Allometric Biomass Estimation and Carbon Storage Quantification in Apple Trees

In relation to potential future temperate Danish agroforestry systems

Master thesis in Agriculture

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Abstract

Today Agroforestry as a tool for mitigating emissions while producing valuable products like food, fodder, and fibre. In the light of a great need for the earth's resources to be used sustainably agroforestry in temperate regions are being investigated. In relation to this, current project will provide knowledge on biomass and carbon storage in apple trees for present and future use in agroforestry systems in a Danish context. Here, biomass and biomass expansion factor functions are crucial to assess. In this study 36 apple trees of the cultivar Elstar was sampled from 10 orchards widely dispersed across Denmark, for the determination of estimating allometric models to project the biomass and thus the C stored in individual tree parts, stem volume, stem-to-aboveground-biomass-expansion factor (BEF) and stem basic density (BD) in danish apple trees. The trees were between 2 and 25 years old, their individual stem diameter in the height of 50 cm above the ground fluctuated from 1.2 to 14.4 cm, and AGB per tree ranged from 0.2 to 44.8 kg tree^{-1}. D50 and height as predictor variables was included in the final recommended models developed for estimating stem volume and leaf- and fruitless AGB of the tree components branch and stem, which explained between 93%-98% of the variation. Biomass values rose exponentially with increasing stem D50, where the trees with a D50 >5 cm also weighed below 5 kg, where every cm of increase in D50 the biomass raised with 2.18 kg tree^{-1}. Stem volume showed same development, where trees with a D50 <10 cm roughly had a stem volume of ≤ 0.01 m^3. For the smallest trees BEF values were around 1.8, and decreased with rising stem D50, where trees with >10 cm roughly had a value around 1.3 BEF. Stem BD was found the highest in trees grown 6-14 m.a.s.l., with an average value of 490 kg m^{-3}, and declined with increasing meters above sea level, where trees grown in 43 m.a.s.l. roughly had a stem BD on 430 490 kg m^{-3}. The existing AGB models in the accessible literature either under- or overestimated the measured sample apple tree AGB. Here several factors of explainable value are possible, and accommodate different growing conditions, management procedures and genetics among species and cultivars. The observation of higher BD in the dwarfing rootstock compared to the Elstar variety stem grated upon, lead to the hypothesis, that estimate differences also occurred due to sample procedures. When either excluding samples from above or beneath the grafting point it may lead to over or underestimation of what was observed in danish orchard Elstar apple trees.

Preface

This master thesis was conducted in collaboration with a four-year research project (ROBUST), the ph.d. student Lisa Mølgård, head of section at IFRO Henrik Meilby, professor Lars Vesterdal, and assistant professor Anders Tærø. All supervisors and support of this project. Hanne Lindhart from Hortiadvice provided information on favorable sites for this project. My cousin Emma helped with the graphic layout, my friend Rasmus with statistical entanglement, and my eternal support Amalie, who helped me through the writing process. The process of producing and analyzing data showed interesting challenges, among snowstorm in Midtjylland, prolonged drying of stem samples, and a steep learning curve in the application of the statistics program R

15.03.22

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ABBREVIATION LEGEND

C = carbon

N = nitrogen

P = phosphorous

LUC = land use change

SOC = soil organic carbon

t = tonnes

Mt = mega tonnes

Gt = giga tonnes

GHG = greenhouse gas

ha = hectare

Mh = mega hectare

AGB = aboveground biomass

BGB = belowground biomass

BEF = biomass expansion factor

1. Introduction

1.1. Background: Agriculture, environment, climate change and agroforestry

1.1.1 Consequences of the green revolution

Agriculture now occupies 50% of the world's habitable land area. Expansion of croplands and pastures replacing natural ecosystems went from concerning an area of 0.4 billion ha in 1020, 1 billion ha in 1720, to 4.87 billion ha in 2016 (Goldewijk et al. 2017; Ritchie and Roser 2020).
This expansion of agriculture into natural ecosystems has prodigious influence on environmental aspects like soil conditions, habitats, biodiversity, and carbon (C) storage (Tilman et al. 2002; Finlayson et al. 2005; Foley et al. 2005; Steinfeld et al. 2006).

According to IUCN Red List[1], the world's most comprehensive inventory of the global conservation status of plant and animal species, since 1500 around 900 species have been proven extinct (Rodrigues et al. 2006). However, Cowie et al. (2022) estimate that the number is much higher, stating that 7.5-13% of the world's ~ 2 million known species have died out since the 16th century. Currently species are vanishing at an increasing rate, qualifying this geographical era as the Anthropocene (Ruddiman 2013), where human activity is taking up space largely through land use changes (LUC) like conversion from natural ecosystems to agricultural production systems, causing the world to experience its sixth mass extinction (Cardinale et al. 2012; Dirzo et al. 2014; E. S. Brondizio, J. Settele, S. Díaz 2019). Of the world's total mammal biomass 4% is estimated to be wild species, and the rest are livestock (excluding humans) (Ritchie and Roser 2020). Estimations by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[2] (IPBES) indicates that 1 million species are threatened with extinction (E. S. Brondizio, J. Settele, S. Díaz 2019). For what is left of the wild animal and plant species of today (in 2019), the Red List state that

[1] The International Union for Conservation of Nature.
[2] An independent intergovernmental body established by States to strengthen the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development.

28.000 of them are documented threatened with extinction, and that agriculture is listed as a threat for 24.000 of them (Ritchie and Roser 2020).

Soil is a non-renewable resource on human time scales, that degrades under physical, chemical, and biological processes. These processes include loss of fertility, soil structure, nutrition, species diversity of soil microorganisms, soil organic carbon (SOC), accelerated erosion, compaction, pollution, salinization, and acidification (Lal 2015), with decline in productivity, ecosystem services and soil quality as a result (Barrow 1991; Lal 2009). Soil degradation affects the overall climate, and food security by declining yields, nutritional value, and input efficiency (e.g., fertilizer, irrigation) (Barrow 1991; McMichael et al. 2007; Lal 2009). Bini (2009) and Oldeman (1992) estimates that 33% of the globes terrestrial surface, and 38% of the agricultural land undergoes anthropogenic degradation of the soil, where 20% is moderately degraded and 6% is strongly degraded. This is due to repeated tillage, heavy farm machinery, water quality and management, use of pesticides, improper use of fertilizers, depleted biodiversity and organic matter (Alam 2014).

Intensification management practices make agricultural systems more productive. They are responsible for most of the yield increases in the past few decades (Foley et al. 2011), through inclined pest resilience and crop growth by practice of pesticides, irrigation and fertilizers (Brady et al. 2008). However, the intensification comes at a great cost. Since 1970 the agricultural crop production has tripled its value (E. S. Brondizio, J. Settele, S. Díaz 2019), meanwhile the worlds fertilizer use has increased fivefold (>8 times for N) (Matson et al. 1997; Tilman et al. 2001; FAO 2021), doubled the area of irrigated cropland (Rosegrant et al. 2002; Gleick 2003; FAO 2021) and increased pesticide use by ~75%[3] between 2019-2020 (Sharma et al. 2019). Like conversion of natural ecosystems to agriculture, this intensification influence the environment by increased use of energy and natural resources, increasing degradation and competition for limited water and soil resources, disrupted nutrient cycles (especially nitrogen (N) and phosphorous (P)) (Vitousek et al. 1997; Smil 2000; Bennett et al. 2001) and widespread pollution (Matson et al. 1997; Vörösmarty et al. 2000; Diaz and Rosenberg 2008). 70 - 85% (~85% of consumptive use) of the global freshwater withdrawals is accounted for agricultural irrigation (Gleick et al. 2009; Gomiero et al. 2011; Hathaway 2016; Ritchie and Roser 2020).

[3] From 2 Mt to 3.5 Mt.

The depletion rate of fossil phosphorus (P) finite reserves is increasing. In 2009 and 2011 they were estimated by Gilbert and USGS respectively to be 65 Gt (Gabriel et al. 2013), where ~77%[4] is low quality characterized by impurities and constraints like hard-to-reach offshore deposits. With the estimated yearly extraction from 2014 on 22 Mt a peak in high quality P is estimated by Lodberg et al. (2016) in 2069.
Agricultural nutrients and nonbiodegradable pollutants (e.g., pesticides) enter terrestrial and aquatic ecosystems through waste streams, leaching and volatilization. Particularly polluting is the bioaccumulating or persistent organic agricultural pollutants (e.g. DDT, PBC, and endosulfan) (Tilman et al. 2002; Tombesi et al. 2014; Antolín-Rodríguez et al. 2016; Takaki et al. 2017).
The efficiency of pesticides is declining as pests and diseases develop resilience, while their environmental presence can harm biodiversity, human and soil health (Tilman et al. 2002; Chen et al. 2004; Zhang 2011, 2018; Kumar et al. 2013; Hathaway 2016).

1.1.2 Climate Change

Another considerable aspect is the agricultural sector's contribution of greenhouse gas (GHG) emissions into the atmosphere, worsening the global warming and thus climate change.
The climatic crisis is reported among other by the United Nations Intergovernmental Panel on Climate Change (IPCC) (Hansen et al. 2008) which states that in 2019 the annual averages of atmospheric carbon dioxide (CO_2) increased to 410 parts per million (ppm), 332 parts per billion (ppb) for nitrous oxide (N_2O), and 1866 ppb for methane (CH_4) (IPCC 2021). These values constitute, respectively, 149%, 123% and 262% of the pre-industrial levels in 1750 (WMO 2020). Half of the emitted CO_2 is captured by sinks in the terrestrial and aquatic ecosystems for now, but the World Meteorological Organization worry the buffer effect will decrease in the future (WMO 2020).
The agri-food production systems are responsible for 26-31% of the world's total anthropogenic GHG emissions according to FAOSTAT[5] database (Poore and Nemecek 2018; Tubiello et al. 2021) due to land use change (LUC), manure and fertilizer management, enteric fermentation by ruminants, and fossil fuel combustion, among other sources (Moran and Wall 2011). According to the non-profit organization GRAIN (2011) agriculture account for half of the emitted GHG when including the

[4] 50 GT.
[5] The Food and Agriculture Organization Corporate Statistical Database.

agricultural related emissions from other sectors including aspects like transportation, production of pesticides and fertilizers, food processing, packaging, storage, waste, and deforestation.
In 2019 it is estimated GHG emitted since preindustrial levels, the global mean annual temperature increased by 0.8 °C, and especially for Europe the climate has changed more than in other places, with a 1.2 °C increase of mean annual temperature, ~25% incline of rainfall in northern Europe and 20% decline in southern. Modelling of future global temperature increase anticipates additional 1.0-5.5 °C in 2100 and extreme weather events will be even more commonly (Christensen et al. 2007; EEA 2008) and cause droughts, intense heat, rainfall, floods, ocean acidification, ice melt, sea-level rise, as well as wide-ranging socioeconomic repercussions (IPCC 2019).
Climate change also affects nature from the level of genetics to ecosystems (E. S. Brondizio, J. Settele, S. Díaz 2019), by e.g. promoting proliferation of established and new invasions, breaking up interrelations between prey and predators causing disruption in ecological cycles, phenological features, food availability, dispersal capability and decline in habitats (Withgott and Laposata 2015) threatening biodiversity further (European Environment Agency 2009).
Climate change also enhance soil degradation through erosion of soil organic carbon stocks released as CO_2 into the atmosphere, which in some areas will participate in desertification (EEA 2008; Correal et al. 2009).

With a projection of a further increase to reach 9.8 billion in 2050, and 11.2 billion in 2100 (UN 2017) as well as economic growth, and inclining middle class citizens globally, causing shifts in diets and level of consumption, and thus further anthropogenic disturbance of the climate stability, the way that food is produced requisite a great demand for a sustainable and holistic green transition (Hathaway 2016; Castro et al. 2018).

1.1.3 Agroforestry as a part of the solution

European Rural Development Council Regulation propose use of agroforestry production methods for adapting our food production to climate change and mitigation by reducing GHG emissions through sequestration and storage of atmospheric carbon in the biomass and soil, to contribute to reaching the climate mitigation goals of the Kyoto Protocol[6] and Paris Agreement[7].

[6] 192 parties committing industrialized countries to limit and reduce their GHG emissions in 1997.
[7] 196 parties committing to a legally binding international treaty on climate change in 2015.

Agroforestry is also considered to potentially mitigate the above-mentioned unsustainable side effects of agriculture by minimizing the need for input of pesticides, fertilizer, and irrigation, by improving soil fertility, water quality, nutrient cycles, water management, conservation of biological diversity through food and habitats above and beneath the ground in producing systems,
while providing market products like food, fodder, fibre, fertilizer, and pharmaceuticals and animal welfare attributes like shelter, shade, natural surroundings and skin care option (Udawatta et al. 2008, 2014; Rawat and Vishvakarma 2011; Rivest et al. 2013; Jose et al. 2015; Gibbs et al. 2016; Dalgaard et al. 2019; Agforward 2020; Lal 2020). Thus, agroforestry fit into the expectations for agricultural properties of the future regarding high productivity in compliance with natural resource cycles, environmental sustainability, life vitality and climate robustness, by new ways of creating interactions between food production and nature (Birk et al. 2021).

Agroforestry lies in an intersection between forestry and agriculture with either mixed farming or with crops or livestock respectively (Fig. 1.1) and is defined as a system where perennial woody vegetation (trees and bushes) are grown in combination with agricultural production of livestock and/ or crops on the same area. Potentially it can create a smaller ecosystem of the different production components with benefit of ecological and economic interactions (Burgess et al. 2015) and classifies through regenerative benefits as an agroecological[8] system (Elevitch et al. 2018).

[8] With focus on the environmental interactions derived from ecology and applying the ecological principles to agricultural practices.

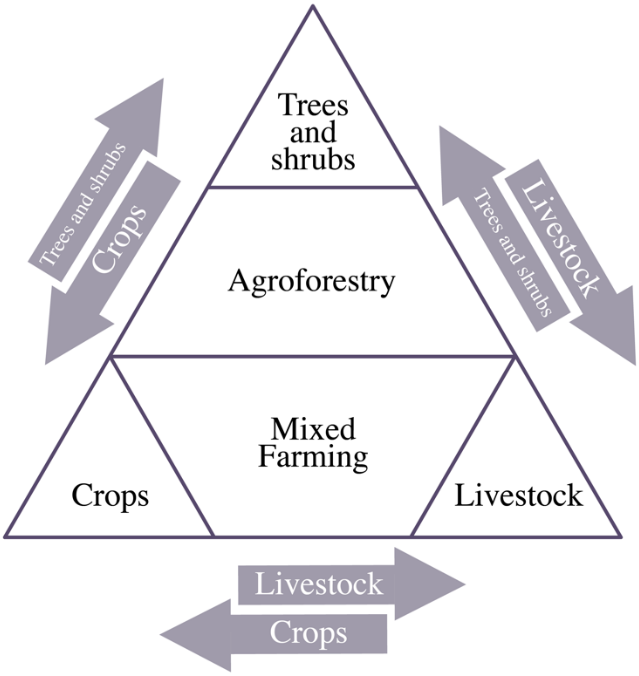

Figure 1.1 – Illustration of correlations and links between different types of agriculture (Raskin and Osborn 2019).

The definition covers many different types of systems, from minor to major degrees of complexity, available in many different sizes and shapes. This includes grasslands with trees, hedgerows, windbreaks, belts, buffer zones, rows of trees, orchards with field crops or grazing livestock, forests with grazing livestock, vegetable production and mushroom cultivation in forests, alleys on fields, forest gardens, and livestock paddocks with trees (Lundgren and Raintree 1982; Mosquera-Losada et al. 2008; Leakey 2017). It is not a fully developed technology, nor does it have a complete universal streamlined design. but mere a flexible concept that can be adjusted to specific situations. Agroforestry systems take shape of the hydrological and soil conditions of the area and the local climate under which it is implemented, as well as the wishes and goals that the landowner intends to meet through implementation like increase in yield, natural and environmental value, reduce inputs etc. One of the principles behind, is to get the maximum benefit out of the piece of land that is available, and most landscapes fit. Agroforestry systems are thus found in a multitude of versions, even in temperate regions, but overall, six different types have been classified by the European Agroforestry Research Project AGFORWARD (Mosquera-Losada et al. 2016) and is described and categorized in table 1.1.

Table 1.1 - Categorization of agroforestry systems based on their location in the landscape and the location of the trees in the system. (Lawson et al. 2016).

	Agroforestry systems	**Description**	**Official land use classification**	
			Forest land	**Agricultural land**
Trees within fields	Silvopastoral	Grazing in forest, plantation or trees integrated into livestock paddocks	Forest Grazing	Wood pasture Orchard grazing Individual trees
	Silvoarabel	Plant breeding in forest, plantation, or trees integrated into arable fields	Forest farming	Alley cropping Alley copice Orchard intercropping Individual trees
	Agrosilvopastoral	Mixtures of the above		
	Forest garden	Complex agronomic systems organized to produce in layers vertically mimicking natural forest edges		
Trees between fields	Buffer zones	Strips or belts of trees to reduce negative side effects from human activities	Forest buffer strips/ belts	Riparian tree strips/ belts
	Windbreaks	Rows of trees to perform shelter		Shelterbelts Wooded hedgerows

In a study Kumar et al. (2014) estimates the area for agroforestry to cover 1.023 Mha[9] globally, and in 2004 the World Bank estimated that 1.2 billion people is practicing some sort of agroforestry on their farm (World Bank 2004). Results from remote sensing and geographical information systems in the study of Kumar et al. (2014) show that > 1,000 Mha of the world's agricultural land holds> 10% tree crown cover, and that 1.8 billion people depend on this area as their habitat, and that the potential for expansion of agroforestry systems is high on degraded or redundant agricultural land. In 2018 the area of European agroforestry was estimated by Mosquera-Losada et al. (2018) to cover ~20 out of the 175 Mha total utilized agricultural area of which ~86% is silvopasture, ~11% is forest garden, 1% is riparian buffers and windbreaks in total, leaving forest farming unquantified (den Herder et al. 2017). In northern temperate regions[10] the total agroforestry area is 1.7 out of 49 Mha utilized agricultural land (ibid.), and in Denmark agroforestry cover 0.016.2 out of ~2.7 Mha (Mosquera-

[9] Ha x 10^6.
[10] E.g. England, Germany, the Netherlands, Sweden, Poland, Latvia, Ireland, Scotland, Denmark, and Belgium.

Losada et al., 2018). Forest grazing, coppicing and free grazing in orchards has been very common on in Denmark (Fritzbøger 1990), but today very few agroforestry systems is left in the landscape (Larsen et al. 2013), apart from most farmers using a minimum of windbreaks on their farm (Fritzbøger 2002). Despite it being a well-known cultivation concept in tropical agriculture, so far, there is only limited documentation of the effects under temperate climatic conditions like those of northern Europe.

1.1.4 Prospects of Danish temperate agroforestry

The Danish Organic Association have, however, built a network of > 1,800 people with an interest in agroforestry (Birk et al. 2021; Facebook 2022). Around 30 danish farmers use agroforestry methods (Økologisk Landsforening; Birk et al. 2021). Some of them work in collaboration with researchers and organisations as part of funded experiments and initiatives to widespread agroforestry internationally and in Denmark – e.g. Økologisk Landsforening, Center for Frilandsdyr, ICROFS[11], AU[12] and Innovationscenter for Økologisk Landbrug, initiating projects like: *InTRÆgrer,* where farmers are inspired and informed about rules, support schemes and share their experiences with each other regarding integration of trees in organic farming, *ROBUST,* where a sustainable agricultural system for plant breeding and milk production is explored, developed and disseminated through use of agroforestry methods, *Organic RDD 6 – OUTFIT*, that develops, demonstrates and investigates new designs of more sustainable paddock systems with trees and pigs, *MIXED*, where a farmers and researchers network across Europe covers a wide range of different mixed agricultural and agroforestry systems to generate new knowledge, and *Projekt Skovgris*, where a network of danish farmers and researchers identify benefits and challenges of commercial free-range pig production in silvopasture systems.

AFTA[13] in north America and EURAF[14] in Europe are examples of associations working internationally, holding conferences, and publishing technical and policy reports so scientific and practical knowledge about temperate agroforestry can be exchanged. Key organs like the UN Climate Panel (Shukla et al. 2019), the UN Food and Agriculture Organization (FAO 2017)and the European

[11] International Centre for Research in Organic Food Systems.
[12] Aarhus University.
[13] Association for Temperate Agroforestry.
[14] The European Agroforestry Federation.

