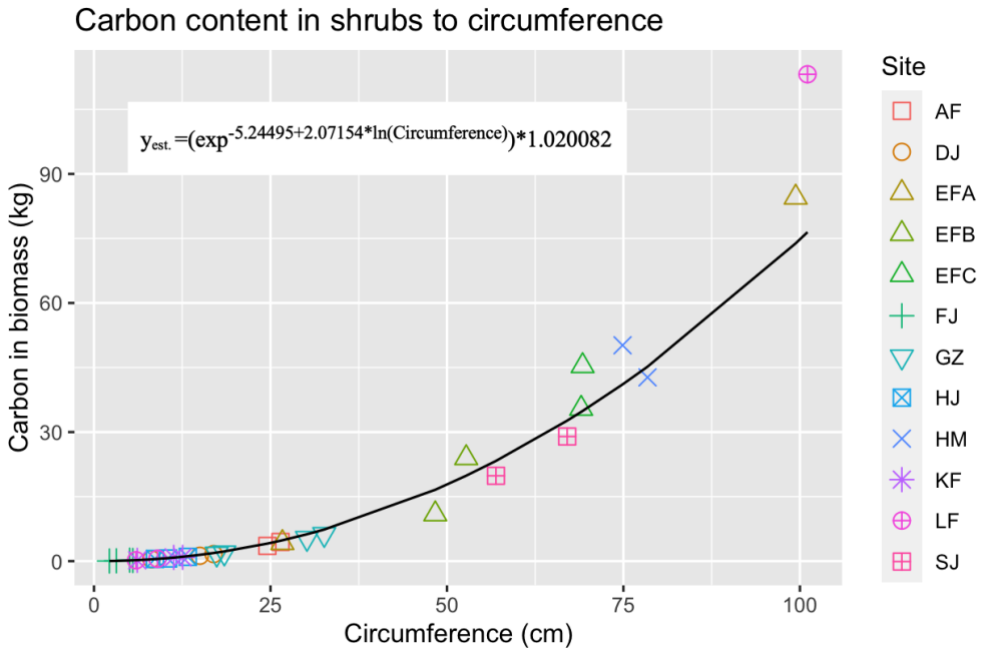


Figure 23: The total carbon content in the measured hazelnut shrubs (including foliage) here estimated using the more "detailed" approach, to the circumference of the summed cross-sectional area of the shrub stems at 0.65 m above ground. The expression of the back transformed loglog-linear regression model including the correction factor is included and drawn in black. The adjusted R^2 is 0.9926, SER is 0.1904 and AIC is -11.4.

The amount of carbon sequestered in the aboveground biomass can also be estimated directly by using some of the same explanatory variables as used for the biomass, as seen in figure 23, where the total carbon in the hazelnut shrubs predicted by the "circumference" variable. This part will not be explored further, since the shrub biomass models in combination with the average carbon content seems adequate.

Table 16: Results of the carbon and nitrogen analysis of pooled foliage samples grouped by sample period and the region of data collection.

Carbon and nitrogen content in leaves of *Corylus avellena*

Sample period	Region	Nitrogen %	Carbon %	Number of samples
End July	Vestjylland	2.534	47.872	4
Start August	Sydfyn	2.149	47.982	5
First half of August	Nordsjælland	2.190	47.393	5
First half of August	Møn	2.825	46.058	3
Second half of August	Sydfyn	2.157	47.047	5

Second half of August	Falster	2.160	46.208	3
Start September	Østjylland	2.321	46.791	6

3.8.3. Nitrogen content

The nitrogen content variated much more between the tested plant parts of the hazelnut shrub, with the highest contents found in the foliage ranging from 2.825 % to 2.149% with a mean of 2.334% (0.059). The nitrogen content of the catkins were in the same range as the leaves of 2.168 %. There were no specific relation between the sample period and change in the nitrogen content of the leaves, as seen in table 16. It could potentially be more related to site conditions, but it is not possible to tell from these results. In table 14 it appears that the nitrogen content of the small stems decrease with sample period, gradually decreasing from a nitrogen content of 0.919% in samples from end July to 0.775% in samples from start September. As excepted, the small branches have a higher nitrogen content of 0.828% in average compared to the larger branches with values of 0.420% for medium branches and 0.232% for large branches. The all green shoots of new branches had a content of 1.499%.

In average 71% of the estimated total stored nitrogen of the sampled hazelnut shrubs were found in the crown biomass, with an average of 47% found in the foliage alone. In the stem of the hazelnut shrubs 44% of the nitrogen is located within the bark of the stem. The mean nitrogen content was 0.795% (0.016) in the bark and 0.238 % (0.020) in the wood.

