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Thuja plicata - Provenance experiments and cultivation trials in South Sweden

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Abstract

In times of climate change and an increasing number of threats for native tree species in Sweden and other countries in Europe, exotics as *Thuja plicata* (Donn ex D. Don) might be considered to a greater extent. This thesis aims to evaluate the establishment and early growth of previously established provenance experiments with *Thuja plicata* in the south of Sweden, to be able to give recommendations for an adequate choice of provenance. In addition, the species´ ecology, as well as experiences of former provenance experiments in other countries than Sweden will be included. Height measurement and damage assessment on four *Thuja plicata* provenances as well as on Norway spruce from two seed orchards as reference, was carried out in four experiments on three sites in South Sweden. At this stage of stand development, results show Norway spruce in most cases superior regarding height growth and vitality. No significant differences between *Thuja plicata* provenances could be shown in relation to height development and damage severity. However, trends indicated Horsey Creek and Bench Road as the best growing provenances, while Yola Creek grew the slowest. Damage assessment has proven Horsey Creek as the most vital provenance, whereas Bench Road was the most severely damaged *Thuja plicata* provenance. Due to highest vitality of the seedlings and good growth on all sites, Horsey Creek will be the recommended provenance for growing conditions in South Sweden.

Key words: *Thuja plicata*, Western red cedar, Provenances, Sweden, South Sweden

Zusammenfassung

In Zeiten des Klimawandels und steigender Gefahren für natürlich vorkommende Baumarten in Schweden, sowie anderen Ländern in Europa, sollten exotische Baumarten wie *Thuja plicata* (Donn ex D. Don) in größerem Maße in Betracht gezogen werden. Diese Arbeit soll die Bestandesbegründung und das Jugendwachstum der Provenienzversuche mit *Thuja plicata* in Südschweden auswerten, um im Anschluss Empfehlungen über die richtige Wahl der Herkunft geben zu können. Außerdem sollen Ökologie sowie vorangegangene Erfahrungen zu Provenienzversuchen in anderen Ländern als Schweden zusammengetragen werden. Neben Höhenmessungen wurden das Ausmaß und der Grund des Schadens für vier *Thuja plicata* Provenienzen sowie für Fichten aus zwei unterschiedlichen Baumschulen als Referenz bewertet. Diese Inventur wurde in vier Experimenten auf drei Standorten in Südschweden durchgeführt. Die Ergebnisse zeigen, dass Fichte in fast allen Fällen bezüglich Höhenwachstum und Vitalität überlegen ist. Es konnten keine signifikanten Unterschiede zwischen den *Thuja plicata* Provenienzen gezeigt werden. Dennoch weisen Trends darauf hin, dass Horsey Creek und Bench Road im Vergleich zu den anderen Herkünften besser wuchsen, während Yola Creek am langsamsten wuchs. Schadensbeurteilung lässt auf Horsey Creek als vitalste Provenienz schließen, während Bench Road am schwerwiegendsten beschädigt wurde. Aufgrund der guten Vitalität, sowie des adäquaten Wachstums empfiehlt sich Horsey Creek als am besten geeignete Herkunft für schwedische Wachstumsbedingungen.

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1. Introduction

There is evidence for *Thuja plicata* (Donn ex D. Don) being present in Europe 2.4 million years ago (Küster, 1998; Trauboth, 2006). This species, also called western red cedar, at present only naturally distributed in North West America (Minore, 1990), has not been able to re-immigrate to Europe after the ice ages (Borchers, 1952). This makes *Thuja plicata* an exotic tree species in Europe.

Sweden deals in forestry to a great deal with three tree species such as Scots pine, Norway spruce and birch, whereas Norway spruce increases to the reduction of the other two species (Anon., 2018). Having climate change and the increasing number of storm damages as well as bark beetle outbreaks in mind, focusing on Norway spruce only, especially in the south of Sweden, might not be the most sustainable solution. As Marini et al. (2017) have shown, climate change with altered weather conditions and more storm felled trees, will have a severe but foreseeable impact on bark beetle outbreaks and loss of timber not only in Central Europe but also in southern Scandinavia. Hence, other suitable forest production species should be found and regarded as potential complements to the three species used in southern Sweden. Moreover, new pest and diseases on native tree species will challenge forestry in Europe increasingly (Bolte et al., 2009; Correia et al., 2018), which may reduce the amount of alternative native tree species to Norway spruce, Scots pine and birch.