Commission's Agricultural Partnership (EIP-AGRI 2017) are positive regarding agroforestry as a tool for a more sustainable food production. *AGFORWARD* is an example of a four-year research project (2014-2017) funded by EU's[15] research funds to collect and disseminate knowledge through research on agroforestry farms and research systems in European countries (Agforward 2020). In addition to this, major political plans in Denmark and EU regarding climate action, nature, and biodiversity, have been discussed in relation to the new seven-year framework of the EU's agricultural policy, EU's Farm to Fork strategy and the associated agricultural support schemes, which will lead to better terms for Danish farmers to convert their agricultural systems into agroforestry in January 2023 (European Commission 2022). Among other, Økologisk Landsforening have worked together with the Danish Agency for Agriculture and the Danish Ministry of the Environment and Food for changing the current support rules to be in favour for planting trees in the open field and grassland (Økologisk Landsforening 2020). Initiatives, funds, and organizations like *Velfærdsdelikatesser*, Permakultur Danmark, Velux Fonden, DN[16] and Ansdelsgarde.dk work for converting Danish agricultural land from conventional to agroecological and agroforestry-based food production systems, to meet future demands on sustainable and ethical food products. Among Danish consumers and citizens there is a growing awareness of the need for sustainable food production, and they are increasingly demanding products produced for the benefit of sustainability, biodiversity, environment, climate and animal welfare (ICROF 2017; SCHRØDER 2017; Landbrug & Fødevarer 2021; Økologisk Landsforening 2021a, b). In a ROBUST market analysis from 2021 it is concluded that future agroforestry products have a market potential for private consumers and in the restaurant, café, and hotel industry (HORECA). There is a small market share for agroforestry products in 2022 among the organic consumers and first movers[17] who are willing to pay more for climate friendly quality products. In 3-7 years, based on future studies, agroforestry will enter the mass market (ROBUST 2021).

1.1.5 Carbon storage quantification and aboveground biomass estimation

Agreements between countries globally on climate change mitigation by reducing greenhouse gas (GHG) emissions and sequestrate GHG from the atmosphere, have encouraged in depth investigation of carbon pools in tree biomass. When calculating the carbon amount of tree biomass of temperate species, it is often assumed to be between 43.4-55.6% of the dry weight (Thomas and Martin 2012).

[15] European Union.
[16] Danmarks Naturfredningsforening.
[17] The most innovative consumers (3%) on the market revealing future consumer trends.

Biomass is often divided into Above-, and below-ground biomass (AGB, BGB). For the former, this includes the stump, stem, branches, fruits, and leaves, and holds the presiding carbon pool in agroforestry systems (Ravindranath and Ostwald 2007). As for the latter, all alive roots are included. Several papers have been published on carbon storage in tree biomass, where forest ecologists have developed various methods to estimate AGB (e.g., Fassnacht et al. 2014; Taeroe et al. 2015; Nord-Larsen et al. 2017; Winzer et al. 2017). One way is through destructive harvest method, where all trees are cut down at ground level, and oven dried until dry weight can be measured (Winzer et al. 2017). This method is greatly precise, but also time consuming and laborious to a degree which often is not cost-effective, while also being a potential source of GHG emissions and harm on biodiversity. A less challenging way to go is to use or developed allometric and geometric equations by measuring the specific tree parameters, followed by use of the harvest method on a sample of trees to determine the relationship between the parameters and the volume or dry weight of the components (He et al., 2016; Zeng et al., 2010) (Russo et al., 2014). This can be done by the version of the "mean-tree" method, where a tree of mean size (e.g., stem volume or mean basal area) of the tree stand population is sampled and measured for dry weight. Then the dry weight value is multiplied with the number of trees in the stand (Schreuder et al. 1993; Devine et al. 2013). Here the number of sampled trees is potentially lowered to a notable degree, thus most of the trees in the stand is possible to remeasure later. However, it is a method most accurate in monotonous forest plantation with proportionally uniform trees. When the relation between tree dry weight and predictor variable (e.g., basal area) advance in accordance with the size of the trees the mean-tree method is less exact. In this case individual-tree biomass are thus more commonly estimated from a studied allometric relationship between the dry weight and an effortlessly measurable dimension (e.g., the stem diameter at breast height[18]). Allometry is a useful study in statistical analysis regarding growth rates and correlation between the size of different components of an organism such as a tree. The growth rate for example of one part of a biological subject is in many cases proportional to that of another (Komiyama et al. 2008), why diameter of the stem at breast height correlates with the weight of the stem. When measuring a broad scale of tree sizes, it is possible to predict the dry weight of the tree through a regression equation. The precision of the AGB estimate depends however on the degree of which the allometric model represents the trees it is used on. Nonetheless, allometric models offer a relative easier way to estimate ABG in e.g., an orchard, compared to direct weighing, and a more precise estimate when tree sizes within stands vary. For most developed allometric models the diameter at

[18] Also known as DBH.

breast height is usually the only parameter needed to calculate AGB, along with height for further precision in some species (Taeroe et al. 2015). However, allometric relationships often show site- or species-dependency. These allometric relations gets described through the models developed to feature species specific and individual specific variations among trees, and several influential factors as for example; type of cultivation system, site quality and conditions, and tree genetics (Jenkins et al. 2003; Petersen et al. 2007; Komiyama et al. 2008; Devine et al. 2013; Taeroe et al. 2015; Nord-Larsen et al. 2017). This relation between the measured quantities and AGB is usually expressed by a power function (1):

$$y = kx^{a}, [1]$$

or by a logarithmic function (2):

$$\ln(y) = k + aln(x) \leftrightarrow y = e^{k+aln(x)}, [2]$$

The estimated biomass of every tree is then summed for estimation of the total AGB. This allometric method can be used by applying equations from other sites through earlier published papers. Presumably, it is less biased to use an equation for AGB developed from site specific trees most representative of those in the orchard or forest. These can additionally be used for biomass of tree components (stem, crown, leaves, fruit), and then the expansion factor (tree biomass divided by stem biomass). Taeroe et al. (2015) discovered that OP42 hybrid poplar clone in southern Scandinavia increased consistently in basic density along the stem from the ground to the top, why measurements along the stem for this specie leads to a more accurate stem biomass and stem basic density estimate. For estimating the basic density of the stem, volume and dry weight measurements are needed, which can be sampled by stem discs sampled from each section in which the stem is divided into at fixed intervals from the trunk height and up. The volume of the disc can be measured by the water retention method, and dry weight of the disc can be measured after oven treatment until stable weight. The basic density of the disc is calculated by dividing the dry weight with the volume, and the volume for each section can be calculated by *Smalain's formula* by the assumption that the section has a geometrical shape like a frustum of a paraboloid (Figure 2.3). The biomass of each section is calculated by multiplying the stem volume with the basic density of the disc belonging to one end of

the segment. The biomass of each segment is summed up to get estimate the biomass of the whole stem. To estimate the total leafless biomass, the branches of the canopy can be treated in an oven and dry weight can be weighed directly or a sample can be taken for fresh weighing, oven treatment, and then the total fresh weight of the branches can be weighed in the plantation with a hanging scale. The results are divided with each other (dry weight sample/ fresh weight sample) to create a dry weight percentage, which can be multiplied with the total fresh weight of the branches to get the total dry weight of the crown. The total biomass of the crown can then be added to the total biomass of the stem, to estimate the total leafless AGB.
Allometric equations have only been developed for a fraction of the world's species (Ravindranath and Ostwald 2007; Global Forest Observations Initiative 2013).

1.2. Objective and delimitations

The master thesis project has been carried out in collaboration with ICØL, who considers apple trees as one of the initially most interesting trees to examine for carbon sequestration potential in relation to present and future conversions of danish agricultural systems to agroforestry.

1.2.1 Objective

The objective of the master thesis project is to shed light on the mitigation potential of apple trees (*Malus domestica*) grown in silvoarable systems in a Danish context. To achieve this the effect of different parameters measured on the trees or of the locality parameters is determined, and aboveground leaf- and fruitless biomass in apple trees under a temperate climate will be examined and allometric models developed. The study builds on the worldwide scientific work on assessing estimations of branch, stem, and total leaf- and fruitless biomass, stem volume, mean stem basic density (BD) functions and stem-to-aboveground biomass ratio (BEF). It takes a similar approach for collecting and processing data to compare results with alike studies of aboveground biomass and carbon sequestration in foremost apple trees, if possible, or else fruit trees under similar conditions. to discuss best qualified future sampling procedures and model accuracy. The models developed should be adapted to precisely predict the aboveground the biomass in apple trees grown under danish conditions. using a conversion factor from biomass to C, the project results can be taken as a measure of carbon storage.

1.1.2 Delimitations

For this project only the aboveground leaf- and fruitless biomass of apple trees was examined, despite the total sequestration capacity in biomass also includes the leaves, fruits and belowground biomass in roots. However, the samples were collected during wintertime, which excludes leaves and fruits being on the sample trees. Also, the time frame and available resources for this project causes downgrading of digging up the whole tree to include root biomass.

The pruning waste produced through the years was not included either, thus the total biomass production is not included, only the aboveground part of a standing tree during winter season (before this year's pruning). The sample trees included are from representative Danish apple orchards grown in slender spindle systems and grafted on weak rootstocks, intensely managed, and pruned, in densely planted rows. However, the partners[19] of the ROBUST project expect to grow apple trees in extensively panted and managed belts in the open landscape, with different pruning techniques and grated on wild-specie rootstocks. The C content of the biomass is not determined but calculated under the assumption that nearly half of the dry weight is C. Due to the focus tree species, the project has been limited to what one could reasonably ask the plantation owners to contribute with, why 10 plantations have been included for reaching enough sample trees for model development (in this case 36 trees). This have conversely meant that the sample is spread fairly across Denmark to include various local factors for this project to examine the effect from. However, due to the limited number of trees per site (and in general) is also limited what effects can be identified.

[19] Danish farmers experimenting with agroforestry on parts of their farm.

2. Materials and Methods

This project included sample stands with a broad scope of trees in different age, height, growing conditions like topography, shelter conditions, local climate, management, former land use, and type of soil. Input data for allometric equations was acquired during two weeks in November and December in 2021 through destructive sampling and non-destructive data collection of afforested apples in the ages between 2–25-year-old found in orchard stands from all over Denmark. Samples of stem discs and branches were taken to the laboratory for treatment and analysis for stem dry weight and volume, and dry weight percentage of the branches. Based on this, the branch dry weight, mean stem segment basic density, and the volume of each stem sections was calculated, to estimate total leaf- and fruitless AGB, stem basic density, expansion factor. A statical program was used to inspect predictor variable correlations with AGB, volume, BEF and BD, and to develop and test allometric models. The vertical development of BD along the stem was, and the available peer reviewed literature was examined to compare and discuss future sampling procedures and model accuracy.

2.1. Data Collection

To exclude uncertainties in standing biomass between cultivars it was decided to exclusively collect samples from the same cultivar. After advice and guidance from Hanne Linhard Pedersen, professional Danish consultant from HortiAdvice, the cultivar Elstar (*Malus domestica cv. 'Elstar'*) was chosen. Elstar seamed most accessible among danish fruit growers, and in this way the project would prove relevant for other countries in temperate regions (WAPA 2021). The potential sites were identified through a list provided by Hanne of contact information on orchard owners interested in participating in the research. The site selection took place through telephone conversations with the apple growers. The selection criteria for the sites included a contribution of minimum three apple trees, that fit the table for securing diverse sizes in relation to stem diameter and tree height. The location of the sites was determined by these factors. Information on growing conditions was obtained through standardized interviews of the apple growers. The site title abbreviations are visible in Table 2.2.

2.1.1 Site characteristics

Potential predictor variables were noted at every site. The 36 trees were sampled from ten intensively driven conventional (except for trees from ÆBF, LBP and half of the trees from TBF, which are grown organically) plantations located all around Denmark (see Figure 2.1).

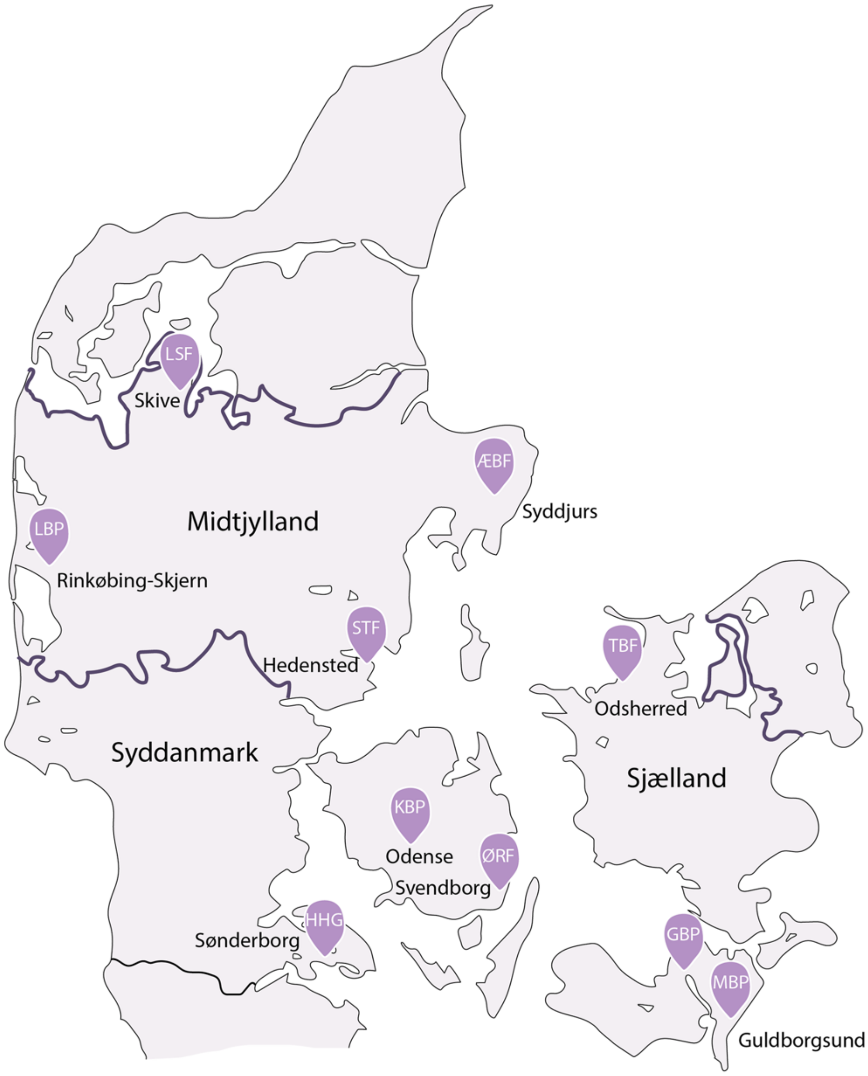

Figure 2.1 – A map of Denmark showing the location of sample stands and the associated initials (google maps).

Elstar is a cultivar most grown in conventional systems, possibly explaining why only nine of the included trees (no 7-9 and 25-30) were grown organically. Site conditions from all Danish regions, except Nordjylland, were included (Figure 2.1; Table 2.1). The plantations were regionally divided between Sjælland (GBP, MBP, TBF), Syddanmark (ØRF, KBP, HHG) and Midtjylland (STF, ÆBF, LBP, LSF). Along with location within the regions relative to distance of waterbodies, exposure to westerly wind, regional-depending methods of apples growing, topography and local climate, the diversity of regional background means various growing conditions among sites (Table 2.1; Table 2.2).

Table 2.1 – The mean annual climate of the three locations Sjælland, Syddanmark and MidtJylland. The Local annual climate data was provided by the weather archive of DMI (2022) and includes data collected between the years of 2011-2021.

	Sjælland	Syddanmark	Midtjylland
Mean annual precipitation bt. 2011-21 (mm)	628	728	801
Mean annual sunshine bt. 2011-21 (h)	1849	1766	1668
Mean wind speed bt. 2011-21 (m/s)	5	4.5	4.5
Mean annual temperature bt. 2011-21 (°C)	9.6	9.4	9

Generally, samples from three trees were collected from the sites, except for TBF and LSF, from where samples from six trees each were gathered. The mean youngest sample trees (2-11 years) were grown at LSF, LBP, and TBF. The age and tree size did not necessarily correlate. Young trees varied in D50 and height as well as the old trees, for some overlapping in sizes. However, the general trend was that the highest mean D50/ height was found within the old stands (Figure 3.1).

Only at STF and LBP were the trees planted in a sandy soil instead of clayey till like the rest of the sites. Only one of the plantations were formerly used as grassland (LBP), the rest were originally agricultural production systems (table 2.2). The type of soil and former land use can have influence on water holding capacity and nutrient status of the soil of which the trees are grown in, thus an effect on management and eventually the growth quality. The topography varied markedly between (and for some also within (e.g., LSF)) the sites, with a distance in meter above sea level ranging between 5.5-7.5 (MBP and LBP, respectively) to 32.5-43 (ØRF and ÆBF, respectively) (Table 2.2).

Tree density can have an effect of internally competition on light, water, and nutrients, and here the least dense plantation was found at ØRF (1633 trees ha^{-1}), while the most densely planted orchard was at ÆBF (3571 trees ha^{-1}) (Table 2.2).

Table 2.2 – Characteristics of the sample orchards. Distribution of soil types on the plantation surface was found at GEUS[20] (2022). The topography and former land use of individual sites was found and identified through the topographical and historical map material the Danish Agency for Data Supply and Efficiency's servers[21] (SDFE 2022). The coordinates were found through Google maps. Stem number was calculated using the information on row and tree spacing.

[20] Geological data center which conducts surveys, research, advice, and mapping.
[21] An agency under the Ministry of Climate, Energy and Supply that provides public and private sectors with geodata.

Site	Tree no	Commune	Region	Coordinates	Sample trees	Mean age	Mean height (m)	Mean D50 (cm)	Soil type	Topography (m asl)	Former landuse	Stem number (ha^-1)
Guldborgland Frugtplantage A/S (GBP)	1-3	Guldborgsund	Sjælland	54 ° 51'56.6 "N 11 ° 42'35.6" E	3	23	3.36	10.6	Clayeytill	14-14.5	Agriculture	2857
Mikael Bertelsen (MBP)	4-6	Guldborgsund	Sjælland	54 ° 44'24.0 "N 12 ° 00'10.4" E	3	25	4.08	12,7	Clayey till	5.5-6	Agriculture	2020
Troldebakkens Frugtplantage (TBF)	7-12	Odsherred	Sjælland	55 ° 45'37.2 "N 11 ° 26'22.0" E	6	5	2.41	3.2	Clayey till	6-6.5 ; 9.50-10	Agriculture	3077
Ørskov Frugt (ØRF)	13-15	Svendborg	Syddanmark	55 ° 07'09.7 "N 10 ° 43'40.5" E	3	23	3.66	12,7	Clayey till	32-32.5	Agriculture	1633
Kærsbo Frugtplantage (KBP)	16-18	Odense	Syddanmark	55 ° 14'49.5 "N 10 ° 15'01.1" E	3	15	3.64	10.6	Clayey till	27.5-28	Agriculture	2857
Hestehavegård Frugtplantage (HHG)	19-21	Sønderborg	Syddanmark	54 ° 56'43.1 "N 9 ° 46'46.2" E	3	18	4.06	13.3	Clayey till	15.5-16	Agriculture	2857
Snaptun Frugtplantage (STF)	22-24	Hedensted	Midtjylland	55 ° 49'03.9 "N 10 ° 03'00.2" E	3	13	3.11	6.7	Meltwater sand	11.5-12	Agriculture	3077
Æbletoften (ÆBF)	25-27	Syddjurs	Midtjylland	56 ° 18'35.0 "N 10 ° 41'27.3" E	3	18	3.03	7.1	Clayey till	42.5-43	Agriculture	3571
Laubjergs Planteskole og Rosenhave (LBP)	28-30	Ringkøbing-Skjern	Midtjylland	56 ° 05'53.6 "N 8 ° 18'22.1" E	3	4	2.78	5.5	Aeolian sand	7.5-8	Grassland	2924
Lyby Frugtplantage (LSF)	31-36	Skive	Midtjylland	56 ° 37'56.1 "N 9 ° 02'57.9" E	6	17	3.05	7.9	Clayey till	13-13.50 ; 19.50-21	Agriculture	3030

To include a shelter effect the type of shelter conditions, distance to nearest windbreak or forest, and distance to nearest windbreak or forest to the west was measured. Also, the distance to the sea and the distance to the west coast have influence on temperature, humidity, and westerly wind exposure, so these measures were included. As for local climate factors measures of communal mean annual precipitation (mm), annual sunshine (h), wind speed (m s^{-1}) and temperature (°C) were included (Table 2.3).

