Productivity and biomass partitioning in 20-year Black cottonwood at variable spacing

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BS – ritgerð   Maí 2011

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Statement

I hereby declare that present thesis is based on my own observations, is written by me and that it has never been in part or as a whole submitted to a higher degree.

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Lena Mikaelsson

Abstract

The main objectives of this study were to investigate the effects of different spacing treatments on aboveground biomass production, bark, sapwood and heartwood ratios and the branching ratio in 20-year old Black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw) experimental plantation within Sandlækjarmýri research forest in southern Iceland. Data and wood samples were collected from 40 trees of 8 different spacing treatments (0.5 x 0.5 m, 0.5 x 1.0 m, 1.0 x 1.0 m, 1.0 x 1.5 m, 1.0 x 2.0, 2.0 x 1.5 m, 2.0 x 2.0 m and 3.0 x 3.0 m) repeated five times in a random manner. Main findings were that overall aboveground biomass per hectare increased with density and reached carrying capacity at approximately 5 000 trees ha^{-1}. Density effects on survival and bark, sapwood and heartwood ratios were insignificant between spacing treatments. Initial spacing, however, did have significant effect on the ratio of branch mass to total above ground biomass that decreased with increasing density.

Acknowledgements

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1. Introduction

In Iceland, the silicon industry is an expanding sector requiring wood chips for the manufacturing process. Industrial plantations of Black cottonwood have been proposed as a possible source of raw materials for the silicon industry (Þorbergur H. Jónsson, 2009a). The objective of the present thesis is to elucidate the growth potential of industrial plantations of Black cottonwood in Iceland and in particular the role of inter tree spacing in that respect.

1.1. General overview of Black cottonwood

Native to North American continent, Black cottonwood is the largest of American *Populus* species, stretching along Pacific coast from Kodiak Island and Kenai Peninsula in Alaska (62°30°N) through California to northern Mexico (lat. 31°N) (Harvey, 1985). Species was introduced widely to northwestern Europe and southwestern Russia where its use is limited to decorative plantings, shelterwoods (DeBell, n.d.) resulting in small naturalized populations.

1.1.1. Taxonomy

Black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw), also known as Western balsam poplar or California poplar (Nesom & Henson, 2003) was formerly considered to be a species of its own (*Populus trichocarpa* (Torr. & A. Gray ex Hook.). Black cottonwood is now classified as a subspecies of Balsam poplar (*Populus Balsamifera* L.) of the genus Cottonwood (*Populus* L.) of the Willows family (*Salicaceae*) and of the order *Salicales* (USDA NRCS, 2011). The fossil records suggest that the genus Populus first appeared at around 50-60 million years ago, i.e. in late Paleocene or early Eocene. Presently, genus Populus is comprised of 29 species divided into 6 sections, one of which, *Tacamahaca*, includes Black cottonwood (Slavov, Zhelev & Jansson, 2010).

Hybridization occurs naturally both within and between the taxonomic sections of genus Populus (Slavov et al., 2010). Black cottonwood commonly hybridizes with other members of the *Tacamahaca* section, such as Narrowleaf cottonwood (*P. angustifolia*) and Balsam poplar (*P. balsamifera* subs. *balsamifera*). Hybridization with members of another Populus section, *Aigeiros*, is also observed, among these are Eastern cottonwood (*P. deltoides* var. *occidentalis*), Fremont cottonwood (*P. fremontii*) and Eurasian Black poplar (*P. nigra*) (Steinberg, 2001). Clones derived by artificial crossing between Black cottonwood and Eastern cottonwood are important timber trees in North America and Europe. In 2007, Iceland Forest Research produced crossings between Eastern cottonwood and Black cottonwood of

Alaskan origins that are presently being evaluated for afforestation in Iceland (Halldór Sverrisson, 2011).

1.1.2. General botanical characteristics

Species of the genus *Populus* are relatively short-lived and fast growing deciduous trees, distributed widely over the Northern hemisphere (Slavov et al., 2010). Black cottonwood is the tallest native North American hardwood. It is normally a medium- to large-sized deciduous broad-leaved tree, at maturity with a narrow, sometimes columnar crown, with thick ascending branches and dark grey bark with irregularly shaped furrows (Bell, 1990). Common tree height is approximately 30 m though occasionally reaching up to 50 m, and mature Black cottonwood trees have diameters at breast height of up to 1 – 1.5 m and life span of 100 to 200 years.

Bark texture and coloring changes with age from smooth, green-brown to olive-gray to gray or gray-brown before breaking into deep furrows and ridges. Bark color and texture as well as branching habit and leaf shape vary between Black cottonwood clones and are useful characteristics for identification of clones in the field (Þorbergur H. Jónsson, 2011).

1.1.3. Reproduction

All species of the genus *Populus* are dioecious with flowers borne in long, drooping aments that appear in spring before leaf emergence, and produce in early to mid summer large quantities of wind-dispersed seeds. Seedlings demand moisture and are shade-intolerant (Slavov et al., 2010). In its native habitat, establishment of Black cottonwood stands by seed occurs erratically with approximately 5 to 10 years intervals, depending on seed viability, deposition time, light availability and soil moisture during first month of growth, forming well defined age groups.

Asexual reproduction by "root suckers" or coppice sprouts is the most common means of regeneration in established Black cottonwood stands (Steinberg, 2001). In appropriate conditions it may be successfully propagated via rooted and unrooted stem cuttings made during the dormant season (DeBell, n.d.; Úlfur Óskarsson et al., 1990). The ability of Black cottonwood scions to set roots varies considerably between clones and the time of year. Most clones set roots profusely if planted in mid to late winter but some clones establish poorly once buds have flushed their leaves (Þorbergur H. Jónsson, 2011). Black cottonwood is successfully reproduced by soft cuttings from elongating shoots (Úlfur Óskarsson, Thorbergur H. Jónsson & Kristján Þórarinsson, 1990). In Iceland, a high output method of propagation

from growing shoot tips produced 700 thousand Black cottonwood plants from 500 initial cuttings in less than two years (Þorbergur H. Jónsson, 2011).

Black cottonwood has a remarkable ability to resprout from the stump after felling. Hence, regeneration may be postponed for several cutting cycles called coppice-rotations. The first harvest called initial rotation, producing second generation of stems called coppice. Featuring multi-stem plants, unlike long-rotation trees that are usually single-stem, successive coppice rotations produce higher yield than the initial rotation, although significant differences in performance are reported among Black cottonwood clones (Stettler, Hinckley, Bradshaw & Heilman, 1996).

1.1.4. Soil preferences and rooting

Black cottonwood has unusual ability to withstand short- and long-term flooding. Its tolerance of high water table gives the species a competitive advantage in areas with intermittently high water table against other, less adaptable tree species, e.g. spruce (*Picea* spp.) and Western red cedar (*Thuja plicata*) (Steinberg, 2001). Black cottonwood prefers riparian habitats and forms various size populations along rivers, streams and, sometimes, floodplains and terraces (Steinberg, 2001). Sites dominated by Black cottonwood are usually situated along moving water.

Black cottonwood is highly adaptable to various external conditions. It occurs on a range of medium- to fine-textured soils, from moist gravels and sands to rich humus and occasionally clay (Harvey, 1985, 5), with pH between 5 and 7.

On deep freely drained soils the rooting depth of trees of the *Tacamahaca* section is frequently observed to 3-5 m. The trees form deep seeking "sinker" roots that originate as horizontal roots and then change growth direction downward much like a taproot (Steinberg, 2001). Nevertheless, roots of Black cottonwood are usually shallow and spreading.

1.1.5. Climate, elevation and weather damage

Black cottonwood is very adaptable and grows in wide range of climatic conditions in the temperate zone (Fowells, 1965). It thrives in areas with coastal climate with temperatures averaging from -3°C in the coldest months to 22°C during summer, but also grows in both humid and dry continental climates of the northern hemisphere where average temperatures in different areas vary from -20°C during winter to 30°C in summer. Climate preferences include areas of diverse annual precipitation ranging from 150 to 3 500 mm, though avoiding very

humid coastal areas, e.g. coast of British Columbia. In North America the species is found at sea level and up to an elevation of 1300 – 2800 m (Steinberg, 2001).

Black cottonwood is susceptible to both late and early frosts and unseasonal frost during the growing season. In south Iceland late frost in April 1963 caused excessive damage to Black cottonwood originating from the Kenai Peninsula, Alaska. In Iceland shoot dieback due to early frosts are common. A notable example was of frost in mid September 1997 causing widespread damage to Black cottonwood trees in south Iceland. Unseasonal frosts in August 1993 and July 2009 caused shoot dieback especially in frost hollows and flat areas inland in south Iceland (Þorbergur H. Jónsson & Aðalsteinn Sigurgeirsson, 2008). Cold, strong winds and salt may cause scorching of leaves and shoot dieback. Deposition of marine aerosols during the dormant season is a common cause of shoot dieback in Black cottonwood in coastal areas in Iceland (Þorbergur H. Jónsson, 2011). Young trees of Black cottonwood are sensitive to abrasion due to sandstorms and blasting by ice particles in strong winds. Excessive snow load may cause snow breakage. Tall trees are exposed to storm breakage and due to their height, frequently loose big branches or the tree top suffering wind throw or stem breakage (Þorbergur H. Jónsson, 2011).

1.2. Black cottonwood in Iceland

1.2.1. Historical background

Black cottonwood was introduced to Iceland in 1944, when scions collected in Kenai Peninsula, Alaska by Vigfús Jakobsson arrived in Iceland. Vigfús was a forestry student in Seattle and went on two consecutive expeditions to the Kenai Lake (60°23'32°N, 149°34'24°W) area in Alaska in and 1943 1944 on request of Iceland Forest Service (Vigfús Jakobsson, 1947). During the latter expedition he collected genetic material near Seward, south of Kenai Lake. Scions were planted in Múlakot in Fljótshlíð (63°43'6.883"N; 19°52'34.37"W). At the time Múlakot was a forest nursery but today is functioning arboretum under the supervision of Iceland Forest Service. Genetic material collection continued during expeditions of 1947 by Vigfús Jakobsson to Cooper Landing near Kenai Lake (Vigfús Jakobsson, 1947), 1950 by Einar G.E. Sæmundsen when 30 000 cuttings were collected in Moose Pass near Kenai Lake on Kenai Peninsula (Einar G. E. Sæmundsen, 1952), and 1952 by Óli Valur Hansson and his colleagues who worked for the U.S. Forest Service in Alaska at the time (Þorbergur H. Jónsson, 1995). Jón Hallgrímur Jónsson and his brother Árni went on a private expedition in 1947 collecting seeds and scions in Alaska which he later planted in

Iceland (Ásta Camilla Gylfadóttir, 2010). These expeditions produced mostly scions with some amount of seeds collected primarily inland, far from the coast line. Taxonomically, collected material is believed to be crosses with Balsam poplar (*Populus balsamifera* L. ssp. *balsamifera*) which overlaps the Black cottonwood distribution range in abovementioned areas of southern Alaska.