Because of this, exotic tree species as *Thuja plicata* should be considered to a greater extent in future forestry planning. Due to milder winters and drier summers, Norway spruce will become less suitable on some sites, especially on clayey soils, whereas *Thuja plicata* is able to grow and survive on these sites (Minore, 1983; Anon., 2009). In addition, a high degree of storm resistance and a higher tolerance towards drought (MacDonald et al., 1957; Stratmann, 1988; Hoffmann et al., 2018) make *Thuja plicata* a valuable substitute for Norway spruce under predicted future climate conditions.

There are only some small stands of *Thuja plicata* in Sweden. Possibly, the most famous on Öland, in the Böda Ekopark in Skäftekärr was established in 1878 by Johan E. Bohman. The seed material was ordered from Germany to establish *Thuja plicata* underneath Scots pine. 1952, mean height was 18-24 m. In 2005, a big part of this stand was damaged by the storm “Gudrun”, due to its high intensity. At that time, trees were around 30 m tall. In the 1930s, it was tested to establish another *Thuja plicata* stand underneath 70-80 year old Scots pine. However, this plantation failed, due to severe fraying damages by roe deer (Svensson, 2008).

To date, *Thuja plicata* is still a popular hedge, park and garden tree in Sweden. Small stands with *Thuja plicata* can be found in the Drafle arboretum outside Härnösand, in Rössjöholm, 10 kilometres west from Örkelljunga and a 60 year old stand exists in the Ekolsunds arboretum (Svensson, 2008).

As Minore (1983) states "much less time, money and effort have been invested in learning how to grow the species [*Thuja plicata*] than in studying its products". Because of this and the chance of an additional tree species for Sweden´s forestry, Södra Skog implemented the experiments in this thesis in cooperation with the experimental forests in Tönnersjöheden and Asa. Different provenances were tested, since genetic differences within a species originating from varying geographical regions can lead to tremendously varying growth and disease resistance patterns (Wright, 1976). Consequently, this thesis aims to evaluate the establishment and early growth of the cultivation tests and provenance experiments of *Thuja plicata* in South Sweden with a focus on height development and damage. In the end, provenance recommendations will be given for growing conditions in Sweden. As an asset, this thesis provides a summarizing overview of *Thuja plicata´s* ecology and experiences regarding provenance choices made so far in other countries than Sweden.

1.1 Natural range

Thuja plicata reaches in its coastal distribution from 40° 10´ N to 56° 30´ N in latitude, whereas the interior distribution ranges from 45° 50´ N to 54° 30´ N (Minore, 1990). The species is limited towards the east through precipitous slopes of the Coastal Mountains but recurs in the inland´s wet belt. *Thuja plicata* grows best in Washington´s Olympic Peninsula and optimal conditions are reached at low elevations (Aldhous and Low, 1974). Total standing volume in British Columbia is estimated to 824 million cubic metres (Quenet and Magdanz, 1988 see Minore, 1990).

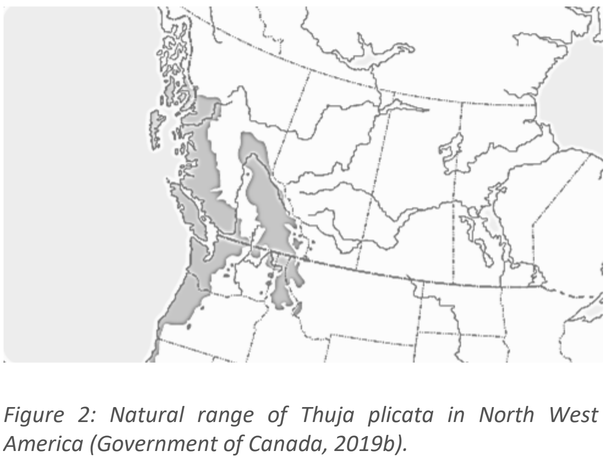

Figure 2: Natural range of Thuja plicata in North West America (Government of Canada, 2019b).

