Juvenile birch in Sweden

Selected stem characteristics for interior and furniture applications

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Abstract

In response to the furniture industry's growing demand for raw material, large volumes of juvenile silver birch and downy birch stems available from pre-commercial thinning operations in Sweden's forests could offer solutions. However, such stems are not currently used on an industrial scale, and most research conducted on birch stems in general has neither focussed on young trees nor the potential use of the central stem part around the tree pith. The resulting lack of knowledge about the juvenile part of birch wood thus requires additional information about the material properties of birch, which could encourage its use for various purposes in the furniture and other industries.

The initial literature review performed for this thesis has highlighted some properties of juvenile birch required for its use as a furniture material, as well as identified topics concerning the physical characteristics of juvenile birch about which knowledge is currently limited. Consequently, the objectives of this thesis were to explore some characteristics of juvenile birch—bark thickness, wood-to-bark bonding ratio after drying, variations in the density and width of growth rings, and anatomical growth response to fertilisation—in order to increase the knowledge.

The material studied came from mixed birch and Norway spruce stands at two sites in southern Sweden, namely Asa and Toftaholm. The birch stems were naturally regenerated silver birch and downy birch, with breast height diameters between 30 and 83 mm. Fertilised and unfertilised silver birch trees were sampled at Toftaholm, whereas unfertilised stems of silver birch and downy birch were sampled at Asa. The characteristics of stems from the pith to bark (radial direction) and along the stem (longitudinal direction) were measured. The wood-to-bark bonding ratio on downy birch after drying was calculated as the percentage of the stem circumference with full contact between the wood and bark, while oven-dry density and basic wood density for silver birch were determined by using the water displacement method. The impact of ring width on wood density was statistically analysed, and an image analysis of the wood anatomy was conducted to elucidate their relationship.

Amongst the results, bark thickness along the stem had the highest deviation in the section closest to the stump. Moreover, the wood-to-bark bonding ratio after drying measured for juvenile downy birch seemed to depend more on the stem's diameter than the sampling height along the stem. Such results are relevant for processors seeking to estimate the volume of wood under the bark. The wood-to-bark bonding ratio was highest for diameters between 30 and 39 mm, and neither did that relationship correlate with the sampling height along the stem.

Variation in wood density in the radial and longitudinal directions in juvenile silver birch suggested that such density negatively correlated with growth rate (ring width). That relationship held true for stems at each site and between the sites, irrespective of management or growing conditions. As expected, mean wood density was lower in fertilised trees than in unfertilised ones, and towards the bark, radial density increased more in trees that grew more slowly. At the same time, variation in longitudinal density in young silver birch trees was low. Quantitative wood anatomy studies confirmed that the fertilised juvenile birch had younger cambia, thinner cell walls, and fewer vessels per mm^2 than unfertilised trees in the same diameter class.

Overall, the knowledge generated in the study may facilitate the industrial use of juvenile birch stems and wood in interior and furniture applications. The role of wood anatomy in determining the mechanical performance of juvenile birch stems should be further examined, however, to possibly reveal new opportunities for the use of juvenile birch.

Keywords: Betula pendula, Betula pubescens, wood density, birch bark

Sammanfattning (in Swedish)

Det finns ett växande behov av råvaror till möbelindustrin. Stammar av juvenil vårtbjörk och glasbjörk finns tillgängliga i stora volymer från röjning i svenska skogar. För närvarande finns det inget storskaligt industriellt nyttjande av det virket. Bättre kunskap om dess virkesegenskaper kan öppna upp möjligheterna till olika användningsområden. Dock har en majoritet av den befintliga björkforskningen ofta exkluderat studier av innersta veden närmast kärnan, vilket resulterat i en låg kunskapsnivå om det juvenila virket.

I den inledande litteraturstudien i denna uppsats belyses vilka krav som ställs på materialegenskaperna i möbelvirke. Vidare identifieras befintliga kunskapsluckor i fysiska och mekaniska egenskaper för juvenil björk. Målet med denna uppsats är därför att utforska några egenskaper, såsom barktjocklek, barkvidhäftning efter torkning, densitet och årsringsbreddsvariation samt hur gödsling kan påverka vedanatomin.

Materialet kom från blandskogsbestånd med gran och björk i Asa och Toftaholm i Götaland. Björkarna var självföryngrad vårtbjörk och glasbjörk och stammarna hade en brösthöjdsdiameter mellan 30 och 83 mm. I Toftaholm var en del av beståndet gödslad respektive ogödslad vårtbjörk. Från Asa togs stammar av både vårtbjörk och glasbjörk. Virkesegenskaper och dess variationer i stammens radiella och longitudinella riktning studerades. Vidhäftningen av barken till veden efter torkning bedömdes procentuellt på omkretsen av ändträet. Relativ torrdensitet och rådensitet mättes. Påverkan av årsringsbredd på veddensitet analyserades statistiskt och vedanatomin studerades med mikroskop och bildanalys för en vidare förståelse av dess samband med gödsling.

Resultaten gällande barktjocklekens variation visade att den nedre delen av stammen hade störst medelavvikelse. Dessa resultat kan vara relevant information för vidareförädling efter avbarkning. Barkens vidhäftning till veden efter torkning mättes på juvenil glasbjörk. Det visade ett visst samband med stamdiameter där den högsta vidhäftningen fanns på stammarna med en diameter mellan 30 och 39 mm. Sambandet var däremot inte korrelerat till stamhöjden där provet togs.

Densitetsvariation i radiell och longitudinell riktning studerades för juvenil vårtbjörk. Densiteten hade en svag negativt korrelation till årsringsbredd. Detta samband sågs både inom bestånd och mellan bestånd med olika tillväxtförhållande samt skötsel. Medeldensiteten för virket var, som förväntat, lägre i de gödslade träden jämfört med de ogödslade.

I den radiella riktningen hade det senvuxna virket en högre faktor på densitetsökningen. Den longitudinella densitetsvariationen i unga vårtbjörkar var låg.

Kvantitativa vedanatomistudier bekräftade att ungdomsveden i gödslad vårtbjörk hade en lägre kambiumålder, tunnare cellväggstjocklek och färre kärl jämfört med ogödslade träd med samma diameter, resultat som tidigare påvisats för mogen björk.

Sammanfattningsvis kan resultaten från den här uppsatsen förbättra kunskapen och därmed underlätta för en industriell användning av juvenila björkstammar inom inredning och möbler. Dock bör vedanatomins påverkan på de mekaniska egenskaperna för juvenila björkstammar studeras vidare. Det kan möjliggöra nya användningsområden för juvenil björk.

Nyckelord: juvenila vedegenskaper, glasbjörk, vårtbjörk, möbelvirke

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Appended papers

This licentiate thesis is based on the following appended papers, which in the text are referred to by their Roman numbers

I. NILSSON, J.A.; JOHANSSON, J; ADAMOPOULOS, S. (2016). Potential of utilizing small-dimensioned roundwood birch. *The 70th Forest Products Society annual convention - new horizons for the forest products industry, June 27-29, 2016, Portland.* (Peer-reviewed paper and presented in conference)

II. NILSSON, J.A., JOHANSSON, J. (2015). Characteristics of un-barked small-dimensioned birch for furniture and interior applications. *Proceedings of the XXVIIth International Conference Research for Furniture Industry, September 2015, Turkey. 175-181*. (Peer-reviewed paper and presented in conference)

III. NILSSON, J.A, RYDELL BLOM, Å.; JOHANSSON, J.; SJÖKVIST (20XX). Variation of stemwood density and bark ratio within juvenile Betula pendula trees. *Submitted*

IV. NILSSON, J.A.; HÅKANSSON, C.; RYDELL BLOM, Å.; JONES, G. (20XX). Effects of fertilisation on wood formation in naturally regenerated juvenile silver birch. *Submitted*

Contributions to the appended papers

Paper I: Nilsson carried out the literature study and wrote the manuscript. The co-authors provided comments and checked the quality of the paper. First author was the corresponding author and presented the paper at the conference.

Paper II: Nilsson and Johansson planned and initiated the experiments while Nilsson carried out the experimental work. Johansson performed the statistical analysis. Nilsson analysed the results and wrote the manuscript under the supervision of Johansson. Nilsson presented the paper at the conference.

Paper III: Nilsson planned and carried out the experiments, interpreted the results and wrote the manuscript. Blom and Sjökvist contributed in writing the manuscript and revising it critically for important intellectual content. Johansson planned the experiment together with Nilsson and contributed in writing the manuscript. All authors read and approved the final manuscript. Nilsson is the corresponding author.

Paper IV: Conceptualization, Nilsson and Blom; methodology, Nilsson and Håkansson; validation, Nilsson and Jones; formal analysis, Nilsson; investigation, Håkansson and Nilsson; resources, Håkansson and Blom; writing—original draft preparation, Nilsson; visualization, Nilsson and Jones. All authors have read and approved the final version submitted for publication. Nilsson is the corresponding author.