In spring of 1963, hard frost set one of the biggest impediments to the Black cottonwood population in Iceland, when the species was killed to the ground over much of southern parts of the island. Temperatures dropped down to -14.1°C on April 11th and to -3.9°C on May 6th at Stórhöfði weather station, a mild offshore site in southern Iceland (Brynjar Skúlason, 2004).

New expeditions were organized soon after the event with an adjusted agenda considering climatic aspects of scion collection sites in Alaska and their fittingness to Icelandic weather conditions. In autumn 1963, Haukur Ragnarsson collected clones of Black cottonwood in 14 different locations (Þorbergur H. Jónsson, 1995) in Alaska, believed to be suitable for coastal south Iceland. Over two decades later, Óli Valur Hansson organized and led the Alaskan expedition of 1985 (Ágúst Árnason, Böðvar Guðmundsson & Óli Valur Hansson, 1986) which resulted in the largest collection of Black cottonwood scions over an extensive territory in southern Alaska and Canada. In 1980 and 1987 several clones of Black cottonwood were imported from Norway.

After the spring frost of 1963, criteria for collection of Black cottonwood clones changed, giving preference to hardy, more climate-resilient variations. Before 1963 there were no Black cottonwood clones sufficiently adapted to south Iceland's oceanic climate, today, clones originating from Copper River Delta, Alaska vegetate southern regions of Iceland. Leaf emergence in these clones occurs later compared to others, requiring more accumulated temperatures (Þorbergur H. Jónsson, 1995) thus the clones are less susceptible to late-winter thaws, and are more resilient in rough winds and salt-spray. Since the 1980-s introduction of new clones has almost ceased. Emphasis has been placed on obtaining suitable clones by crossings and breeding which resulted in a number of promising clones of Black cottonwood as well as very vigorous hybrids between Black cottonwood and Plains cottonwood (*Populus deltoides* ssp. *monilifera*) (Halldór Sverrisson, 2011).

1.2.2. Pests & pathogens

Contrasting native North American counterparts, Icelandic Black cottonwood population experiences much less attention from vermin and deseases. Young trees and seedlings may be host to caterpillars of July Highflyer (*Hydriomena furcata*) and Winter Moth (*Operophtera brumata*) but are seldom severely damaged by these. Out of 70 known vermin found on Black cottonwood worldwide, only few are found in Iceland, among these are *Polyporus delectans* and *Pholiota destruens* (Þorbergur H. Jónsson, 1995). In recent years, two new previously unknown to Iceland pathogens of cottonwood were discovered: in 2005, Brassy Willow Beetle (*Phratora vitellinae* (L.)) which was found on several tree species of *Salicaceae* family including Black cottonwood in surrounding woods at Mógilsá Forest Research Station (Erling Ólafsson, 2007), and *Melampsora larici-populina* - the causal agent of poplar leaf rust, first discovered in towns of Hveragerði and Selfoss, southern Iceland during the summer of 1999, and had since spread over vast surrounding territories. *Melampsora* rust effects differ among Black cottonwood clones depending on their age-related susceptibility to the disease. Pending further research, it may cause severe damage and death in certain circumstances (Jaspar Albers, Ólafur Eggertsson, Halldór Sverrisson & Guðmundur Halldórsson, 2006).

Black cottonwood attracts ruminants and birds throughout the year. Birds, including ravens, peck on shoots and damage young plants, thin stems breaking unable to support bird's weight. Sheep and horses, freely roaming the countryside during summer and sometimes winter seasons, present a threat to young trees susceptible to browsing damage (Þorbergur H. Jónsson, 1995).

1.3.   Utilization

1.3.1. General use of Black Cottonwood

In native North America, Black cottonwood has been used for many centuries by native tribes for dugout canoes and friction fire sets; its inner bark for soap production, and anti-infectant resin contained in buds is to this day used in natural ointments relieving cough and congestion (British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2010).

Today Black cottonwood has wide range of applications. The wood is light in weight and color, has fine texture and good nailing characteristics which makes it an excellent material for particle board, plywood, veneer and lumber. Considered of relatively low quality, it is widely used for concealed parts of furniture, pallets, boxes and crates. Black cottonwood coppice is used for pulp for tissue and high-grade book and magazine paper manufacturing

due to its fine short fibers. Fast growth and fine decorative value make Black cottonwood a good candidate for conservation, reclamation and ornamental plantings. Leftover material from pulp or timber processing can be converted to pelletized fuel for use in power stations and home heaters (Nesom & Henson, 2003). In the 1970-s, complete tree utilization concept for short-rotation Black cottonwood was proposed by Smith and DeBell (1973) in order to satisfy ever-growing demand for fibre-based products and alternative ways to obtain additional raw wood. Carlson and Berger (1998) demonstrated that 10 year old plantations of Black cottonwood used primarily for pulp, can be utilized as a timber source for variety of products from saw timber to decorative items depending on production costs, timber supply and market acceptance.

1.3.2. Icelandic timber market and the metallurgical industry

In Iceland Black cottonwood is a common garden tree and is increasingly planted in shelterwoods and commercial forests (Aðalsteinn Sigugeirsson, 2001). Use of local Icelandic timber is rather limited due to meager timber reserves. With settlement by Norsemen, Iceland's indigenous birch forests became nearly extinct due to excessive deforestation and exploitation for charcoal production together with continuous browsing by domestic animals, and, arguably, climate fluctuations (Wöll, 2008). Today Icelandic woodlands are either partially or completely man-made with few patches of natural birch forests remaining. Therefore, industrial use of such forests is inapplicable. Imported timber is currently the only realistic option for any large scale industrial wood utilization. High transportation costs are an important limitation for any industry that depends on wood as a raw material. For that reason, afforestation establishing local high-quality timber resource is a great alternative to expensive imported wood. In regard to Icelandic metallurgical industry this presents a massive setback for industry's expansion from ferro-silicon (FeSi75) and silicon-metal toward sought after high purity ferro-silicon (HP FeSi) and solar grade silicon (Si) production, hence Iceland's affordable sustainable energy that represents more than 20% of final product cost in other regions of the world (Þorbergur H. Jónsson, 2009a).

Manufacturing process of silicon-products, especially high-purity ferro-silicon and solar grade silicon requires presence of timber in carbon-source material mix consisting primarily of coal and coke given their accessibility and reasonable price. Timber quality and quantity differ among silicon-products. For instance, ferro-silicon needs only about 5% and silicon-metal about 25% of its carbon source to consist of wood chips. Ferro-silicon produced with low quality timber as a carbon source is used as a component in steel alloys and is tolerant to trace

element pollution in raw materials. One of Elkem Grundartangi ovens has been specifically modified for an unprecedented purpose of second-hand timber utilization supplied by Icelandic waste disposal company SORPA. High purity ferro-silicon production does not allow high proportion of impurities in raw materials, especially titanium (Ti), but is sufficed by barked timber or charcoal. Silicon-metal production requires much higher percentage of wood or charcoal, and is more sensitive to trace element content. Therefore, timber is debarked before chipping to minimize final product contamination with unwanted trace elements and maintain its high quality (Þorbergur H. Jónsson, 2009a). In order to expand production range to very cost-effective solar grade silicon manufactured only using highest-purity silicon-metal, virtually uncontaminated with trace elements carbon source is required. If local timber were used fort his purpose, proper handling during harvest and transportation must be ensured as contamination with rich in titanium (Ti) Icelandic soil may compromise trace element content of raw material and, as a result, lower the quality of final product. To meet industrial demand for local timber as a carbon source for high grade silicon production, medium length rotation forest plantations are a plausible option. Short-rotation plantings are less relevant due to specific technical aspects. For instance, certain stem size requirements have to be met if timber to be used as a carbon source in silicon production and be cost-effective (Þorbergur H. Jónsson, 2009b). In conclusion, industrial-oriented forests need to be highly productive generating continuous timber supply of certain stem size within sensible periods of time. As for tree species capable of delivering required results, selected clones of Black cottonwood had proven to be most suitable for long-rotation industrial plantations in southern Iceland – a key region within reasonable transportation range from the present Elkem Iceland Grundartangi facilities and a new silicon metal plant at Helguvík.

1.4. Stand density and rotation length

Black cottonwood is light-loving, competition-sensitive tree that, on good sites given appropriate treatment, demonstrates rapid growth and high stem diameter increment rates. A tradeoff exists between stand density, yield, tree size and rotation length (Savill & Evans 1986). Higher stand densities are required to maintain maximum yield at short rotations resulting in smaller tree dimensions. At the other end lower stand densities or successive thinning are required together with long rotations to obtain large tree sizes. Short rotations are employed where the main objective is bulk high fiber biomass used e.g. for pulp (Carlson & Berger, 1998) and as an energy source (DeBell, n.d.). Long-rotation plantations carry different exploitation perspectives, including saw timber, pulpwood for paper production, and other

industrial and decorative uses. Due to variable growth rates and crown development suitable spacing may differ among clones with respect to one or more of the following: target diameter, stand density, or rotation age (DeBell, Harrington, Clendenen, Radwan & Zasada, 1997). Maintaining high stand density throughout rotation allows for faster canopy closure, eliminating the need to otherwise suppress competing vegetation. This approach is important for species sensitive to competition from grasses and herbs (Niemec, Ahrens, Willits & Hibbs, 1995) during the establishment period, minimizing necessary weed control operations thus lowering initial plantation costs. Later in the rotation, moderate density helps reduce branchiness and forking, induces self-pruning and maintains required stem form (Niemec et al., 1995). Therefore spacing between trees has to be either initially sufficient or adjusted by thinning for each stage of the rotation in order to maintain high growth rates and maximize the final yield. Regular spacing is important for mechanized forest operations. As demonstrated by Perlack, Wright, Huston & Schramm (1995) harvesting of trees with larger (15.2 cm) stem diameter rather than smaller one (7.6 cm) proved to be more productive and cost efficient. Overall, spacing trials provide valuable data for appropriate design of commercial plantations, based on clone characteristics, site properties, climate and influential external aspects.