1.2 Site requirements

1.2.1 Climate

Thuja plicata grows best in warm, moist and temperate climates (Krajina, 1969). In its coastal distribution, rainfall lies between 890 to 6600 mm/year, most of it as winter rainfall. In the interior region, however, the annual precipitation is between 710-810 mm and 1240 mm in the southern parts, with mainly spring and autumn rainfall. Whereas precipitation is growth´s limiting factor in Sweden, the species is limited by low temperatures in its natural range, if sufficient precipitation is given. This is reflected in the northern limit of *Thuja plicata´s* distribution, which equals the 11.1-11.7 °C mean summer temperature isotherm. Along the coast, the species experiences 100-300 frost-free days of growing, whereas the interior provenances grow in 75 frost free days (Krajina, 1969).

1.2.2 Soil

Deep, moist and freely drained brown earths are recommended for optimal growth of *Thuja plicata* (Wilson et al., 1993; Pyatt et al., 2001). Moreover, growth is highly influenced through soil moisture, so that the best growing conditions exist on nutritious alluvial soils in Europe (Stratmann, 1988). In addition, Lembcke (1973) describes better growth of *Thuja plicata* compared to Norway spruce on moist and nutritious sites in Germany. Furthermore, slower growth could be observed, the drier the soil was. Additionally, Lembcke (1973) describes stagnating height growth in older age classes due to limited water availability, whereas nutritious limitations have less strong effects on *Thuja plicata´s* growth. Olesen (1962) states as well that sufficient soil moisture is important for good growth. However, this species tolerates stagnant water up to 15 cm soil depth and it can survive and grow on soils with low nutrient availability (Minore, 1990), although productivity is likely to increase with fertilization (Radwan and Harrington, 1986; Minore, 1990). Furthermore, planting *Thuja plicata* is improving soil conditions due to fast mineralising needles (Spee 1952 see Olesen, 1962; Panka, 2014) and the foliage´s high calcium concentration, which rises the cation-exchange capacity, base saturation, exchangeable calcium as well as the pH (Alban, 1969; Bothwell, 1998).

1.3 Establishment and Growth

There is not much experience regarding natural regeneration of *Thuja plicata* in Europe. Moreover, Savill (2013) states a lack of knowledge concerning this topic in Britain. Although, establishment of natural regeneration is possible under various light and soil conditions, Antos et al. (2016) have shown most effective and successful natural regeneration in gaps and open areas in *Thuja plicata* stands, with the highest success in openings less than 50 m wide (Heineman et al., 2002). In Germany, natural regeneration in small openings could be observed in some stands (Appendix, p. 64). In a 55 year old mixed *Thuja plicata*, Douglas fir stand, 16 year old natural regeneration was observed in the inventory 2009. The regeneration established itself in patch-wise formation (Anon., 2009). In the same forest area, additional stands with *Thuja plicata* showed natural regeneration (Guba, 2019). Besides generative reproduction, *Thuja plicata* has a strong ability to regenerate vegetative, through layering and rooting on fallen branches or trees (Minore, 1990).

If the aim is to establish *Thuja plicata* artificially in spring, planting may take place at the end of May, since roots start growing late (Olesen, 1962). In this way, a critical establishment phase can be reduced to a minimum risk level. Conversely, in Canada, *Thuja plicata* could take advantage of better growing conditions when sown in September compared to April, due to completed seed germination and better root development (El-Kassaby, 1999). Nikolova et al. (2016) have proven better survival in Switzerland, when planted in autumn compared to April. In addition, O'Reilly et al. (2001) tested the establishment success of bare-rooted and containerized seedlings in Ireland. Results have shown increased survival and early height growth with containerized compared to bare-rooted seedlings. This effect was mainly explained by the increased tolerance of containerized seedlings towards handling as well as desiccation stress. In general, establishment is seen as one of the most critical stages of *Thuja plicata´s* life-cycle (Antos et al., 2016). As an example, this species is not suitable for exposed and clear-felled sites, so that shelter is recommended for establishment success (Niefnecker, 1989; Wilson et al., 2016). Several authors describe successful plantations of *Thuja plicata* underneath shelter from e.g. pine, larch, birch and aspen (Niefnecker, 1989; Bothwell, 1998; Wilson et al., 2016). Moreover, Aldhous and Low (1974) show 30 % reduced mortality, comparing growing conditions in the open and below shelter, underneath which temperatures increase by three to five degrees.