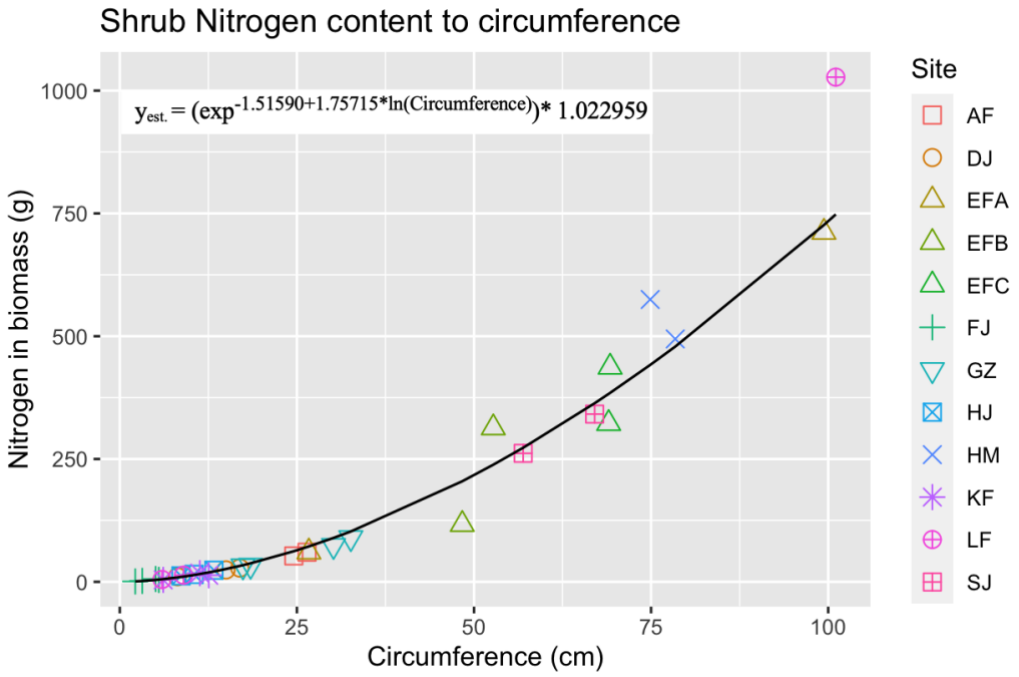


Figure 24: The estimated total nitrogen content in the sampled shrubs (including foliage) to the circumference of the summed cross-sectional area of the shrub stems at 0.65 m above ground. The expression of the back transformed loglog-linear regression model including the correction factor is included and drawn in black. The adjusted R^2 is 0.9871, SER is 0.2131 and AIC is -4.2.

The detailed estimated total nitrogen in of the 32 sampled shrubs can be found in appendix B.28. The total nitrogen ranged from 0.8 g to 1027.4 g with a mean of 162 g and a smaller median of 32.8 g. As for the carbon, the nitrogen in the shrubs can also be estimated through regression models based on the same explanatory variables that worked for predicting the aboveground biomass. In figure 24 an example of such is provided, using the circumference variable to predict shrub nitrogen in the aboveground biomass.

3.9. Prediction of carbon sequestration in three systems with European hazelnut

In order better evaluate the ability of hazelnut shrubs to sequester carbon, three scenarios are calculated as to see the effect on a spatial scale.

3.9.1. Accumulated carbon in a hazelnut orchard

1a) First a hazelnut orchard of the same design as met at site EF, with 4 m in between rows and 4 m within rows of the hazelnut shrubs. This gives a maximum of 25 rows per hectare with 25 hazelnut shrubs in each, leading to 625 hazelnut shrubs per hectare. The average aboveground biomass excluding foliage of the four shrubs sampled at field EFB and EFC is 54.6 kg. The foliage is excluded since this is a yearly fluctuating carbon pool and will be handled separately. The belowground biomass is considered to be equal to 26% of the aboveground biomass, which then for the average 45 year old orchard hazelnut shrub in this scenario will be 15.6 kg, calculated from the total AGB including foliage. The carbon content in the more permanent part of the stem and branches including the estimated belowground biomass is found by multiplying with the average carbon content excluding foliage of 47.85%, giving an AGB shrub carbon content of 33.6 kg. With these information, the total stored carbon in the above and belowground biomass in a 45 year old hazelnut orchard is 21 Mg C/ha. Given the orchard is 45 years old the yearly carbon sequestrated per hectare in the above and belowground biomass

is then 0,47 Mg C/ha/year equalling to a yearly uptake of 1.7 Mg CO_2/ha/year[13]. This number is excluding carbon stored in the material removed during yearly pruning, harvested nuts, leaves and carbon stored within the soil. The average foliage biomass of the four hazelnut shrubs were 4.7 kg per shrub, which multiplied by the average carbon content in the leaves (47.05%) and extrapolated to the field level gives an additional 1.4 Mg C/ha/year (5.1 CO_2 Mg C/ha/year), for a mature hazelnut orchard of 45 years.

1b) The scenario 1b is considering a young orchard with same plant distances as above, but with the average biomasses from site AF, DJ, GZ and KF, all representing vegetatively propagated hazelnut shrubs of productive cultivars and with a stand age of 5-6 years. The average AGB excluding foliage was 4.1 kg, the belowground biomass estimated at 1.3 kg and the average foliage 0.7 kg. This results in 3.4 Mg C/ha stored in the standing biomass, indicating a yearly carbon sequestration of 0.62 Mg C/ha/year (2.28 Mg CO_2/ha/year) and an additional 0.4 Mg C/ha/year from the foliage (1.47 Mg CO_2 /ha/year), estimated from the shrubs of 5 to 6 years in age.