Compared to Table 2.1, Table 2.3 show the effect better when segregating Syddanmark into Jylland and Fyn, where the difference between the mainland and the Danish islands is clarified. Generally, Danish islands' climate is warmer, dryer sunnier and less windy. ØRF and KBP is located on Fyn with HHG placed in Jylland, where the general trend for mean annual precipitation, and windspeed is lower, the number of mean annual sun hours is higher, but with the exception the mean annual temperature being higher in the commune where HHG is located (Sønderborg) compared to ØRF and KBP (Svendborg and Odense) (Table 2.3).

At ÆBF and GBP a nearby forest was used for shelter, where at the other plantations windbreaking hedgerows were used. The sample trees at GBP and some from TBF had the greatest distance no nearest windbreak (100-350 m). Other shelter conditions were found at the other part of the sample trees from TBF, STF and HHG with only 3.10 m of distance to nearest windbreak. The height of the windbreak and the distance to the tree is essential for the shelter effect (Cui et al. 2012).

Table 2.3 – Distance to shelter effects which may affect the trees, local climate, and other characteristics of the sample orchards. Local climate data at municipal and annual level was provided by the weather archive of DMI[22] (2022) and includes mean wind, precipitation, temperature and sun hours between the years of 2011 to 2021 in the Danish commune. The distance to shelter and coast was measured through the websites: https://da.distance.to and https://www.google.dk/maps/.

Site	Type of shelter	Nearest distance to windbreak (km)	Distance to windbreak in West (km)	Nearest distance to Sea (km)	Distance to sea in West (km)	Mean annual precipitation bt. 2011-21 (mm)	Mean annual sunshine bt. 2011-21 (h)	Mean wind speed bt. 2011-21 (m/s)	Mean annual temperature bt. 2011-21 (℃)
Guldborgland Frugtplantage A/S (GBP)	Forest	0 .36	0 .44	0 .91	3 .8	629	1863 .3	5 .5	9 .6
Mikael Bertelsen (MBP)	Windbreak	0 .04	0 .04	1 .71	54 .37	629	1863 .3	5 .5	9 .6
Troldebakkens Frugtplantage (TBF)	Windbreak	0.012	0 .012	0 .81	1 .22	626 .5	1820 .8	5 .3	9 .5
	Windbreak	0 .1	0 .4	0 .79	4.47				
Ørskov Frugt (ØRF)	Windbreak	0.003	0 .002	1 .92	42	718 .6	1764 .8	4 .2	9 .3
Kærsbo Frugtplantage (KBP)	Windbreak	0.03	0 .05	11 .6	22 .51	712 .8	1791 .9	4 .2	9 .3
Hestehavegård Frugtplantage (HHG)	Windbreak	0.01	0 .4	4 .68	72 .36	752 .7	1743 .5	5	9 .7
Snaptun Frugtplantage (STF)	Windbreak	0.009	0 .04	0 .34	117 .23	780 .3	1641 .3	3 .8	9
Æbletoften (ÆBF)	Forest	0.08	0 .08	157 .27	9160	670 .9	1731 .9	4 .3	9 .4
Laubjergs Planteskole og Rosenhave (LBP)	Windbreak	0.03	0 .04	12 .39	12 .39	922 .4	1632 .8	4 .9	9 .2
Lyby Frugtplantage (LSF)	Windbreak	0.02	0 .02	0 .4	54 .7	828 .6	1664 .4	5	8 .8
	Windbreak	0.02	0.03	0.04	55. 1				

To include effect of management and other growing conditions, whether the trees were grafted on an interstem rootstock or directly onto the M9 dwarfing rootstock, grown organically or conventionally, pruned by machine or exclusively by hand, root pruned in one sides, two sides or not root pruned at all, the distance between rows and between the trees in the rows, whether chemical for reduced shoot growth (regalis plus) was used or not, if the trees were planted in single or double rows, if a stem cut procedure was performed or not, if the trees were fertilized and controlled for weeds or not, whether the trees where vertically standing up right or were tipped and when the last time of pruning was the same year, was measured and described (Table 2.4).

Only one plantation had pruned the trees canopy in the summer of 2021 (MBP), two in spring same year (HHG, ÆBF), and the rest pruned in winter around January-February in 2021 (Table 2.4). The time and method of pruning effects standing AGB. At LSF the canopy of the trees was pruned by machine in the top and at MBP they were machine pruned at the side turning toward the middle rows

[22] The Danish Meteorological Institute under the Ministry of Climate, Energy and Supply, which handles the meteorological social tasks in Denmark.

and the top (Table 2.4). All other plantations practised pruning by hand, which is most common, but several of the owners of the included sites were considering adopting machine pruning in the nearest future. To hamper shoot growth of the tree, and thus make it focus the resources on producing fruits, the roots were cut in 6 of the 10 plantations. At one orchard stem-cut[23] was performed for the same purpose (LSF) (Table 2.4). In terms of use of chemicals defined as water-dispersible granules which reduces the growth of annual shoots[24]. Only two plantations applied it frequently (once a year (LSF), twice a year (KBP)). Four plantations had used small amounts a while ago (MBP, TBF, STF, LSF) and the rest had never applied any regalis to the trees (Table 2.4).

At ÆBF the trees were not fertilized and weed control management was not performed inside the tree rows. Among the other sites, fertilisation and weed control was practised (Table 2.4), which is more common, to secure high yields and prevent resource competition and deficiency. Three of the trees from LSF were planted more densely (0.5 m between in the tree row) than all the other included sample trees (Table 2.2). This was only done in some of the rows, as spare trees to take over if another died.

The trees provided for this study from MBP were planted in double rows (with 1,5 m oblique distance) (Table 2.4). This is an old method for apple tree growing which has run out of fashion due to low yields and laborious elements regarding pruning and harvest.

Six of the trees, coming from HHG and LSF were tipped over and were thus standing in an oblique angle (Table 2.4). This might have influenced the functions of the trees including growth.

Trees from TBF, STF, ABF and LSF were grafted on an interstem rootstock (typically golden delicious), the rest was grafted directly on to the dwarfing rootstock[25] (Table 2.4). In this case it is done in order for the genes of Elstar to better corroborate with those of M9 (Ponchia et al. 1997).

The trees at GBP, ØRF, KBP, LBP, and half from LSF were grown as what in Dutch is called *Knibbaum*. A cultivation method, where a tree variety is grafted onto a rootstock in the height of 20 cm. The first year the cultivar grows into a long branch without side branches. The following year, the tree is cut to approx. 50 cm height. This causes the tree to better form good side branches in the second year.

The plantations MBP, LSF and ÆBF were standing out in more than three factors (Appendix).

[23] A management procedure of cutting into the stem with a chainsaw.
[24] Regalis Plus, a registered trademark of the BASF Group, containing the active substance prohexadione calcium.
[25] A combination of two rootstocks grafted together, with the scion (fruiting) cultivar grafted on top.

Table 2.4 – Management and growing conditions of the sample orchards. (1) and (2) is the separation of trees with same age from the same plantation. The last time of pruning was in 2021.

Site	Grafted on a middle stem	Organically grown	Pruned by machine	Root pruned	Row and tree distance	Chemical for reduced shoot growth	Double row	Stem cut	Absense of fertilization and weed control	Tipped trees	Last time of pruning
GBP				✓	3.5 x 1						January
MBP			✓	✓	3.3 x 1.5	✓	✓				September
TBF (1)	✓	✓			3.25 x 1						January
(2)	✓			✓	3.25 x 2	✓					January
ØRF				✓	3.5 x 1.75						January
KBP				✓	3.5 x 1	✓					January
HHG				✓	3.5 x 1					✓	March
STF	✓				3.25 x 1	✓					January
ÆBF	✓	✓			3.5 x 0.8				✓		April
LBP		✓			3.8 x 0.9						January
LSF (1)	✓			✓	3.3 x 0.5	✓					February
(2)			✓	✓	3.3 x1.5	✓		✓		✓	February

2.1.2 Field measurements

Each selected sample apple tree was marked at 50 cm above ground (cleared surface). After felling the height was measured using the 50 cm mark as baseline, with diametrical and metric measuring tapes. Also, two diameter measures were taken at 15 cm above ground, and every 50 cm until highest point on the stem, with a cross-calipering for volume and biomass estimation of the individual sections, as well as the whole stem. Stem discs were also sampled at these intervals. Branches and stem were divided, and branches were weighed for fresh weight with a hanging scale at the precision of 0.1 kg. The cut branches were afterwards concentrated in a pile and a random fresh weight sample corresponding to what could fill a 32 x 47 cm paper bag of small, medium, and parts of the big branches, was taken and weighed and brought back to the laboratory for dry matter determination. Apple fruits and ground litter were not included, but remaining leaves and withered fruits on branches were. Trees <300 cm in height or <5 cm in average diameter (seven trees), was cut in sections and weighed, and the total branch content and stem was brought back to the laboratory. No dead, nor particularly growth-challenged trees were sampled.

Figure 2.2 – An image of how the field sampling was performed with separation of woody parts and the car hooked hanging scale.

The seven trees where the age between 2-11 years old and from the plantations of TBF, STF and LSF. Three additional young trees (no. 28, 29, and 30) in the age of 4 came from LBP, but these were too big for including the whole trees in a direct weighing of the stem dry matter.

2.1.3 Laboratory analyses

Branch samples and small stems were oven dried at 55 °C for 7 days and weighed. Afterwards they were weighed and dried repeatedly until stabilization of the weight, which lasted 14 more days. In the case of drying the stems from the seven small trees, the time of the drying process exceeded a month. This was due to the oblong shape of the stem pieces, where bark dominated the sides and the removal of moisture inside the tree tissue was delayed by the included bottleneck effect. The stem discs were saturated in water for 2 hours, after which the water displacement method was used to determine the disc volume. Then the discs dried in an oven at 103 °C, also until the weight stabilized and then weighed. Stem volume was not measured for the seven smallest trees.

2.2. Calculations

The volume of each stem segment over bark was calculated by Smalian's formula. Every segment in the *B* section (Figure 2.3), were perceived as a frustum of a paraboloid. Segment *a* in the bottom section *A* (stump section) from H0 to H15 (cm relative height) was perceived as a cylinder, where the lower stem cross-segment area of segment *a* (g_a) was assumed identical to the to the upper stem cross-segment area of segment *a* (g_{a+1}). Segment *c* in the top section *C* was assumed to have the shape of the top of a paraboloid, where the upper stem cross-segment area of segment *c* in the was calculated as equal to 0:

$$v_j = \frac{g_j + g_{j+1}}{2} l_j, \text{ [3]}$$

where v_j is the volume of stem segment *j*, g_j is the lower stem cross-segment area of segment *j*, g_{j+1} is the upper stem cross-segment area of segment *j,* and l_j is the length of segment *j.* The stem cross-segment area *g* is found as the area of a circle by:

$$g = \pi \left(\frac{d_{j1} + d_{j2}}{2}\right)^2, \text{ [4]}$$

where d_{j1} d_{j2} are diameters measured in two perpendicular directions. The stem volume of tree *i* was calculated as the sum of all sections:

$$V_i = v_A + v_B + v_C, \text{ [5]}$$

where v_A is the volume of section A, v_B is the volume of section B (segment bI + bII + … +bN, where N is the number of segments) and v_C is the volume of section C. The basic density of the individual stem discs bd_j was calculated as:

$$bd_j = \frac{dw_j}{v_j}, [6]$$

where v_j is the corresponding volume of the water saturated stem disc and dw_j is the dry weight of the stem disc. The dry weight of each segment dw_j was calculated by calculating a weighted average of the basic density of the discs around the individual segment and multiply by the volume of the segment:

$$dw_j = v_j \; \frac{(bd_j \, g_j + bd_{j+1} \, g_{j+1})}{(g_j + g_{j+1})}, [7]$$

The dry weight of the whole stem was calculated as the sum of all sections:

$$DW_{\text{stem},i} = dw_A + dw_B + dw_C, [8]$$

where $DW_{stem,i}$ is the dry weight of the whole stem of tree *i*, dw_A is the dry weight of section A, dw_B is the dry weight of section B and dw_C is the dry weight of section C.

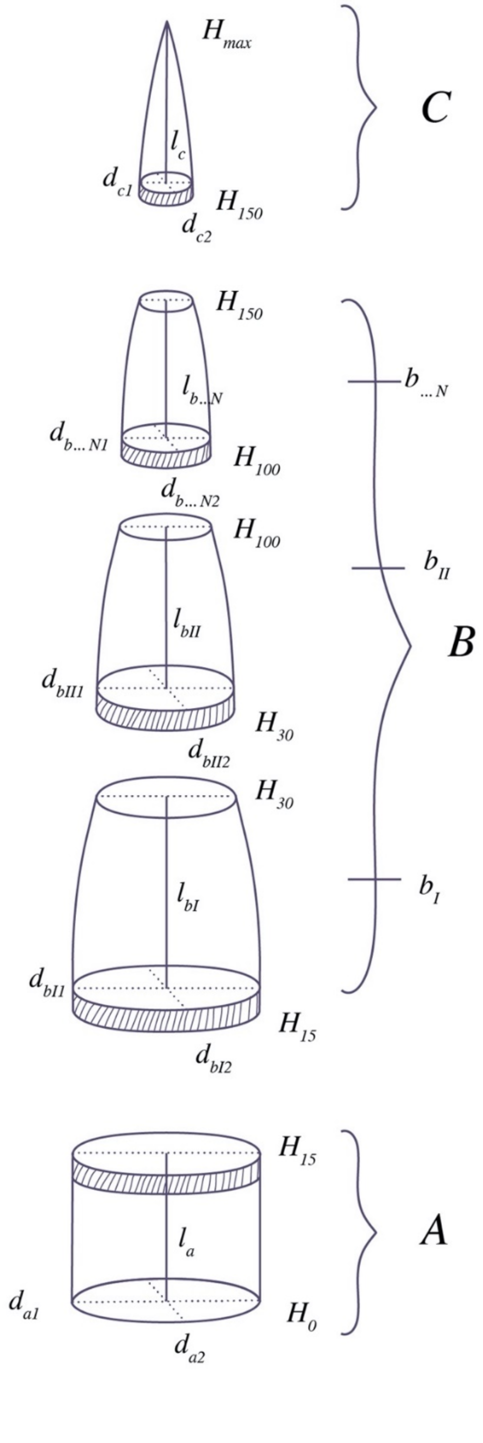

Figure 2.3 – Illustration of the elements used when calculating the stem volume and biomass of tree$_i$ using Smalian's formular. The shaded elements illustrate sample discs. A is the bottom section, B is the middle sections, while C is the top of the tree. b…N means that there can be more than 3 segments of section B. $d_{..1}$ and $d_{..2}$ is the diameter of the segments in two diagonal directions. H_x is the start and end height of the different segments and l is the length of the segments.

The mean basic density of the whole stem of tree i was calculated as:

$$BD_i = \frac{DW_i}{V_i}, [9]$$

The dry weight of the branches from the crown section of the tree was calculated as the dry weight percentage determined from the samples multiplied with the fresh crown weight:

$$DW_{crown,i} = (dw_{crown,j}/fw_{crown,j}) * FW_{crown,i}, [10]$$

where $DW_{crown,I}$ is the dry weight of branches of tree i, $dw_{crown,j}$ is the dry weight of branch sample j, $fw_{crown,j}$ is the fresh weight of branch sample j, and $FW_{crown,I}$ is the fresh weight of the branches of tree i. The total aboveground biomass DW_{AGB} was calculated as the sum of DW_{crown} and DW_{stem}. The biomass expansion factor for tree i, BEF_i, was defined as the ratio between the aboveground biomass of tree i and stem biomass of tree i:

$$BEF_i = \frac{DW_{AGB}}{DW_{stem}}, [11]$$

2.3. Statistical modelling

In this project Microsoft Excel and the statistical program R-studio version 2022.02.0+443 was used for statistical modelling with the basic package for primary use. The use of a linear model function made it possible to determine the parameters of linear regressions using the least squares method (OLS[26]). Due to the nature of the models with a none-linear relationship, and to ensure homogeneity and normality of the variance a logarithmic transformation of the dependent variables and the selected predictor variables was performed:

$$LN(Y_i) = \alpha + \beta ln(X_i) + \gamma Z_i + e_i \ [12]$$

[26] Ordinary Least Squares.

Where Y_i is the dependent variable (AGB, stem biomass, branch biomass, stem volume, BEF and BD), X_i and Z_i are the predictor variables (stem diameter, tree height, topography, and various site effects), α, β and γ are parameters to be estimated, i is 1…n, and e_i is residuals (which are normally distributed with mean value 0 and variance sigma squared.

Potential predictor variables were tested for the purpose of valuing different effects among e.g., growing conditions of the site, internal competition within the tree rows and the size of the trees. The strategy was to analyse models including either D50, height or both D50 and tree height as predictor variables. Next, other predictor variables of site effects (like those shown in Table 2.2, 2.3, and 2.4) were successively included additional to D50 and height, when the ANOVA test showed they corelated significantly ($P<0.05$). However, some of the site variables showed a significantly low P value, but due to interpretation complications regarding too few alike representatives (<2)[27], or very low applicability[28] they were not included in the final selection of models. The vertical development of BD within the stem was tested for significant variance between the bottom section measured in 15 cm above the ground and every other section until the top, respectively, using *t*-test. The homogeneity of variance and performance of the models was evaluated by inspecting qq- and residual plots visually. A likelihood ratio test was used by inspection of P-values. The precision of the models was evaluated by estimation of root mean square error (RMSE) and coefficient of determination (R^2).

2.4. Litterateur search

Different strategies for the literature search involved searching through the following of the Royal Library's article databases: CAB Abstract, Google Scholar, and Web of Science, with different methods and keywords, for finding relevant articles on the topic.

The *initial search* (mainly Google Scholar) was an exploratory approach and thus characterized by a random induction by using familiar concepts and key words on the whole research topic: "temperate agroforestry", "biomass in apple trees", "carbon sequestration in fruit trees", "carbon storage in apple plantation", "biomass in fruit orchard", "allometric models for fruit trees", "stem basic density in

[27] Whether the tree rows among site were fertilized and weed controlled or not, the use of stem cut, if the trees were planted in double rows, and former land use (Table 2.2; 2.4)
[28] Stem volume requires laser scanning or photogrammetry, which both is too demanding to be included as predictor variable in this project.

apple trees”, “biomass in North European apple orchard”, “root to top ratio for Malus domestica” etc. Also, this method can be used for finding topics, inspiration, and keywords for further searching.

Topic search is a strategy for exploring publications that were not yet known, using keywords, and gaining access to articles of relevance. It is a further search for articles with a feel for the various article databases with articles added keywords.

Citation search, also called chain search (predominantly Web of Science), where sources found through the bibliography from key scientific articles, where direct search of other articles that have cited the central article is used, among key terms from newly found articles for further searching in the various databases.

Systematic search (CAB Abstracts only) where several of the terms from previous searches were used together and separately to discover articles.

Many articles were selected based on title, and after skimming the abstract and conclusion at first, and more in depth reading several were excluded for lack of relevance. The literature was continuously found throughout the project and several sources appeared on an ongoing basis. Several sources were found through the bibliography from central scientific sources.

Due to sparse literature on the subject “biomass in danish apples” the search strategy was to go relatively broad into the dimensions of climate, plant, and treatment. For the climatic angle the prioritization hierarchy was 1. Northern Europe and other cool temperate areas, 2. Central and Southern Europe and other warm temperate regions, and 3. subtropical areas. The plant dimension included following layers: 1. Apple trees, 2. Fruit trees in the rose family (pear, plum, peach), 3. Other fruit trees (e.g., citrus species, mango, avocado) 4. Other agroforestry species.

The bibliography was created using the Mendeley reference program.