1.5.   Research questions

The aim of present research was to examine the relationship of density and aboveground biomass production of Black cottonwood grown for industrial purposes in climatic conditions of southern Iceland. In particular, Black cottonwood is a promising species for industrial timber plantations further used as a carbon source in manufacturing process of silicon alloys and silicon metal, high-purity ferro-silicones and solar silicon. The study is based on evaluation of a spacing experiment which is a part of a long term research project designed to explore wood production possibilities for the silicon industry in Iceland.

Plantation density influences on forest productivity aspects assessed in present thesis were expressed through following research questions in regard to Black cottonwood:

Do different spacing treatments affect and how do they affect:

1. total aboveground biomass production?
2. a) bark b) sapwood and c) heartwood ratios?
3. branch mass ratio (BRM) and therefore on commercially valuable wood production?

2. Materials & Methods

2.1. Site description

The spacing experiment that is the subject of present thesis is located in Sandlækjarmýri research forest (64° 3.005'N, 20°22.231'W 73) see Figure 3. With a total area of 85 ha, it is situated at Gnúpverjahreppur, south Iceland. The research forest is divided into two parts 17 ha of planned experiments and 68 ha of trial forest for operations research. It is part of a 5-year Industrial Timber Project, approved by the Icelandic government in July 1989 (Thorbergur H. Jónsson, 2011). Project was an interactive collaboration of forest scientists and forestry farmers in an attempt to create and develop the basis for poplar timber production models designed to satisfy industrial timber demand of Elkem Iceland ferrosilicon plant at Grundartangi (Þorbergur H. Jónsson & Jón G. Ottósson, 1989). The research forest was designed and planted by employees of Forest Research, Mógilsá on previously drained homogeneous flat moorland.

Sandlækjarmýri area is known to be frost-prone during the growing season. Over the years, three major shoot dieback incidents took place in the plains of south Iceland: in August 1993, mid-September 1997 (Thorbergur H. Jónsson & Úlfur Óskarsson, 2007) and July 2009.

Figure 1. Biomass team in Sandlækjarmýri research forest. From left: Lena Mikaelsson, Ingvar Örn Magnússon and Sigurður Geirsson.

Figure 2. Black cottonwood trees in the Sandlækjarmýri experimental forest.

2.2. Experiment setup

Random block design (Jayaraman, 1999) was employed in present experiment with five replications of eight spacing treatments; 1) 0.5 x 0.5 m, 2) 0.5 x 1.0 m, 3) 1.0 x 1.0 m, 4) 1.0 x 1.5 m, 5) 1.0 x 2.0, 6) 2.0 x 1.5 m, 7) 2.0 x 2.0 m and 8) 3.0 x 3.0 m (Table 1). The treatment plots were randomly located within each of the five blocks (Table 2).

During early spring of 1991 the spacing trial area (Figure 4) was ploughed, rotavated twice and divided into total of five blocks of eight 20x20 m plots (400 m2), forming continuous 1.6 ha rectangle shaped tract oriented NE-SW lengthwise (see Table 3 for geographic coordinates of the experiment). The south west corner of the rectangle was assigned as Block and Plot number 1, continuing block numbering in NW and plot numbering in SE directions respectively (Table 2).

The spacing trial is monoclonal; composed of Black cottonwood clone 'Iðunn', Iceland Forestry research number 63-10-002 (Líneik Anna Sævarsdóttir & Úlfur Óskarsson, 1990).Plantation took place in July 1991 using artificially propagated (Úlfur Óskarsson, Thorbergur H. Jónsson & Kristján Þórarinsson, 1990) plants of Black cottonwood. In June-July of 1992 all dead plants were replanted. Fertilizers were applied to the entire area during spring of 1993, consisting of 80 kg triple phosphate ($Ca(H_2PO_4)_2$) and 75 kg potassium sulfate (KSO_4) per hectare.

Table 1. Treatment number, spacing between rows and between trees within rows, number of trees per plot and equivalent stand density per hectare.

Treatment	Spacing	Trees plot^{-1}	Trees ha^{-1}
1	0.5 x 0.5 m	1,600	40,000
2	1.0 x 0.5 m	800	20,000
3	1.0 x 1.0 m	400	10,000
4	1.0 x 1.0 m	267	6,667
5	1.0 x 2.0 m	200	5,000
6	2.0 x 1.5 m	133	3,333
7	2.0 x 2.0 m	100	2,500
8	3.0 x 3.0 m	44	1,111

Table 2. Location of treatment plots within blocks. Plots identified by Arabic numerals c.f. table 1 are shown in a sequence indicated by upper case letters. The arrow indicates geographic north.

Block	Plot (alphabetical sequence)								
No.	A	B	C	D	E	F	G	H
V	5	2	8	6	3	7	1	4
IV	8	2	5	3	4	6	1	7
III	3	2	1	7	6	4	8	5
II	2	6	5	3	4	7	8	1
I	7	6	4	2	3	1	8	5

N

Figure 3. Sandlækjarmýri experimental forest. Points and reference numbers indicate permanent yield plots by the Icelandic National Forest Inventory. Map: Björn Traustason, Iceland Forest Research, Mógilsá.

Figure 4. Location of spacing experiments in Sandlækjarmýri experimental forest. The spacing experiment reviewed in present thesis is demarcated by the points forming a rectangle to the left (West). Map: Björn Traustason, Iceland Forest Research, Mógilsá.

Table 3. Geographic coordinates of the Sandlækjarmýri spacing experiment.

Latitude	Longitude
64°2'43,662"N	20°22'16,719"W
64°2'40,921"N	20°22'6,955"W
64°2'43,596"N	20°22'2,799"W
64°2'46,405"N	20°22'12,492"W

2.3. Field measurements

2.3.1. Plot density

Trees of each plot were counted using a common convention, starting from SE corner moving toward NW corner proceeding up and down every second planting row (Figure 5). Living trees at the plot border were counted individually. Living and dead trees were counted separately in order to establish survival rate. All measurements were standardized according to Philip (1983).

A tree was selected randomly for biomass studies based on the count of living trees excluding the trees at the plot border by equation 1:

$$M_j = (R_N C) + 0.5, \tag{1}$$

Where:

M_j = sample tree identification number in plot j

R_N = random number generated by Microsoft Excel Random Number Generator

C = number of living trees counted from the starting point at the SE corner of the plot, excluding trees at the plot border (Figure 5)
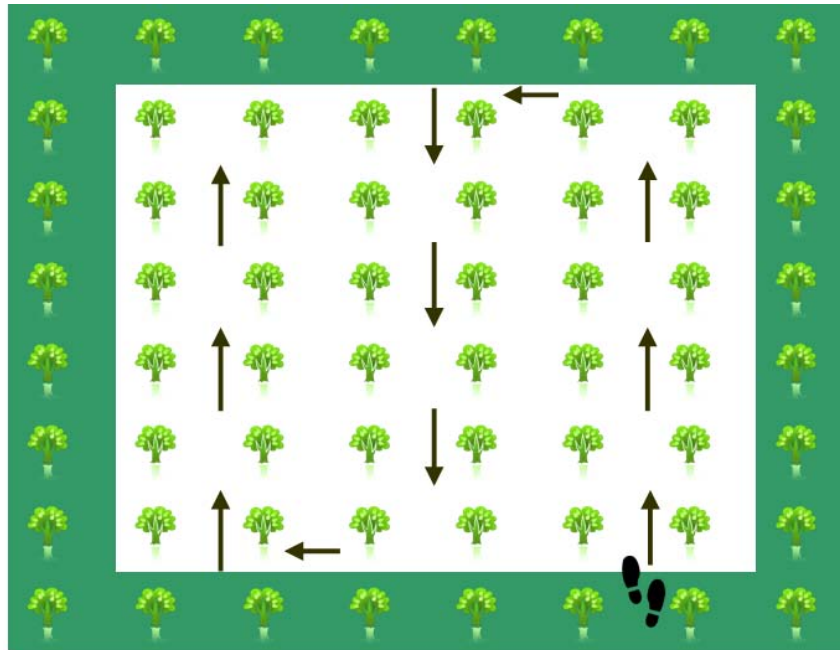

Figure 5. Counting convention used to enumerate the population for selection of random candidate tree for sampling. The trees were enumerated from the SE corner progressing toward the W corner by going up and down every second row. Living trees at the plot borders were enumerated separately.

2.3.2. Position of competitor trees

The distance (m_i) between the sample tree (M) and the eight closest trees (T_i) surrounding the sample tree was measured. The measurements were conducted in a clockwise sequence starting with the closest tree in the north east direction and in the same planting line as the sample tree (T_1). The distance between the eight surrounding trees (b_i), the diameters at 25 and 130 cm elevation from the ground were also recorded (Figure 6). At each position on every measured tree two diameters were measured with a caliper and recorded to the nearest millimeter. The first diameter was recorded in the general direction of the planting line (north east to south west) and the second diameter perpendicular to the first. All measurements were recorded in centimeters between the centre points of each tree at ground level. In the ideal case of no mortality T_1 and T_5 were the closest trees in the same planting line as sample tree M, trees T_2, T_3 and T_4 were in the closest planting line to the south east of the sample tree and trees T_6, T_7 and T_8 in the closest planting line to the north west of the planting line of the sample tree. In the case any of the original closest trees were dead or missing the next tree in the general direction of the missing tree from the sample tree was selected as a new tree for that position.
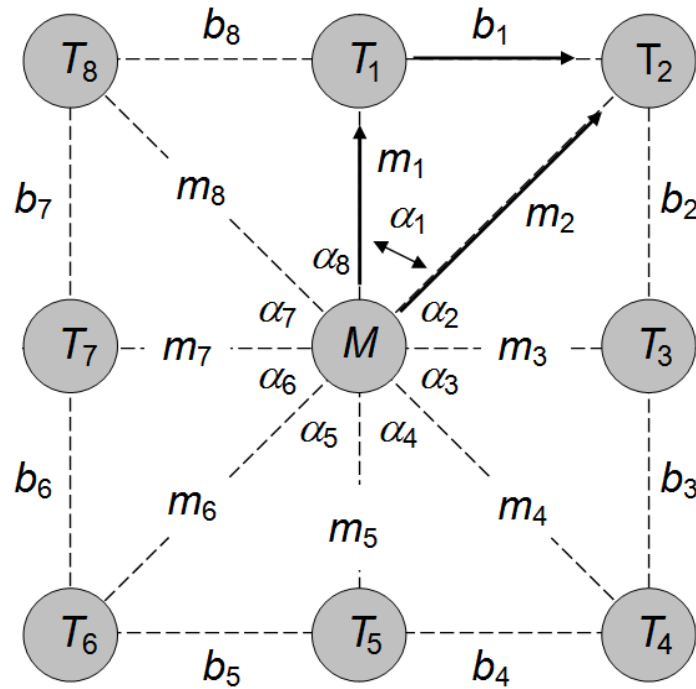

Figure 6. Layout of the measurement sequence for eight trees surrounding the selected sample tree.