3.9.2. Accumulated carbon in an alley cropping system

2a) The second scenario is in an alley cropping system using the same spacing as site FJ with 32 m in the alleys and a double row of hazelnut shrubs with 4 m distance within rows and 4 m between rows. In one hectare around three such double rows could fit, each with 2 times 25 hazelnut shrubs, resulting in 150 hazelnut shrubs per hectare. In a mature system, with a stand age of 45 years and intensively manged by pruning, the hazelnut shrubs would sequestrate 150*33.6 kg= 5040 kg. This would be approximately 5.04 Mg C/ha over the course of the 45 years, which divided by stand years would be 0.11 Mg C/ha/year equalling to 0.41 Mg CO_2 /ha/year. This is however without the foliage which would contribute with an additional 0.33 Mg C/ha/year for mature trees with a well-developed, pruned and therefore light open crown.

2b) If the shrubs on the other hand were managed more extensive with no pruning activities the biomass would be more similar to e.g. the hazelnut shrubs sampled at site SJ. Here the average shrub AGB without foliage were 44.7 kg, the belowground biomass estimated to be

[13] It is assumed that 1 kg of carbon is equal to 3.67 kg of carbon dioxide, given that the atomic mass of carbon is 12 and the molecular mass of CO_2 is 44, therefore 44/12 = 3.67.

13.1 kg, the foliage 4.8 kg and a stand age of 16 years. This would in an alley cropping system like described above result in a carbon sequestration of 4.15 Mg/ha in 16 years, giving an average yearly sequestration of 0.26 Mg C/ha/year (0.95 Mg CO_2/ha/year) excluding foliage. The foliage would additionally add 0.34 Mg C/ha/year for a 16 year old stand.

3.9.3. Accumulated carbon in living fence

3) The third scenario is considering the carbon sequestration of a living fence entirely made up by hazelnut shrubs, arranged in one row with 1 m in between the plants. A fence following one side of a hectare for instance separating a road and a crop field, would approximately constitute of 100 hazelnut shrubs. Theses shrubs would most likely be pruned, at least to one side, as was done for both old fences at site LF3 and HM. The average carbon stored in the living fence will be based on the shrubs measured at site HM, since the shrub at site LF3 had been coppiced. The total carbon stored in the above and belowground biomass excluding foliage is estimated at 52.5 kg leading to a total carbon storage within the fence of 5.3 Mg C. The leaves would contribute with an additional 0.31 Mg C/ha/year for the mature +50 years old fence. The yearly uptake is not calculated in this case, because the stand age is not completely known, but only a rough estimate given by the owners.

Section 4: Discussion

4.1. Comparing models with generic allometric biomass models for shrubs

The shrub level models including the composed variable “circumference” showed superior fit to any other shrub level model for total aboveground biomass including and excluding foliage. Even when compared to models including three variables of both crown diameter, height and diameter range, as done in shrub AGBF model 5, the single circumference model had a higher adjusted coefficient of determination of 0.9932 against the highest other fit of 0.9529 for the three variable model. Adding the height to the circumference variable improved the explanatory ability of the biomass models predicting foliage, branches and stems excluding crown biomass. These results are in line with findings by both Paul et al. (2016) and Conti et al. (2019) in their work of developing allometric biomass models for shrub and multiple stemmed trees across species and ecozones of Australia and globally. In both studies they found

that the variable of basal diameter, being defined as diameters at 10 cm above ground in Paul et al. (2016) or 30 cm in Conti et al. (2019), were the best single predictor variable at explaining shrub/multiple stemmed trees aboveground biomass. In both studies emphasis was put on the lacking consensus among researchers of sample height of this diameter measurement, as well as how this was approached if the plants ramified below the 10 cm or 30 cm, as being the case for *Corylus avellana*. Some of the included datasets in Conti et al. (2019) were reported to measure the diameter of the largest stem within the shrub, resembling the approach of diameter range tested within this study.

In Paul et al (2016) it was suggested to create a combined basal diameter of the multiple stems, if the plant ramified below the point of measure – here 10 cm, by the following equation:

$$BD_{composed} = \sqrt{\sum D_i^2}$$

This is in fact the diameter of the summed cross-sectional area of the stems, which therefore is the exact same approach as the circumference variable tested within this study. However, the diameters were measured at a higher point aboveground for the hazelnut shrubs, due to difficulties and inconsistency collecting the lower stem diameter information. Both studies highlight that even though this variable is the best fit, it is a variable prone to imprecision due to practical challenges collecting this data in the field, as was also found to be true for *Corylus avellana*. The composed or actual basal diameters in Paul et al. (2016) were able to explain 96.8% and 93.7% of the variation within the AGB of the multiple species dataset of the plant functions "multiple stemmed tree" and "shrubs", respectively. For the species specific models develop within this study, the circumference variable was able to explain 99.32% and with a lower RSME (for the AGBF). Being a species specific model, it is not surprising to have a higher R^2 or lower RSME, than the broader multiple species models developed in Paul et al. (2016). It does point to the possibility of using stem diameters measured at a higher point above ground e.g. at 65 cm as done within this study, and still achieve a high degree of explanation. This would ease the troubles gathering the data and potentially decreasing the error margins of diameter measures in shrubs.