3 Results

The measured, as well as the calculated variables of the apple trees in this project differed relatively broad. The D50 fluctuated from 1.2 to 14.4 cm, the tree height from 183 to 480 cm, tree age from 2-25 years and the total aboveground dry weight from 0.21 to 44 kg tree^{-1} (Table 3.1; Appendix). Among sites the mean D50-to-height ratio varied between 0.75 to 3.6, for dry weight of the branches, the trees varied between 0.2-7.4 kg tree^{-1}, 0.17-20.5 kg tree^{-1} for stem dry weight, 0.01-0.04 m^{3} for stem volume, 1.21-1.75 for BEF, and 422-512.3 kg m^{-3} for stem BD (Table 3.1). HHG showed the highest rank in several variables including mean D50 (13.3 cm), tree height (406 cm), stem, and branch dry weight (20 and 7.4 kg tree^{-1}, respectively) (Table 3.1). The young trees at TBF (1) showed both highest and lowest mean values among several variables: the highest branch-to-stem ratio (1.18) and BEF (1.75), and the lowest mean D50 (1.4 cm), tree height (191 cm), D50-to-height ratio (0.75), and stem and branch dry weight (0.12 and 0.17 kg tree^{-1}) (Table 3.1). KBP ranked highest in mean branch-to-stem ratio (0.21) and lowest in BEF (1.21). The highest mean D50-to-height ratio was found at LSF (3.6), highest BD among the trees from LBP (512 kg m^{-3}), and the lowest BD at ÆBF (422 kg m^{-3}) (Table 3.1). Generally, the highest stem-to branch ratios were found among the stands of young trees, like the D50-to-height ratio increased with age among the sample trees (Table 3.1)

*Table 3.1 – Statistical measurements (mean, SD, and range) of the trees from the different plantations. *The BD of the sample trees from the stand at STF shown in the table x was calculated as a mean of BD from tree no. 23, and 24. (1) and (2) is for the separation of tree groups of three with same age from the same plantation. The last time of pruning was in 2021.*

Site	Stand age	Number of trees	Statistic	D50 (cm)	Tree height (cm)	D50 (cm)/ height (m) ratio	Branch dry weight (kg tree^-1)	Stem dry weight (kg tree^-1)	Stem volume (m^3)	Biomass expansion factor	Whole stem basic density (kg m^-3)	Branch to stem ratio
GBP	23	3	Mean	10.6	336	3.1	4.1	10.3	0.02	1.42	484.3	0.4
			SD	*(3)*	*(36)*	*(0.7)*	*(2)*	*(0.6)*	*(0.01)*	*(0.07)*	*(21)*	N/A
			Range	7.75-14.35	305-375	2.54-3.82	2.42-6.67	4.86-17.54	0.0096-0.036	1.38-1.50	462.72-504.62	N/A
MBP	25	3	Mean	12.7	408	3.1	4.9	16.7	0.03	1.29	482.5	0.29
			SD	*(2)*	*(68)*	*(0.4)*	*(2)*	*(0.3)*	*(0.01)*	*(0.08)*	*(22)*	N/A
			Range	11-14.9	344-480	2.75-3.53	2.7-6.74	12.94-22.57	0.028-0.045	1.21-1.37	457.73-498.75	N/A
TBF	2	6	Mean	1.4	191	0.75	0.13	0.17	0.034	1.75	N/A	1.18
(1)			*SD*	*(0.2)*	*(11)*	*(0.08)*	*(0.05)*	*(0.3)*	*(0.0006)*	*(0.2)*	N/A	N/A
			Range	1.2-1.6	183-203	0.65-0.8	0.08-0.19	0.12-0.19	0.003-0.004	1.57-1.94	N/A	N/A
	7		Mean	5	292	1.71	0.9	1.7	0.029	1.53	489.3	0.53
(2)			*SD*	*(0.4)*	*(15)*	*(0.05)*	*(0.3)*	*(0.2)*	*(0.007)*	*(0.1)*	*(16)*	N/A
			Range	4.55-5.3	275-305	1.65-1.74	0.56-1.25	1.47-2.05	0.022-0.036	1.37-1.62	471.3-499.6	N/A
ØRF	23	3	Mean	12.6	366	3.46	5.3	13.3	0.02	1.39	450.9	0.4
			SD	*(0.7)*	*(20)*	*(0.09)*	*(2)*	*(0.3)*	*(0.002)*	*(0.05)*	*(27)*	N/A
			Range	11.9-13.25	350-388	3.4-3.6	3.33-7.79	9.34-17.51	0.02-0.03	1.36-1.45	421.96-475.51	N/A
KBP	15	3	Mean	10.6	364	2.92	2.3	11	0.04	1.21	481	0.21
			SD	*(0.6)*	*(50)*	*(0.4)*	*(0.3)*	*(0.08)*	*(0.02)*	*(0.01)*	*(9)*	N/A
			Range	10-11.1	320-418	2.65-3.37	2.06-2.6	10.33-11.99	0.02-0.07	1.19-1.28	471.34-486.53	N/A
HHG	18	3	Mean	13.3	406	3.27	7.4	20.5	0.01	1.37	483.8	0.36
			SD	*(3)*	*(29)*	*(0.9)*	*(4)*	*(0.5)*	*(0.004)*	*(0.04)*	*(4)*	N/A
			Range	11.3-16.6	388-439	2.56-4.27	4.85-11.33	11.57-33.43	0.01-0.02	1.34-1.42	481.23-488.63	N/A
STF	13	3	Mean	6.7	311	2.16	2.2	4.5	0.01*	1.44	492.5	0.5
			SD	*(3)*	*(84)*	*(0.9)*	*(2)*	*(1)*	*(0.007)*	*(0.1)*	*(29)*	N/A
			Range	3.45-9.95	225-393	1.53-3.15	0.27-3.34	0.88-7.45	0.005-0.02	1.31-1.55	472-513	N/A
ÆBF	18	3	Mean	7.1	303	2.36	1.7	4.3	0.01	1.45	422	0.4
			SD	*(2)*	*(40)*	*(0.4)*	*(0.7)*	*(0.7)*	*(0.004)*	*(0.1)*	*(22)*	N/A
			Range	5.4-9.45	264-344	2.04-2.74	1.05-2.42	2.12-7.58	0.01-0.02	1.32-1.52	398.92-442.13	N/A
LBP	4	3	Mean	5.5	278	1.97	1.1	2.1	0.01	1.51	512.3	0.52
			SD	*(0.4)*	*(44)*	*(0.4)*	*(0.6)*	*(0.1)*	*(0.007)*	*(0.3)*	*(13)*	N/A
			Range	5-5.8	230-315	1.72-2.52	0.58-1.75	1.8-2.26	0.005-0.02	1.27-1.77	501.04-525.7	N/A
LSF	11	6	Mean	4.2	290	1.44	0.5	1	0.04	1.44	N/A	0.5
(1)			*SD*	*(0.3)*	*(14)*	*(0.1)*	*(0.1)*	*(0.1)*	*(0.0006)*	*(0.1)*	N/A	N/A
			Range	3.8-4.4	278-305	1.32-1.54	0.32-0.56	0.91-1.18	0.003-0.005	1.36-1.57	N/A	N/A
	23		Mean	11.6	320	3.61	2.6	10.2	0.02	1.26	467	0.25
(2)			*SD*	*(2)*	*(35)*	*(0.7)*	*(0.8)*	*(0.3)*	*(0.006)*	*(0.02)*	*(15)*	N/A
			Range	9.6-13.6	280-342	2.84-4.11	1.98-3.48	7.37-12.71	0.02-0.03	1.23-1.27	452.95-482.64	N/A

The correlation between the non-log transformed tree's height and their diameter in the height of 50 cm is visualised with a trendline highlighting the general linear relationship with a positive progression (and a linear regression model would explain 65.5% of the hight variations with a significance of <0.00001). Some of the beforementioned sites with the uttermost mean values among sample tree variables also appeared with outlying locations in Figure 3.1, and Figure3.2. For instance, tree no 4 at MBP had the second largest stem D50 (14.9 cm) and highest value of height (480 cm) (open diamond; Appendix; Figure 3.1). HHG provided the second highest sample tree no 21 (439 cm), and no 20 had the widest D50 (16.6 cm) (open circle), respectively. However, according to the trendline, the D50 value of no 21 would place it with a height of ~360 cm, and the height of tree no 20 place it with D50 of ~14 cm. Tree no 24 from STF were almost 100 cm higher (393 vs ~300 cm) than the linear prediction for a tree with a D50 of 6.75 cm (Downward facing open triangle; Appendix;

Figure 3.1). The trees from LSF (marked as an x) and the young trees from TBF (1) (closed square) show a general lower placement of height values, compared to the general trend of D50 sizes, whereas the trees from ÆBF (marked as an *) and the older trees from TBF (2) fit the trendline relatively better (Figure 3.1). Summing it up, the observations regarding height and diameter are well dispersed, creating fine prerequisites for model development.

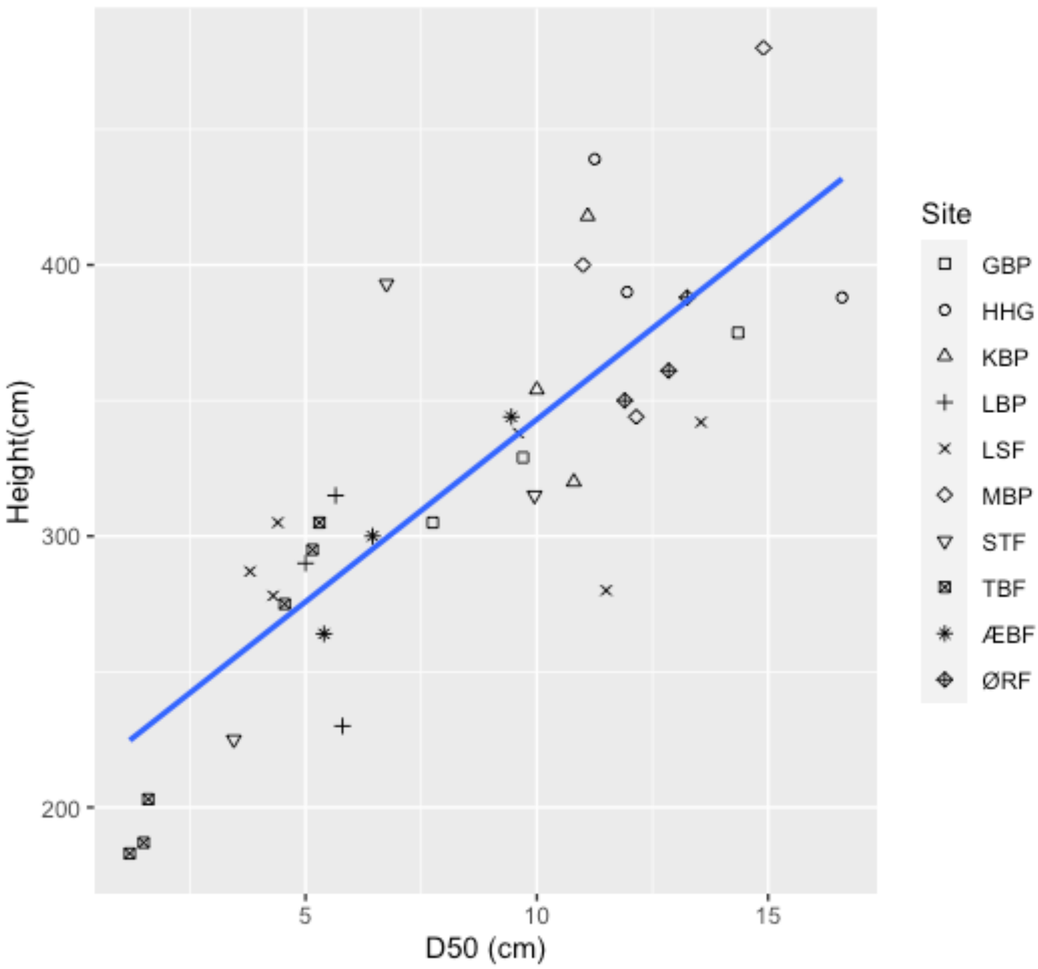

Figure 3.1 –A linear correlation between diameter and height of the ten sample sides included in this study.

Figure 3.2 show a greater correlation of D50, with the dependent variables of stem volume, AGB and BEF. Here the response variables (stem volume and AGB) increase nonlinear, when D50 increases, and BEF decrease nonlinear when D50 increase. The trend line showed less fitting of the datapoints for BEF, which imply higher variance Figure 3.2. Some of the same outlying datapoints is shown as in Figure 3.1 (tree no 21 and 20 from HHG, tree no 4 from MBP and no 35 from LSF).

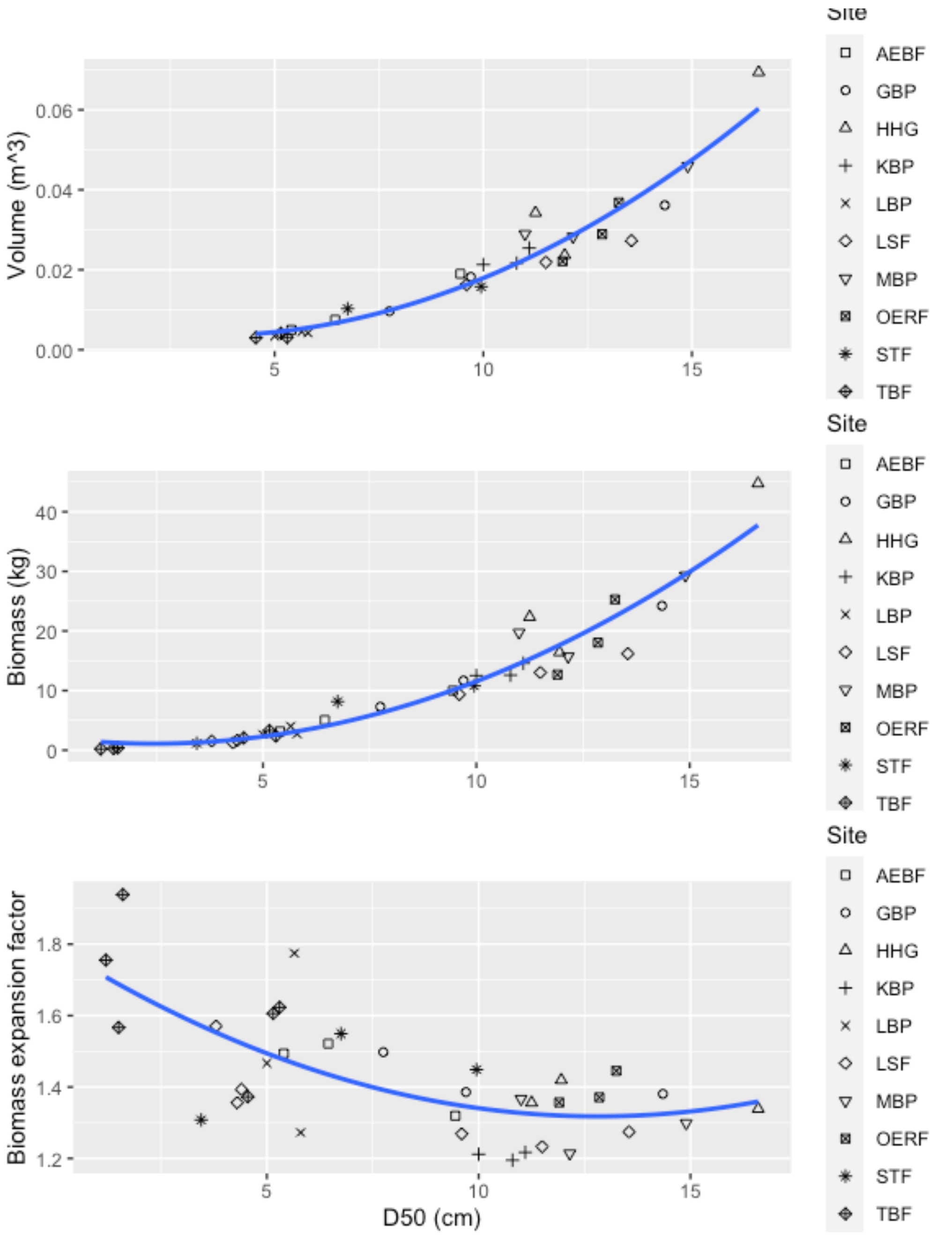

Figure 3.2 – Observed values and model trajectories of the diameter as a function of volume (m^3), biomass (kg), and biomass expansion factor, respectively. The symbols divide the data into the different plantations. the biomass curve parable show AGB

Mean values of this study's results are shown in Table 3.2. Here the mean aboveground biomass per hectare is calculated from the mean AGB per tree multiplied with the mean stem number of the orchards (2790 trees ha^{-1}).

Table 3.2 – Statistical measurements (mean, SD, and range) of all the sample trees.

	Stand age	D50 (cm)	Tree height (cm)	D50/ height ratio	Branch dry weight (kg tree^-1)	Stem dry weight (kg tree^-1)	Whole stem basic density (kg m^-3)	Biomass expansion factor	Branch/ stem biomass ratio	Mean aboveground biomass (kg tree^-1)	Mean aboveground biomass (Mg ha^-1)
Mean	15,2	8.4	322.1	2.5	2.8	8	476.6	1.4	0.4	10.7	
SD	7.2	3.5	0.5	2.2	2.2	7	27.6	0.2	0.2	9.9	29.9
Range	2-25	1.2-14.4	1.8-4.4	0.7-4.3	0.09-11.3	0.1-33.4	421-513	1.2-1.9	0.2-0.9	0.2-44.8	

When estimating C storage of apple trees temperate agroforestry, the mean biomass per tree or hectare of a broad range of sizes and ages as seen in table 3.2, is most likely not the realistic scenario. Thus, the estimation of CO_2 storage calculated in this section is based on a setup of a scenario, where the assumption is that all the trees investigated are more uniform in size and hence in aboveground leaf- and fruitless biomass (10 cm in D50, which is a representative size of a tree in the age of 23 years old sampled in this study).

We assume that all trees to have a D50 of 10 cm. From the aboveground biomass (1) model in Table 3.2 the estimated total biomass can be calculated using function (2).

$$Aboveground\ biomass = e^{-2.2017+2.01837 \cdot ln(10)} = 11.54\ kg/tree, \text{[13]}$$

In a prospect by one of the (now former) ROBUST project partners Mette Kronborg from Økologisk Landsforening, she estimates that 150,000 ha will be covered by agroforestry in 2030 (GUDP 2022). For the sake of making a simple example calculation scenario, we assume that alle this area will be alley cropping including apple trees. These areas are thus in this scenario reduced and homogenized to consisting of rows with alternately 16 m and 3,5 m between rows of apple trees with 1 m in-between. This gives the following total number of trees:

$$\frac{100\ m/ha \cdot 100\ trees/row}{\frac{16\ m + 3.5\ m}{2}} \cdot 150{,}000 = 1.54 \cdot 10^8\ trees\ in\ total, \text{[14]}$$

From the total number of trees and the aboveground biomass per tree we can calculate the total amount of CO_2 stored in the trees. It is assumed that half of the biomass, i.e. 5.77 kg/tree, consists of carbon. This gives the following amount of stored CO_2.

$$\frac{1.54 \cdot 10^8 \; trees \cdot 5.77 \; kg \; C/tree \cdot 44.01 \; g/mol \; CO_2}{12.01 \; g/mol \; C} = 3.3 \cdot 10^9 \; kg \; CO_2 \sim 3.3 \; Mt \; CO_2, [15]$$

The total number of models developed during this project were thirty-three, of which eleven were chosen as the primary models. These regards five models with only D50 as predictor variables (1) and five models accommodating both D50 and height (2), and one not correlating with tree size measurements, but instead effects from site related growing conditions, here topography (Table 3.3). The models Aboveground biomass (AGB) (1, 2), Stem biomass (1, 2), Branch biomass (1, 2), Stem volume (1, 2), and Biomass expansion factor (BEF) (1, 2) included D50, or D50 with tree height as significant predictor variables ($P<0.00001$). The Stem basic density (BD) model included topography as significant predictor variable. Model AGB (1) and stem volume (2) explained 97 %, while model AGB (2) and stem biomass models (1, 2) explained 98%, and the models for biomass explained 91%, and 93% of the variation (Table 3.3). The model for stem volume (1) explained 96% of the variation, while the models for BEF (1, 2) and BD explained 45%, 49% and 54% of the variation, respectively.

Table 3.3 – Model parameter estimates and statistical components of biomass dry weight of three different tree components, stem volume, biomass expansion factor (BEF) and stem basic density from the sample trees. The models are further described in appendix.