2.3.3. Measurements on sample trees

Sample tree (M_j) was tagged with a color dot at 25 cm above ground for reference in subsequent stem length measurements and then the tree was cut approximately 10 cm above ground. Stem length was measured on the felled tree from 25 cm mark to the base of the living crown. Crown base was defined as the lowest branch with live foliage excluding small epicormic shoots. Total tree length was measured by two consecutive methods; 1) as a straight line from 25 cm mark to the tip of the top shoot taking care that the measuring tape was tight and 2) following the contours of the tree stem from 25 cm mark to the tip of the top shoot. Tree length measurements were performed with a steel measuring tape recording to the nearest centimeter.

In case the tree had multiple stems, the lesser stems were cut and weighted and recorded separately. Also, if the tree had forking of the main stem, lesser stems were cut and weighted and recorded individually.

The tree crown was divided into thee sections of equal length and the limits for each section derived by equation 2 and marked on the tree stem:

$$l_{cq} = l_b + \left(\frac{l_{t2} - l_b}{3}\right)(q-1),$$ (2)

Where:

l_{cq} = length along the stem (m) from the 25 cm mark at the stem base to the base of crown section q (integer numbers 1, 2 and 3 for lowest, middle and top sections of the crown respectively)

l_b = length from the 25 cm mark to the crown base (m)

l_{t2} = tree length from the 25 cm mark at the stem base to the tip of the tree measured along the stem profile (m)

One randomly located branch was sampled in each of the three elevation sections of the crown. Location of each sample branch as obtained by equation 3:

$$b_q = \left(R_N \left(\frac{l_{t2} - l_b}{3} \right) \right) + l_{cq} \, , \qquad\qquad (3)$$

Where:

b_q = position of sample branch in crown section q defined as the distance to the branch along the stem contour from the 25 cm mark at the stem base

R_N = defined in legend to equation 1

l_q = length along the stem (m) from the 25 cm mark at the stem base to the base of crown section q derived by equation 1

l_b and l_{t2} = see legend to equation 1

Each sample branches was cut flush to the stem, weighted, tagged and placed separately in a sealed and airtight polythene bag for laboratory analysis. The remaining live branches from each crown section separately were cut flush to the stem and weighted. All dead branches and necrotic twigs were cut from the stem and pooled for the whole tree and weighted. A sample of one dead branch was selected haphazardly and contained in a sealed, airtight and labeled polythene bag for laboratory analysis.

Leaves remaining on buds on the stem and live epicormic shoots below the crown base were cut from the stem and weighted together with any leaves that had fallen to the ground during the tree sectioning process.

Two random points A and B were marked on the tree stem for sections used in analysis of wood and bark properties, only the results for section A are reported herein. Random points were located based on the diameters of the tree at 25 cm calculated by equation 4:

$$d_{Rt} = \sqrt{R_N \left(\frac{d_{25a} + d_{25b}}{2} \right)^2} \, ,$$

(4)

Where:

d_{Rt} = stem diameter (cm) at random point along the stem for section sample t, where t identifies sample A

R_N = see legend to equation 1

d_{25a} = diameter (cm) measured at the 25 cm mark in the perpendicular direction a (see measurements before cutting)

d_{25b} = diameter (cm) measured at the 25 cm mark in the perpendicular directions b (see measurements before cutting)

π = Pythagoras number ($\pi \approx 3.1415$)

The stem was sawn in about 3 cm sections at the marked random points along the stem, sections weighted, labeled and put in sealed polythene bags for laboratory analysis. The branch and stem section samples contained in airtight polythene bags were stored in a cooled room maintained at constant +4°C until laboratory analysis.

2.4. Laboratory measurements

Random sections A were weighted (g wet mass) and their volume measured by xylometry (water displacement) (Chave 2005, West 2009). The disks were briefly submerged in a container with water on a balance, recording the increased mass as the sections were completely submerged. Needles were used to hold the sections sunken. The sections were only held submerged for few seconds to avoid significant infiltration of water from the water bath into the wood matrix. Then random sections A were split into bark, sapwood and heartwood using as necessary hammer and chisel. The bark, sapwood and heartwood pieces were weighted (g wet mass) and placed separately in labeled paper bags.

The sample branches from the upper, middle and lower crown sections as well as the samples of dead branches were weighted separately with and without the polythene bags within which

the branches had been stored. The weight (g wet mass) of each primary and secondary branch, long shoots, leaves on long and short shoots were recorded separately.

The samples of branches including both live and dead branches separately, long shoots and leaves were placed in labeled paper bags.

Samples of wood sections A, as well as of branches and leaves were dried in a fan ventilated convection oven at 85°C for 72 hours or until constant weight was achieved. Samples were periodically removed from the oven and reweighed in order to determine if constant moisture contents had been achieved. When the drying process was complete, the samples were removed from the oven and cooled in a desiccator lined with desiccant. When cool, samples were weighed swiftly on a balance recording the mass to 0.0001g precision (g dry mass) to avoid hydration from the air moisture.

2.5. Calculations

2.5.1. Stand density

Growing space per tree was expressed as stand density (number of live trees per hectare) and as the horizontal land areas occupied by the trees (m^2). Two measures of stand density expressed as numbers of trees per unit land area (ha^{-1}) were evaluated; 1) nominal density (N_1) and 2) point density (N_3). Two expressions of space per tree (m^2) were assessed; 1) area potentially available (A_2) and adjusted area potentially available (A_3).

Nominal density (N_1) is the initial density of the treatment plots, i.e. the designated treatment density. Nominal density was derived from tree spacing by equation 5:

$$N_1 = \left(\frac{100}{s_a}\right)\left(\frac{100}{s_b}\right),$$

(5)

Where:

N_1 = nominal stand density (ha^{-1})

s_a = average distance between trees in the planting line (m)

s_b = average distance between planting lines (m)

Point density (N_3) was the observed stand density immediately surrounding the sample tree at the time of sampling (20 years from planting), i.e. the density as experienced by the sample tree. The centre points of the eight closest surrounding trees form a polygon surrounding the sample tree. It can be shown that this polygon encompasses four trees. In the case of a perfect square tree spacing, the trees include the sampling tree, half of four trees and a quarter of four trees. In the case of less perfect spacing the sum of all sectors of the basal area of the surrounding trees that are within the polygon would be three and the total number of trees would be four including the sample tree. Hence, the point density of the stand by the sample tree was estimated by equation 6:

$$N_3 = \frac{40000}{A_0},$$ (6)

Where:

N_3 = stand density (ha^{-1}) immediately surrounding the tree (point density)

A_0 = area within the polygon formed by the centre points of the eight surrounding trees (calculated by equation 7).

The sample tree and each pair of closest trees form a triangle with the corner points M, T_i and T_{i+1} and the sides m_i, m_{i+1} and b_i (Figure 6). The centre points of the eight surrounding trees (T_1, T_2, T_3, T_4, T_5, T_6, T_7 and T_8) form a polygon composed of eight triangles. Heron's formula was used to calculate the areas of each triangle and the result summed to derive the total area of the polygon (Equation 7):

$$A_0 = \sum_i^8 \frac{1}{4} \sqrt{\left(m_i^2 + m_{i+1}^2 + b_i^2\right)^2 - 2\left(m_i^4 + m_{i+1}^4 + b_i^4\right)},$$ (7)

Where:

A_0 = area of a polygon (m^2) formed by the centre points of the eight closest trees surrounding the sample tree and composed of eight triangles between these points and the sample tree

m_i = distance between the sample tree and the nearest tree i (Figure 6)

b_i = distance between the sample tree and nearest tree $i+1$ (Figure 6)

Area potentially available (A_2) is the space occupied by a tree in a forest of continuous crown cover. The areas of polygons derived by partitioning of the distances between respective trees by their relative basal areas are generally good indicators of the effective growing space occupied by the trees. In the case of canopy closure the radial distance from the sample tree to its nearest surrounding eight neighboring trees was partitioned between the respective trees by equation 8:

$$m_{ai} = m_i \frac{g_M}{g_M + g_i}, \tag{8}$$

Where:

m_{ai} = segment length (m) attributed to sample tree M along the radial distance (m_i) between sample tree M and its nearest neighbor T_i

g_M = basal area (m^2) of tree M

g_i = basal area (m^2) of tree T_i

The cosine law was used to estimate the angle α_i subtended between the two sides of m_i and m_{i+1} (Equation 9, Figure 6):

$$\alpha_i = \arccos \frac{m_{ai}^2 + m_{ai+1}^2 + b_i^2}{2m_{ai}m_{ai+1}}, \tag{9}$$

Where:

b_i = the distances between the sample tree and the nearest tree i and nearest tree $i+1$ respectively (Figure 6)

m_i = see legend to equation 8

The sum of the eight angles between the sample tree and the eight closest surrounding trees should be 2π radians. A correction factor to account for measurement errors was thus applied to all the angles derived by equation 9 (Equation 10):

$$\alpha'_i = \alpha_i \frac{2\pi}{\sum\limits_i \alpha_i}, \tag{10}$$

Setting the radii derived by equation 8 in the direction of the nearest neighbor tree (T_i) as the distance (m_{ki}) and applying the same numbering convention as before, the distance (b_{ai}) between the two adjacent points on the tree perimeter was estimated by the cosine law (Equation 11):

$$b_{ai} = \sqrt{m_{ai}^2 + m_{ai+1}^2 - 2m_{ai}m_{ai+1}\cos\alpha'_i}, \tag{11}$$

The area potentially available (A_2) then estimated by Heron's formula (Equation 7, substituting A_2, m_{ai}, m_{ai+1} and b_{ai} for A_0, m_i, m_{i+1} and b_i respectively).