There is two downsides associated to this well preforming variable. First of all, measuring every single stem diameter in a multi stemmed species like *Corylus avellana*, where the number of stems can become plus 50 when not managed, is laboursome and tedious. It might be relevant within academia if very precise estimates are needed or in an orchard setting, where only two

to six well developed stems are kept. But this is not a viable option for estimating more extensively managed hazelnut shrubs. Secondly, as pointed by Conti et al. (2019) it is not adequate to explain the dimensions and volume taken up by shrubs, simply by the diameter(s) of the stem(s) and in general single variable models is not recommended for models describing shrubs, giving their larger variability. The crown do constitute a larger percentage of shrubs and should preferable also be described within a well predicting shrub model.

In consistence with the findings in Conti et al. (2019) for a large compiled dataset on global shrub models, the crown diameter showed good explanatory abilities in describing the AGB(F) of hazelnut shrubs. If combined with shrub height this serves as a useful alternative to the, in some cases, difficult measure of stem diameters. He et al. (2016) further points that crown area or crown diameter does improve the fit of species specific shrub models. But neither serve as a useful single predictor variable, because it only describes horizontal growth (He et al., 2016). Adding the height or a measure of stem diameter (in this study diameter range or circumference) will include the aspect of vertical growth. The height and measures of stem diameter are highly correlated with Spearman's correlation coefficients within this study of 0.8644 for diameter range and height and 0.9542 for circumference and height. The stem diameter does to some degree explain the height, if for instance pruning interventions are disregarded. This was also pointed in Paul et al. (2016) to be one of the reasons why the inclusion of height in a model with basal diameter did not seem to improve the fit of total AGB shrub models significantly. In this study it was similarly found that including the height variable to the circumference model, did not improve the fit of the total ABG and ABGF models. But adding the height to the less precise diameter measure of diameter range however did. In Conti et al. (2019) the best model was selected to be a three variable model including both basal diameter (BD), height (H) and crown diameter (CD):

$$AGB = \exp\left(-2.281 + 1.525 * \ln(BD) + 0.831 * \ln(CD) + 0.523 * \ln\left(H\right)\right)$$

This model is similar to the AGBF shrub model 5 in this study. However, it is using diameter range instead of basal diameter. A three level model will require both an additional field measurement and does contain the issue of multicollinearity among all three variables, impacting the values of the regression coefficients. The two variable models were therefore emphasized as better options within this study. Especially the model combining crown diameter and height. This combination of variables was also highlighted by Conti et al. (2019) as the

best alternative to models without basal diameter. The dataset in Conti et al. (2019) is dominated by shrubs from tropical and subtropical regions. The generic shrub models suggested in Conti et al. (2019) are therefore not tested on the dataset of this study.

An additional point favoring the use of the height and crown diameter models is the increased interest in using remote sensing for measuring carbon stocks worldwide. Here the use of crown dimensions in the allometric models has also for single stemmed trees gained increased interest (Chen et al., 2023; Zianis et al., 2005). Through laser scanning imagery it is possible to measure height of trees and crown width in an area far above what could be measured on the ground, within limits of reasonable time and cost. Having species specific allometric models developed using height and crown width as predictor variables would, if made precise, serve as the necessary ground truth data to make the best biomass predictions from the remote sensing recorded information (Conti et al., 2019; Zianis et al., 2005).

4.2. Species specific allometric biomass models for Corylus avellana in the literature

Only three[14] species specific allometric biomass models for *Corylus avellana* were found within the literature. One is based on hazelnut shrubs grown as an understory species in a forest ecosystem in Lithuania (Škėma et al., 2018), one for hazelnut shrubs grown in a coppice-with-standards forest in Central Germany (Albert et al., 2014) and one for cultivated hazelnut shrubs grown in orchards focused on nut production in Italy (Pacchiarelli et al., 2022). In a study by He et al. (2016) allometric biomass models were developed for the similar species *Corylus mandshurica* also grown as an understory vegetation in a mixed broadleaved and coniferous forest in Northeastern China. Pacchiarelli et al. (2022) tested the fitness and predictability of the equations of the forest ecosystems by Škėma et al., (2018) on the data collected from the open field environment in Italy. The allometric biomass model did not perform well. This is explained by the big differences in light availability and therefore the differed carbon allocation strategy of the trees. In a shaded environment the trees will priorities growth in height to compete with other trees, resulting in thinner branches. In an open field setting, the hazelnut shrubs will often obtain a more rounded bush like shape, with thicker stems and branches,

[14] One model estimating volume were found in Zianis et al. (2005) dating back to 1966 in Norway:
$V = -1{,}86827 + 0{,}21461*D^2 + 0{,}01283*D^2*H + 0{,}0138*D*H^2 - 0{,}06311*H^2$
This was however not included for further comparision.