Other publications related to the topic of this thesis

NILSSON, J.A., JOHANSSON, J. (2016). Customer requirements on solid wood material : A birch roundwood case-study. *Proceedings of the 12th meeting of the Northern European Network for Wood Science and Engineering (WSE): Wood Science and engineering* - *a key factor on the transition to Bioeconomy. 22-28.*

NILSSON, J.A, 2019, ”Växande möjligheter efter stormarna”, i Thomas Thörnqvist (red.) Eken och andra lövträd – Ekfrämjandet 75 år (1944 – 2019), Ekfrämjandet, s. 99 – 109. (Swedish), chapter in book. *In print*

Content

1. Introduction

1.1 Context

Growing interest and demand for wood and other bio-based materials in the sector for interior decoration leads to increased competition for raw material. New sources are being explored to meet the demand of the interior decoration industry for a more sustainable indoor environment (Trischler et al., 2014). At the same time, most of the by-products from the forest industry are currently not fully exploited, and there are few examples of their commercial added-value for furniture material applications in Sweden.

The main assortment of birch (*Betula* spp) wood, not meeting the present dimensional requirements of industrial wood, come from pre-commercial thinning (PCT). These are the removal of small-sized trees in mainly conifer plantations (Holmström et al., 2015). Consequently, naturally regenerated birches represent a significant biomass resource since birches are the most common deciduous tree species in Sweden.

Birch is an industrial species widely used in northern Europe for its mechanical properties (Hynynen et al., 2010). The demand for birch wood is increasing and the prices for birch wood from large sized trees has risen in the last decade (Christiansen, 2013). Although the growing stock of birches in Sweden is increasing, there are challenges with industrial utilisation of the Swedish birch, as the main volume is harvested mainly in connection with silvicultural measures where no or little interest in the quality is shown. While there is a great abundance of small trees, they are presently of no great importance as little is known of their properties. Research related to small dimensions of round-wood timber has focused on its heating and fibre properties, since it is mostly driven by the industry for making pulp- and paper, or for thermal energy recovery. Consequently, to meet the demand from the furniture industry, a series of studies to increase the utilisation of these trees is needed.

1.2 Background

New sources of raw material to feed the bio-economy

With the world population projected to reach 9.6 billion by 2050 of which 70% is expected to live in urban areas, one of the global megatrends that is expected to drive the need for new sources of raw material is urbanisation (DESA, 2019). Many will escape from poverty into the middle classes. The new middle class will demand new products and services. A growing prosperous middle class will increase their consumption of goods and packaging. (Olsmats and Kaivo-oja, 2014). Consequently accelerating the global demand for and consumption of forest products and services and putting pressure on forests. The United Nations vision is of a world in which all types of forests and trees outside forests are sustainably managed, contribute to sustainable development and provide economic, social, environmental and cultural benefits for present and future generations (MacDicken et al., 2016). Although there is a need for new ways to extract more value from fewer and less resources, the proportion of forest products which comes from sustainably managed forests must be significantly increased. Forest certifications schemes like Forest Stewardship Council (FSC) has become one way for companies to warrant responsible wood sourcing. In Swedish forests, the compliance of the FSC standard requires a minimum of 10% of deciduous trees within the conifer monoculture stands. The extensive certification of forests has been one driver behind the increased volume of deciduous trees in Sweden (Lefhaili, 2014).

An increase in demand for wooden material might impact the view of self-regenerated birches, from being seen as a burden to a resource. Apart from the positive effects off birches on the biodiversity (Felton et al., 2016), increased production of sustainable wood based products could be the most efficient way to use the forest ecosystem to sequester atmospheric carbon (Kyrklund, 1990), as the main carbon sink in fertile stand is located in the wooden part of the stem (Uri et al., 2012). Forestry's contribution to climate change mitigation could be significantly increased if more wood were used to substitute fossil fuels and energy-intensive materials (Lundmark et al., 2014; Poudel et al., 2012). Pompa-García and Venegas-González (2016) argued that greater knowledge about growth rate effect on wood properties will facilitate the possibility to accurately estimate carbon sequestration, which could be useful for environmental mitigation strategies. Learning more about the variation in wood of birch could furthermore facilitate its increased use in durable products such as furniture, flooring and interior decorations. For an increased knowledge about how growth rate is related to the carbon sequestration in birch, and which wood properties that are relevant to study from perspective of the furniture and interior decoration industry, more research is needed.

Silver birch and downy birch

Sweden is home to 23.2 million hectares of productive forest land, 13% of the standing volume of which is covered by birch, a deciduous tree that grows naturally in the Northern Hemisphere (Christiansen, 2013). As a result, birch is currently the third most common tree species in Sweden (Strömberg and Svärd, 2012). There, as well as in Finland and Russia, silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubesens* Erhr.) are the most common species of birch, both of which grow all over those countries. Silver birch grows vigorously in light, acidic, well-drained soils, whereas downy birch can tolerate moister soil conditions. Silver birch has shown greater growth capacity than downy birch (Ferm, 1993) and is the species that accounts for the majority of saw timber in Finland, though downy birch has a higher areal proportion in the country (Loustarinen and Verkasalo, 2000). In Sweden, although the two species are not distinguished in the national inventory, the inventory nevertheless shows that the total volume of birch trees has increased in Sweden during the last decade (Christiansen, 2013). A major factor of that trend has been the large-scale certification of forests according to the FSC (MacDicken et al., 2016), which in Sweden requires a minimum of 10% deciduous trees for certification. Furthermore, as statistics from the Swedish Forest Agency's annual questionnaire survey of forest owners have revealed, in 2013 the pre-commercial thinning of young forest increased to 282,000 hectares (Christiansen, 2013), which suggests that available volumes of birch from such management operations are expected to rise.

Birch has traditionally been used for its wood as well as for its bark, the latter of which accounts for 10.5% of the weight of birch logs (Jensen, 1948). Durable, water repellent, and flexible, birch bark is a natural membrane that has been used by humans for millennia. Birch bark can be used as paper, in materials for products ranging from food containers to building material for boats, and for protection in exposed locations in structures (e.g. roofs). On living trees, birch bark also has a protective function; secondary organs of softwoods and hardwoods develop a periderm (bark) not only for protection against mechanical and chemical injuries but also to prevent water loss to dry atmospheres (Schönherr and Ziegler, 1980). As a birch tree grows, its bark will stretch and eventually fall from the tree, all while new bark is continuously formed. Ultimately, that process allows for the removal of bark as long as the zone for increment (cork cambium) is not damaged (Pallardy, 2010).

Bark is a complex tissue composed of different types of cells, the principal constituents of which include cellulose, hemicelluloses, pectic (carbohydrate) substances, lignin, and suberin (Srivastava, 1964). When the fibres of the bark are mixed with extractive, the bark possesses a high heating value (2470 kcal/kg) when burned for energy (Jensen, 1948), and the richness in extractives can also make bark suitable for the extraction of bio-chemicals (Nurmi, 1993; Tolstikov et al., 2005). The white colour of birch comes from the extractive betulin, a triterpene found in rich quantities in the outer layer of birch bark (Jensen, 1963). The bark on young birch stems is mostly smooth, and though brown in the first few years, its colour changes to the characteristic white later on. The structure of the bark can also change with time; both silver birch and downy birch can develop rhytidome, a thick-fissured bark that is cracked in the longitudinal direction. Rhytidome is most common on silver birch, whereas the plain white bark is most common on downy birch. Fissured rhytidome formation starts at the base of the trunk and progresses upward (Srivastava, 1964), although the fissured bark of downy birch reaches only approximately 1 m above the ground. Several centimetres thick, fissured rhytidome offers good protection against fire and is mostly found on birches in southern Sweden, where fires have historically been more common than in other parts of the country (Nylinder, 2001). The impact of the latitude of seed origin on bark thickness has been examined in a comparison of the Baltic versus Finnish origins of silver birch, the results of which revealed that bark thickness decreased as the latitude of seed origin increased (Viherä-Aarnio and Velling, 1999). Apart from that study, however, determining birch bark thickness has been a rare undertaking among researchers (Jensen, 1948; Näslund, 1947). Nevertheless, if small stems from pre-commercial thinning are to be used, then the bark ratio might play an important role, given its effects on the volume of yield. Thus, additional studies on longitudinal variation in bark thickness are needed. Although bark is formed by the vascular cambium similar to wood, its growth via the division of cambial cells occurs less frequently than the production of the secondary xylem tissue (Eaton and Hale, 1993).

Production of secondary xylem

Formed by the apical meristem, the vascular cambium develops the xylem tissue (wood) in the direction towards the pith and the secondary phloem (bark) on the outside of the vascular cambium via the production of new cells in the radial direction (Pallardy, 2010). Growth occurs in the apical meristem, which continuously drives the tree’s growth upwards to the light and air in order to facilitate photosynthesis (Iqbal and Ghouse, 1990). Lundqvist et al. (2018) have referred to the age of the apical meristem as the *total physical tree age*. Throughout the growing season, the vascular cambium produces different types of xylem tissue and forms a concentric pattern of growth rings due to the formation of different types of cells. Counted from the pith, the growth ring number is generally understood to mean the cambium’s age. Unlike the total physical tree age, the cambium’s age relates only to the age when the vascular cambium was formed Lundqvist et al. (2018). The xylem in hardwoods produced by the vascular cambium has an advanced structure of fibres that contribute to the mechanical support for the tree and vessels elements (vessels) to conduct water from the roots to the leaves. Additionally, rays extend from the pith with parenchyma cells for food storage and axial parenchyma (Kollmann and Côté, 1968). The structure of birch wood is diffuse-porous, with large vessels scattered between the libriform fibres (fibres) in the growth ring. Fibres developed early in the growth season are referred to as *earlywood*, whereas fibres produced later on are called *latewood*. The proportion of latewood, though small in birch, is rather constant between growth rings and trees (Luostarinen and Möttönen, 2010).The overall mixture and proportion of cells and extractives in wood affect its structure and density.