Adjusted area potentially available (A_3). In the case of incomplete canopy closure the area potentially available as derived by Voronoi tessellation would overestimate the share of the subject tree in the forest canopy. Therefore, the measured crown radii were set as the maximum extent of radii m_{ai} defining the growing space by the logical expressions below (Equations 12 and 13):

$$c_i + k_m d_{Tji} \leq m_i \Rightarrow m_{ai} = m_i \frac{g_M}{g_M + g_i} , \tag{12}$$

$$c_i + k_m d_{Tji} > m_i \Rightarrow m_{ai} = c_i , \tag{13}$$

Where:

c_i = length of crown radii of sample tree M to the crown perimeter in the direction of nearest neighbor tree T_i

d_{Tji} = diameter (cm) of nearest neighbor tree i surrounding sample tree j

m_i, m_{ai}, g_M and g_i = see legend to equation 8

k_m = maximum crown ratio estimated by equation 14:

$$k_m = \frac{\sum\limits_{j}^{n} \dfrac{c_{mj}}{d_{gj}}}{n} , \tag{14}$$

Where:

k_m = average maximum crown ratio

c_{mj} = maximum crown extent of tree j (m)

d_{gj} = diameter of sample tree j derived from cumulative basal areas 1.3 m above ground of all stems of that tree (cm)

subscript m = maximum value

subscript g = derived from basal area

subscript n = total number of trees

The third side (b_{ai}) of a triangle (m_{ai}) and (m_{ai+1}) was calculated for each of the eight triangles by the cosine law and the area within the perimeter, i.e. adjusted potentially available area (A_3), by cumulative Heron's formula (Equation 7) as described for unadjusted area potentially available above.

2.5.2. Survival

Survival rate (*SR*) was estimated by average plot survival derived by equation 15:

$$SR = \frac{N_3}{N_1},$$ (15)

Where:

SR = average plot survival rate ($0 \leq SR \leq 1$)

N_3 = point density (ha^{-1}) derived by equation 6

N_1 = nominal density (ha^{-1}) derived by equation 5

2.5.3. Height

Tree height (*h*) was defined as the straight line from the centre of the tree stem at ground level to the tip of the top shoot and derived by equation 16:

$$h = l_{t1} + l_{t2},$$ (16)

Where:

h = tree height (m)

l_{t1} = straight line length (m) of the stump to the 25 cm mark

l_{t2} = straight line length (m) of the stem from 25 cm mark

2.5.4. Diameters

Stem diameter at breast height (*d*) at 1.3 m above ground is a reference diameter used in forestry and forest science (Philip, 1983). It was derived from two perpendicular measurements of diameters on the sample tree by equation 17:

$$d_{130} = \frac{d_{130A} + d_{130B}}{2},$$ (17)

Where:

d_{130} = diameter at breast height (130 cm above ground)

d_{130A} = measured diameter at breast height in the SW-NE perpendicular direction

d_{130B} = measured diameter at breast height in the SE-NW perpendicular direction

The trees hand in many cases multiple stems at 1.3 m above ground. A combined diameter at breast height was derived by equation 15 from the cumulative basal area of all stems at breast height:

$$d = \sqrt{\frac{4\sum_{i}^{n} \pi \frac{\left(\frac{d_{130Ai} + d_{130Bi}}{2}\right)^2}{4}}{\pi}},$$ (18)

Where:

d = diameter (cm) derived from cumulative basal area of all stems 1.3 m above ground

d_{130Ai} and d_{130Bi} = measured diameters (cm) at 1.3 m above ground of stem i of n stems

π = Pythagoras constant ($\approx$ 3.1415)

2.5.5. Stand basal area

Stand basal area (*G*) is the cumulative cross sectional area per hectare of all stems 1.3 m above ground. Stand basal area was estimated from measured diameters of all stems on a sampling tree and unadjusted area potentially available (*A₂*) by equation 19:

$$G = 10.000 \frac{\sum_{i}^{n} \pi \left(\frac{d_{130Ai} + d_{130Bi}}{200} \right)^2}{A_2}, \tag{19}$$

Where:

G = stand basal area (m^2 ha^{-1}) based on unadjusted potentially available area

d_{130Ai} and d_{130Bi} = measured diameters (cm) at 1.3 m above ground of stem i of n stems

π = Pythagoras constant (≈ 3.1415)

A_2 = unadjusted area potentially available

2.5.6. Volume

Volume of the main stem (*V*) was estimated from dry mass and average dry bulk density (equation 20):

$$V = \frac{DMst}{\frac{1000 \sum_{j}^{n} b_j}{n}}, \tag{20}$$

Where:

V = volume of main stem of sampling tree j

$DMst$ = stem dry mass (kg) of tree j derived by equation 22

b_j = dry bulk density of tree j

n = number of sample trees

Stand volume (*V₁*) was estimated from volume of main stem (equation 17), basal areas of the main stem and all stems on the sample tree and unadjusted potentially available area by equation 21:

$$V_1 = \frac{10{,}000 \left(\dfrac{\sum\limits_{i}^{n}\left(d_{130Ai} + d_{130Bi}\right)^2}{\left(d_{130A} + d_{130B}\right)^2} \right) V}{A_2}, \tag{21}$$

Where:

V_1 = standing volume (m^3 ha^{-1})

d_{130Ai} = measured diameter (cm) 1.3 m above ground in direction *A* of stem *i* of *n* stems

d_{130Bi} = measured diameter (cm) 1.3 m above ground in directions *B* of stem *i* of *n* stems

d_{130AMj} = measured diameter (cm) 1.3 m above ground in direction *A* of sample tree *M$_j$*

d_{130BMj} = measured diameter (cm) 1.3 m above ground in direction B of sample tree M$_j$

A_2 = area potentially available

V = see legend to equation 20

2.5.7. Biomass

Stem dry mass (*DMst*) was estimated from wet mass and the dry mass ratio derived from random wood sample *A* (equation 22):

$$DMst = \left(\frac{w_{DB} + w_{DR} + w_{DK}}{w_{WB} + w_{WR} + w_{WK}} \right) \sum_{i}^{n} w_{si}, \tag{22}$$

Where:

DMst = stem dry mass (kg DM)

w_{DB} = dry mass of bark

w_{DR} = dry mass of sapwood

w_{DK} = dry mass of heartwood

w_{WB} = wet mass of bark

w_{WR} = wet mass of sapwood

w_{WK} = wet mass of heartwood

w_{si} = wet mass of stem section *i*, counting from the stem base to the tree top (section *n*)

Dry mass of living branches in the crown was estimated separately for the upper third, middle and lower third of the tree crown and the summed to obtain the total branch mass for the tree by equation 23:

$$w_{DG} = w_{DE} + w_{DM} + w_{DN}, \qquad (23)$$

Where:

w_{DG} = dry mass of living branches excluding leaves on the tree

w_{DE}, w_{DM} and w_{DN} = dry mass of branches excluding leaves in the upper third, middle third and lower third of the tree crown

The dry mass of w_{DE}, w_{DM} and w_{DN} was estimated by equations 24, 25 and 26 respectively:

$$w_{DE} = \left(a - b\sqrt{N_1}\right)f_D w_{WE}, \qquad (24)$$

Where:

w_{DE} = dry mass (kg DM) of branches in the top third of the canopy

N_1 = nominal density (ha^{-1})

f_D = ratio of dry mass to branch mass in the upper third of the canopy derived as the average value for random sample branches from the top third of the canopy

w_{WE} = wet mass of branches in the top third of the canopy

a and b = constants (a = 0.5451, b = 0.0013, N = 12, R^2 = 0.659) estimated with least square linear regression of wet mass ratio of branches and shoots to total branch mass (branches, shoots and foliage) in the upper third of the crown on square root of nominal density):

$$w_{DM} = f_{Mc} f_{DM} w_{WE}, \qquad (25)$$

Where:

w_{DM} = dry mass (kg DM) of branches in the middle third of the canopy

f_{Mc} (value 0.61) = ratio of branches without leaves to branches with leaves (wet mass) to branch mass in the middle third of the canopy

f_{DM} (value 0.49) = ratio of dry mass to branch mass in the middle third of the canopy

w_{WE} = wet mass of branches in the lower third of the canopy

$$w_{DN} = \left(a - b\sqrt{N_1}\right)\left(c - d\sqrt{N_1}\right)w_{WN}, \qquad (26)$$

Where:

w_{DN} = dry mass (kg DM) of branches in lowest third of the canopy

N_1 = nominal density (ha^{-1})

a, b = constants derived by least square linear regression of wet mass ratio of branches and shoots to total branch mass (branches, shoots and foliage) in the lowest third of the crown on square root of nominal density ($a = 0{,}817$, $b = 0{,}0008$, $N = 12$, $R^2 = 0{,}327$)

c, d = constants derived by linear regression of ratio of dry mass to wet mass of branches in the lowest third of the canopy

Dry mass of dead branches was estimated by equation 27:

$$w_{DD} = f_D w_{WD}, \qquad (27)$$

Where:

w_{DD} = dry mass of dead branches

w_{WD} = wet mass of dead branches

f_D = ratio of dry mass to wet mass of dead branches estimated as 0.7 from samples of dead branches

Dry mass of major branches (stem forks) in the canopy was estimated from measurements of wet and dry mass for stems and branches by equation 28:

$$w_{DO} = \left(\frac{DMst + w_{DE} + w_{DM} + w_{DN}}{w_{WS} + w_{WE} + w_{WM} + w_{WN}}\right)w_{WO}, \qquad (28)$$

Where:

w_{DO} = dry mass of major branches

w_{WO} = wet mass of major branches

for other variables see legends to equations 24, 25 and 26

Dry mass of other stems of the sampling tree was estimated in analogy to dry mass of major branches by equation 29:

$$w_{DP} = \left(\frac{w_{DS} + w_{DE} + w_{DM} + w_{DN}}{w_{WS} + w_{WE} + w_{WM} + w_{WN}} \right) w_{WP}, \qquad (29)$$

Where:

w_{DP} = dry mass of other stems with branches

w_{WP} = wet mass of other stems with branches

for other variables see legends to equations 24, 25 and 26

Total tree above ground biomass (DMtrTOT) was the sum of stem (*DMst*), branches in the upper (w_{DE}), middle (w_{DM}) and lower (w_{DN}) thirds of the crown, major branches (w_{DO}), other stems (w_{DP}) and dead branches (w_{DD}) attached to the tree derived by equations above.