because they often do not compete for light and are pruned periodically (Pacchiarelli et al., 2022). This fits with the description of the European hazelnut in Hicks (2022) as being a phenotypically plastic pioneer, given its effectiveness at moderating the allocation of resources to the surrounding environment and level of competition. It also makes the model established by He et al. (2016) seem irrelevant for direct comparison with the models established within this study for more light open conditions. To what degree the hazelnut shrubs in the study by Albert et al. (2014) were shaded is not clearly stated in the text. The over-story standard trees are reported to be more than 120 years old (Albert et al., 2014). Even though knowledge of the distance between the coppice species and the single stemmed standards is not known, the age and the system design leads to the assumption that these hazelnut shrubs receive more shadow than a hazelnut shrub in an open field.

Only the model provided by Pacchiarelli et al. (2022) seems to have relevance for this particular study focusing on hazelnut shrubs (*Corylus avellana*) grown in open field conditions. This finding was further confirmed by checking with the international data sharing platform GlobAllomeTree.org. The platform contains allometric equations, wood densities, and raw biomass data shared by organisations like the Food and Agriculture Organisation of the United Nations and The French Agricultural Research Centre for International Development (CIRAD), but also researchers from all over the world dating back to 2013. No additional equations or datasets were available for *Corylus avellana.*

Interestingly, the study by Pacchiarelli et al. (2022) is using a stem level model to predict the aboveground biomass on field level, however referred to as “branches” within the study. The model is a single variable model using the explanatory variable of stem diameter at 0.6 m sample height, for predicting the stem aboveground biomass including foliage (AGBF):

$$AGBF\ (kg) = 0.784*D_{0.6}-1.199 \quad (R^2 = 0.78)$$

The corresponding model developed within this study is stem level AGBF model 1:

$$Stem\ AGBF\ (g) = \exp(4.7288+2.0714*\ln(D0.65))*1.1476 \quad (R^2 = 0.9246)$$

The model from Pacchiarelli et al. (2022) was tested for its ability to predict the AGBF of the 84 felled stems within this study, using the stem diameters at 0.65 m instead of 0.6 m. Since no information as to whether the model was log-log transformed, it had to be assumed, given

unrealistic negative values, plotting the diameters directly in the model. After having back transformed the model, though without any correction factors, the results still seemed greatly erroneous. This could be caused by a wrong use of the model, given a lack of information within the article. It could also be due to the warmer climate, volcanic soils, different cultivars (Tonda Gentile Romana and Nocchione) and different horticultural practices applied at the sites where the stems for calibrating the model were collected. A third explanation of the bad predictive ability of the model on the Danish hazelnut stems, could be the result of only including one predictor variable and then extrapolating it to sites outside the range of calibration. Site conditions were in neither the study by Conti et al. (2019) nor Paul et al. (2016) found to have a significant explanatory ability of the variation found in the biomass of shrubs and multi stemmed trees across large compiled data sets of different species. Paul et al. (2016) notes that the factors of climate and management practices do not impact the overall aboveground biomass of the plants. But they do create altering allocation strategies of plants from same species or plant type. Since the stem level models is not dealing with only a part of the hazelnut shrubs, the site factors could potentially have a higher effect given the findings in Paul et al. (2016). Models using the constructed explanatory variable of the squared diameter at 0.65 m multiplied by stem length (LD^2) is seen as a more secure model in terms of extrapolation, in this study. Despite AGBF model 1 having better goodness of fit statistics (see table 9).

The stem level models presented in table 9, might be relevant for use in orchard where all shrubs are trained to have the same amount of stems per shrub, as done in Pacchiarelli et al. (2022). It would be expected to range from two to three larger stems as for site EF, or five to six stems as suggested in the cultivation guide on hazelnut shrubs from Danish SEGES (Sørensen, 2022). The stem level models could also be relevant for estimating the biomass of an old living fence, where it is no longer possible to distinguish the individual shrub due to the outward expanding yearly shooting of basal shoots from the partly underground stool (Hicks 2022). The residual plots of the shrub level models were, however, significantly more homogeneous than the stem level models. The coefficient of determination reached higher values among the shrub level biomass models and lower AIC values, compared to the stem level models. This could highlight the weakness of the stem level models, because the stems are not individual plants, but a part of an entity sharing and competing for resources.

4.3. Applicability and validity of the developed biomass models

Developing accurate and precise allometric biomass models for multi stemmed trees or shrubs is recognized to be more difficult than estimating single stem trees. This is further true when shrubs and trees are grown on open land as opposed to within a managed forest stand, where the dimensions tend to vary less (Conti et al., 2019; He et al., 2016). For this particular study there was an interest in creating a broad model for European hazelnut shrub grown in open field conditions. The model was sought to be calibrated on a wide ranging dataset representing different settings from hazelnut orchards with yearly pruning to more extensive systems without continued pruning and even including systems without intentions of harvesting any yields of hazelnut nor wood.