Model	Intercept *(SE)*	Ln (D50) *(SE)*	Ln (height) *(SE)*	Topography *(SE)*	SD(εij))	P value	R^2	RMSE
Aboveground biomass (1)	-2.2017 *(0.229)*	2.0184 (0.058)			0.050518	<0.00001	0.97	0.21
Aboveground biomass (2)	-7.0214 *(1.623)*	1 .7375 (0.108)	0.9341 (0.314)		0.040915	<0.00001	0.98	0.19
Stem biomass (1)	-2.7764 (0.107)	2.1351 (0.051)			0.039940	<0.00001	0.98	0.19
Stem biomass (2)	-6.2218 (1.5134)	1.9343 (0.101)	0.6677 (0.293)		0.035454	<0.00001	0.98	0.18
Branch biomass (1)	-2.98339 (0.197)	1.7637 (0.095)			0.137456	<0.00001	0.91	0.36
Branch biomass (2)	-11.4316 (2.634)	1.2713 (0.175)	1 .6373 (0.509)		0.107830	<0.00001	0.93	0.31
Stem volume (1)	-9.3279 *(0.192)*	2.3123 *(0.085)*			0.029900	<0.00001	0.96	0.17
Stem volume (2)	-13.4247 *(1.257)*	2.0738 *(0.103)*	0.7943 *(0.242)*		0.021936	<0.00001	0.97	0.14
BEF (1)	0.57467 *(0.046)*	-0.1168 *(0.022)*			0.007398	<0.00001	0.44	0.08
BEF (2)	-0.7996 *(0.657)*	-0.1968 *(0.044)*	0.2663 *(0.127)*		0.006727	<0.00001	0.49	0.08
Stem basic density	6.23801 *(0.015)*			-0.00395 *(0.001)*	0.001787	<0.00001	0.54	0.04

In the process of successively finding and inflicting additional predictor variables besides D50 and height, accommodating effects from growing conditions and management. Additional twenty-two models constituting significant correlating site factors like precipitation, temperature, root pruning, use of shoot reducing chemicals containing prohexadione calcium[29], distance to the nearest coast to the west, distance to nearest windbreak, type of soil and topography. All with varying P- and adjusted squared R-values (Table 3.4). Also, models showing how well the height correlates with the dependent variables consisting of AGB, stem biomass, branch biomass.

Table 3.4 - Model parameter estimates and statistical components of models from Table 3.3 including site variables.

Formula	P value	R^2	α parameter Pr(>|t|) value	β parameter Pr(>|t|) value	γ parameter Pr(>|t|) value	δ parameter Pr(>|t|) value	ε parameter Pr(>|t|) value	ζ parameter Pr(>|t|) value
ln(AGB) ~ ln(height)	<0.00001	0.8052	<0.00001	<0.00001				
ln(AGB) ~ ln(D50) + ln(height) + precipitation	<0.00001	0.9794	0.00065	0.04981	0.0816	0.04981		
ln(AGB) ~ ln(D50) + ln(height) + Temperature	<0.00001	0.9828	<0.00001	<0.00001	0.01	0.0021		
ln(Stem biomass) ~ ln(height)	<0.00001	0.7898	<0.00001	<0.00001				
ln(stem biomass) ~ ln(D50) + ln(height) + sunhours	<0.00001	0.9834	<0.00001	<0.00001	0.0463	0.08		
ln(stem biomass) ~ ln(D50) + ln(height) + temperature	<0.00001	0.9852	<0.00001	<0.00001	0.0623	0.0098		
ln(Crown biomass) ~ ln(height)	<0.00001	0.8159	<0.00001	<0.00001				
ln(Crown biomass) ~ ln(D50) + ln(height) + temperature	<0.00001	0.9407	<0.00001	0.00599	0.006322			
ln(Crown biomass) ~ ln(D50) + ln(height) + root pruning	<0.00001	0.9392	<0.00001	<0.00001	0.000324	0.0096		
ln(Crown biomass) ~ ln(D50) + ln(height) + root pruning + temperature	<0.00001	0.9493	<0.00001	<0.00001	0.000896	0.01	0.0119	
ln(Crown biomass) ~ ln(D50) + ln(height) + regalis	<0.00001	0.9518	<0.00001	<0.00001	0.000325	0.0014245		
ln(Crown biomass) ~ ln(D50)+ln(height) + root pruning + temperature + regali	<0.00001	0.9574	<0.00001	<0.00001	0.00016	0.05297	0.08724	0.02192
ln(Stem volume) ~ ln(height)	<0.00001	0.5674	<0.00001	<0.00001				
ln(Stem volume) ~ ln(D50) + ln(height) + distance to west coast	<0.00001	0.9774	<0.00001	<0.00001	0.00219	0.01979		
ln(BEF) ~ ln(height)	0.004	0.1937	<0.00001	0.004215				
ln(BEF) ~ ln(D50) + ln(height) + root pruning	<0.00001	0.5613	0.075664	0.000105	0.01	0.03		
ln(BEF) ~ ln(D50) + ln(height) + regalis	<0.00001	0.6325	0.093785	<0.00001	0.012368	0.004345		
ln(BD) ~ soil type	0.01	0.1664	<0.00001	0.0161				
ln(BD) ~ shelter type + shelter distance towards west	0.008	0.2561	<0.00001	0.267				
ln(BD) ~ shelter type + shelter distance	0.0002	0.4419	<0.00001	0.792				
ln(BD) ~ shelter type + shelter distance + soil type	<0.00001	0.5882	<0.00001	0.4663	0.0135			
ln(BD) ~ distance to west coast	0.001	0.2907	<0.00001	0.0015				
ln(BD) ~ distance to west coast + soil type + topography	<0.00001	0.6118	<0.00001	0.03528	0.04844	0.00466		

Figure 3.3 and Figure 3.4 show the nonlinear correlation between the non-log transformed D50 and the various non-log transformed dependent variables: AGB, stem and branch biomass, stem volume and BEF, sideways with the values for the log transformed models. The general trend is for the biomass to increase with D50. The visualisation of the plot for the correlation between branch biomass and D50, show accordance with the R^2 value shown in Table 3.3, where the log transformed model for stem biomass and AGB fit better compared to branch biomass model (1). The datapoints in the residual plots is placed somewhat randomly and form a roughly horizontal band around the line where residual = 0. For AGB, stem and biomass a slight overweight of data concentrate on the positive side of the predicted scale, and what appears to be the same three datapoints shown located around x = -2.

[29] Referred to as Regalis in these models.

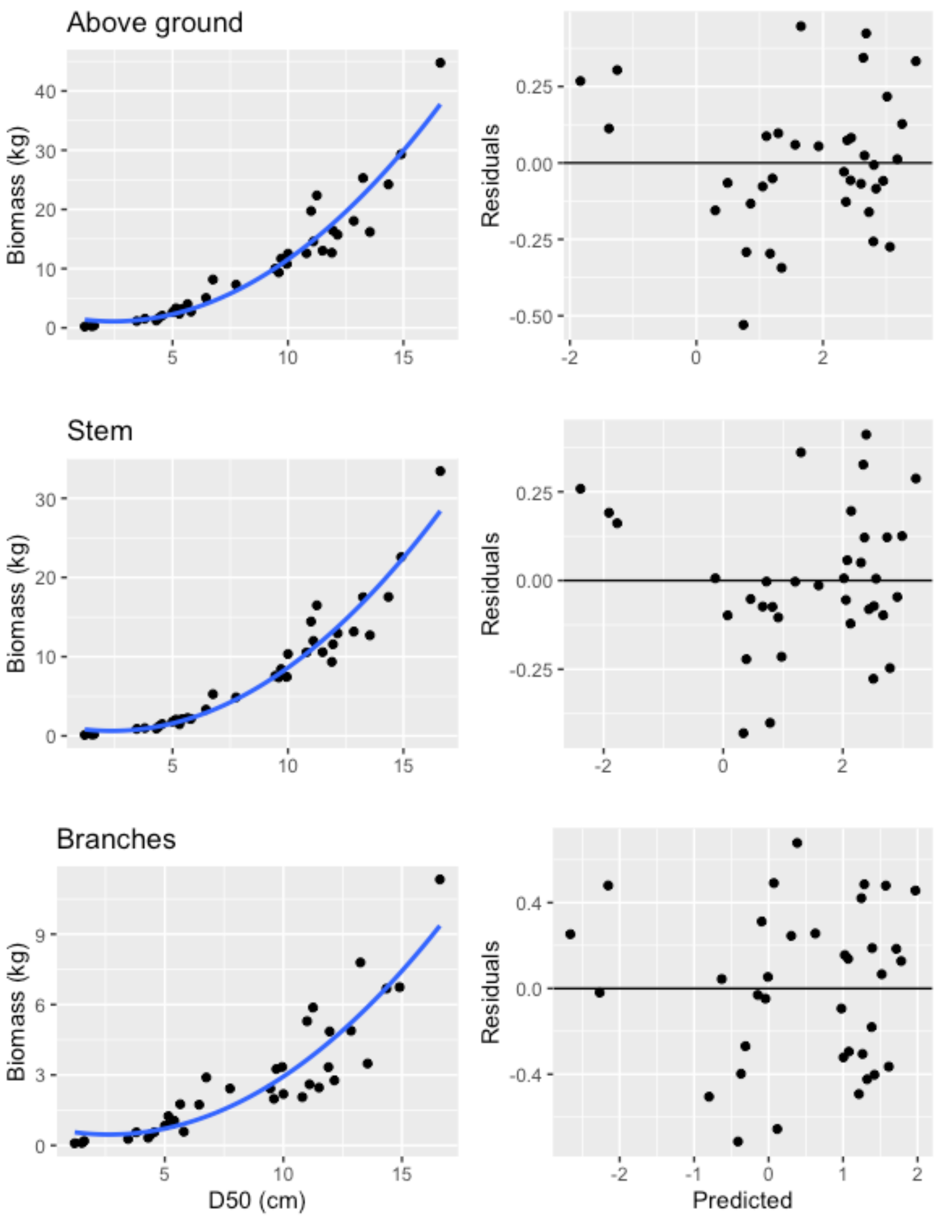

Figure 3.3 – Observed values (dots) and model predictions of the aboveground, stem and branch biomass, respectively (lest graphs), and model residuals (right).

Comparing the stem volume and D50 plot shown in Figure 3.4, with the biomass plots in Figure 3.3 fewer data points are shown between 0-5 cm, due to the seven small trees which were not measured for volume. The same outlying datapoint in the top values seem to occur in the four plots for biomass and volume. The correlation is non-linearly with a negative slope for BEF plotted against D50 (Figure 3.4). The residuals for the log transformed volume and BEF models (1) show fine and random dispersion of datapoints. For BEF a concentration is located between x = 0.2-0.4, and three datapoints seems more isolated at x >0.5 (Figure 3.4)

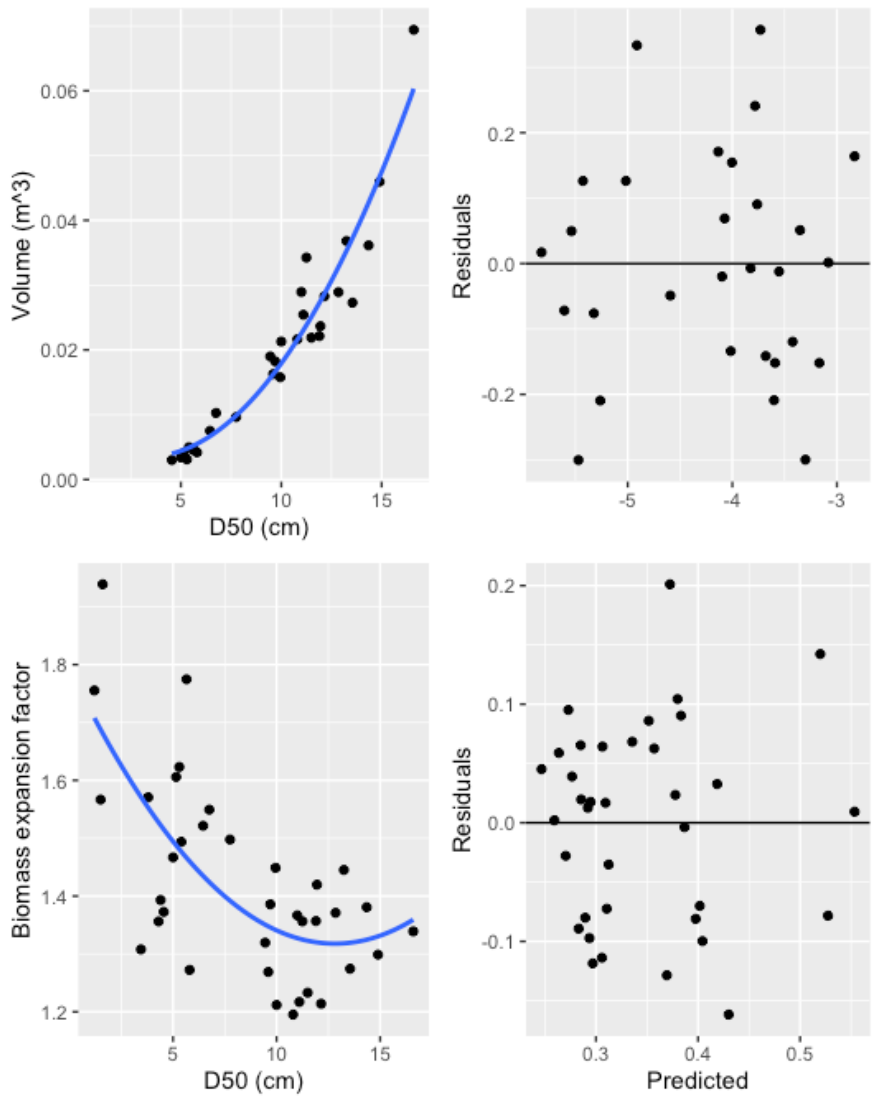

Figure 3.4 – Observed values and non-linear modelled prediction of the volume (m³) and biomass expansion factor (left graphs), and model residuals (right graphs).

Due to the uncertainty related to the topography variable, where the site effect value is equal for trees from the same site, where the height above sea-level vary among trees from the same stand, the correlation for BD is shown as a boxplot Figure 3.5. The BD decreases as the distance to sea level rise. The data points in the corresponding plot for model residuals shows random distribution.

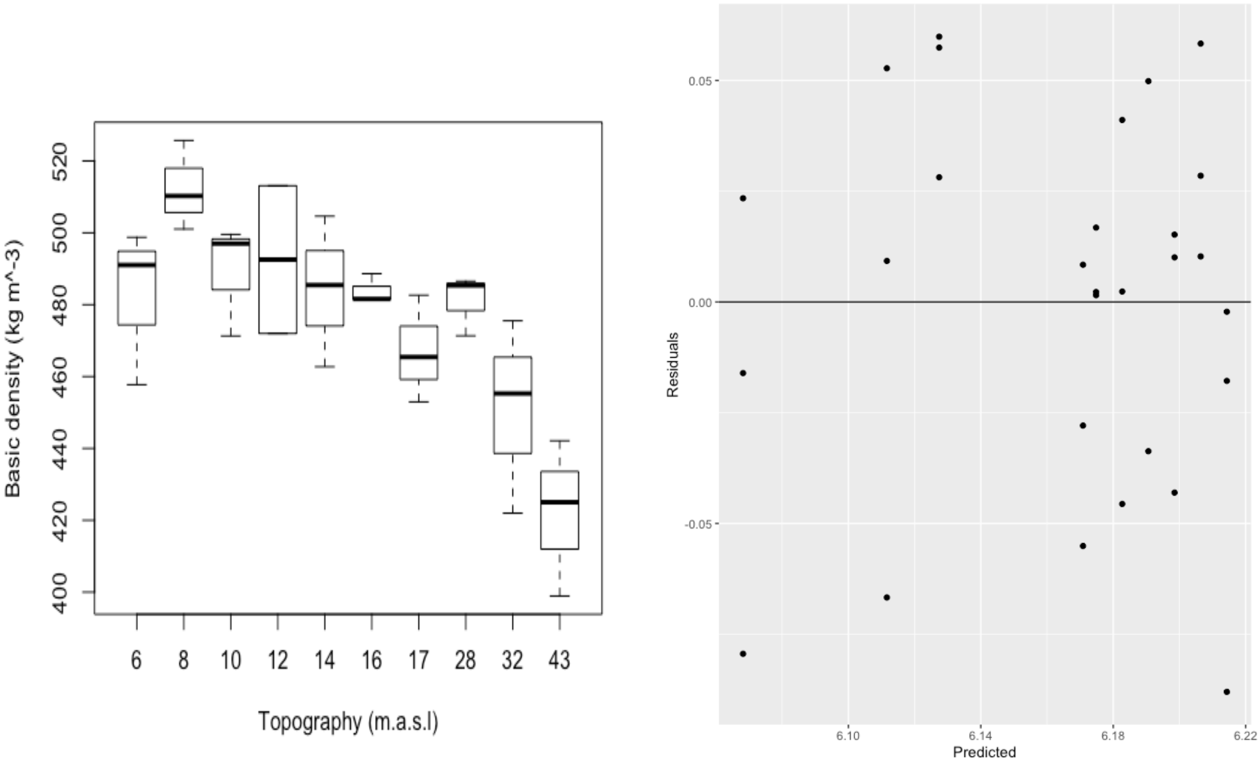

Figure 3.5 – Boxplot of the correlation between topography (meters above sea level) and basic density (kg m^{-3}) of all sample trees (left graph). The right graph shows the corresponding residual plot.

For the models including height, AGB (2), stem biomass (2), branch biomass (2), stem volume (2) and BEF (2), the relationship between observed and predicted values are shown as data points in respective plots where the line represents a 1:1 estimation. The general trend for the model plots, with exception of the BEF model (2), that the data points lie close to the 1:1 line, except for one outlier (tree no 20) with an AGB value ~15 kg tree^{-1} over the predicted value. The model residuals on the logarithmic scale show similar datapoint pattern around the residual = 0 line, with three isolated datapoints nearby x = -2, in the positive area of the residual scale, and 1-2 datapoints below y = -5 (Figure 3.6).