Wood density depends on the amount of the solid cell wall material, as well as the air space from vessels and cell lumens. The average oven-dry density for cell walls in wood tissue is 1500 kg/m^3, although the combination of the cell walls' three major components (i.e. cellulose, hemicellulose, and lignin) can vary and affect the density (Stamm, 1964). Although it has been suggested that the density of the cell wall is rather constant, the expansion of cells, the thickening of their walls, and the total air space in the wood are influenced by numerous factors related to growth. For one, abiotic and biotic growth conditions affect the synthesis of structural compounds and the anatomy of wood at the same time as they affect growth. Furthermore, plant hormones such as auxin and ethylene stimulate cell division and wall thickening (Hellgren, 2003). As for the impact of genetic makeup, wood density can be greater in naturally regenerated trees than in planted ones (Möttönen and Luostarinen, 2006). In addition to genetic effects, environmental factors such as access to water, length of day (photoperiod), and temperature affect the growth of birches. Similar to genetic ones, environmental factors also strongly influence bud burst and growth termination (Rousi and Pusenius, 2005).

Adding nitrogen and mineral nutrients to enhance growth (fertilisation) has been successful for different kinds of trees and forests (Landsberg and Sands, 2011). Studies on intensive forest management in Sweden have additionally shown that fertilisers can increase production volumes by to 250% (Bergh et al., 1999). However, literature addressing the response of birch to fertilisation has been inconsistent. Whereas Moilanen (1985) and Paavilainen (1990) found that birch usually responds more poorly to fertilisation than softwoods, Hoyle and Bjorkbom (1969) reported an increase in birch growth after fertilisation. Kaunisto (1987) also found that, on mined peatlands, fertilisation with nitrogen, phosphorus, and potassium slightly increased the growth of birch seedlings. Additionally, many studies exists on how fertilisation affects herbivore resistance in birches (Keinänen et al., 1999; Laitinen et al., 2000; Mutikainen et al., 2000), but they do not consider the wood characteristics. Fertilisation has occasionally been found to have no impact on ring width or to affect anatomical characteristics (Luostarinen et al., 2017). Growth rate has a major effect on wood quality in terms of the closeness of the growth rings, whose width in turn influences the wood's attractiveness for use in solid wood products such as veneer, plywood, and timber. Apart from the aesthetic appearance of birch wood, other properties that make it popular as furniture material include its high wood density and, in turn, its exceptional stiffness (Heräjärvi, 2002). Wood density is often used as an indicator of quality, for it suggests the mechanical performance of the wood. Tensile, bending, and shearing strength, as well as hardness, have especially strong correlations with density (Kollmann and Côté, 1968; Rowell, 2012). Although it is generally accepted that no definite relationship between growth rate and wood density exists in diffuse-porous hardwoods (Zobel and Buijtenen, 1989), that relationship has been the focus of many studies on birch.

Growth and wood density in birch

Hakkila (1966) found that aside from cambium age, another cause of in-stem density variation in mature silver birch is the changing width of growth rings. However, it remains unclear whether that dynamic also applies to naturally regenerated juvenile silver birch grown in mixed-species forests.

Wood density in birch trees grown on different soil conditions (i.e. poor versus fertile soils) has previously been studied (Liepiòð and Rieksts-Riekstiòð, 2013; Johansson, 2007). Somewhat recently, Luostarinen et al. (2017) studied the associations of growth and wood density with wood anatomy in downy birch grown in two types of soil: poor peat soil and mineral-rich soil. The growth rate and density differed between trees grown in the different soils, although the double thickness of fibre walls did not. Trees grown in peat had thinner fibre walls when growth rates were higher, whereas fibre wall thickness in trees grown in mineral-rich soil had no such correlation. This was found for a maturing cambium at both soil types (Luostarinen et al., 2017).

More than a decade ago, Johansson (2007) studied differences in basic wood density in planted birches grown in different soils and with different spacing between trees. Trees grown in medium clay soils had higher density than ones grown in fine sand soil, although no correlation between spacing and wood density was found. Basic density for silver birch, sampled at a height of 3 m, ranged from 408 to 442 kg/m^3 for trees with diameters between 47 and 70 mm at breast height. Considering planted trees protected from browsing, Johansson (2007) found that soil type did affect wood density, though that correlation proved to be difficult for the author to explain. Notably, Johansson (2007) study involved different growth conditions typical of mixed-species forests without protective fences. Although birch has been found to experience more root competition from other birches than from conifers (Perala and Alm, 1990), data about how the growth of juvenile birches in mixed-species forests affects the wood anatomy remain limited.

Most recently, Luostarinen and Hakkarainen (2019) observed that soil type indeed affects wood anatomy as well as wood chemistry in downy birch. Their finding of a strong positive correlation between the double wall thickness of fibres and holocellulose emphasises the effect of good growth on cellulose formation in fibres. Changes in chemical components influence the mechanical components of wood, and lignin content critically affects tensile strength and the elongation of the individual wooden conifer tracheid (Zhang et al., 2013). Thus, a change in lignin content in downy birches depending on soil type could also affect stiffness, as confirmed for fibres in a diffuse–porous hybrid species of aspen (*Populus tremula* × *Populus tremuloids*), in which a major reduction in lignin prompted a small but significant reduction in longitudinal stiffness. By contrast, the longitudinal tensile strength was not reduced (Bjurhager, 2011). A search of the literature revealed few similar studies concerning the wood anatomy of juvenile silver birch grown with more or fewer nutrients.

Effects of juvenile wood

The term *juvenile wood* refers to wood in the centre of the stem formed when the cambium's age is low and when the wood has properties other than those of mature wood. Several such properties are generally expected to increase with as the cambia age in softwoods: wood density, cell length and strength, cell wall thickness, transverse shrinkage, and the amount of latewood. Conversely, fibril angle, longitudinal shrinkage, moisture content, and spiral grain generally decrease with the maturation of the vascular cambium (Tsoumis, 1969; Zobel and Buijtenen, 1989; Zobel and Sprague, 1998). Although the properties of juvenile wood in hardwoods have not been investigated to the same extent as those in softwoods (Evans II et al., 2000; Lachenbruch et al., 2011), some of those variations related to the cambium age also seem to hold true for juvenile birch wood. Strong growth and, in turn, wide growth rings are characteristic of juvenile wood, and on an experimental scale, height growth in juvenile silver birches can exceed 1 m per year in favourable conditions (Koski and Sievanen, 1985). Other evidence indicates that a more mature cambium in silver birch produces denser wood (Bhat, 1980a; Hakkila, 1966; Heräjärvi, 2002; Liepiņš, 1933), which was confirmed for planted juvenile silver birch grown on former farmlands in Latvia (Liepiòð and Rieksts-Riekstiòð, 2013). Möttönen and Luostarinen (2006) also detected differences between the cambium's age by class and the wall thickness of downy birch fibres; nevertheless, their sample did not include naturally regenerated trees in the age class of 0 to 10 years. The microfibril angle in juvenile silver birch, ranging from 9° to 26°, was shown to be lower than that in the juvenile wood of Norway spruce, which can increase to as much as 46° (Welander et al., 2002). Relative to those in mature birch wood, the pulping properties in juvenile silver birch with improved genotypes had lower pulp yield, a higher lignin number after cooking (kappa number), and the fibres were shorter, less coarse, weaker, and of lower basic density (Hedenberg et al., 2002).

1.3 Aim, research questions and objectives

The principal objective of this thesis was to study the variation in the stem and wood properties of juvenile birch (*Betula pendula* Roth and *Betula pubescens* Erhr.) in Sweden.

The work was carried out with the goal of producing a scientific basis for development processes in the wood product industry and, in particular, enhancing the raw material utilisation of small-dimensioned birch. In this context, the following research questions was defined:

RQ1. Do the material characteristics in small-dimensioned round-wood birch stems meet the requirements for industrial utilisation in indoor furniture applications?

RQ2. Do the wood characteristics vary within the stem and between slow-grown and fast-grown wood?

RQ3. How could this material be industrially processed, in its solid state, into components for indoor furniture?

The following specific objectives were then defined to answer the research questions:

OBJ1. To confirm which material properties should be determined (Paper I).

OBJ2. To explore wood-to bark bonding after kiln-drying (Paper II).

OBJ3. To determine within-stem variations of properties (Paper III, Paper IV).

1.4 Limitations and delimitations

This thesis focuses on material characteristics of juvenile silver birch that is naturally regenerated in mixed forests stands together with Norway spruce. Small dimension birch often is a waste material from pre-commercial thinning and not used for any mechanical processing, but left to degrade in the forest. The initial research question asked if these small-dimensioned birch stems could be utilised as a furniture component for example, a chair leg with only minimal processing, such as length adjustments and drilling of holes for screws or fittings. Therefore, the focus was on solid roundwood characteristics not the material in the form of chips or fibres.