2.5.8. Standing dry mass

Total above ground biomass (*M*) (tDM ha^{-1}) in stems and branches was estimated by equation 30:

$$M = \frac{10 DMtrTOT}{A_{2j}}, \qquad (30)$$

Where:

M = above ground biomass (tDM ha^{-1}) in stems and branches estimated based on sample tree *j* (kg)

DMtrTOT = above ground biomass of sample tree *j* (kg)

A_2 = unadjusted potentially available area of tree *j*

2.5.9. Dry bulk density, branch, bark and sapwood ratios

Live branch ratio (*LGRH*) was estimated as the ratio of dry mass of live branches without leaves to total above ground biomass of the tree without leaves (stems and branches) by equation 31:

$$LGRH = \frac{w_{DG}}{w_{DG} + DMst},$$ (31)

Where:

LGRH = live branch ratio

w_{DG} = dry mass of branches without leaves

DMst = stem dry mass

Bark ratio (*BRKH*) was estimated by equation 32:

$$BRKH = \frac{b_{DB}}{w_{DB} + w_{DR} + w_{DK}},$$ (32)

Where:

BRKH = bark ratio (dry mass ratio of bark to total dry mass of stem section with bark)

w_{DB} = dry mass of bark

w_{DR} = dry mass of sapwood

w_{DK} = dry mass of heartwood

Sapwood ratio (RYSH) was estimated by equation 33:

$$RYSH = \frac{w_{DR}}{w_{DR} + w_{DK}},$$ (33)

Where:

RYSH = sapwood ratio

For other variables see legend to equation 32

Dry bulk density was estimated from samples of sections A by equation 34:

$$f_{DBD} = \frac{w_{DB} + w_{DR} + w_{Dk}}{u_j},$$ (34)

Where:

f_{DBD} = dry bulk density of wood section *A* from tree *j*

w_{DB} = dry mass of bark

w_{DR} = dry mass of sapwood

w_{DK} = dry mass of heartwood

u_j = volume of section *A* from tree *j* measured by water displacement

2.6.   Statistical analysis

Analysis of variance and linear contrasts with survival rate as a covariate were used to compare density and chosen aboveground biomass parameters between 8 different treatments. Relationships were estimated using ANOVA analysis and non-parametric Kruskal-Wallis test for ratios. The data were analyzed with the STATISTICA software, Kernel release 5.5 A, © 1984 – 1999 by StatSoft, Inc. Models were fitted to relationships by SigmaPlot 2000 for Windows Version 6.10. © 1986-2000 SPSS Inc.

3. Results

3.1. Stand characteristics

Survival rate (SR) did not vary significantly between treatments (Kruskal-Wallis H (7, $N = 39$) $= 6.851$, $P = 0.446$) as shown in Table 4. Tree height (h), tree diameter at breast height (d) and total basal area per hectare (G) varied significantly between treatments (h: $F_{7,30} = 2.587$, $P = 0.033$; d: $F_{7,30} = 9.936$, $P < 0.001$; G: $F_{7,30} = 13.187$, $P < 0.001$). Tree height and tree diameter at breast height decreased with increasing stand density (h: linear trend: $F_{1,30} = 10.655$, $P = 0.003$, Figure 7, B; d: linear trend: $F_{1,30} = 66.199$, $P < 0.001$, Figure 7A. Stand basal area increased significantly with stem density (G: linear trend: $F_{1,30} = 86.993$, $P < 0.001$, Figure 7C) to a maximal value, asymptote $a = 32.859 \pm 1.376$ m^2 (value $\pm$ SE), $t_7 = 23.886$, $P < 0.001$, Figure 7C).

Table 4. Survival rate (SR), dead branch ratio ($DGRH$), bark ratio ($BRKH$) and sapwood ratio ($RYSH$) by the 8 spacing treatments and Kruskal-Wallis test H with degrees of freedom and number of observations within bracket and P-level (H, P-value).

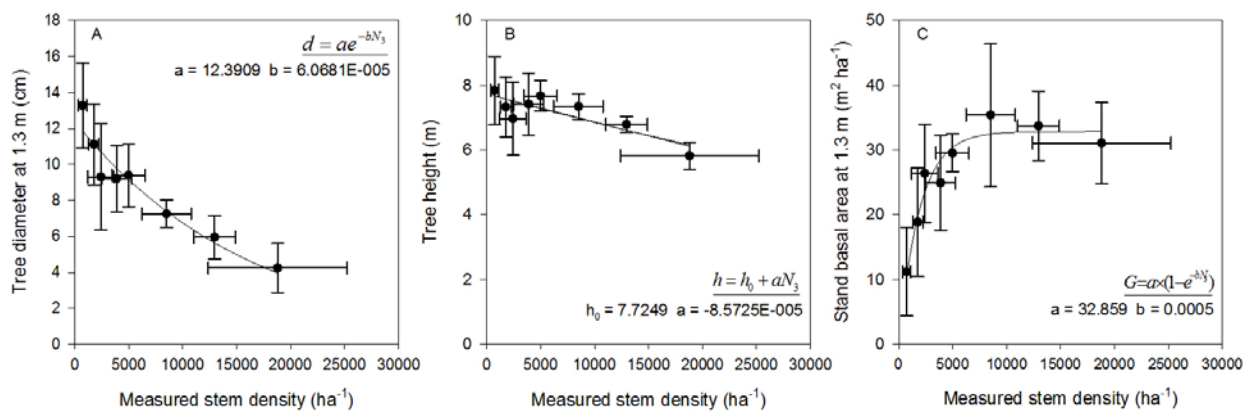| Tree parameters	Spacing (m)								
	0.5x0.5	1x0.5	1x1	1x1.5	1x2	2x1.5	2x2	3x3	H, P-value
Survival rate	0.47	0.65	0.85	0.75	0.77	0.72	0.70	0.66	H (7, N = 39) = 6.85 P = 0.445
Dead branch ratio	0.10	0.09	0.11	0.09	0.09	0.06	0.07	0.01	H (7, N = 39) = 13.06 P = 0.07
Bark ratio	0.15	0.12	0.16	0.11	0.11	0.12	0.12	0.11	H (7, N = 40) = 5.48 P = 0.602
Sapwood ratio	0.90	0.74	0.93	0.70	0.69	0.71	0.81	0.78	H (7, N = 40) = 9.99 P = 0.188

Figure 7. Relationships between measured stem density per hectare (N_3) and (A) tree diameter at 1.3 m (d) above ground, (B) tree height (h) and (C) stand basal area at 1.3 m (G).

Growing space expressed as Adjusted area potentially available (A_3) stem volume (V), stem dry biomass ($DMst$), total tree biomass without leaves ($DMtrTOT$), tree biomass without leaves and necromass ($DMtrLIFE$) varied significantly between treatments, decreasing with increasing stem density (A_3: $F_{7,30} = 17.224$, $P < 0.001$, linear trend: $F_{1,30} = 100.19$, $P < 0.001$, quadratic trend: $F_{1,30} = 19.072$, $P < 0.001$, Figure 9C; V: $F_{7,30} = 5.568$, $P < 0.001$, linear trend: $F_{1,30} = 34.551$, $P < 0.0\,01$, Figure 9A; $DMst$: $F_{7,30} = 5.568$, $P < 0.001$, linear trend: $F_{1,30} = 34.551$, $P < 0.001$, Figure 9E; $DMtrTOT$: $F_{7,30} = 5.755$, $P < 0.001$, linear trend: $F_{1,30} = 34.393$, $P < 0.001$, Figure 9D; $DMtrLIFE$: $F_{7,30} = 8.071$, $P < 0.001$, linear trend: $F_{1,30} = 48.183$, $P < 0.001$, quadratic trend: $F_{1,30} = 4.327$, $P = 0.046$, cubic trend: $F_{1,30} = 4.28$, $P = 0.047$, Figure 9B). Stem and branch biomass (M) and standing volume (V_1) increased significantly with stem density (M: $F_{7,30} = 4.667$, $P < 0.001$, linear trend: $F_{1,30} = 28.064$, $P < 0.001$, Figure 9F; V_1: $F_{7,30} = 4.468$, $P < 0.001$, linear trend: $F_{1,30} = 27.197$, $P < 0.001$, Figure 8). Stem and branch biomass increased to a maximal value (asymptote a: $a = 61.001 \pm 3.767$ m^2 (value $\pm$ SE), $t_7 = 16.195$, $P < 0.001$, Figure 9F). Dead branch ratio ($DGRH$) did not differ significantly between treatments (Kruskal-Wallis test: H (7, $N = 39$) = 13.055 $P < 0.071$, Table 4.
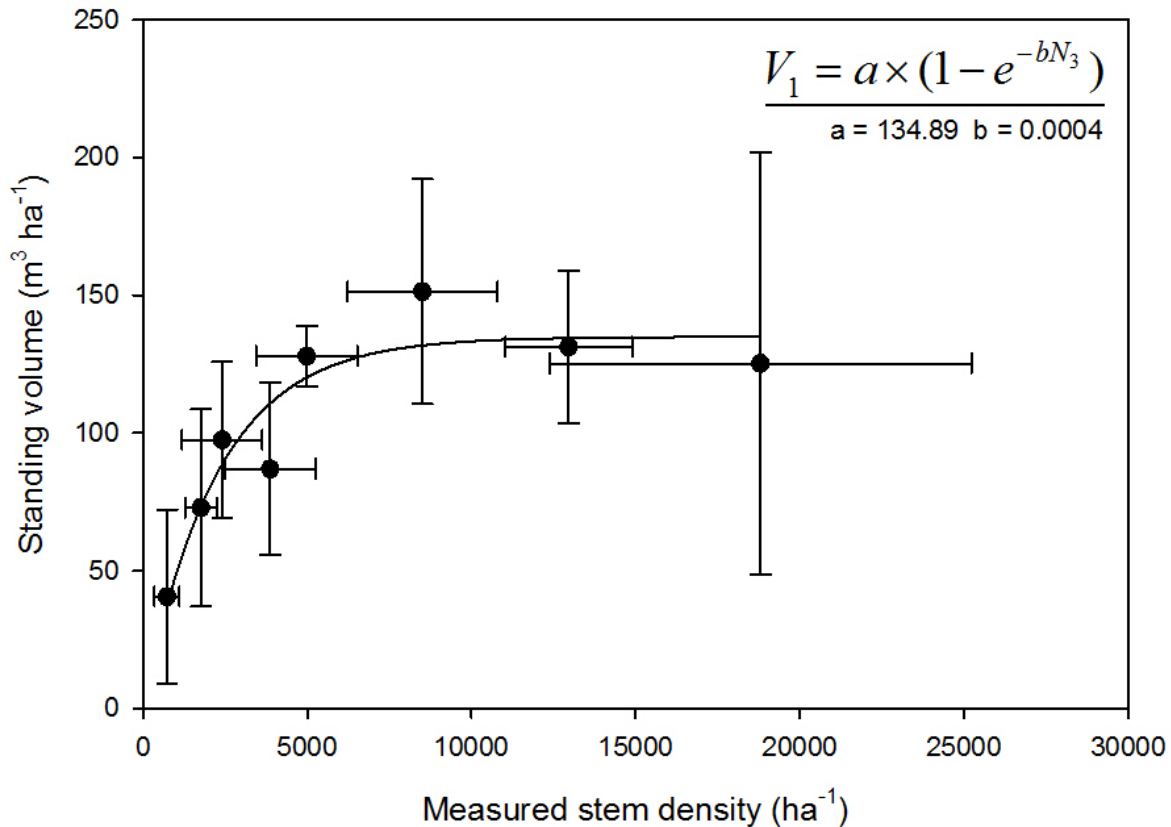