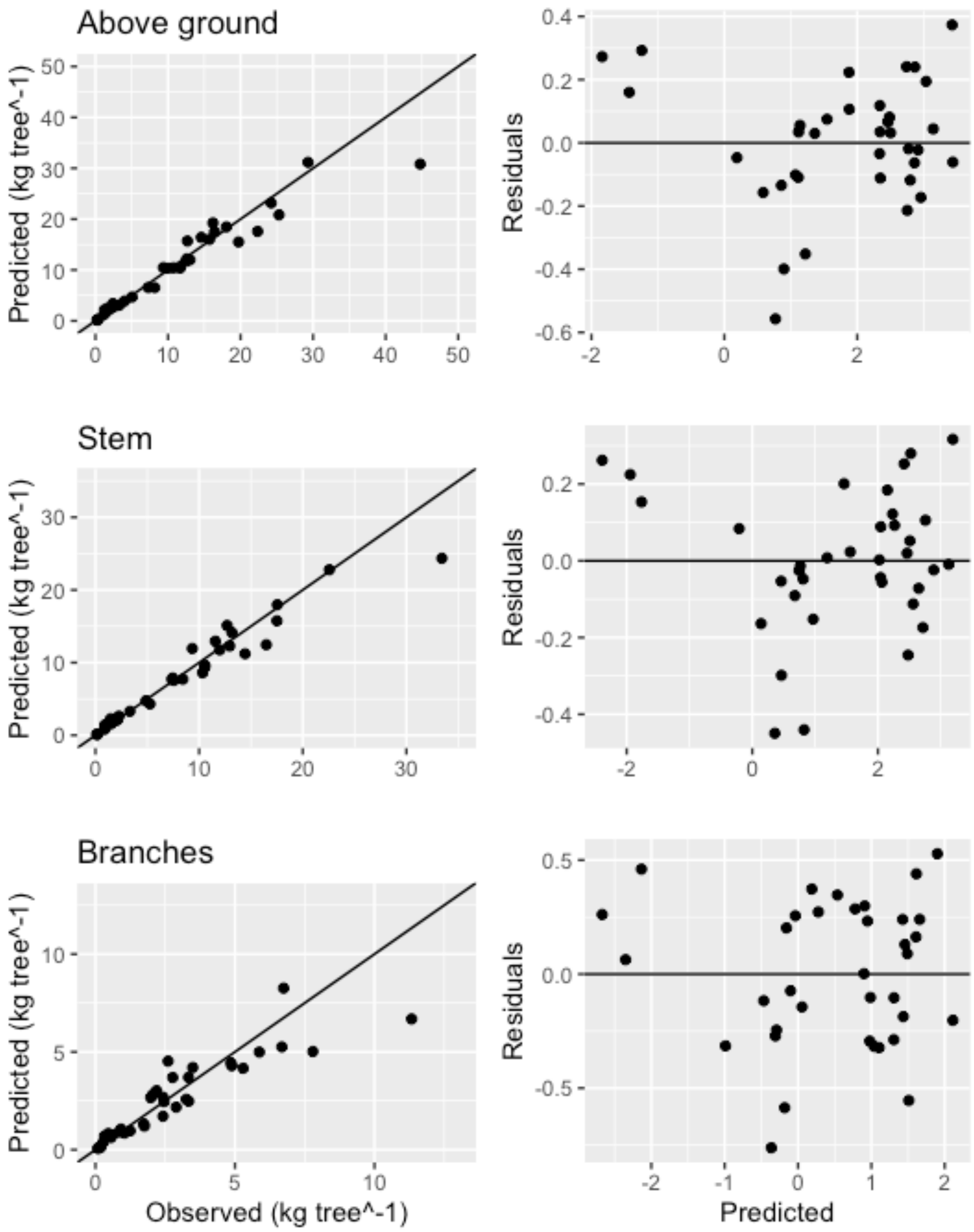

Figure 3.6 - Biomass ~ D50 + height as predicted and residuals

For the models including height, AGB (2), stem biomass (2), branch biomass (2), stem volume (2) and BEF (2), the relationship between observed and predicted values are shown as data points in respective plots where the line represents a 1:1 estimation. The general trend for the model plots, with exception of the BEF model (2), that the data points lie close to the 1:1 line, except for one outlier (tree no 20) with an AGB value ~15 kg tree^{-1} over the predicted value. The model residuals on the logarithmic scale show similar datapoint pattern around the residual = 0 line, with three isolated

datapoints nearby x = -2, in the positive area of the residual scale, and 1-2 datapoints below y = -5 (Figure 3.7). The datapoints of the BEF (2) model generally over- and underestimate
the predicted BEF values and the dispersion the 1:1 estimation line is generally scattered with residuals ~0.1. Near five datapoints were precisely estimated, and two major outliers (tree no 7 and 8), where underestimated BEF with ~0.23 of residual value (Figure 3.7).

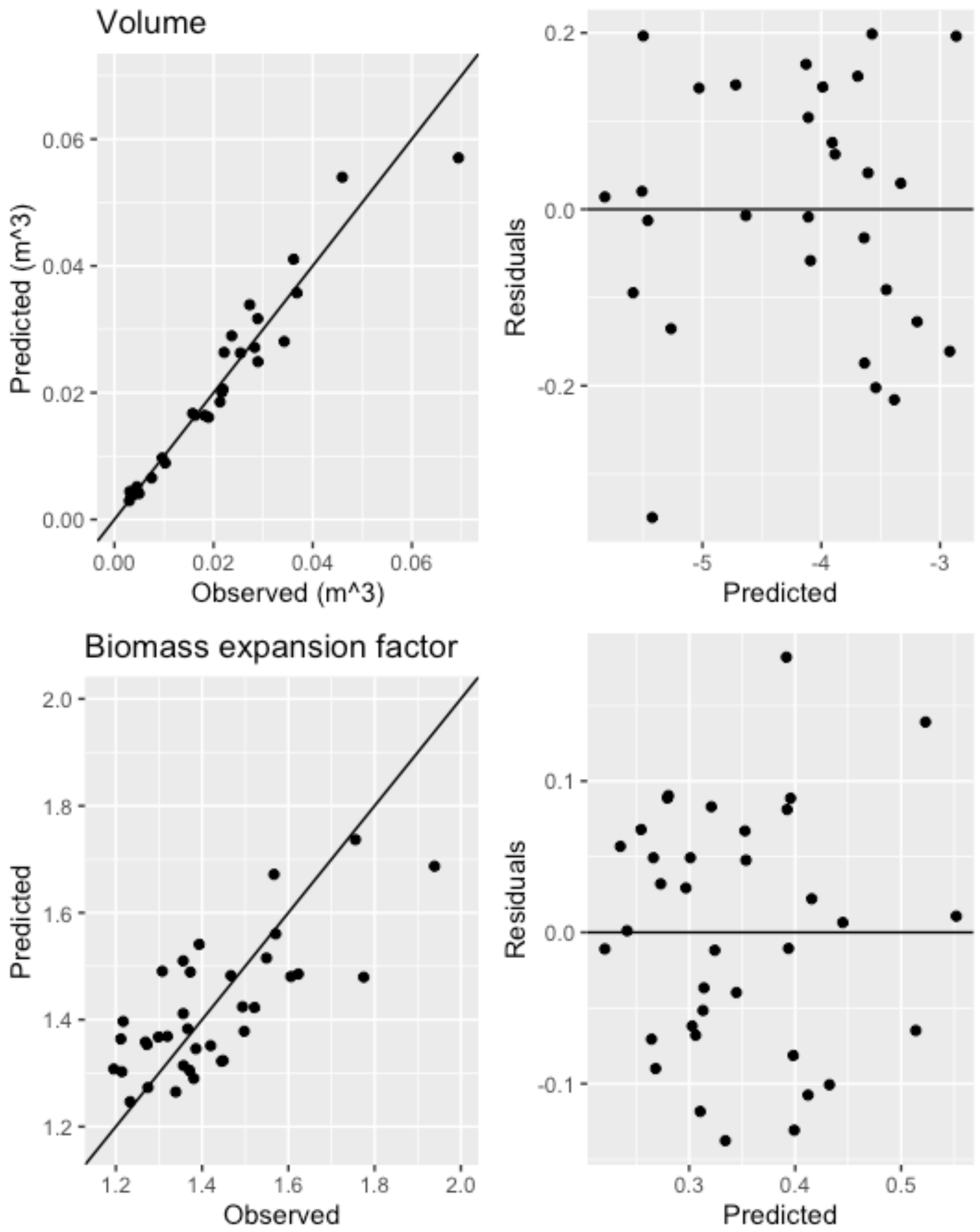

Figure 3.7 - Volume, BEF ~ D50 + height as predicted and residuals

4 Discussion

4.1. Own results

An easy way to predict the biomass would have been if age described biomass accurately. The procedure for biomass estimation of an orchard would then be to look up the year of planting and find the associated biomass per tree value in a table for biomass according to tree age. However, the age of the trees does not describe the biomass very accurately (only 40% the variation is explained by tree age). Despite age, the size of apple trees (and trees in general) varies greatly within the same age. As for example the trees at LBP, were four years old, organically grown, located near the west coast of Jutland, were bigger and showed higher mean AGB values (3.2 kg tree^{-1}), than elder conventionally grown trees of TBF (2) and LSF (1), where the tree age was seven and eleven years and more isolated from the westerly wind (2.6 kg tree^{-1} and 1.5 kg tree^{-1}, respectively). Nonetheless, a general correlating trend for D50-to-height ratio and age, and branch-to-stem-ratio and age did occur, where the first mentioned pattern seems to increase with age, and the latter seem to decrease (Appendix). For many studies of the biomass in forest tree plantations the diameter measured at breast hight (dbh) is enough to explain most of the variation, due to the correlation between dbh and tree height. In a study of biomass in southern Scandinavian plantation grown poplars, Taeroe et al. (2015) experienced a development of an increasing logarithmic function, when plotting the tree height against stem dbh. The same development would probably have appeared in Figure 3.1, if not for the immense pruning applied to the apple trees in the danish slender spindle systems included in this study. The management in these systems strongly affect the height and standing biomass of the individual tree compared to apple trees grown in extensive production systems. In the poplar study, they also found that some site effects hampered the tree height in one of the stands, why including the tree height as a predicter variable in their model, no other variables were needed for describing the total leafless AGB of the studied poplar clone. In this study D50 explains 65.5% of the variation in height of the apple trees (Figure 3.1). As shown in Figure 3.1, high trees can have slender stems in the height of 50 cm and small trees can have a wide stem D50. A general rule of thumb calculation[30] when in need of a quick biomass estimation (RTQC) is to multiply the stem volume with 1.2 and 0.5, which in this study estimate the observed biomass very accurately (Appendix; $R^2 = 0.9857$[31]). However, D50 and

[30] Source: supervisor Anders Tærø Nielsen. Equation: AGB = stem volume * 1.2 * 0.5
[31] Higher than any of the included models, with top $R^2 = 9852$.

height are more easily accessible observations. Furthermore, all possible variables need to be tested to exclude or include them in the final a most precise model for AGB estimation in danish apple trees. Despite the high pruning pressure, the tree height still added some precision to the developed models. Due to the pruning, site variables still showed an effect when added to the models, contrary the findings of Taeroe et al. Another contrast-filled result in this study, is that the branch biomass and height were more possetively correlated than the stem biomass and height, where the opposite proved valid in the poplar study. Mannagement and growning condition variables generally increased the squared R values of the developed models in this project, thus holding a part of the variance explanation. For most of the models (except AGB biomass (2)) D50 and height does not hold the entire rough description of the dependent variable variation.

The model development strategy for this project has been in three levels of complexity: models with the stem diameter alone, models with stem diameter and height, and models with stem diameter, height, and variables of site, to produce the best combination of usable and accurate models.
The inclusion of site variables was also to ensure no crucial factors were overlooked in the model development.
High correlation was found between D50 and biomass, and stem volume (R^2 = 0.91-0.98). Less did the BEF correlate with D50 (R^2 = 0.45), and the BD showed to correlate best with the site variable topography (R^2 = 0.54) (Table 3.3). The height as a predictor variable alone for AGB explained 81% of the variance, stem biomass 79%, branch biomass 82%, stem volume 57% and BEF 19%. This same correlation pattern could be seen when adding height along with D50 to predict the same beforementioned dependent variables: the variation of AGB was slightly better explained with the height compared to without the height (R^2 = 0.98 vs 0.97) (Table 3.3). Same additional effect did height have on branch biomass, stem volume and BEF, increasing squared R values from 0.91 to 0.93, 0.96 to 0.97, and 0.45 to 0.49, respectively. There was no additional effect of tree height on stem biomass (Table 3.3).

Adding significant site variables ($P<0.05$) to the models (2) accommodating D50 and tree height e.g., root pruning and temperature, or use of the shoot hampering chemical regalis plus raised the squared R value in Branch biomass (2) from 0.93 to 0.95 (Table 3.3 and 3.4). Combining all three site variables and adding to Branch biomass (2) increased the squared R value to 0.96, creating the model with the highest number of included predictor variables. The P value for the response variable relationship of two of the predictor variables (root pruning and temperature), on the other hand, exceeded the limit of significance (P=0.053 and 0.087) (Table 3.4).

Adding more predictor variables to the models (1) generally increase the R^2 value as they explain more of the variation from the best fitted regression line, increasing the precision of the models (Table 3.3; 3.4). However, when doing so, the application range of the models gets reduced, as it becomes more specific and modified to the trees from the orchards of this study. A considerable part of the variation in the model then gets explained by the sites from where data was assembled. Applying the models to apple trees managed in systems with varying allometric properties will therefor risk biased predictions. Another aspect is the additional labour and costs associated with the collection of field observations when increasing the model complexity with every extra variable added. The simplest models developed with only D50, or topography included show highest applicability for measuring the biomass of many trees, while adding height reduces the amounts of trees possible to measure during a limited time span, relatively. Even more when also adding site variables. On the other hand, for the purpose of developing the most precise model, adding height and site factors generally increased the precision of the models.

When including site effects, co-variance can occour, which can be troublesome when trying to obtain clarity over cause and effect. The expectations as a starting point as be that these site effects are some of the same additional overlapping basic factors that, for example, influence stem volume and stem biomass, while crown biomass is probably affected in a different and more direct way by pruning practice, compared to the stem. The total biomass is then affected by everything that affects the stem and the crown.
For AGB mean annual communal precipitation and temperature provided small increases in squared R values (from 0.9774 to 0.9794 and 0.9828, respectively). Stem biomass showed significant statistical relationship with mean annual communal hours of sun and temperature, achieving the highest squared R values of the models developed in this project by increasing from 0.9823 to 0.9834 and 9852. These four site variables can be interpreted as proxies for some of the same regional covariation. The sun shines more, the temperature is higher, and the climate is dryer in the area of Storebælt, and on Bornholm than in Midtjylland for example, and it is also warmer in the east than in Midtjylland (Table 2.3). Site effects correlating with stem volume would here be expected to be something that could be interpreted as a correlating regional basic effect, however the only predictor

variable showing a significant relationship with the volume when D50 and height already are included was the distance to the nearest coast to the west, increasing the squared R value from 0.9729 to 0977. This variable is somehow also related to regional effects, and a hypothesis can be that it is treatment or wind conditions. When estimating biomass the experience is that the variance hardly is due to temperature, precipitation and sunshine, when D50 and height already have been taken into account, but it can covary with something else (e.g., Faqi et al. 2008; Zanotelli et al. 2015; Brunori et al. 2017). However, mean annual communal wind and distance to shelter do not occur with stastistical significant relation to any of the response variables, like neither any of the treatment parameters (Table 3.3; Appendix). Site management effects did however show correlation with branch biomass, as presented earlier, and BEF, affecting by root pruning, use of regalis. Exclusively for branchbiomass, temperature also show an effect here. The squared R value increased from 0.9271 to 0.9392 for branch biomass, and from 0.49 to 0.56 for BEF, when including root pruning (Table 3.4), and when including regalis, it rose to 0.9518 for branch biomass and 0.6325 for BEF, when D50 and height already was withtaken (Table 3.4). Despite the expected, no additional effect from pruning showed on branch biomass. In denmark the methods for apple tree growing and production is very much alike, hence pruning being a constant factor setting the overall frame for standing biomass, and some factor that vary between sites. The site variables correlating with branch biomass and BEF might also infact correlate with the variables affecting stem biomass and AGB. Possibly also stem volume. Here all until now mentioned significant site effects may be acting as proxys for the same. The aplication of root pruning nor regalis did, nevertheless, not follow any regional pattern matching the significant effects of local climatic factors. However, other management aspects, and herby also including pruning, could be something which varied among regions, but just not something visible in the variables included in this study. It could be trees from a few sites which were manneged specially. Taking a closer look at site specific mean values of the trees' D50-to-height ratio and branch to stem ratio, no significant high or low numbers shown, with the exception the three young trees (no 7-9) from TBF (1) with a mean value of 0.75 and 1.18, respectively (where the others range from 1.44-3.46, and 0.21-53) (Table 3.3). Here it would be interesting to investigate if any of the sites showed perticilularly high or low residuals. For the mean observed values of the groups of three trees among sites minus the mean predicted values all plantations showed a mean residual value within +1 to -1, except for HHG (exceeded with a value of 5.9) (Appendix). Looking at the style of management, effects related to shelter conditions, windexposure or any other location related effects nothing particular stands out for these two sites. The trees where tipped at HHG and the trees at TBF the youngest of the included sample age range. Inspecting the distribution of residuals plotted against fitted values of Aboveground biomass (1), (2), Stem biomass (1), (2), Branch biomass (1), (2), Stem Volume and BEF and the corresponding sample quantiles compared to those of normal distribution, mostly single trees frem every plantation was projected as outliers. Tree no. 10, 20, 21, 30 and 32 were consistently highlighted with outlying values (for description of their growing conditions read text in Appendix). Inspecting tree individual extreme values for residuals when using RTQC-equation, residuals for model AGB (2), D50-to-height ratio, and branch-to-stem ratio, TBF (1), (2), HHG, and LSF (2) had more than one tree with extreme values (Table 4.1). Especially tree no 20, showing some high values for residuals and D50-to-height ratio. Also tree no 13 from showed high residual values from the two biomass models.

Table 4.1 – where RTQC is abrivation for "rule of thumb quick calculation", AGB (2) the model for Aboveground biomass including D50 and height.

Site	Tree no	RTQC residuals	AGB (2) residuals	D50-to-height ratio	Branch-to-stem ratio
GBP	3	2.5			
MBP	6	2.4	4.5		
TBF (1)	7			0.7	0.76
	8			0.8	0.94
	9			0.8	
(2)	10				6.2
	11				6.1
ØRF	13	3.2	4.5		
HHG	19	2.2			
	20	3.1	14	4.4	
	21		4.4		
LBP	28				7.7
LSF (2)	34			4.1	
	35		-3.1	4	

A broad scope of site characteristics and growing conditions can result in various allometric trends. At this point it is difficult to determine the actual underlying cause of the effect on the site related response variables.

For BD a statistically significant relation showed to the predictor site variables shelter distance to the west, shelter type, shelter distance, soil type, distance to the nearest coast to the west (Table 3.3 ;

Table 3.4). The soil type, shelter type included with shelter distance, shelter type included with shelter distance to the west, and distance to west coast showed lower squared R values (0.17, 0.26, 0.44, and 0.29, respectively) compared to that of topography (0.54). Including shelter type, shelter distance and soil type in one model, the squared R value surpassed that of the BD model including topography (0.59) (Table 3.3; Table 3.4), however, inspecting a residual plot for this model, a big overweight of data points show in the one side (Appendix). Including distance to the west coast, soil type and topography in one model for BD, increases the squared R value to the highest for a BD model in the project (0.61) (Appendix). However, the P value for the predictor variables distance to west coast and soil type, show very high compared to topography, and for the purpose of developing a simple and precise model, only topography is recommended for the estimation of stem BD (Table 3.4). With if material was included, where trees where grown sites with a broader range of soil types, this could be an interesting parameter as well for the BD estimation. The trees from the two sandy sites showed higher BD values than of those trees grown in clayey till (Appendix)

In the absence of more comparable model studies comparing the fitness of the models developed by Taeroe et al. (2015) show almost identical results. The branch biomass (2) explained less of the variation in apple trees (91%), compared to that of branch biomass in poplar (97%). Conversely, topography explained 54% of the apple tree stem BD variation, compared to that of poplar stem basic density (46%). The explanation rate of the BEF in apple trees of this study is significantly lower (49%) compared to the one in the poplar study (81%) (Table 3.3; table 3.4). However, the poplar study included a predictor variable of relative tree size (dbh/ quadratic mean diameter), which seem more fitting to describe biomass expansion factors in trees generally, than stem diameter and height.

For simple and sufficiently precise estimation of aboveground biomass (total, and components), stem volume, biomass expansion factor, and basic density in danish intensely grown apple orchard trees, it is by this project recommended to use the models of (1) needing measurements of D50, and for BD topography measurements. For higher precision, but with more laborious demand for variable estimation, models of (2) including measures of D50 and height. For the high complex models including site variables besides D50 and height, interpretation challenges regarding cause and effect due to covariation among growing condition factors, low contribution in R^2 increase, and comprehensive work put into additional measures, makes them the least recommended in this project.

4.2. Model review of other studies

The preponderance and ease of use of the developed models of this project is to be evaluated when applied in the future to other temperate treatment systems and diverse sites around the north-western Europe. Nevertheless, by comparing model parameter results of this study to other studies alike, and assessing their execution, a sense of the utility value of the models can be obtained.