No mature birch wood was studied and the definition of the wood being juvenile was irrespective of tree height based on the cambium age (ring number from pith) being below 15 years for all of the studied trees.

Detailed specifications of the stands were not collected as data. Hence family data is unknown and competitive status within the stand of the individual tress has not been collected. Neither were any of the stands protected against browsing.

The method for density determination did not allow for ring to ring comparison, neither were individual trees compared.

The findings in this thesis are furthermore based on a small number of trees from each site, within 100-kilometer radius. The results should therefore be viewed as general trends.

2. Methodology, materials, and methods

2.1 Positionality

Research questions were formulated by the industry and presented to researchers at Linnaeus University, resulting in a PhD-project. In the problem description, information concerning the preliminary studies and hand-crafted prototypes was given to the PhD candidate. The prototypes had a satisfactory aesthetical design and seemed to have a satisfactory level regarding strength properties. This might have caused a stubborn belief that stems of juvenile birch wood indeed could serve as a component material to the indoor furniture industry. However, at the time, it was common knowledge within the wood science society that juvenile wood misbehaves once dried, develops cracks, and high skewness, and has a poor mechanical performance. The PhD candidate had previous experience working with the wood manufacturing industry, sawmills, and had conducted qualitative studies concerning customer requirements on "visual wood". This could have influenced the research design to only use quantitative studies and excluding qualitative studies e.g. interviews and questionnaires, instead of using both in a mixed method. The researcher, at the time of the studies, was employed at the University and did not have any economic benefits from the outcome of the project.

2.2 Research design

The research approach in this study partly follows the traditional positivist research design introduced by Williamson (2002). The traditional positivist research includes testing of hypothesis, where data are collected to support the hypothesis and theories. The research design in this study starts with a definition of the topic of interest (Fig 1). Once the first step is accomplished, a literature review is conducted to gain new and deep understanding in the field of interest. The literature review is also used for identifying any research gaps, as well as a delimitation of the research questions. This procedure defines specific objectives and hypotheses. Later the research is carried out to collect data and methods are selected for analysing whether or not the hypothesis is supported, in order to meet the objectives.

The topic of interest was defined as “utilisation of juvenile birch in furniture production.” The literature review was conducted to identify the research gap. Considering the identified research gap, two hypotheses were developed: “Basic wood properties varies within and in-between stems of juvenile birch” and “Wood properties variation within the stem of juvenile birch, impacts the mechanical performance of furniture components manufactured thereof.” For testing the hypotheses, this study was divided into two sections: first, the explorative literature study presented in Paper I was conducted to identify which wood properties were relevant to characterize; in the second section, the descriptive studies II, III, and IV investigated those properties through experimental studies.

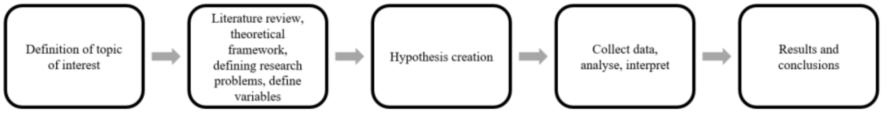

Fig 1. Traditional positivist research

2.3 Data gathering techniques

The literature review was the initial data gathering technique in this study, presented in Paper I. The online process of seeking literature followed the iterative routine described by Rumsey (2008), where the results are constantly evaluated, and the search gets narrower and more specific along the way. The main data gathering technique was the undertaking of experiments resulting in Papers II, III, and IV. The methods are further described in following sections of this chapter.

2.4 Experimental design

Depending on the design of the test, different claims can be made. A test with a small clear sample could say something about the characterization of the timber investigated if the purpose is to make a comparison between juvenile/core/pith wood and mature wood from the birch tree. The material properties have been controlled through techniques that are standard for the field. International standards have been used when applicable. One example is ASTM D143 – 14 Standard Test Methods for Small Clear Specimens of Timber1. Another example is ASTM D2915, Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products. According to the standards, only small clear samples of wood is to be tested. Due to the nature of this thesis project, small clear samples could only be used in the case of wood density and in measurements of wood cells. In the case of testing wood to bark bonding after kiln drying, none of the standards were directly applicable. Nevertheless, they have been used as guidelines to ensure the quality of the research when applicable. The methods used are further described in Chapter 2.8 Methods.

2.5 Quantitative data analysis

In order to find and recognize useful information for the objectives, statistical methods were used throughout the studies for data analysis, mainly analysis of variance ANOVA and regression analyses. The criterions for the different statistical analysis to be applicable such as assumption of normal distribution were controlled for all data.

2.6 Validity and reliability

The reliability of the measuring instruments has been verified using fixed references for calibration, of which a record has been kept over time. The internal validity has been done through control settings and control measurements on randomly selected samples and analysis of statistical results by more than one researcher. The study material was collected at the Asa Experimental Forest and Research station together with staff from the Swedish University of Agricultural Sciences, or at the Toftaholm estate together with staff from the forest management team. The sampling plots were as close to a "real life situation" as possible, but with known forest management and land conditions. For validation of the results, material was also used from "real life storm damaged land" with naturally regenerated birch and planted spruce. As the two native birch species silver birch and downy birch can be hard to tell apart, the material was sampled together with personnel from the research station and when in doubt the species was later verified as silver birch through microscopy studies (Bhat, 1980b).

2.7 Materials

Description of sampling sites and stands

The study material was collected at two different sites located in Kronoberg county in Götaland, a part of Sweden where a considerable proportion of the cutting potential of birch from cleaning operations is located (Figure 2).

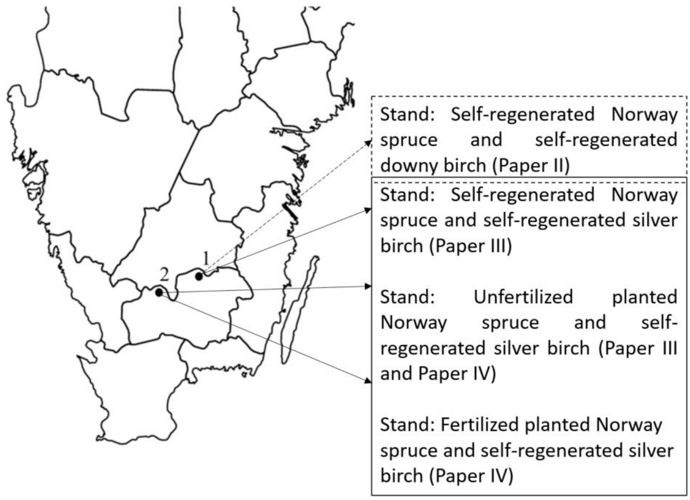

Figure 2. Map of southern Sweden with numbered areas with the sampling sites included in the thesis. (1: Asa, Papers II and III. 2: Toftaholm, Papers III and IV)

Asa Experimental Forest and Research Station is located 37 km north of Växjö Sweden, latitude. 57°10'N, longitude. 14°47'E (Figure 2). Two different stands were used for sampling of the study material. In Paper II, the material was sourced from a mixed stand of downy birch and Norway spruce (*Picea abies* Karst.) in April 2015. The site had previously been clear-cut during the fall of 1998 with only a few spruce trees as seed trees. In the following year, the soil was scarified and left for natural regeneration. Some of the seed trees were harvested in early spring of 2013. The birch therefore stemmed from natural generation with a maximum age of 15 years. The site was located 180 meters above sea level. The site class index according to Hägglund and Lundmark (1977) was G28. The ground was considered as moist.

Half of the study material in Paper III came from the second site at Asa research station. Again, the site had previously been clear-cut during the fall of 1998. The year after the soil was scarified and left for natural generation. The site is located 250 meters above sea level with moraine soil type and the soil moisture is considered as mesic. The topography within the stand varies from lower parts with more moist soil and higher parts with bare rock. The selected stand has a site productivity slightly below the average for this region, with mean site production of 8.6 m^3sk/ha and year. The site class index of the site was G27.

Toftaholm is located in south-west Sweden (57°0'N, 14°3'E) (Figure 2). The site at Toftaholm estate was wind-felled by the storm Gudrun in 2005 and then clear-cut. The climate is humid continental, and the mean annual temperature is 6.3-8.3 °C, with 766 mm mean annual precipitation. The site had soil scarification and was reforested with planted Norway spruce and natural birch regeneration. Pre-commercial thinning occurred once in 2017. Mesic sandy moraines dominate the site, featuring smaller wetter areas with a thin peat layer on a bedrock of mainly acid granite with some ultrabasic rock. The terrain is levelled with only minor variation in elevation. The site class index is G32, corresponding to a mean annual increment of 11.3 m^3/ha potential yield of Norway spruce (Bogghed). At the Toftaholm site, two adjacent stands were established to study the effect of fertilisation. The fertilisation experiment consists of two adjacent stands, with one stand fertilised by helicopter in April 2014 and 2016. The unfertilised stand provided study material to Paper III and Paper IV. The fertilised trees were studied in Paper IV.