Figure 8. Relationship between standing volume (V_1) and measured stem density (N_3).
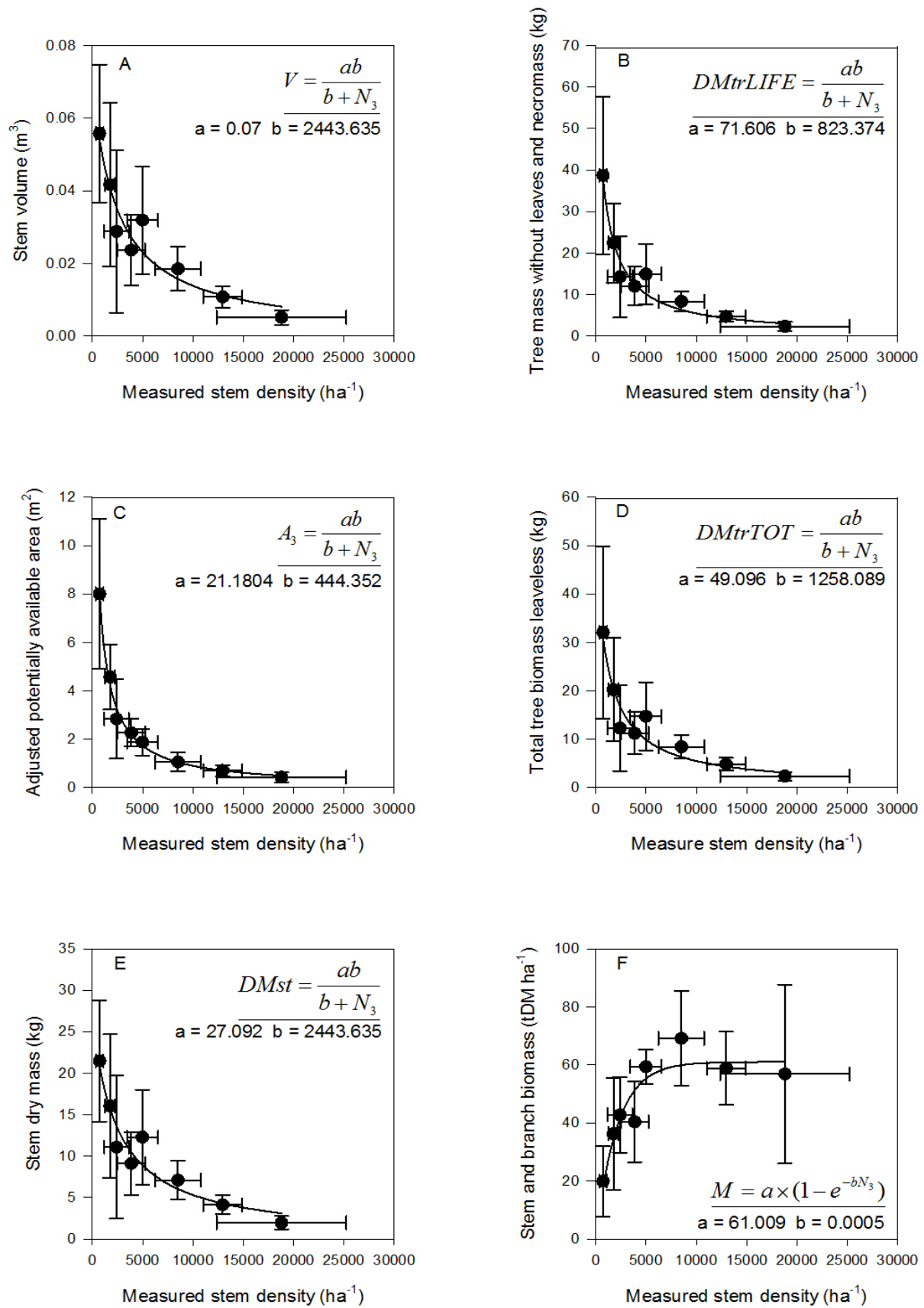
Figure 9. Relationship between (A) stem volume (*V*), (B) tree biomass without leaves and necromass (*DMtrLIFE*), (C) adjusted potentially available area (*A₃*), (D) total tree biomass without leaves (*DMtrTOT*), (E) stem dry mass (*DMst*) and measured stem density per hectare (*N₃*).

Bark (*BRKH*) and sapwood (*RYSH*) ratios did not vary significantly between treatments (*BRKH*: Kruskal-Wallis test: H (7, $N = 40$) = 5.479 $P = 0.602$; *RYSH*: Kruskal-Wallis test: H (7, $N = 40$) = 9.99 $P = 0.189$). Live branch ratio (*LGRH*) varied significantly between treatments (Kruskal-Wallis test: H (7, $N = 39$) = 28.09 $P < 0.001$) decreasing with increasing stem density (Figure 10).
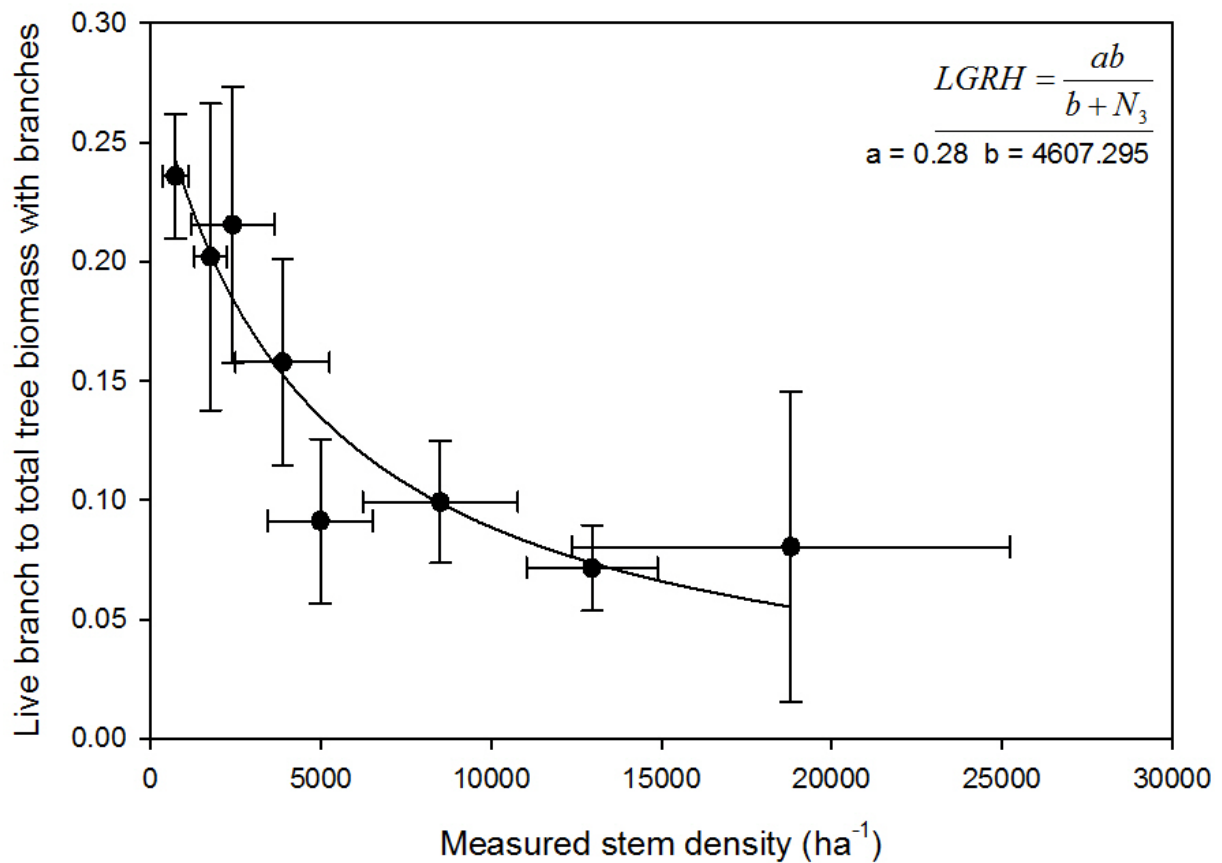

Figure 10. Relationship between live branch ratio to total tree biomass with leaves (*LGRH*) and measured stem density (N_3).

4. Discussion

It is generally observed that mortality is higher in dense forest stands due to self-thinning Morrow (1978). In this study, survival rate was not conclusively shown to be affected by stand density (Table 4). The spacing trial reported here is composed of a single clone, of only moderate growth rate and relatively recent canopy closure. Thus, inter tree competition leading to mortality might be less severe than in more diverse stands.

According to size-density theory (Daniel, Helms & Baker 1979), height growth is comparably unaffected by competition between trees in a stand. Results of the present study demonstrate a different trend (Figure 7B), with tree height decreasing with increasing stand density. These unexpected results might suggest that resources are severely constrained in the high stand density treatments. Except for tree height, size-density relationships reported herein for Black cottonwood trees at the age of 20 years were consistent with patterns frequently observed in trees of temperate forests, i.e. smaller stem dimensions with increasing stand density (c.f. Harper, 1977).