Thuja plicata can either be established in an even-aged mixture or in monoculture. Due to its shade-tolerance, *Thuja plicata* can be inter- and underplanted in mature stands, as well as used for supplementary plantings (MacDonald et al., 1957; Wilson et al., 2016).

Initial height growth of *Thuja plicata* is rather slow compared to Douglas fir and Sitka spruce (Aldhous and Low, 1974; Lines, 1987; Weber et al., 2017). In later stages, however, some authors claim better height development and growth than Norway spruce and Sitka spruce. Thus, Diez and Bürgi (1991) have shown faster height increment of *Thuja plicata* than Norway spruce in Switzerland. In Ireland, the species proves higher productivity compared to Norway spruce on fertile sites but less on poorer soils (Bothwell, 1998). Moreover, the same study shows faster height growth than Sitka spruce up to the age of twenty years. Despite slower height growth, especially in youth, *Thuja plicata* reaches up to 912 m^3/ha standing volume and 1838 m^3/ha total production in British Columbia in 80 years (Hamilton and Christie, 1971; Minore, 1990). In Denmark, 914 m^3/ha standing volume and 1240 m^3/ha total production at the age of 66, in Oreby is recorded, corresponding to a mean annual increment of 18.8 m^3/ha, (Olesen, 1962). This is mainly due to the possibility of keeping a very dense stand compared to other species, because of *Thuja plicata*´s slim crown morphology (MacDonald et al., 1957). However, it needs to be kept in mind that *Thuja plicata* responses more to site conditions than other species, so that in Britain, this conifer represents a valuable substitute to other tree species on the best lowland and "heavy impeded" soils only (Aldhous and Low, 1974).

1.4 Silviculture and light requirements

Thuja plicata occurs mainly in association with other conifers, such as Douglas fir, Western hemlock, Redwood, Grand fir and Western larch in its natural habitat in North West America (Minore, 1990). Generally, *Thuja plicata* is considered to be very shade-tolerant and late successional (Carter and Klinka, 1992; Wilson et al., 2016). However, *Abies amabilis* and *Tsuga heterophylla* are regarded as more shade-tolerant (Minore, 1979). In addition, *Thuja plicata* starts growing in the understorey and moves subsequently to full light into the forest canopy, when regenerated naturally (Daniels, 1994). Due to this and the strong reaction to increased light levels, *Thuja plicata* is considered as pioneer and late-successional species at the same time (Packee, 1976 see Minore, 1990).

Moreover, *Thuja plicata* is highly suitable as an admixture to other conifers and broadleaves. For instance, this species can be used as serving tree in oak stands to reduce epicormics due to its strong stem shading ability (Wilson et al., 2016). Additionally, *Thuja plicata* does not interfere and compete with the mixed crop species because of the species´ narrow crown development (Olesen, 1962; Savill, 2013). Finally, it is simple to create a mixed two-storied stand from even-aged plantations with *Thuja plicata* (Spellmann and Schober, 2001), not at last because of the species´ slow initial growth, high shade-tolerance and low crown space requirements (Wilson et al., 2016).