Description of sampling material-trees and wood samples

In Paper II, the purpose was to characterise unbarked juvenile birch trees. Hence, downy birch was investigated, as its bark is smooth and rarely contains the fissured bark, which is commonly found on silver birch. In Papers III and IV, the main purpose was to study the wooden material of the stem, although some stem characteristics were also studied in Paper III. The thesis aimed to investigate stems that could be the result of waste material from a cleaning operation, pre-commercial thinning, as the diameters were smaller than that of pulp logs. Hence, all the sampled trees were selected based on their diameter. All the investigated trees had a diameter including bark at breast height (1.3 m) in the range of 33-66 mm (Paper II), 33-76 mm in Paper III, and 31-83 mm in Paper IV.

2.8 Methods

Literature review

The literature review was done as an independent work in Paper I and as embedded work to inform primary research in Papers II, II, and IV. The review included books, peer-reviewed conference and journal articles, and reports. The literature was searched and gathered mainly via OneSearch, a search engine provided by the University. OneSearch accesses the main databases within the field, identified through the University’s library. Google Scholar was also used. Keywords were selected based on the aim of the study. For selecting the most relevant literature, the abstract, keywords, and conclusion of literature were read. The topic of the study presented in Paper I was to review and synthesise past research on the potential of utilising small-dimensioned round-wood birch in furniture and interior applications. The review considers 61 sources and the publication date of the included articles ranging from the years 1945 to 2016. The length of the review was adjusted to fit the paper format given by the conference where the paper later was published. Keyword searches such as “round-wood utilisation” and “furniture” were initially used. Through relevant citations from the sources found, the review advanced to include other references. The selection of literature aimed to find aspects of usage of solid wood from small-dimensioned timber as well as some useful concepts for successful material selection in product design. Therefore, based on customer requirement concepts, it was analysed which wood material properties are important for furniture or joinery applications from hardwoods, and how small-dimensioned round-wood birch could meet the requirements. Proposals are made for future research. These findings are important in a change towards the bio-based economy and the increased competition for supply of raw materials.

Variation of some properties along the stem

Some properties were measured along the stem height. Diameter with and without bark was measured along the stem in Paper II and Paper III. In Paper IV, only the diameter at breast height was measured. The diameters were measured as an average of the smallest and largest diameter of each stem disc. Taper was calculated as the percentage difference in diameter between two heights at the stem. A high tapering value indicates a slow rate of narrowing. Taper was calculated for lengths of 0.45 m in Paper II and for lengths of 1.00 m in Paper III. Bark thickness was calculated as the external diameter minus the wood diameter and the value is given as double bark thickness. Moisture content (MC) was measured during drying in Paper II. After drying the samples, the wood bark boding was measured by visual grading. Wood bark bonding was graded as percentages of full contact between the circumferences of the wood to the bark. Full contact of wood to bark was recorded as 100% and no contact was recorded as 0% bonding.

Growth ring width

Numbers of growth rings and their width was measured in Papers III and IV. In Paper III, average growth ring width was calculated as the diameter divided by the number of growth rings. In Paper IV, individual growth rings were measured on wood cross sections mounted on microscopic slides. Micro-sections were prepared using a sledge microtome (WSL lab-microtome, Switzerland). Thin section (ca 20 µm) were cut, stained with 1% safranin solution, washed with series of alcohol solution and finally mounted in Canada balsam following the procedure as described in von Arx et al. (2016). Disposable and high-quality NT cutter blades were used to ensure clean and quality sections (Fujii, 2003;

Gärtner and Nievergelt, 2010). The semi-automated uplift function of the sample was used to ensure constant thickness of the samples during the cutting procedure.

Two different diameter groups, Dsmall and Dlarge with narrow and wider ring widths is studied in Paper III. In Paper IV where the effect of fertilisation is studied, growth before and after the fertilisation is evaluated by the width of growth rings. Mean ring width for four years before treatment, 2010-2013, was measured to denote the trees' vigour before fertilisation. The ring widths for the years after fertilisation were presented as a ratio with the mean ring width before treatment, as the fertiliser was applied in 2014 and 2016. This means that the trees growth after treatment was analysed in relation to the growth before the time of the treatment. Basal area increase was calculated as an approximation of overall tree growth and bark thickness was not included in the analysis (Biondi and Qeadan, 2008).

In Paper III and Paper IV, the correlation between growth rate and wood density is statistically investigated.

Wood cells

Three growth rings were photographed for trees that were fertilised and unfertilised in Paper IV. The open source freeware ImageJ 1.52j (Ahmed et al., 2013; Tng et al., 2018) was used for the measurements of number of vessels and double cell wall thickness, hereafter called cell wall thickness. The change in cell wall thickness and number of vessels with increase in cambium age was statistically compared between the fertilised and unfertilised group.

Wood density

The water-displacement method as described by Siau (1995) was used to determine the oven-dry density in Paper III and the basic density in Paper IV. The oven-dry density was determined using paraffin coated oven-dry samples, and calculated as the oven-dry matter (kg) divided by the oven-dry volume (m^3) of the specimen. In Paper IV, the basic density was calculated as the oven-dry matter (kg) divided by the green volume (m^3) of the specimen. The basic density for the fertilised and unfertilised was measured on a wood strip taken from pith to bark. The strip was taken from the south direction of the tree stems at breast height (1.3 m).

Longitudinal density variation was measured for wood samples from different heights in Paper III. Furthermore, radial density variation was measured by sectioning a transverse wood strip in centimetre cubes (Figure 3). The relationship between density and radial distance from pith was analysed statistically, which is further described in the next section.

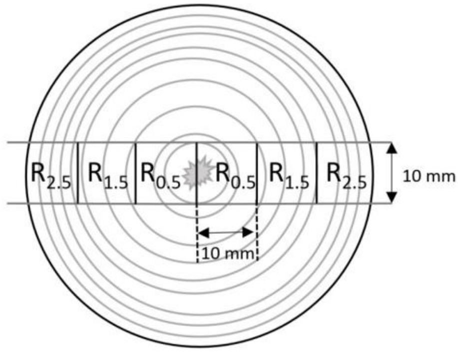

Figure 3. For each stem and height, a bark-to-bark strip about 10 mm thick tangentially was prepared from the stem disc. The strip was divided into radial samples, taken at 10 mm ± 1 mm intervals, from both sides of the pith outwards to the bark. Hence, each strip generated two density samples with the same radial distance from pith.

2.9 Statistical analyses

The results were analysed with the SPSS 25.0 statistical software (SPSS, Chicago IL). Assumptions of normal distribution and homogeneity of variance for the samples were tested. The difference between the studied variables was tested using analysis of variance (ANOVA), Student's t-test (t-test), and Tukey's HSD post hoc test. The comparisons were made with the nonparametric Kruskal-Wallis test in the cases were the assumptions for the Students t-test were not met in Paper IV.

Linear regression models (Eq 1) were used to analyses the results of the relationship between variables. Mainly the relationship between density and growth ring width were used (Papers III and IV) but density and distance from pith (Paper III) and density and cell wall thickness were analysed in Paper IV.

$$Y = a + \beta X + \varepsilon \qquad (1)$$

where density is the dependent variable, β is the regression coefficient, X is the independent variable (average cell wall thickness /average ring width/ radial distance from pith), a is the intercept and ε is any unexplained variance (the model error term). A significance level of $p \leq 0.05$ was used throughout the studies, except for the regressions, which were based on the t-test ($p < 0.001$). In Paper III, the correlation coefficient (also called 'R-value') is used to measure the strength of the linear relationship between the variables. The coefficient of determination ('R^2-value') is used in Papers III and IV to explain how the independent variable can predict the variance in the dependent variable in the regression model.

3. Results and discussion

3.1 Literature review

For forestry, *Betula pendula* Roth and *Betula pubescens* Ehrh (hereafter birch) is considered to be the most important broadleaved tree species in Northern and Eastern Europe (Nilsson et al., 2014). Birch is the third most common tree species in Sweden (Nylinder and Woxblom, 2005). Studies about utilisation of small diameter stems have focused on sizes ranging from 10 cm up to around 15 cm (Bumgardner et al., 2000; Bumgardner et al., 2013; Choong and Tesora, 1974; Hakkila et al., 1979; Ranta-Maunus, 1999). To identify the possibility to utilise even smaller dimensions it is important to identify customer requirements and how to translate them into desired wood properties. Some demands posed upon the materials are common for both the processing industry and the end customer:

- Appearance/aesthetics and tactile properties
- Accuracy in dimension and geometry
- Material free from cracks
- Dimensional stability/controlled movements in the wood material with changing humidity
- Strength and hardness
- Durability/above-ground durability

In the review, an alternative way of opening up for new utilisation opportunities for low-grade woods was found. Character marked is a branding of low-grade wood in order to open new market opportunities to sell this assortment of timber. Character marks, part of the natural variability in wood, includes knots, burls, colour streaks or spots, holes or differences in colour between heartwood and sapwood (Dinwoodie, 2000; Nicholls and Bumgardner, 2015). Nicholls and Bumgardner (2015) have contributed to the field of knowledge with a thorough review of solid wood manufacturing and marketing of low-grade and character-marked hardwoods. New technical solutions like scanners can help the wood processing industry to meet the customer's aesthetical material requirements.