During the literature search, it became clear of the sparsity on the subject of biomass estimation and C sequestration in temperate apple orchards. Consequently, aboveground biomass estimation studies of intensively managed apple trees or fruit trees in general, were conducted under differing types of climates than temperate, except for Winzer et al. (2017), conducted in Germany under temperate climate (Appendix). However, focus was here to estimate biomass by weighing the dry weight of the whole tree in order to estimate bioenergy. Just like several other studies were studying the partitioning of dry matter and C allocation in the adverse above and belowground tree organs (e.g., Marcelis et al. 1998; Génard et al. 2008; Panzacchi et al. 2012; Fanwoua et al. 2014), biomass yields and quality for bioenergy and useability of the pruning litter (Winzer et al. 2017; Kowaluk et al. 2020; Matłok and Gorzelany 2020; Yang et al. 2020), carbon fluxes and LCA[32] in an fruit orchard (Zanotelli et al. 2015), fruit trees' C storage in soil, the effect of input and management on biomass yields in fruit trees (Buwalda and Lenz 1992; Milosevic and Milosevic 2009; Montanaro et al. 2012), biomass and C sequestration in fruit trees of different agroforestry systems (Goswami et al. 2014; Lauri and Dufour 2016; Dold et al. 2019; Zahoor et al. 2021), and internal competition when intercropping fruit trees (e.g., Gao et al. 2013). Thus, focus in most of the found literature was not on allometric model development and did not provide comparable parameters for estimation, but instead e.g., biomass per tree or hectare. Other articles provided allometric equations, but with differing structure, components, and units, e.g., where Y = biomass volume, where X = wood density multiplied with tree hight, or where the parameters = $e^{a}X^{b}$ (Panzacchi et al. 2012; Fernández-Puratich et al. 2013; Zahoor et al. 2021; Appendix). Other articles again accommodated the right format of the model equation, but were in conducted under climate too adverse or concerned too tropical fruit trees to compare (e.g., mango, coconut, guava and jamun; subtropical; Shinde et al. 2015; Zahoor et al. 2021). However, for three of the studies enough characteristics were relatively comparable in order to use for the purpose (Wu et al. 2012; Zanotelli et al. 2015; Brunori et al. 2017; Appendix). These studies used the same format of the power equation and all used stem diameter as predictor variable. However, the sample

[32] Life-cycle assesment.

trees were grown under differing types of climates (humid continental, continental, continental Mediterranean, Mediterranean sub arid), with higher, almost double the mean annual local temperature (11.5-17.2 °C), broad range of stand density (70-3300 tree ha^{-1}), in other types of soil and with half the amount of sample trees (Appendix). The study of Wu et al. (2012) use stem diameter at 20 cm above the ground for estimating stem and branch biomass in apple trees of the cultivar Fuji and Makino grown in and sampled from three orchards of the Chinese Changpin District. Three trees were sampled from each orchard in the age of 5, 18 and 22. The adjusted squared R value for branch and stem biomass were 0.984 and 0.997 respectively (Table 4.2; Appendix). The study of Zanotelli et al. (2013) use stem diameter at 10 cm above grafting point as predictor variable to describe aboveground biomass in apple trees where the cultivar Fuji is grafted on a dwarfing rootstock (M9), organically grown in slender spindle systems of a high density Italian apple block in South Tyrol. 11 trees in the age of 12 were sampled, and the model for aboveground standing biomass explained 91% of the variation (Table 4.2; Appendix). In the absence of a more fitting third comparable study the one conducted by Brunori et al. (2017) was included, where the stem diameter in the hight of 30 cm above ground was used as describing variable for aboveground biomass in olive trees, where the cultivar Leccino was grafted onto a M9 rootstock and grown in six Italian orchard vase systems dispersed between Umbria, Tuscany and Sicily. 18 trees were sampled in the ages between 8-67. The developed model explained 99% of the variance.

Table 4.2 – Articles reviewed for model estimation and their charecteristics

Reference	Species		Sample trees	Height of stem diameter above ground (cm)	Intercept *(SE)*	Exponent (SE)	R^2	P value
Wu et al., 2012	Malus domestica	Stem:	9	20	0.178 *(N/A)*	1101 *(N/A)*	0.99	N/A
		Branch:	9		0,124 *(N/A)*	1.234 *(N/A)*	0.98	
Zanotelli et al., 2013	Malus domestica		11	10 (above grafting point)	229.3158 *(1.382)*	1.6115 *(0.179)*	0.91	<0.001
Brunori et al., 2017	Olea europaea		18	30	0.0538 *(N/A)*	2.408 *(N/A)*	0.99	<0.001

The review of the foreign models was conducted by the procedure of applying them to the data of this project and evaluate the performance. Of the three revived models, the one of Brunori et al. (2017), after visual inspection of the observed values from this study plotted against the predicted values of the Italian olive model with Apple tree stem D50 data, showed the greatest fit. This was unexpected due to a model developed for estimation of aboveground biomass in a different fruit tree species grown under different climatic conditions, and in a very different growing system. The residual values are low for x = 0-10 and then the precision decline and a general trend for x = 10-45 is overestimated predicted values. Next best fit was performed by the model of Zanotelli et al. (2013), with a general underestimating trend from x = 5, and with increasing residual value.

In the case of the branch and stem biomass models of Wu et al. (2012), they consequently overestimate the biomass in the sample trees of this study (Figure 4.1). Inspecting the models, branch biomass fit the observed values well, but the stem biomass shows same overestimating trend (Appendix). The development is a linear increase; however, the coefficient (0.178) is too high, and would have fit if it was 0.078. Taking the other coefficients of the other models developed in the study of Wu et al. into account, it does not appaer to be likely that the overestimation is caused by a typing error.

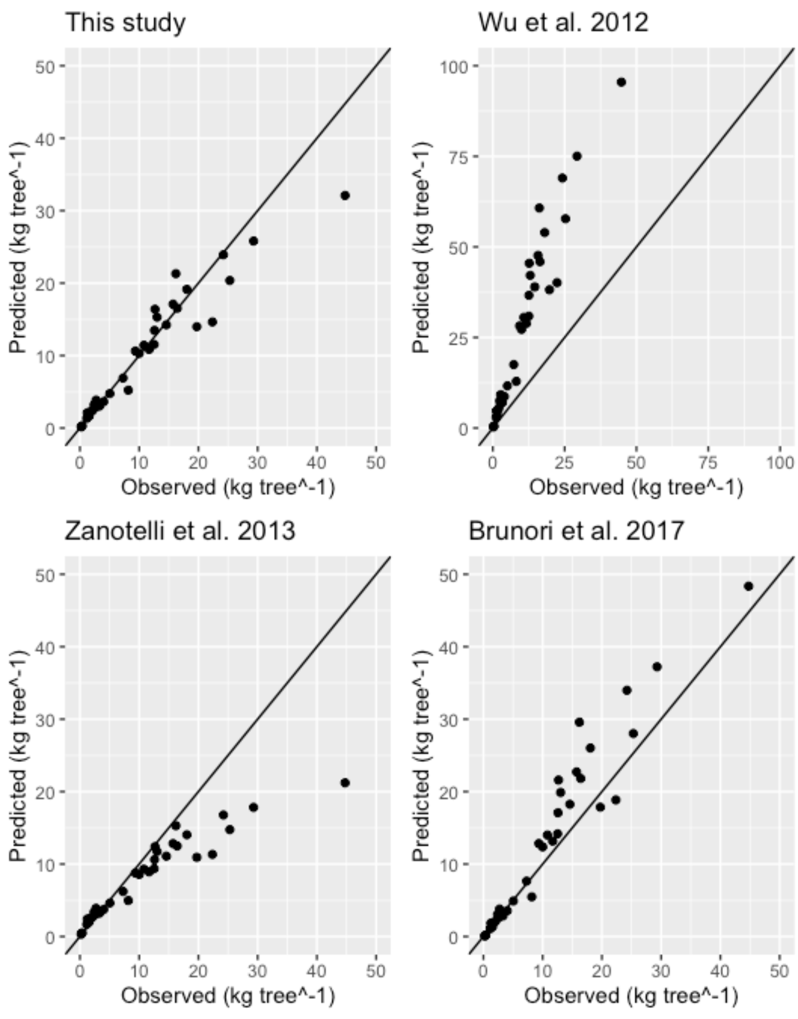

Figure 4.1 – Relationship between observed values (sample trees from this study) and predictions of the biomass from other studies. The line represents a 1:1 estimation.

4.3. The vertical developmant of stem basic density

The under- and overestimations of the aboveground biomass of material from this project can probably be attributed to the different climate, siteconditions, genetics variotaon among cultivars and fruit tree species, mannagement systems, the age of the trees, or the procedures for sampling.

Figure 4.2 show the vertical development of BD of the stem in 29 sample trees, where the BD in the height og 15 cm from the ground show significantly higher values ($P<0.001$) than the rest (Appendix).

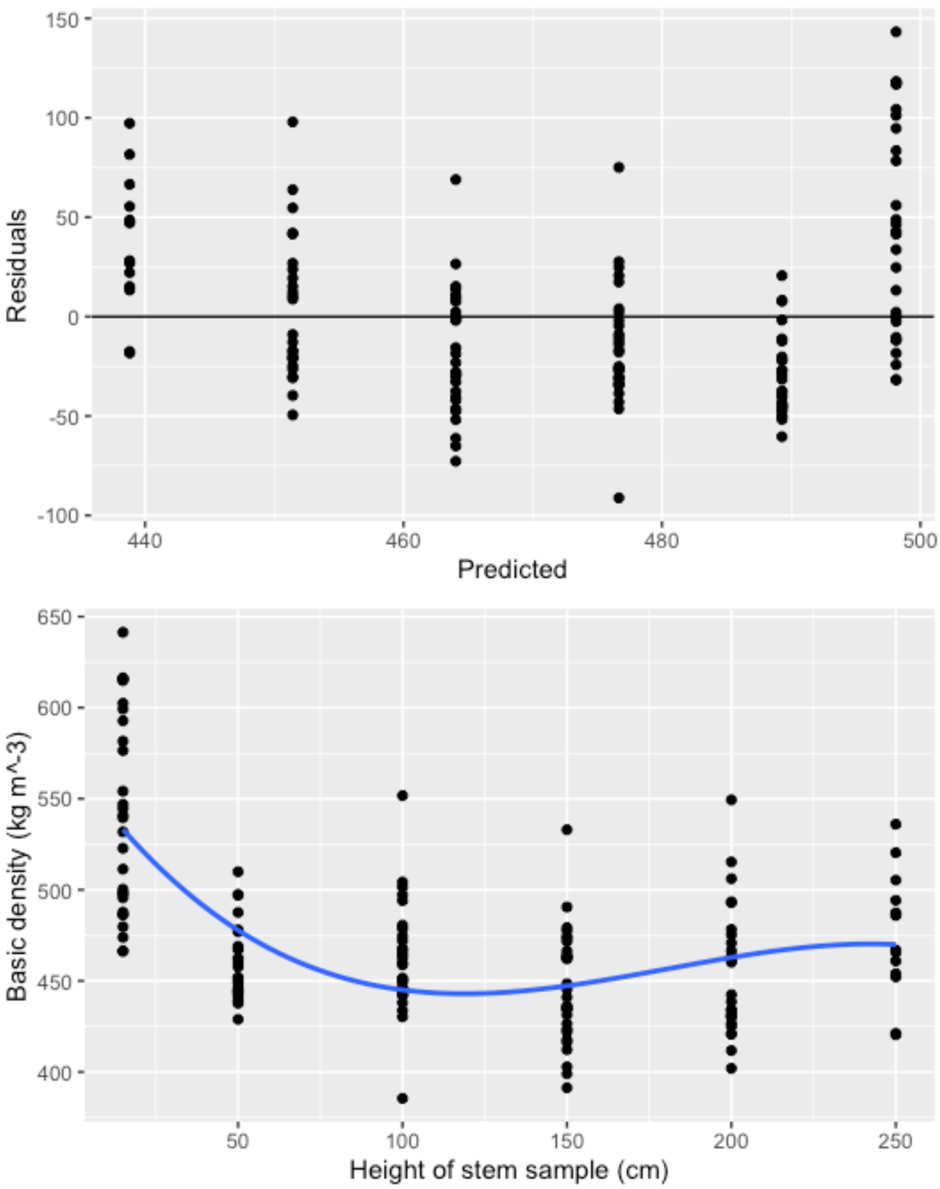

Figure 4.2 – Vertical development of the BD in the 29 observed apple trees (bottom), residual dispersion (top).

When only sampling stem discs in the height of 20-30 cm above the ground as in the studies of Wu et al. (2012) and Brunori et al. (2017), and use as representative for the whole stem it might be biased, due to the higher BD arund the grafting point located in this height abouve the ground. This would cause a general overestimation. On the other hand consequently sampling the stemdiscs only from 10 cm above the grafting point, as in the study of Zanotelli et al. (2013), the predicted values might underestimate biomass of the stem. It is thus the recommendation of this project as a minimum to sample in the hight of the grafting point an above, in order to develop precise models for BD and stem biomass.

4.4. The CO_2 calculation scenario

As for the scenario with the example calculation in section 3. Results, most danish farmers undertaking agroforestry into their production systems, will most likely do as in the case of the project partners of ROBUST, where the apple trees are planted and managed expensively (e.g., the case of Bjarne planting trees extensively with 4 meters of distance between the trees in a row, grafted onto a wild rootstock, and way less pruning as compared to an intensely managed apple production orchard system). Thus, the biomass and carbon of these agroforestry apple trees will most likely show another allometric pattern the ones included in this study. However, the models are still relevant in the case of providing a minimum estimation of CO_2 mitigated when planting apple trees into the open landscape. Furthermore, it is still a possibility for farmers to plant orchard like apple tree belts for intense apple production, or if apple growers are interested in knowing their mitigation value in their orchards, in these cases very precise estimations are now possible with these models.

5 Conclusion

Agroforestry currently experiences increasing interest worldwide in projects for reducing and mitigating emissions related to agriculture. In the light of a great need for the earth's resources to be used sustainably agroforestry in temperate climates are being investigated, among other in a danish context through the project ROBUST, of which this project contributes to with knowledge on biomass and carbon storage in apple trees.

Assessing the C storage ability in aboveground apple tree biomass for e.g., agroforestry systems, biomass and biomass expansion factor functions are crucial. In this study 36 apple trees of the cultivar Elstar was sampled from 10 orchards widely dispersed across Denmark, for the determination of estimating allometric models to project the biomass and thus the C stored in individual tree parts, stem volume, stem-to-aboveground-biomass-expansion factor (BEF) and stem basic density (BD) in danish apple trees. The trees were between 2 and 25 years old, their individual stem diameter in the height of 50 cm above the ground fluctuated from 1.2 to 14.4 cm, and AGB per tree ranged from 0.2 to 44.8 kg tree^{-1}. D50 and height as predictor variables was included in the final recommended models developed for estimating stem volume and leaf- and fruitless AGB of the tree components branch and stem, which explained between 93%-98% of the variation. Biomass values rose exponentially with increasing stem D50, where the trees with a D50 >5 cm also weighed below 5 kg, where every cm of increase in D50 the biomass raised with 2.18 kg tree^{-1}. Stem volume showed same development, where trees with a D50 <10 cm roughly had a stem volume of ≤ 0.01 m^{3}. For the smallest trees BEF values were around 1.8, and decreased with rising stem D50, where trees with >10 cm roughly had a value around 1.3 BEF. Stem BD was found the highest in trees grown 6-14 m.a.s.l., with an average value of 490 kg m^{-3}, and declined with increasing meters above sea level, where trees grown in 43 m.a.s.l. roughly had a stem BD on 430 490 kg m^{-3}. The existing AGB models in the accessible literature either under- or overestimated the measured sample apple tree AGB. Here several factors of explainable value are possible, and accommodate different growing conditions, management procedures and genetics among species and cultivars. The observation of higher BD in the dwarfing rootstock compared to the Elstar variety stem grated upon, lead to the hypothesis, that estimate differences also occurred due to sample procedures. When either excluding samples from above or beneath the grafting point it may lead to over or underestimation of what was observed in danish orchard Elstar apple trees.

The tree height and stem diameter observations in this study were sufficiently dispersed among stands with diverse tree sizes. These each were very finely correlated with biomass of the tree components

and the stem volume, thus models of high application range explaining most of the variation with few variables. However, the BEF correlated less with these variables, and BD showed to be completely size independent. Instead, some correlation appeared with topography. The inclusion of site variables was to ensure no crucial factors were overlooked when aiming for the most optimal balance between precise and applicable models. Including height as a predictor variable among D50, higher model precision was provided generally. For simple and sufficiently precise estimation of aboveground biomass in tree parts, stem volume, biomass expansion factor, and basic density in danish intensely grown apple orchard trees, it is by this project recommended to use the models of (1), which involve measurements of D50, and for BD topography measurements. For higher precision, but also with higher cost when complexing the model further, increasing the labour related to variable measurements, models of (2) are recommended. These involves measures of D50 and height. For the high complex models including site variables besides D50 and height, interpretation challenges regarding cause and effect due to covariation among growing condition factors (and too limited material to rigorously test the influence of these), low contribution in R^2 increase, and comprehensive work put into additional measures, makes them the least recommended models of this project.
The models developed in this project can be used (with an assumption of a conversion factor) for minimum estimation of mitigation value of apple trees in present and future agroforestry systems.

6 Perspectives

As an opportunity for future agroforestry farmers, dense apple tree belts can be planted between fields e.g., 16 m wide, intensively managed for renting out to the increasing number of hobby and cooperate cider producers in Denmark (Effektivt Landbrug 2021). This way the farmer is diversifying the income from the fields, securing improved conditions for biodiversity in and pollination of the monocultural annual crops, improving the climate adaption for future weather extremes, and gets compensated by the future subsidies on climate mitigation initiatives in the food production. Besides the carbon sequestration and storage in apple tree biomass, it would be interesting to further investigate the total carbon storage capacity considering e.g. the number of fine roots to increase SOM (Dresner et al. 2007), root exudates to local microbial communities, litter to the ground and the C stored in roots and into the soil. Also, other types of beneficial effects from trees when integrated in agricultural systems e.g., N retention, fodder value, animal welfare, climate adaption. According to the market analysis of ROBUST, there is a great potential from first movers, and for the present and coming years it will be a task for producers of agroforestry products to inform and disseminate through marketing and knowledge sharing to include the consumers.