As stated in the literature (Dutchă et al., 2020; Paul et al., 2016; Piccard et al., 2012) an allometric biomass model is most accurately predicting the biomasses of shrubs with dimensions falling within the dataset, to which the models were calibrated. The diameter of the stems sampled at 0.65 m ranged from 0.2 cm to 16 cm, the shrub crown diameter ranged from 56 cm to 650 cm and the shrub height from 96 cm to 855 cm, all indicating a relative large variation, which is good in regards to predictive power. The intention was to gather an equal, or near equal, representation of stems within the different diameter strata groups to improve the model prediction accuracy of shrub sizes that do not lie in the middle of the range used to calibrate the models. This was not succeeded, with the dataset being highly skewed towards smaller stems and shrubs. Several owners did not agree to fell the largest stems of the shrubs, because they were the ones with biggest commercial value. Another reason for the skewed data was that seven out of thirteen sites (with the subdivision of site EF and LF) only had stand ages of three to six years. This had implications as to within what range the developed models can be expected to be accurate. The developed model within this study would be expected to be most accurate and precise for shrubs with sizes in the middle of the range described above. The fairly broad range covered it should fit with most hazelnut shrubs used within a system where some degree of management is applied. Wild, unmanaged, hazelnut shrubs without competition, can become up to 13 m in height to which the models presented in this study would not be expected to accurately predict the biomass (Hicks et al., 2022).

A sample of 32 shrubs would by some authors be disqualified of being too small to adequately represent the population variation (Paul et al., 2016; Roxburgh et al., 2015). Partly because of

the high level of variability within shrubs as a plant functional type and partly because site-level sampling errors are assessed to be the biggest source of error, which can be minimized by increasing the number of samples (Conti et al., 2019; Paul et al., 2016). The hope is therefore that data collected within this study could be supplemented with additional data in the future to recalibrate the models to increase their statistical validity. The methods used within the data collection have been described in great detail as to ensure reproducibility and consistency if others were to increase the units of the dataset. The models are however assessed to be functional to use in a Danish setting to give a qualified estimate of the biomass of hazelnut shrubs grown in various systems of nut production or as living fences. Considering that no other relevant allometric biomass models are available for European hazelnut shrubs grown in light open conditions in Northern Europe, the models within this study serve as best current options, until further research are conducted.

4.4. Comparing the carbon and nitrogen content with findings in other studies

An analysis of carbon and nitrogen content in the different plant parts of European hazelnut was conducted. The results of this analysis can in combination with the biomass models developed within the study give qualified estimates of the nitrogen and carbon stored in situ of hazelnut shrubs grown in climatic conditions like Southern Scandinavia, more specifically Denmark. As noted by Thomas & Martin (2012) many studies estimating carbon storage from biomass estimates use the value of 50%, even though this tends to cause errors of ≈ 5%. Since the secondary objective of this study was to evaluate the potential of European hazelnut as a carbon sink within Danish agroecosystems, here among in an agroforestry setting, a more accurate estimate of carbon content was derived. The overall average across different plant tissues were 47.79% (0.073). That turned out to be just as good at estimating the whole shrub level aboveground carbon storage, than estimating each plant part of branches, foliage and stem separately. Estimates could have been done in further detail e.g. estimating the carbon content for each stem section based on the diameter and sample height and a more accurate determination of bark percentage. This approach would however only have been possible to follow through for the 85 felled stems and to estimate the whole shrub level carbon content, would have required additional stem-level models, as done for the biomass. This path was not pursued. Partly because other studies tend to utilize overall plant tissue carbon estimates to convert biomass to carbon and partly due to time constraints. A potential cause of error of the

estimated carbon contents of the different hazelnut plant tissues, is the volatile carbon components within the wood. This fraction of carbon is lost through the removal of moisture when drying the samples in an oven. This part of the wood carbon content can, according to Thomas & Martin (2012) potentially underestimate the carbon stored in live wood with 1.5% to 2.5%.

The average carbon content of 47.79% (0.073) is significantly larger than the value used in the study by Pacchiarelli et al. (2022) of 44.65% to convert the estimated biomass of orchard hazelnut shrubs to carbon. The value of 44.65% is determined in a study by Picchi et al. (2018) examining the combustion abilities of orchard residues here among *Corylus avellana*. In another study by Hadrović et al. (2021) the carbon and nitrogen content within bark and wood of five wild fruit and nut species in Southwest Serbia were examined. Here among *Corylus avellana*. The percentages of carbon and nitrogen were in this study also different from the ones found for the Danish hazelnut shrubs, with a generally smaller carbon content and higher nitrogen content: The wood contained 1.27% (0.22) nitrogen and 42.64 % (2.72) carbon in the study by Hadrović et al. (2021) against the 0.238% (0.02) nitrogen and 47.82% (0.05) carbon in the wooden hazelnut tissue sampled within this study. For the bark Hadrović et al. (2021) reported values of 1.60 % (0.20) nitrogen and 38.05% (2.18) carbon against the 0.80 % (0.02) nitrogen and 47.78 % (0.16) carbon found in this study. This difference could be attributed to the climatic, edaphic and topographic difference among the sites or indicate local differences within the species of *Corylus avellana*. It is widely acknowledged to be a broad ranging polymorphic species given its long history of different strings of domestication and breeding around the Northern hemisphere and its wide adaptation to different climatic conditions (Hicks 2022; Mehlenbacher & Molnar, 2022).