Birch wood attributes were categorised into five main groups, presented in Table 1.

Table 1. Synthesis of wood properties and what factors that impact them (Dinwoodie, 2000; Farmer, 1972; Hoadley, 1990; Nylinder et al., 2006; Stamm, 1964).

Properties	Explanation:	Factors impacting
Physical properties	Macrostructure, density	Macrostructure, moisture content
Aesthetical/Appearance	Knots, type of wood (heart/sap) Colour, Grain orientation, rays, processing, cracks, year rings & their orientation, lustre, textural characteristics, defect caused by wood boring insects, chemical and physical	Forest management, extractives, drying, cracks, macro structure (pore arrangement) density, chemical composition, e.g. furniture beetle, physical: morphology, roughness, smoothness, permeability
Strength	MOE (modulus of elasticity), MOR, bending, hardness, tension, compression, toughness , shear, elasticity, viscoelasticity, creep,	anisotropy, cell length, type pf wood, ultra/macrostructure, density, moisture content, radius of bending, time under load, temperature, cross grain & irregularities, grain angle
Dimensional	type of wood: juvenile, mature, reaction wood (tension), anisotropic, hygroscopic, microfibril angle	macro structure, density/chemical composition, moisture content
Moisture	Macrostructure (capillary characteristics), density, permeability, diffusion, drying, dimension, mechanical and elastic and thermal	chemical composition, macro structure
Psychological	colour, odour, resonance, taste, tactile, trendiness	processing, chemical composition, density
Environmental	Origin, vulnerability, forest certification, recyclability	

Panshin and De Zeeuw (1980) determine the physical properties of wood by the following five factors: 1. amount of cell wall substance in a given volume; 2. amount of water present in the cell wall; 3. the chemical composition of the cell wall and the nature of the extraneous substances present; 4. the arrangement and orientation of the cell wall materials in the cells and different tissues; 5. the kind, size, and proportions and arrangement of the cells making up the woody tissue. The comprehensive literature study of birch as sawn timber by Loustarinen and Verkasalo (2000) provide specific information about wood properties in mature downy birch and silver birch.

The importance of juvenile wood and the impact it could have on the physical and mechanical properties was identified (Dinwoodie, 2000; Rowell, 2012). The Evans II et al. (2000) review on juvenile wood in red alder shows some of the difficulties and shortcomings concerning research about juvenile wood in hardwoods. Different radial growth patterns were found and the need to identify the growth pattern in downy birch and silver birch was identified. The existing literature in the matter showed that no radial variability had been determined in birch (Bhat, 1980a; Lundqvist, 2012). Examples of where the properties of juvenile wood showed an impact on strength performance compared to that of mature wood was also found (Adamopoulos et al., 2007).

The aesthetical characteristics of birch wood were also studied in the review. There are no colour differences between innerwood and outerwood in young birches (Loustarinen and Verkasalo, 2000). Kilpeläinen et al. (2011) found that in younger birch trees, brown streaks caused by larval tunnels of *Phytobia betulae* Kangas and discolours or firm-decayed wood caused by different mammals could be frequent. Grain orientation and frequency of knots will also influence the appearance of the wood.

Mechanical properties depend very much on both moisture content and growth rate (Rowell, 2012). A rapid growth does not diminish the wood quality of birch fibres (Johansson, 2013); instead its strength is improved (Jalava, 1945), hence studying the wood density would be important in order to understand the performance as a furniture material.

Furthermore, the knowledge about the juvenile birches' dimensional and moisture properties was also identified as important. Practical implications of the wood-water relations are related with kiln-drying of wood, impregnation or moisture content variations in exterior or interior wood applications such as furniture (Siau, 1995). Treating the birch in an impregnation process could increase the outdoor durability of birch that otherwise is poor (Loustarinen and Verkasalo, 2000). Other wood qualities that were identified in the literature review were related to the human perception of wood as a direct and unchanged product of nature with undeniable attraction. The importance of wood, leather, and wool testify to the aesthetic and psychological value of natural materials (Hoadley, 2000). Rice et al. (2007) studied how people's psychological health and wellbeing are connected to wood used in appearance applications. Wood evoked descriptors as "warm", "comfortable", "relaxing", "natural" and "inviting". Their findings suggest that marketing, including the potential psychological benefits of wood products, help the producers to differentiate themselves. The natural aspect of wood is considered in the environmental properties of wood material. Those properties would include wood origin, forest certification, processing, possibility for recycling and eventually disposal (Mangonon, 1999). If the trees remain in the forest when harvested, the biodegradation process will transfer carbon from the stem to soil carbon stocks (Lundmark et al., 2016). If kept in the solid wood state, the $CO2$ is stored in the product until the end of the products life-cycle.

A specific material may have superior properties but if with low or no commercially availability it will not be possible to use (Karana et al., 2008; Neyses and Sandberg, 2015). Small dimensioned birch occurs in great abundance in Sweden (Nilsson et al., 2014). For sound silviculture, different timber assortment plays an important role and PCT is also important as a forest management tool (Savill, 1997). If round-wood components of birch from PCT could bring an income to the forest owners, it could have an effect on the view of mixed-forests regimes that would be an alternative to conifer monocultures.

Löf et al. (2014) found silver birch to be a good nurse tree, which could increase the biomass production and provide an income within a short period. Furthermore, positive outcomes from mixtures include increased biodiversity, water quality and resilience to extreme weather (Felton et al., 2016; Keskitalo et al., 2016). Addressing the environmental concerns was found in this review to be important for the successful marketing of character-marked wood. Similarly, there can be possibilities of using the intangible characteristics of the juvenile birch round-wood material. This would lead to finding a suitable customer segment instead of going into markets that already have low tolerances to deviation in knottiness, colour, and textural effects (Johansson et al., 2013). The example of character-marked timber shows that there are researched opportunities to sell wood with other features beyond the traditional square and straight grained. Successful product development requires data about material characteristics and the review revealed that little is known of juvenile birch. Due to a strong statistical relationship between wood density and mechanical properties, the wood density variation pattern in the horizontal direction (pith to bark) in silver birch and downy birch would be an area of interest. To fully explore the potential of using small-dimensioned round-wood birch for furniture applications, more research is needed.

3.2 Variation of some properties along the stem

The bark was found to be thickest closest to the stump, both for downy birch (Paper II) and for silver birch (Paper III). Previous studies had similar results and demonstrate that the silver birch bark thickness varies strongly with height level and stem diameter (Bhat, 1982; Näslund, 1947). Depending on the intended use of the material, the bark-to-wood ratio and stem taper could be of interest for practical applications, such as efficient use of the material in manufacturing table legs, components, boxes, and etcetera. The findings of this study also show that young trees have a high proportion of bark, especially in the stump section.

The 450 mm long downy birch samples had an average tapering of 94%, and the value for the full 2.5 m was 66% (Paper II). The stem taper values for silver birch were between 50 to 60% from the stem height of 0.3 – 3.3 m (Paper III). Samples closest to the stump had the lowest tapering in both species.

Regarding drying, the debarked samples was shown to dry quicker compared to the unbarked samples (Paper II). Callin (1959) also showed that bark covered birch dried slower than debarked wood. Although it was out of the scope of the study, it was noted that none of the samples had major checks that is normally found in dried cross-sections caused by the different moisture related movement in the radial and tangential direction.

No correlation between in stem height position and in loss of wood to bark bonding was noticed. The smaller diameter of samples, the higher percentage of intact wood to bark bonding after drying. The mean bark bonding after drying was 44%. The timing of the year when the sampling was done might have an effect on the result. The sampling was done in the Swedish spring when the flow of sap is the largest. According to Kubler (1990) researchers suggest that the weak bond between the wood and the bark in this period is affected by the activity of the dividing cells in the cambium rather than the flow of sap itself. The radial wall stretches and becomes weak through attenuation. In the dormant period (the fall and winter), cambial cell walls are most likely hardened and better resist rupturing (Bűsgen et al., 1929).

Overall, these results strengthen the idea that the strongest wood to bark ratio and diameter variation is at stump height (Fig 2). Thus, by avoiding the stem close to the stump, the remaining part of the stem is expected to have homogeneous wood to bark ratio and stem taper.

Fig 2. Stem discs of downy birch taken close to the stump. Bark thickness varied from 9 to 4 mm in double bark thickness on a 400 mm long stem section.

3.3 Growth ring width

The growth ring-width (hereafter called ring-width) at breast height ranged between 4.6 and 9.9 mm (Table 3) for the per tree average ring-width in the naturally regenerated silver birch (Paper III). In Paper III, the sampled trees from each site were analysed as two different groups depending on their diameter. The small diameter group at both sites had more narrow rings when compared to the large diameter group.

Regarding the effect of fertilisation in juvenile silver birch, the mean growth ring width was 2.79 mm in the 10 trees from the unfertilised stand and 3.84 mm in the 10 trees from the fertilised stand. The number of growth rings was on average 2.50 fewer in the fertilised stand (Paper IV).