Literature

Agforward (2020) Home - Agforward - Dansk. https://www.agforward.eu/index.php/dk/forside.html. Accessed 17 Mar 2020

Alam A (2014) Editorial Publication Soil Degradation : A Challenge to Sustainable Agriculture. Int J Sci Res Agric Sci 1:50–55

Antolín-Rodríguez JM, Sánchez-Báscones M, Martín-Ramos P, et al (2016) Estimation of PCB content in agricultural soils associated with long-term fertilization with organic waste. Environ Sci Pollut Res 23:12372–12383. https://doi.org/10.1007/s11356-016-6439-1

Barrow CJ (1991) Land degradation: development and breakdown of terrestrial environments. Cambridge University Press

Bennett EM, Carpenter SR, Caraco NF (2001) Human impact on erodable phosphorus and eutrophication: a global perspective: increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. Bioscience 51:227–234

Bini C (2009) Soil: A precious natural resource. Conserv. Nat. Resour. 1–48

Birk JR, Ladegaard MK, Nielsen KM, et al (2021) Skovlandbrug i praksis. 40

Brady NC, Weil RR, Weil RR (2008) The nature and properties of soils. Prentice Hall Upper Saddle River, NJ

Brunori A, Dini F, Cantini C, et al (2017) Biomass and volume modeling in Olea europaea L. cv "Leccino". Trees - Struct Funct 31:1859–1874. https://doi.org/10.1007/s00468-017-1592-9

Burgess PJ, Crous-Duran J, Den Herder M, et al (2015) AGFORWARD Project Periodic Report. 18:1–61

Buwalda JG, Lenz F (1992) Effects of cropping, nutrition and water supply on accumulation and distribution of biomass and nutrients for apple trees on'M9'root systems. Physiol Plant 84:21–28. https://doi.org/10.1111/j.1399-3054.1992.tb08759.x

Cardinale BJ, Duffy JE, Gonzalez A, et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67. https://doi.org/10.1038/nature11148.Access

Castro J, Ostoić SK, Cariñanos P, et al (2018) 'Edible' Urban Forests As Part of Inclusive, Sustainable Cities

Chen J, Lin G, Zhou B (2004) Correlation between pesticides exposure and morbidity and mortality of breast cancer. CHINESE J PUBLIC Heal 20:289–290

Christensen JH, Hewitson B, Busuioc A, et al (2007) Regional climate projections. Chapter 11

Correal E, Erena M, Ríos S, et al (2009) Agroforestry systems in southeastern Spain. In: Agroforestry in Europe. Springer, pp 183–210

Cowie RH, Bouchet P, Fontaine B (2022) The Sixth Mass Extinction: fact, fiction or speculation? Biol Rev. https://doi.org/10.1111/brv.12816

Cui Q, Feng Z, Pfiz M, et al (2012) Trade-off between shrub plantation and wind-breaking in the arid sandy lands of Ningxia, China. Pakistan J Bot 44:1639–1649

Dalgaard T, Jensen M, Kongsted AG, et al (2019) Scenarier for skovlandbrug i Danmark - effekter på miljø, klima og biodiversitet - del 1 og 2

den Herder M, Moreno G, Mosquera-Losada RM, et al (2017) Current extent and stratification of agroforestry in the European Union. Agric Ecosyst Environ 241:121–132. https://doi.org/10.1016/j.agee.2017.03.005

Devine WD, Footen PW, Harrison RB, et al (2013) Estimating tree biomass, carbon, and nitrogen in two vegetation control treatments in an 11-year-old douglas-fir plantation on a highly productive site. USDA For Serv - Res Pap PNW-RP 1–24. https://doi.org/10.2737/PNW-RP-591

Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. Science (80-) 321:926–929

Dirzo R, Young HS, Galetti M, et al (2014) Defaunation in the Anthropocene. Science (80-) 345:401–406

DMI (2022) DMI

Dold C, Thomas AL, Ashworth AJ, et al (2019) Carbon sequestration and nitrogen uptake in a temperate silvopasture system. Nutr

Cycl Agroecosystems 114:85–98. https://doi.org/10.1007/s10705-019-09987-y
Dresner S, Ekins P, McGeevor K, Tomei J (2007) Forest and climate change global understandings and possible responses. For Clim Chang CAB Int Wallingford, UK 38–48
E. S. Brondizio, J. Settele, S. Díaz and HTN (editors) (2019) Global Assessment Report on Biodiversity and Ecosystem Services | IPBES
EEA EEA (2008) Impacts of Europe's Changing Climate – 2008. 1–6
Effektivt Landbrug (2021) Cider for fremtiden. https://effektivtlandbrug.landbrugnet.dk/artikler/afgroeder/70449/cider-for-fremtiden.aspx
EIP-AGRI (2017) Introducing woody vegetation into specialised crop and livestock systems. 32
Elevitch CR, Mazaroli ND, Ragone D (2018) Agroforestry standards for regenerative agriculture. Sustain 10:1–21. https://doi.org/10.3390/su10093337
European Commission (2022) Farm to Fork strategy. https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en
European Environment Agency (2009) Progress towards the European 2010 biodiversity target
Facebook (2022) Skovlandbrugsnetværk. https://www.facebook.com/groups/skovlandbrug/members
Fanwoua J, Bairam E, Delaire M, Buck-Sorlin G (2014) The role of branch architecture in assimilate production and partitioning: The example of apple (Malus domestica). Front Plant Sci 5:1–6. https://doi.org/10.3389/fpls.2014.00338
FAO (2021) FAOSTAT. https://www.fao.org/faostat/en/#data/QCL
FAO (2017) Fao soils portal, Management, Soil Carbon sequestration. http://www.fao.org/soils-portal/soil-management/soil-carbon-sequestration/en/. Accessed 21 Apr 2020
Faqi W, Haibin L, Baosheng S, et al (2008) Net primary production and nutrient cycling in an apple orchard-annual crop system in the Loess Plateau, China: A comparison of Qinguan apple, Fuji apple, corn and millet production subsystems. Nutr Cycl Agroecosystems 81:95–105. https://doi.org/10.1007/s10705-007-9155-x
Fassnacht FE, Hartig F, Latifi H, et al (2014) Importance of sample size, data type and prediction method for remote sensing-based estimations of aboveground forest biomass. Remote Sens Environ 154:102–114
Fernández-Puratich H, Oliver-Villanueva J V., Alfonso-Solar D, Peñalvo-López E (2013) Quantification of potential lignocellulosic biomass in fruit trees grown in mediterranean regions. BioResources 8:88–103. https://doi.org/10.15376/biores.8.1.88-103
Finlayson M, Cruz RD, Davidson N, et al (2005) Millennium Ecosystem Assessment: Ecosystems and human well-being: wetlands and water synthesis. Island Press
Foley JA, DeFries R, Asner GP, et al (2005) Global consequences of land use. Science (80-) 309:570–574
Foley JA, Ramankutty N, Brauman KA, et al (2011) Solutions for a cultivated planet. Nature 478:337–342. https://doi.org/10.1038/nature10452
Fritzbøger B (1990) Ældre Danske Skovtaksationers Tolkning Og Anvendelse Til Belysning Af Skoves Størrelse. Fortid og Nutid 37:126
Fritzbøger B (2002) Bag hegnet: historien om levende hegn i det danske landskab
Gabriel S, Baschwitz A, Mathonnière G, et al (2013) A critical assessment of global uranium resources, including uranium in phosphate rocks, and the possible impact of uranium shortages on nuclear power fleets. Ann Nucl Energy 58:213–220. https://doi.org/https://doi.org/10.1016/j.anucene.2013.03.010
Gao L, Xu H, Bi H, et al (2013) Intercropping Competition between Apple Trees and Crops in Agroforestry Systems on the Loess Plateau of China. PLoS One 8:1–8. https://doi.org/10.1371/journal.pone.0070739
Génard M, Dauzat J, Franck N, et al (2008) Carbon allocation in fruit trees: From theory to modelling. Trees - Struct Funct 22:269–282. https://doi.org/10.1007/s00468-007-0176-5
GEUS (2022) Topografi. https://www.geus.dk/produkter-jenester-og-facikter/data-og-kort/danske-kort
Gibbs S, Koblents H, Coleman B, et al (2016) Avian diversity in a temperate tree-based intercropping system from inception to now.

Agrofor Syst 90:905–916. https://doi.org/10.1007/s10457-016-9901-7
Gilbert N (2009) Environment: The disappearing nutrient. Nature 461:716–718. https://doi.org/10.1038/461716a
Gleick PH (2003) Global freshwater resources: soft-path solutions for the 21st century. Science (80-) 302:1524–1528
Gleick PH, Cooley H, Morikawa M, et al (2009) The world's water 2008-2009: The biennial report on freshwater resources. Island Press
Global Forest Observations Initiative (2013) Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests
Goldewijk KK, Beusen A, Doelman J, Stehfest E (2017) Anthropogenic land use estimates for the Holocene - HYDE 3.2. Earth Syst Sci Data 9:927–953. https://doi.org/10.5194/essd-9-927-2017
Gomiero T, Pimentel D, Paoletti MG (2011) Is there a need for a more sustainable agriculture? CRC Crit Rev Plant Sci 30:6–23
Goswami S, Verma KS, Kaushal R (2014) Biomass and carbon sequestration in different agroforestry systems of a Western Himalayan watershed. Biol. Agric. Hortic. 30:88–96
GRAIN (2011) Food and climate change: The forgotten link [Online]. In: Against the grain
GUDP (2022) Skovlandbrug gør køer og planter mere klimavenlige
Hansen J, Sato M, Kharecha P, et al (2008) Target Atmospheric CO 2 : Where Should Humanity Aim?
Hathaway MD (2016) Agroecology and permaculture: addressing key ecological problems by rethinking and redesigning agricultural systems. J Environ Stud Sci 6:239–250. https://doi.org/10.1007/s13412-015-0254-8
ICROF (2017) Vil forbrugerne betale mere for lokale økologiske varer? https://icrofs.dk/aktuelt/nyheder/nyhed/artikel/vil-forbrugerne-betale-mere-for-lokale-oekologiske-varer/
IPCC (2021) Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
IPCC (2019) Climate Change and Land: an IPCC special report. Clim Chang L an IPCC Spec Rep Clim Chang Desertif L Degrad Sustain L Manag food Secur Greenh gas fluxes Terr Ecosyst 1–864
Jenkins JC, Chojnacky DC, Heath LS, Birdsey RA (2003) National-scale biomass estimators for United States tree species. For Sci 49:12–35. https://doi.org/10.1093/forestscience/49.1.12
Jose S, Holzmueller EJ, Gillespie AR (2015) Tree-Crop Interactions in Temperate Agroforestry. North Am Agrofor An Integr Sci Pract 57–74. https://doi.org/10.2134/2009.northamericanagroforestry.2ed.c4
Komiyama A, Ong JE, Poungparn S (2008) Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot 89:128–137. https://doi.org/10.1016/j.aquabot.2007.12.006
Kowaluk G, Szymanowski K, Kozlowski P, et al (2020) Functional Assessment of Particleboards Made of Apple and Plum Orchard Pruning. Waste and Biomass Valorization 11:2877–2886. https://doi.org/10.1007/s12649-018-00568-8
Kumar JIN, Bora A, Kumar RN, et al (2013) Toxicity analysis of pesticides on cyanobacterial species by 16S rDNA molecular characterization. Proc Int Acad Ecol Environ Sci 3:101
Kumar P, Singh RP, Kumar A, Kumar V (2014) Quantification and distribution of agroforestry systems and practices at global level. HortFlora Res Spectr 3:1–6
Lal R (2009) Soil degradation as a reason for inadequate human nutrition. Food Secur 1:45–57. https://doi.org/10.1007/s12571-009-0009-z
Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustain 7:5875–5895. https://doi.org/10.3390/su7055875
Lal R (2020) The technical potential for soil carbon sequestration
Landbrug & Fødevarer (2021) Markedsrapport. 1–7
Larsen JB, Præstholm S, Lassen JN, Simonsen TR (2013) Danmarks nye skove : håndbog i skovrejsning og skovudvikling, 1. udgave. Landskabsværkstedet, Frederiksberg
Lauri P, Dufour L (2016) Fruit-Trees in Agroforestry Systems - Review and Prospects for the. 23–25

Leakey RRB (2017) Definition of Agroforestry Revisited. In: Multifunctional Agriculture. Academic Press, pp 5–6

Lodberg A, Rehman MU, Fayyaz U, Thomsen K (2016) Bæredygtig brug af fosfor. Dansk Kemi 97:18–19

Lundgren BO, Raintree JB (1982) Sustained agroforestry. In: Agrucultural research for development: Potentials and challenges in Asia. The Hague, Netherlands. : ISNAR, International Service for National Agricultural Research, pp 37–49

Marcelis LFM, Heuvelink E, Goudriaan J (1998) Modelling biomass production and yield of horticultural crops: A review. Sci Hortic (Amsterdam) 74:83–111. https://doi.org/10.1016/S0304-4238(98)00083-1

Matłok N, Gorzelany J (2020) Assessment of cost and energy effectiveness of modified technologies for production of young fruit trees, taking into account the use of waste biomass for energy and soil amendment related purposes. Energy 190:. https://doi.org/10.1016/j.energy.2019.116428

Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. Science (80-) 277:504–509

McMichael AJ, Powles JW, Butler CD, Uauy R (2007) Food, livestock production, energy, climate change, and health. Lancet 370:1253–1263. https://doi.org/https://doi.org/10.1016/S0140-6736(07)61256-2

Milosevic T, Milosevic N (2009) The effect of zeolite, organic and inorganic fertilizers on soil chemical properties, growth and biomass yield of apple trees. Plant, Soil Environ 55:528–535. https://doi.org/10.17221/107/2009-pse

Montanaro G, Dichio B, Briccoli Bati C, Xiloyannis C (2012) Soil management affects carbon dynamics and yield in a Mediterranean peach orchard. Agric Ecosyst Environ 161:46–54. https://doi.org/10.1016/j.agee.2012.07.020

Moran D, Wall E (2011) Livestock production and greenhouse gas emissions: Defining the problem and specifying solutions. Anim Front 1:19–25. https://doi.org/10.2527/af.2011-0012

Mosquera-Losada MR, McAdam JH, Romero-Franco R, et al (2008) Definitions and Components of Agroforestry Practices in Europe. In: Agroforestry in Europe. Springer Netherlands, pp 3–19

Mosquera-Losada MR, Santiago-Freijanes JJ, Pisanelli A, et al (2018) Agroforestry in the European common agricultural policy. Agrofor Syst 92:1117–1127. https://doi.org/10.1007/s10457-018-0251-5

Mosquera-Losada MR, Santiago-Freijanes JJ, Pisanelli A, et al (2016) Extent and Success of Current Policy Measures to Promote Agroforestry across Europe. EU FP7 Res Proj AGFORWARD 613520 Deliverabl:95

Nord-Larsen T, Meilby H, Skovsgaard JP (2017) Simultaneous estimation of biomass models for 13 tree species: Effects of compatible additivity requirements. Can J For Res 47:765–776. https://doi.org/10.1139/cjfr-2016-0430

Økologisk Landsforening Netværk for skovlandbrug. https://okologi.dk/landbrug/skovlandbrug/netvaerk-for-skovlandbrug. Accessed 11 May 2020

Økologisk Landsforening (2020) Fra Jord til Bord. 117

Økologisk Landsforening (2021a) FOODSERVICE - Markedsrapport

Økologisk Landsforening (2021b) ØKOLOGISK MARKEDSRAPPORT 2021

Oldeman LR (1992) Global extent of soil degradation. In: Bi-Annual Report 1991-1992/ISRIC. ISRIC, pp 19–36

Panzacchi P, Tonon G, Ceccon C, et al (2012) Belowground carbon allocation and net primary and ecosystem productivities in apple trees (Malus domestica) as affected by soil water availability. Plant Soil 360:229–241

Petersen KS, Ares A, Terry TA, Harrison RB (2007) Vegetation competition effects on aboveground biomass and macronutrients, leaf area, and crown structure in 5-year old Douglas-fir. New For 35:299–311

Ponchia G, Fila G, Gardiman M (1997) EFFECTS OF ROOTSTOCK AND INTERSTEM ON GROWTH, PRODUCTIVITY AND MINERAL NUTRITION OF a GOLDEN DELICIOUS APPLE TREES. Acta Hortic 107–112

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science (80-) 360:987–992. https://doi.org/10.1126/science.aaq0216

Raskin B, Osborn S (2019) The Agroforestry Handbook - Agroforestry for the UK, 1st edn. Soil association

Ravindranath NH, Ostwald M (2007) Carbon Inventory Methods Handbook for Greenhouse Gas Inventory, Carbon Mitigation and

Roundwood Production Projects: Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects, 1. Aufl. Springer Netherlands, Dordrecht
Rawat YS, Vishvakarma SCR (2011) Pattern of Fodder Utilization in Relation to Sustainability under Indigenous Agroforestry. Environ We An Int J Sci Technol 6:1–13
Ritchie H, Roser M (2020) Environmental impacts of food production Environmental impacts of food and agriculture. Our world Data 1–40
Rivest D, Lorente M, Olivier A, Messier C (2013) Soil biochemical properties and microbial resilience in agroforestry systems: Effects on wheat growth under controlled drought and flooding conditions. Sci Total Environ 463–464:51–60. https://doi.org/10.1016/j.scitotenv.2013.05.071
ROBUST (2021) Markedsanalyse 2021
Rodrigues ASL, Pilgrim JD, Lamoreux JF, et al (2006) The value of the IUCN Red List for conservation. Trends Ecol Evol 21:71–76. https://doi.org/https://doi.org/10.1016/j.tree.2005.10.010
Rosegrant MW, Cai X, Cline SA (2002) World water and food to 2025: dealing with scarcity. Intl Food Policy Res Inst
Ruddiman WF (2013) The anthropocene. Annu Rev Earth Planet Sci 41:45–68. https://doi.org/10.1146/annurev-earth-050212-123944
Schreuder HT, Gregoire TG, Wood GB (1993) Sampling methods for multiresource forest inventory. Wiley, New York, N.Y
SCHRØDER M (2017) Økologiske forbrugere mener det alvorligt. In: Aarhus BSS. https://bss.au.dk/aarhus-bss-nyheder/samfund-2/2018/oekologiske-forbrugere-mener-det-alvorligt
SDFE (2022) Geodata
Sharma A, Kumar V, Shahzad B, et al (2019) Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci 1:1–16. https://doi.org/10.1007/s42452-019-1485-1
Shinde SM, Turkhade PD, Deshmukh SB, et al (2015) Carbon sequestration potential of some fruit trees in Satara District of Maharashtra, India. Ecol Environ Conserv 21:337–340
Shukla PR, Skea J, Slade R, et al (2019) IPCC Special Report on Climate Change and Land - Technical Summary. Clim Chang L an IPCC Spec Rep Clim Chang Desertif L Degrad Sustain L Manag food Secur Greenh gas fluxes Terr Ecosyst 35–74
Smil V (2000) Phosphorus in the environment: natural flows and human interferences. Annu Rev energy Environ 25:53–88
Steinfeld H, Gerber P, Wassenaar TD, et al (2006) Livestock's long shadow: environmental issues and options. Food & Agriculture Org.
Taeroe A, Nord-Larsen T, Stupak I, Raulund-Rasmussen K (2015) Allometric Biomass, Biomass Expansion Factor and Wood Density Models for the OP42 Hybrid Poplar in Southern Scandinavia. Bioenergy Res 8:1332–1343. https://doi.org/10.1007/s12155-015-9592-3
Takaki K, Wade AJ, Collins CD (2017) Modelling the bioaccumulation of persistent organic pollutants in agricultural food chains for regulatory exposure assessment. Environ Sci Pollut Res 24:4252–4260. https://doi.org/10.1007/s11356-015-5176-1
Thomas SC, Martin AR (2012) Carbon content of tree tissues: A synthesis. Forests 3:332–352. https://doi.org/10.3390/f3020332
Tilman D, Cassman KG, Matson PA, et al (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677. https://doi.org/10.1038/nature01014
Tilman D, Fargione J, Wolff B, et al (2001) Forecasting agriculturally driven global environmental change. Science (80-) 292:281–284
Tombesi N, Pozo K, Harner T (2014) Persistent Organic Pollutants (POPs) in the atmosphere of agricultural and urban areas in the Province of Buenos Aires in Argentina using PUF disk passive air samplers. Atmos Pollut Res 5:170–178. https://doi.org/https://doi.org/10.5094/APR.2014.021
Tubiello FN, Karl K, Flammini A, et al (2021) Pre- and post-production processes along supply chains increasingly dominate GHG emissions from agri-food systems globally and in most countries. Earth Syst Sci Data Discuss 2021:1–24.

https://doi.org/10.5194/essd-2021-389
Udawatta RP, Kremer RJ, Adamson BW, Anderson SH (2008) Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. Appl Soil Ecol 39:153–160. https://doi.org/10.1016/j.apsoil.2007.12.002
Udawatta RP, Kremer RJ, Nelson KA, et al (2014) Soil Quality of a Mature Alley Cropping Agroforestry System in Temperate North America. Commun Soil Sci Plant Anal 45:2539–2551. https://doi.org/10.1080/00103624.2014.932376
UN (2017) World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. In: Dep. Econ. Soc. Aff. - News. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html
Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science (80-) 277:494–499
Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science (80-) 289:284–288
WAPA (2021) Prognosfruit2021. Apple Crop Forecast 10
Winzer F, Kraska T, Elsenberger C, et al (2017) Biomass from fruit trees for combined energy and food production. Biomass and Bioenergy 107:279–286. https://doi.org/10.1016/j.biombioe.2017.10.027
Withgott JH, Laposata M (2015) Environment: The Science behind the Stories, PDF ebook. Pearson Higher Ed
WMO (2020) WMO Greenhouse Gas Bulletin. Sulphur 5–8
World Bank (2004) World Bank. Sustaining forests : a development strategy (English). Agriculture and rural development. Washington, DC: World Bank.
Wu T, Wang Y, Yu C, et al (2012) Carbon sequestration by fruit trees - Chinese apple orchards as an example. PLoS One 7:1–13. https://doi.org/10.1371/journal.pone.0038883
Yang X, Kang K, Qiu L, et al (2020) Effects of carbonization conditions on the yield and fixed carbon content of biochar from pruned apple tree branches. Renew Energy 146:1691–1699. https://doi.org/10.1016/j.renene.2019.07.148
Zahoor S, Dutt V, Mughal AH, et al (2021) Apple-based agroforestry systems for biomass production and carbon sequestration: implication for food security and climate change contemplates in temperate region of Northern Himalaya, India. Agrofor Syst 95:367–382. https://doi.org/10.1007/s10457-021-00593-y
Zanotelli D, Montagnani L, Manca G, et al (2015) Net ecosystem carbon balance of an apple orchard. Eur J Agron 63:97–104
Zanotelli D, Montagnani L, Manca G, Tagliavini M (2013) Net primary productivity, allocation pattern and carbon use efficiency in an apple orchard assessed by integrating eddy covariance, biometric and continuous soil chamber measurements. Biogeosciences 10:3089–3108. https://doi.org/10.5194/bg-10-3089-2013
Zhang W (2018) A long-term trend of cancer-induced deaths in European countries. Network 3:1–9
Zhang W (2011) Constructing ecological interaction networks by correlation analysis: hints from community sampling. Netw Biol 1:81