However, if the aim is to produce sawn timber, pure stands with long rotations are better suited. Bothwell (1998) for example recommends even-aged and pure stands of *Thuja plicata* with narrow spacing or mixtures with species of the same shade-tolerance, to reduce stem taper. Furthermore, it must be considered that artificial pruning is essential, due to poor and late self-pruning as well as increasing branchiness when trees turn older (Smith, 1988 see Minore, 1990; Trauboth, 2006), especially if this species is grown in wide spacings. Yet, this problem can be reduced through narrower plantations (Minore, 1990). In addition, Diez and Bürgi (1991) have found only one-third straight trees, whereas 20 % have been "somewhat bending" and the rest was "very poorly shaped". Other characteristics are fluted stem bases, medium sized branches and epicormics, if the trees are exposed to sudden light.

Depending on the situation and stand´s character, thinning from below or above can be applied. If *Thuja plicata* is mixed with Douglas fir, Grand fir or Western hemlock in Europe as well as in North America, it is often overgrown by these admixed species. Hence, thinning from above can be an opportunity to support *Thuja plicata´s* growth. In uneven-aged stands, however, thinning from below might be the better choice (Minore, 1990). If thinning or any mechanical operations take place, those must be carried out carefully, since *Thuja plicata* is rather sensitive to machinery damage, not at last due to its thin bark (Panka, 2014).

1.5 Threats and Diseases

1.5.1 Frost

Frost sensitivity of *Thuja plicata* depends on the choice of provenance. As such, inland provenances are more tolerant to frost than provenances from the coastal range (Sakai and Weiser, 1973). However, *Thuja plicata* is widely known for its frost sensitivity, especially early autumn and late spring frost (Aldhous and Low, 1974; Wilson et al., 2016). Olesen (1962) describes the death of many seedlings because of late spring frost in Denmark, possibly due to the species´ native occurrence under dense shelter, especially in young stages.

1.5.2 Game

Whereas most authors say, *Thuja plicata* is heavily browsed by deer, elk and rodents, in some cases up to 76 % (Curran and Dunsworth, 1988; Niefnecker, 1989; Bothwell, 1998;Brodie and DeBell, 2013), others claim, game is fraying the seedlings only instead of browsing them (MacDonald et al., 1957; Kristöfel, 2003; Trauboth, 2006). Furthermore, Niefnecker (1989) states that this species can resist browsing damage, but will remain for a long time in the critical stage. Martin and Baltzinger (2002) studied deer browsing on Queen Charlotte Island, Canada. As a result from this study, already low hunting pressure can evidently reduce strong browsing damage on *Thuja plicata* regeneration.

1.5.3 Insects

Thuja plicata hosts a variety of insects. However, in most cases, besides single tree mortality no severe damages are found on this tree species. As such the western cedar bark beetle (*Phloeosinus punctatus*) is considered a low priority pest in North America (Fox, 1984). Moreover, the western cedar borer (*Trachykele blondeli*) devalues timber through degradation. Seedlings in British Columbia are sometimes damaged by the weevil *Steremnius carinatus*, whereas seeds are attacked by the gall midge *Mayetiola thujae* (Furniss and Carolin, 1977). While most of the insects occur in *Thuja plicata´s* natural range, some are also present in Europe. Among others, the bark beetle *Phloeosinus thujae* or European wood borers attack *Thuja plicata* (Minore, 1983).

1.5.4 Fungi

There have been discovered more than 200 fungi on *Thuja plicata*. Yet, this tree species is less susceptible to the attacks, than most other species (Oliver et al., 1988). One major fungal threat, however, is *Didymascella thujina*, also called cedar leaf blight (Figure 2). Cedar leaf blight is mainly a seedling disease being more severely damaging in Europe than in North West America and Canada. Especially two and three-year-old seedlings in nurseries are affected by this fungus (Minore, 1990). If the saplings are older than six to eight years, the same may get infected, although the outcome will be less severe compared to younger ages (Søgaard, 1969). Most pesticides, except cycloheximide, applied two to three times,

Figure 3: Cedar leaf blight on Thuja plicata (Pscheidt and Ocamb, 2019).

have proven to be insufficient as repellent (Burdekin and Phillips, 1971). Yet, crossing *Thuja plicata* with the Japanese *Thuja standishii* leads to resistance of this fungal infection.