Stand productivity culminated at a density of about 5 000 trees ha^{-1}, i.e. an average spacing of about 1.4 m, as shown by stand basal area (Figure 7C), standing volume (Figure 8) and above ground standing biomass (Figure 9D, B). The estimated standing volume and biomass production of 135 m^3 ha^{-1} and 61 tDM ha^{-1} indicate a mean annual growth rate at an age of 20 years of 6.8 m^3 ha^{-1} a^{-1} and 3 tDM ha^{-1} a^{-1}, respectively.

Arnór Snorrason & Stefán Freyr Einarsson (2002) presented a standing volume on age relationship for poplars in south Iceland. Based on their model 20-year poplar stands in south Iceland have an expected standing volume of 95 m^3 ha^{-1}. Brynjólfur Jónsson (1988) reported an average stand density of 2829 trees ha^{-1} in 17 poplar stands throughout Iceland with a range of 611 to 6887 trees ha^{-1}. Hence, we might expect stand density of about 2800 trees ha^{-1} for older poplar stands in Iceland. For a stand density of 2800 trees ha^{-1} density to productivity relationships established herein would predict 46 m^2 ha^{-1}, 91 m^3 ha^{-1} and 46 tDM ha^{-1} for basal area, standing volume and above ground biomass, respectively (see Figure 7C, Figure 8, Figure 9D, B for formulae).

Arnór Snorrason (2006) estimated average carbon stock in Black cottonwood plantations in Iceland based on an extensive inventory throughout the country. Based on his carbon stock on age relationship a 20-year Black cottonwood stand might contain about 30 tC ha^{-1}. Assuming carbon content of 0.5 gC gDM^{-1} woody biomass and that above ground carbon stock is about 80% of total tree carbon stock then average above ground woody biomass for poplars in

Iceland might be about 48 tDM ha^{-1}. Thus, based on the above estimate the Sandlækjarmýri spacing experiment might seem reasonably representative of poplars in Iceland.

In 1989, at the beginning of the Industrial Timber Project average biomass yield for Black cottonwood in Iceland was estimated at 3.3 tDM ha^{-1} a^{-1} and it was proposed that well managed industrial poplar plantations might yield about 5 tDM ha^{-1} a^{-1} (Þorbergur H. Jónsson & Jón G. Ottósson, 1989). The yield reported herein from dense poplar treatments is close to the original national estimate, but is lower than the anticipated yield for well managed industrial plantations. The clone used in spacing experiment was at the time considered high yielding (Líneik Anna Sævarsdóttir & Úlfur Óskarsson, 1990), but since then tree breeding and clone trials have established considerably higher yielding poplar clones (Halldór Sverrisson, 2011). Growth rates of Black cottonwood stands are highly variable between sites and the best sites yielding up to twice the average (e.g. Arnór Snorrason & Stefán Freyr Einarsson, 2002). Hence, the anticipated yield 5 tDM ha^{-1} a^{-1} might not be far off the mark for well managed plantations with high yielding clones.

In Europe Black cottonwood is planted on good lowland sites with considerably higher yield potential than those found in Iceland. Jobling (1990) reported a standing volume of 19-year Black cottonwood with 2.7 m square spacing at Alice Holt in England at 366 m^3 ha^{-1} (19 m^3 ha^{-1} a^{-1}), i.e. a yield three times that of the close spacing treatments of the present study. Yield tables in Jobling (1990) for poplars in Gwent Wales at a density of 2057 trees ha^{-1} show standing volume of 383 m^3 ha^{-1} in 21 years. Cannell (1980) estimated a mean annual increment in above ground biomass of 7.8 tDM ha^{-1} a^{-1} for a 12-year Black cottonwood stand in Britain at a spacing of 2066 trees ha^{-1}. These yields are considerably higher than for the treatment of 2500 trees ha^{-1} in present study.

A stand density of 5 000 trees ha^{-1} is high compared to common practice in poplar cultivation on medium to long rotations in Europe. As an example Stanturf, van Oosten, Netzer, Coleman & Portwood (2001) suggested an optimum initial spacing of 3.7 x 3.7 m in poplar plantations for the production of pulpwood and sawlogs. Jobling (1990) suggested 2 – 3 m spacing for Black cottonwood grown on a 10 – 15 year rotation for pulpwood with diameters of final crop trees with diameters of 10 – 20 cm.

Site conditions, i.e. stand yield and stand densities proposed for production of industrial round wood in Iceland is more comparable with forest plantations of light demanding conifers in Europe managed for timber. Morrow (1978) and Novák, Slodičák & Dušek (2011) reported tree size to stand density relationships in 25 and 20 year European larch (*Larix decidua* L.), respectively, that were comparable to those presently reported for Black cottonwood.

Similarly, Rubtsov V.I., Novoseltseva, Popov & Rubtsov V.V. (1976) presented results of tree size by stand density for 20 year Scots pine (*Pinus sylvestris* L.) that show similar trends as those of the present study (Figure 11).

In dense treatments growing area of individual trees is much smaller than in the wide spacing treatments. According to Kearney, James, Montagu & Smith (2007) initial planting density might not have significant influence on crown development prior to canopy closure, but thereafter competition for space and light affects canopy development. The time of canopy closure varies with tree spacing, growth rate and inherent crown size characteristics (Savill & Evans 1986). In present study, branching ratio, i.e. the ratio between branch mass and total above ground mass of the tree was strongly affected by closer spacings (Figure 10). These results might have important bearing on optimum tree size for industrial applications as branchy trees are more costly to handle and small size wood chips are unsuitable for the silicon industry (Jónsson 2009b).
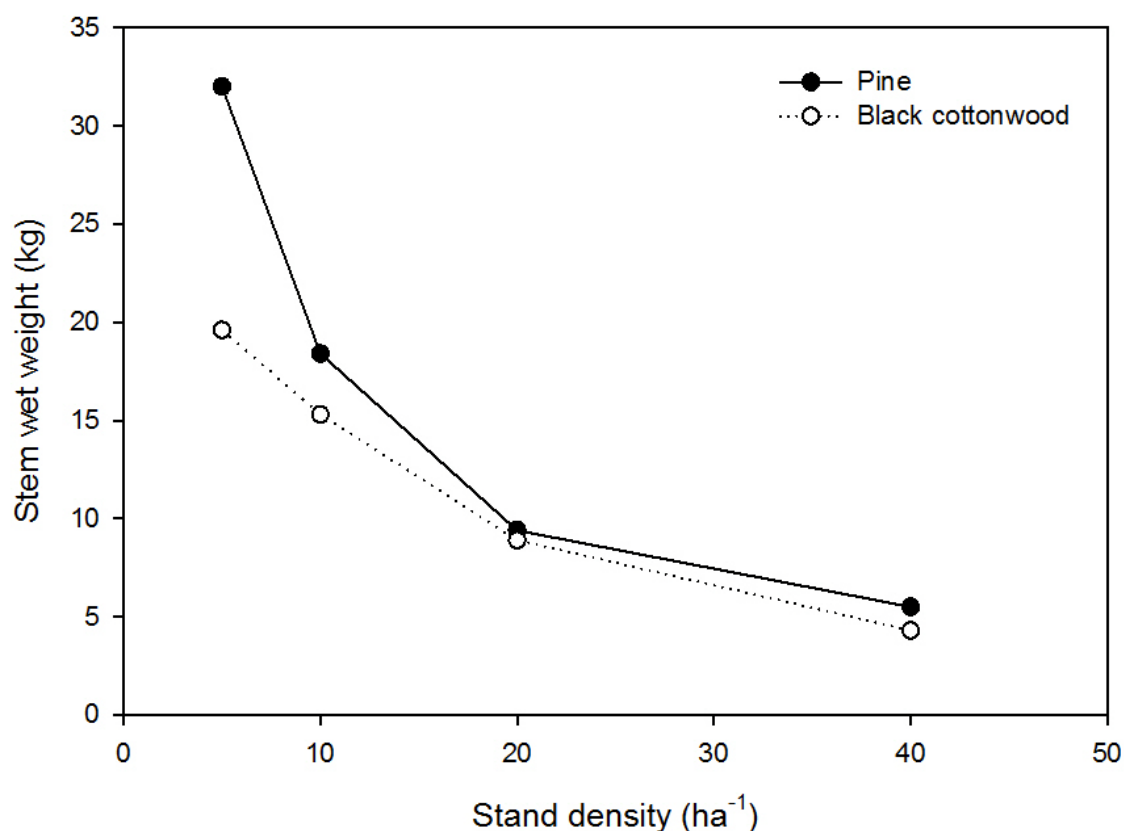

Figure 11 Stem weight by stand density (x 1 000 trees ha^{-1}) of 20-year Scots pine in Russia (Rubtsov et al. 1976) and Black cottonwood in Iceland (present study).

Total mineral content of the bark is relatively high due to physiological processes within the tree and the external contaminants e.g. trace elements in precipitation and soil during logging and transportation. The silicon industry is sensitive to trace element concentrations in its wood supply particularly titanium in ferrosilicon and phosphorous in silicon metal production (Icelandic Alloys Ltd 1982). Therefore, bark is often removed before the wood is utilized as in the case of high grade silicon-products (Jónsson 2009b). Sapwood generally has a lower mineral content than heartwood (Meerts 2002) and is thus preferred as raw material for a number of manufacturing processes, including high grade silicone production. Therefore, an effect of stand density on the ratio of sapwood to the apparent heartwood in poplars might affect optimum spacing for industrial application of poplar wood. In present study neither the bark to total stem mass nor the sapwood to heartwood ratios were significantly shown to vary with stand density. Therefore, optimum spacing would not vary depending on chemical quality of produce.

5. Conclusion

Stand basal area, standing volume and above ground biomass increased with stand density to a 5 000 trees ha^{-1} limit, above which these indices reached a relative plateau in denser spacings. Therefore, stand yield can be increased in a 20-year rotation by greater planting density up to the 5 000 trees ha^{-1} density limit.

Branching increased significantly with availability of growing space, especially in plots where density did not exceed 5 000 trees ha^{-1}. Consequently stem wood proportion increased with higher density treatments.

No significant variation between spacing treatments was in bark, sapwood and heartwood ratios. That leaves wide range of possible initial spacing models for the manager to choose from depending on the objectives and final utilization requirements of each particular Black cottonwood plantation.

Figure 12. Different treatments viewed from 3 x 3 m spacing toward 0.5 x 1 m. Photo: Þorbergur H. Jónsson (27.01.2010).

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