The fertilised trees showed an increase in relative growth for the two years that fertiliser was applied, in 2014 and 2016. The Kruskal-Wallis H test showed that there was a statistically significant difference in relative growth for the year 2014 between the fertilised trees and the control trees. 2016 when the site was fertilised for the second time, the growth was poor compared to the first year of fertilisation, in 2014, and in comparison, to the years before treatment for the unfertilised trees. For the fertilised trees, the growth in 2016 was better than the years before treatment, but only half of the value for 2014.

Relative basal area increased from the time before treatment until the end of growing the season in 2017, and showed a statistically significant difference between the fertilised and the unfertilised trees.

These results confirm that growth rate can be enhanced and diameters could be reached earlier with fertilisation of juvenile silver birch. The average ring width for all years was larger for trees, which received fertiliser than for trees that were unfertilised. This is in line with previous findings from greenhouse experiments (Moilanen, 1985; Mutikainen et al., 2000). Paavilainen (1990) encountered a weak response to fertilisation of downy birch on a fertile site and there was no considerable improvement in growth. It is possible the difference between the fertilised and unfertilised birch stems would be greater on a nutrient restricted site than the five percent difference in growth in this study (Paper IV). The results show that it is possible to increase the growth of juvenile birches with early management measures. Furthermore, sorting of same size diameter stems from naturally regenerated birches growing in a mixed forest could give a range of ring width assortment. Apart from the deluxe assortment of birch wood, curly birch, the highest value of birch is found on the high quality veneer stems (Loustarinen and Verkasalo, 2000). Ring width and fibre orientation effects the aesthetic impression of the wood and influences the desirability of solid wood products such as veneer, plywood and timber.

The correlations between ring width and studied properties will be further presented and discussed in the two following chapters.

3.4 Wood cells

Cell wall thickness had higher variation between different years in the fertilised silver birch trees. The fertilised trees' average cell wall thickness varied from 4.46 µm in 2015 to 4.68 µm in 2017. Fertilised cell wall thickness was lower than the unfertilised values of 5.08 µm, to 5.44 µm respectively. The standard deviation for cell wall thickness was 0.9, regardless of year or treatment (Paper IV).

The average number of vessels per mm^2 decreased between 2015 and 2017 for both the fertilised and the unfertilised trees. Fertilised trees had 140.32 vessels per mm^2 in 2015, and 102.24 in 2017, which was more than the unfertilised group. For the same years, the unfertilised trees had 119.68 to 99.20 vessels per mm^2 in 2015 and 2017, respectively.

Within a single growth ring, fertilised silver birch with low cambium age has a thin cell wall. Unfertilised trees with higher cambium age developed notably thicker cell walls during the same growing season. It is possible to see that the fertilised stem has thinner cell walls than the unfertilised stem, but the vessel sizes look similar. The fertilised stem, is younger than the unfertilised stem, and has more vessels per mm^2 but the vessels appear slightly smaller.

A plot of average cell wall thickness (2015-2017) against average ring width (2015-2017) indicated that cell wall thickness was poorly explained by ring width (Fig 2). The linear regression models were insignificant for both fertilised and unfertilised samples ($p > 0.05$). The R^2 value was higher for the unfertilised samples ($R^2=0.39$) than for the fertilised samples ($R^2=0.11$), indicating that either no correlation or a weak correlation existed between cell wall thickness and ring width.

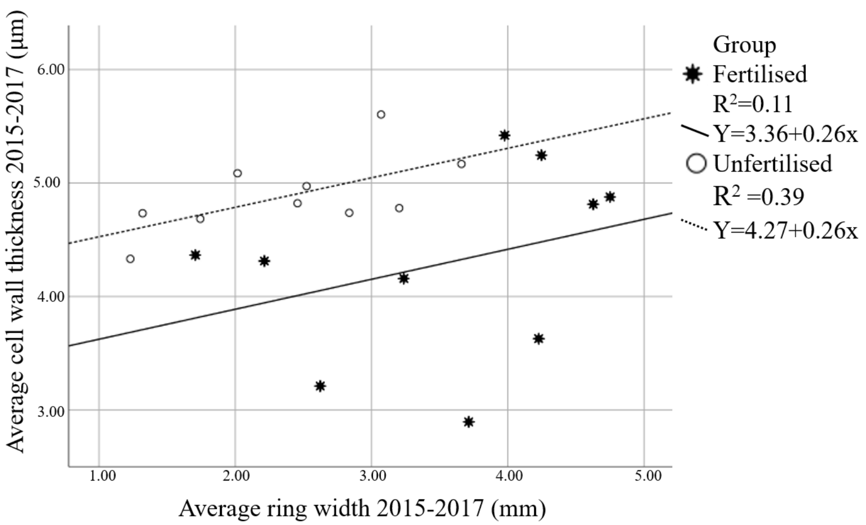

Figure 2. Average double cell wall thickness correlation to average ring width for the years 2015 – 2017 for the fertilised and the unfertilised group.

Although the model could not explain the correlation between cell wall thickness and ring width in the fertilised stand, the cell wall thickness was to some degree correlated to ring width for the trees from the unfertilised group. The design of the study does not allow identification of the causal agent behind the observation of different strengths of correlation. Possibly, there is a trade-off in the nutrient limited stems so that an increase in ring width requires a reduction in cell wall thickness, and this limitation was not present in the fertilised stems. Cuny and Rathgeber (2016) made extensive studies of wood xylogenesis in conifer species. On a weekly basis, during three years, they took micro increment cores and could monitor tree-ring formation thoroughly. They found that cell size was driven by cell enlargement duration to 75% and by rate of wall deposition to 25%. Although they quantify the relationship between the durations and rates of processes, and show that they are not correlated, they do not fully explain the drivers behind these patterns that they present. Cuny and Rathgeber (2016) refute the theory that it is the fixation of more biomass wall that drives cell wall-thickening. Although that might not be the driver of the process, it could still be the reason behind this development. Theories of the increased need for support as the mechanical constraints are changed in the growing tree are well supported (Schniewind, 1962; Woodcock and Shier, 2002). Also, by the theory presented in Hacke et al. (2001), the fibre matrix is approximately proportional to that of the conduit system, hence the thickness of the cell wall must increase when the vessels increase in size to avoid implosion.

Although the driver behind the observation of thinner cell wall thickness in fertilised juvenile silver birches was not explained by the study presented in Paper IV, the results still confirmed that juvenile silver birch followed a growth pattern after fertilisation which has previously been observed in other species in Northern Europe (Hedwall et al., 2014). The results also indicate that the wood formation is affected although the competition for nutrients is hard due to ground vegetation in a young stand that did not yet reach canopy closure. Due to the nutrient optimisation where the foliage requires the most nutrients (Perala and Alm, 1990), one could speculate that the results presented shows that the fertilisation managed to provide good enough conditions so that the foliage managed to increase the rate of wood formation.

The low degree of explanation in the simple linear regression model (Equation 1) may be due to the strong impact of cambial age on cell wall thickness (Bhat, 1981), which was not accounted for in this model. It is still possible that there is a weak correlation between cell wall thickness and ring width within the juvenile wood of silver birch, and a larger dataset and more advanced modelling would help to confirm this. From the microscope work it was apparent that fertilised stems had thinner cell walls and more and smaller vessels than the unfertilised stems. The observation of more vessels in the fertilised trees is in line with the theory that higher nutrient availability can support more foliage, which requires a larger number of vessels to supply water to the crown (Sellin et al., 2008). The nutrient availability is more likely the causal agent why more vessels were found in the fertilised trees although Cuny and Rathgeber (2016) and others highlight the influences of climatic factors. Furthermore, the differences in climate between the sites are accounted for to be no greater than within the site as the two sites were adjacent. Therefore, the temperature sum and day length did not differ between the fertilised site and the unfertilised site, and hence the growth period should be equally long (Koski and Sievanen (1985), and reviewed in Perala and Alm (1990). The indifferent climatic conditions between the two sites strengthen the explanation that the fertilisation indeed had an effect on the wood anatomy in the fertilised trees.

3.5 Wood density

The densities varied between the two different stands Asa and Toftaholm (Paper III). Density also increased with increasing distance from pith in samples from both sites.

Radial wood density variation was found to have a similar pattern independent of site and diameter group. The fit of the model (Eq. 1) was best at the samples from one of the sites, Asa with an R^2 value of 63%. The highest increase in density with increasing distance from pith was found in the small dimension sample group which was also the slow grown sample group (Table 2). An ANOVA analysis provided values for the significance in density difference relative the distance from pith of the samples. The slow grown trees had stronger density variation in the radial direction. In the fast-grown trees, longer radial distance between sampling points was needed to give significantly different results. A strong relationship between increased cambium age, increased distance from pith, and higher density, was also reported for mature silver birch in Finland (Hakkila, 1966; Heräjärvi, 2004). In the fast-grown trees, the centimetre sampling distance will not give a big age difference in the sampled wood, therefore no age-related density increase is expected (Bhat, 1980a). The findings in Paper III suggest that young silver birch trees have an in-stem wood density increase from pith to bark, similar to that previously observed in mature trees. The observed density increase seems to be independent of ring-width since the trend was present in both stem diameter groups. Furthermore, the similar results from both sites indicate that the in-stem density variation is not site specific.