4.5. Carbon in hazelnut orchards

The estimated carbon storage potential of the orchard scenario with plant distances of 4 m times 4 m gave a total accumulated carbon within the below and aboveground biomass of 21 Mg C/ha, with an additional 1.4 Mg C/ha/year from the foliage in a 45 years old orchard. This calculation is based on four hazelnut shrubs exposed to yearly pruning of branches to promote nut yields and manual removal of new basal shoots. This estimate is almost double of the findings in Pacchiarelli et al. (2022). Here a 50 years old hazelnut orchard in Italy with similar plant density of 625 hazelnut shrubs per hectare, was estimated to have accumulated 11.19 Mg

C/ha in the above and belowground biomass. In the same study young orchards with stand ages ranging from three to five years were found have accumulated 0.6 to 3.4 Mg C/ha, which are more consistent with the estimated 3.4 Mg C/ha for a five to six year old orchard in Denmark. The yearly pruning material and hazelnut yields would increase the total assimilated carbon further.

At site EF, one of the fields had not been pruned in 10-15 years, but was the same age as the shrubs at field EFB and EFC. Shrub EFA1[15] had a total carbon stored within the ABGF of 84 kg where EFB2 had 24 kg, giving a difference of 60 kg. The two shrubs were otherwise same cultivar and had earlier on been managed in the same way. The difference does indicate the potentially large amount of carbon, removed from the continuous pruning of the hazelnut shrubs. The direct comparison can however not be made, since the growth patterns and allocation strategies of the hazelnut shrubs, based on observations and the biometric measurements, were very different. Within the unmanaged field of EFA the shrubs had allocated many resources in to elongating the stems due to a high competition for light between the hazelnut shrubs. For the shrubs at EFB, the stems and branches were wider and the management led the shrubs to allocate larger resources in to the development of nuts. The owners reported yields of one ton hazelnuts per hectare, but with large fluctuations and years without any yields, mainly caused by spring frost (Birk et al., 2022b). This indicates that some of the differences between the accumulated carbon in two shrubs should be attributed to nut yields leaving the system and decreasing the staying and stored carbon in EFB2. Several of visited orchard owners considered to implement the pruned material either directly within the orchard or apply it to other fields, which would enhance the carbon storage of the system.

4.6. Comments on the variable “pruned”

This also brings lights to the variable “pruned” within the developed biomass models that gave positive regression coefficients, indicating that the plants that were pruned, had a higher biomass. This seems to be true when combined with the other biometric variables, because pruning alters the allocation of resource and therefore the allometric relationships studied, as highlighted for EFA and EFB/C. The size of the regression coefficient of the variable “pruned” in the presented models in table 9 and 12, might be exceptionally large, due to the distribution of the sampled shrubs. Most large shrubs within the dataset had been pruned and most small

[15] EFA2 were considerably smaller than most other shrubs at field EFA and were therefore suspected to be planted later than EFA1 and most other shrubs within that field.

shrubs had not been pruned. This uncertainty was besides the fit statistics a reason for not including the variable "pruned" in most shrub level models. On the other hand, hazelnut shrubs in the arable land, being in a fence or in a extensively managed agroforestry system, will most likely be pruned at some point, given its ability to grow very wide and tall (Hicks, 2022). Paul et al. (2016) tested a binary variable of managed = 1 and not managed = 0, which for shrubs led to an improved model fit with lower AIC and RSME values. The inclusion of a management variable might contribute to even better models, making them more precise across management intensities. The binary format tested within this study seems to work for the stem level models, but it was not convincing for the shrub level models. A further degree of detail of the management variable as to whether it was top or side pruning, yearly or only occasionally could be considered for future models.

4.7. Carbon sequestration potential in an alley cropping system with hazelnut shrubs

The theoretically estimated alley cropping system accumulates 5.04 Mg C/ha in the standing biomass of the 150 hazelnut shrubs over a 45 year period, with an additional 0.33 Mg C/ha/year from the foliage (at mature age). Once again this was estimated using hazelnut shrubs that have been exposed to continuous pruning. For the other calculated example, using the biomass of shrubs with a stand age of 16 years without any pruning, the total accumulated carbon were 4.15 Mg/ha and with 0.34 Mg C/ha/year from the foliage. Recalculated as carbon stock accumulation rates the alley cropping systems accumulate between 0.44 Mg C/ha/year and 0.60 Mg C /ha/year. In a French study three silvoarable agroforestry systems with rows of walnut (hybrid or walnuts) and tree densities of 100-110 per hectare, were estimated to have an average yearly carbon accumulation in the above and belowground biomass ranging from 0.62 Mg C/ha/year to 1.85 Mg C/ha/year (Cardinael et al., 2017).

Even though the yearly storage in the hazelnut biomass is smaller in comparison with the walnut trees, especially considering the higher number of shrubs per hectare, it does however indicate that the estimates fall within an realistic range. An important missing factor within these spatial estimates of carbon storage is the effect on the soil organic carbon. In a review of potential effects of agroforestry systems in a Danish context, it was estimated that agroforestry systems could be expected to increase soil organic carbon content with 0.2 Mg C/ha/year (Daalgaard et al., 2019). This would give an average yearly carbon accumulation of around 0.72 Mg C/ha/year.

In a theoretical scenario, where one fourth of all $1.3*10^6$ ha cereal fields in Denmark was transitioning to an alley cropping system with rows of hazelnut shrubs with a density of 150 shrubs/ha, it would accumulate 234,000 Mg C/ha/year. Recalculated as carbon dioxide it would be 858,780 Mg CO_2 /ha/year. In relation to the Danish national GHG emission of 44.55 million Mg CO_2 equivalents, transitioning to alley cropping systems on one fourth of all Danish cereal fields would mitigate 1,93 % of national emissions (2021 data, Our World in Data, 2023). Such a high adaptation rate of agroforestry systems does seem unrealistic, but it gives an indication of the carbon storage potential within agroforestry systems, hereunder alley cropping with wide alley spacing. Potentials as to combine higher shrub densities as in orchards with other activities such as intercropping with alfalfa, wild flowers or potatoes in between the rows of young hazelnut shrubs, as seen at site LF and DJ or having sheep grazing as at site EFC, are other examples of diversified usage of perennial agricultural systems, which would be expected to give higher rates of carbon accumulation.

Section 5: Conclusion

Focussing on the carbon sequestration potential is an important dimension of agroforestry systems,. As presented in the first sections of the thesis, agroforestry is promoted due to several beneficial synergetic effects among the components in the systems. The ecosystem service of capturing and storing carbon dioxide is just one of these. In a future where farmers could be expected to offset their GHGs emissions, the ability to more accurately estimate the biomass and carbon within the perennial components of such systems is important.

Given the very limited adaptation of agroforestry systems in Denmark, it is difficult to predict how the systems will be managed, especially regarding fertilization, irrigation and pruning. The allometric biomass models developed within this thesis therefore aimed to span a wide range of management intensities, cultivars, system designs and site conditions. This was achieved by collecting destructive and non-destructive data for 32 hazelnut shrubs at 10 sites geographically spread around Denmark. Several biometric measures were tested as explanatory variables for predicting the total aboveground biomass of hazelnut shrubs, as well as in models for predicting independent plant parts of the stems, branches and foliage. The best model at predicting overall aboveground biomass was the two variable model using crown diameter and shrub height as input variables, with an adjusted R^2 value of 0.9412, AIC

of 55.7 and RSME 0.5465. Shrub height and crown diameter are measurements that are reasonable to gather at field level and they can be obtained by satellite images for application on a larger spatial scale. The best biomass models for predicting the separate plant parts of stems, branches and foliage, had the composed variable "circumference" and shrub height as input variables. The circumference variable is constructed from the total sum of the cross sectional area of all stems within the shrub. It showed a greater ability to explain the variation within the biomass than any other tested variables. Models including circumference showed significantly higher adjusted R^2 values ranging from 0.9808 to 0.9952 and smaller values of AIC and RSME. Even though it requires additional measurement at the field level to construct the circumference variable, the models including the circumference variable should be considered in situations where the highest possible accuracy is required. Biomass models on the individual stem level were furthermore developed, which might be of usage in certain situations. However, the shrub level models are found to be of higher statistic quality.
When comparing the sampled material with a model developed for Italian orchards, it was not compatible, indicating altering allometric relations. As so, the developed models in this study are species specific and site specific, meaning that they can only be expected to give acceptable predictions within the same region of Southern Scandinavia, and for dimensions that falls within the calibrated dataset. The number of individuals sampled is within the small end of statistical validity and some authors exclude studies of this size from meta and cross study analysis of allometric data. The hope is that, given a detailed description of the methods applied during data collection, the data and models within this study can serve as a starting point. Gathering additional data for improving the models further would be of great use. Utilising the data in a Scandinavian cross species allometric model focussing on shrub plant functional types could be another great potential usage.

Carbon and nitrogen contents of different plant parts of merged samples of *Corylus avellana* were also estimated. The overall estimate of carbon content in the biomass of hazelnut shrubs were 47.79% (0.073). Even though the nitrogen contents of the different plant parts of *Corylus avellana* were not explored to same extend as the carbon, it is important to be able to estimate the input and output of key plant nutrients in agroforestry systems. When integrating the foliage or pruning materials in the system, it is important for regulating the needed fertilizers applied. The results given within this thesis can hopefully be a source for this kind of estimates. Overall, the result in this thesis falls within the academic tradition of developing allometric biomass models. More specifically developed for usage in the open field

environment found in the arable land. It is furthermore a contribution to the research done within project ROBUST, building the fundamental data of the impact of agroforestry under Danish conditions.

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