The longitudinal density variation was small in the investigated silver birch trees (Paper III). The density variation along the stem was limited. The same pattern of larger density variations within the slow grown trees was found also in the longitudinal direction. This was found at both sites. The findings from this study suggest that wood density is weakly correlated with the longitudinal position along the stem for juvenile silver birch. These results are not contradictory to the findings of longitudinal density differences in full grown trees (Velling, 1979; Repola, 2006) where the proportion of juvenile and mature wood and the correlated density differences varies with height (Kollmann and Côté, 1968).

Table 2. Oven-dry density for wood samples from pith to bark at the two sites and diameter groups, sampled at height 0.3 m. Number of samples (No), standard deviation in parenthesis.

Diameter group	Radial distance from pith (cm)	Asa		Toftaholm	
		No	Density (kg/m3)	No	Density (kg/m3)
Small <50mm	0.5	9	524 (26)	10	496 (34)
	1.5	9	570 (41)	10	532 (43)
	2.5	6	616 (50)	9	576 (51)
Large >50mm	0.5	11	506 (21)	9	476 (40)
	1.5	11	545 (31)	9	492 (39)
	2.5	10	587 (27)	9	535 (57)

The studies of the effect of ring width on wood density in juvenile silver birch did not provide a uniform answer. The small diameter group had more narrow growth rings and higher density when compared to the large diameter group (Paper III). This was found in trees from both the sites Asa and Toftaholm. Both the ring-width and density analysis showed significant differences in the t-test analysis between diameter groups. The linear regression analysis between ring-width and wood density showed a negative correlation (Paper III). The tree mean values for ring width and wood density in silver birch was investigated for discs sampled at breast height (Paper IV). The Student's t-test comparison between the mean values from the fertilised trees and the unfertilised trees showed that the fertilised trees had significantly wider growth rings and lower wood density compared to the unfertilised trees.

Nonetheless, studies on specific growth rings (2015-2017) showed that wood density had no correlation to ring width in the fertilised trees or the unfertilised trees (Fig 3). The linear regression models failed to explain the correlation between ring-width and wood density. Still, an interpretation of the differing inclinations of the slopes indicate that increased growth in fertilised trees might not decrease wood density in a tree where maturation of the cambium anyhow still alters the density values.

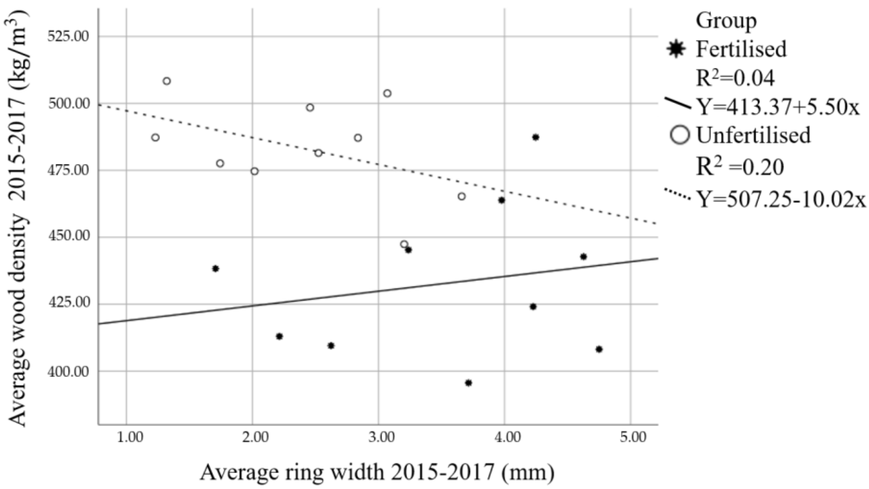

Figure 3. Linear regression lines illustrating the dependence of average wood density to average ring width for the years 2015 – 2017 for the fertilised and the unfertilised group.

One explanation for the fertilised trees having higher density and wider rings could be that the additional nutrients enabled the trees to increase growth without jeopardizing strength properties (Dunham et al., 1999). This is supported by the positive correlation between ring width and cell wall thickness, when for many other species ring width and density are negatively correlated (Kollmann and Côté, 1968). Although Velling (1979) found no difference in density between rapid and slow growing birches, others have reported a negative correlation between ring width and wood density in mature silver birch (Bhat, 1980a; Repola, 2006) and for juvenile silver birch (Liepiòð and Rieksts-Riekstiòð, 2013). Which are also the results of the mean tree density and ring-with analyses in Papers III and IV. In Paper III the samples from Asa came from a less fertile site than the samples from Toftaholm, this likely explains that the same between site relations for wood density exists as was found between the fertilised and the unfertilised site in Paper IV. Faster growth rate is associated with both response to fertilisation, fertile soils and younger stems vitality. The wood that is first formed in the tree, the juvenile wood, often has wide growth rings (Dinwoodie, 2000). As trees become older, ring width generally decreases (Biondi and Qeadan, 2008). In juvenile silver birch were the maturation of the cambium is increasing the wood density, the low density in the wide ringed first formed wood not to be confused with low density in wide growth rings in mature wood. An experimental setup where same aged trees did or did not receive fertilisation, could allow for further insights on the development of wood density. It is likely that the variation of mean density were fertilised trees had slightly lower whole tree mean density (421.77 kg/m^3) than the unfertilised stems (456.54 kg/m^3), could be ignored for furniture production. Although, light-weight furniture has gained increased market shares as there are both economic and environmental incentives related to transportation (Nilsson, 2018).

Luostarinen and Hakkarainen (2019) found a negative correlation between double wall thickness of fibres and the amount of lignin. Additionally, fertilised induced growth has been observed to decrease lignin content in the juvenile wood of *Populus* (Novaes et al., 2009). A change in lignin content has critical effect on tensile strength and elongation of the individual wooden conifer tracheid (Zhang et al., 2013). Thus, a change lignin content in downy birches depending on soil type could affect the stiffness performance. In furniture components such as a leg of a chair, the stiffness requirements are high. If the difference in density also affects the mechanical performance of juvenile birch wood requires further studies.

Furthermore, apart from increased growth fertilisation was found to also increase the drought resistance of silver birch (Perala and Alm, 1990) which could be another important property encountering climate change. Also the ability in birch to quickly get seedling or graft to flower and set seed within a few years, is a crucial advantage relative to conifers (Koski, 2005) in terms of climate adaptation.

4. Conclusion and future work

This thesis work was motivated by the needs of the furniture industry. The focus of these studies was on improving the knowledge on the material properties of juvenile silver birch and downy birch needed for the industry. This work has increased the knowledge about juvenile birch material characteristics, mainly; stem taper, variation of bark thickness along the stem, density variation and radial changes in wood anatomy depending on growth rate. Furthermore, the knowledge about fertilised juvenile silver birch wood anatomy and density was also increased.

Stems of juvenile silver birch or downy birch are available in large volumes from pre-commercial thinning operations. Currently they are not used industrially on a large scale and hence could provide a new raw material supply. The scientific support for successful utilisation of alternative wood sources than the traditional are numerous. Thus, material characteristics must be known for successful product development.

The variations along the tree stem, measured and statistically analysed, showed that the section closest to the stump has the largest variation, both in bark thickness and stem taper. There seems to be a relation between wood to bark bonding and the diameter of the wood pieces although no relation was found with sampling height on the stem. Quick and aggressive drying of wood with bark did not stimulate bark removal.

Same diameter trees can have a variation of ring width, within stands and between stands. Fertilised juvenile silver birches had increased growth compared to unfertilised trees. Standard wood anatomy studies revealed that the fertilised trees had a younger cambium and thinner cell wall thickness and fewer vessels. These results indicate that fertilised trees outperformed unfertilised trees in growth rate after treatment.

In line with density variations patterns known for mature birch, the density is increases with increasing distance from pith. The radial density increase is higher in slow grown trees. Height position in the stem showed low impact on density variation in young silver birch trees. Density seems to be negatively correlated with growth rate. This was found within sites and between sites with differing growth conditions. Furthermore, the mean wood density was lower in the fertilised trees compared to wood density in same diameter trees, which were not fertilised. Although differences in density between slow grown and fast grown were significant, their magnitude could be characterised of small practical importance for the furniture industry.

This thesis work can be summarised as: it is possible with silvicultural practices to affect the wood properties in juvenile birch. Hence, to get birch with special characteristics as the growth rate will affect the ring width and furthermore the wood density and aesthetic qualities. Sorting of stems according to ring width could result in different material characteristics. One can obtain a wood material that has limited variation in wood-to-bark ratio and wood density by avoiding the lowest section of the stem.

This work has highlighted the need for further studies on juvenile wood in general and in hardwoods particularly. Short lengths of juvenile birch stems can be dried quickly with or without bark without visual cracks or wrapping. The knowledge about moisture related movements in round stems of juvenile wood could be further researched. Further studies of the mechanical performance of this wood could reveal new opportunities for utilisation. Cambium fly was only noticed in the but-log. That stem section also showed the largest variations in other properties. Pre-commercial thinning in the way that leaves high-stumps could be an area for further research, in-terms of the wood that would come out and the effect it would have on a stand level in terms of browsing.

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