Older *Thuja plicata* stands are likely to get infected by *Heterobasidion annosum* and *Armillaria mellea,* which sometimes have a severe influence (Diez and Bürgi, 1991; Kristöfel, 2003). Bothwell (1998) points out the higher susceptibility of this species towards *H. annosum* and *A. mellea* in Ireland. However, Oliver et al. (1988) still see *Thuja plicata* as an alternative to Douglas fir and Western hemlock, if *A. mellea* or *H. annosum* are present, due to the less severe outcome compared to the named species. Supporting this, Olesen (1962) states that *H. annosum* does not go as high up in the stem as it does in Norway spruce and while Douglas fir was killed by root rot in another study, *Thuja plicata* has still been alive (O'Callaghan et al., 2012).

Other diseases attacking *Thuja plicata* are *Pestalotia funera* with insignificant meaning (Olesen, 1962) and the cypress aphid, which leads to browning of the foliage and can easily be mixed up with frost scorches (Wilson et al., 2016).

1.5.5 Wind and Drought

Thuja plicata is seen as one of the most wind stable tree species. However, records show that windthrow is possible on waterlogged and very wet soils (MacDonald et al., 1957; Stratmann, 1988; Kristöfel, 2003).

Regarding drought, Hoffmann et al. (2018) have found higher tolerance towards drought compared to Norway spruce. This might be due to *Thuja plicata*´s broad ecological amplitude and its wide native range and maritime influence. Nonetheless, drought has been identified as a problem in Ireland (Bothwell, 1998). However, the exact growing conditions under which the problem has been found are unknown. Hence, several factors as a very dry summer or non-suitable soil may be the reason for drought stress in Ireland.

1.6 Wood characteristics and uses

Wood from *Thuja plicata* has a mean density of 376-400 kg/m³ and moisture of 72-114 % (Aldhous and Low, 1974). The wood is one of the lightest softwoods with high durability and a high degree of rot resistance. The durability results from the extractives as thujaplicin, thujaacids and methyl ethers. However, thujaplicin has fungitoxic, poisonous characteristics and is soluble in water. Additionally, plicatic acid, as it is found in *Thuja plicata* wood, leads to occupational asthma among workers in sawmills with *Thuja* *plicata* in British Columbia (Moira, 1982). The acidic properties lead as well to corrosion on metal, as nails for example. Moreover, screw and nail holding capacity are rather low, although this problem can be solved by special nails (Forest products research, 1957; Olesen, 1962; Bothwell, 1998). Furthermore, manipulation and treatment are more difficult (MacDonald et al., 1957) since the wood bonds well but splits easily due to the straightness of grains. Contrary to this, Wilson et al. (1993) award *Thuja plicata* wood a good nail holding capacity and low risk of splitting. Another advantage of the wood is the low volumetric shrinkage, which makes it well suited for structural applications (Bothwell, 1998).

The wood is characterized through the high proportional reddish coloured heartwood, even in young ages (Aldhous and Low, 1974; Wilson et al., 1993; Bothwell, 1998). Directly after drying, the colour shifts into reddish-brown, yet long exposure outdoors turns it into a greyish colour. In addition, *Thuja plicata´s* heartwood is tremendously more durable compared to the sapwood (Wilson et al., 2016).

Sawing has proven to be no problem if standard machinery is applied, whereas debarking is more difficult compared to other conifers. Additionally, pulping is more challenging due to the reddish colour of the heartwood. The outcome in sulphate-pulping is rather small due to the low wood density. Moreover longer cooking time and stainless steel machinery would be required due to the corrosion risk because of the extractives (Aldhous and Low, 1974).

Due to its durability, *Thuja plicata* wood is greatly used for outdoor purposes, as for shingles, doors, windows but also for fencing and gardening accessory in general. However, the market is rather small in Europe, partly due to the low amounts of available products. Nonetheless, good prices are paid, if it is possible to retail the timber, for high quality and niche products (Aldhous and Low, 1974; Wilson et al., 1993; Kokocinski et al., 2003).

1.7 Experiences with *Thuja plicata* in Europe

1.7.1 Great Britain

Great Britain has been the first place of *Thuja plicata´s* introduction to Europe in 1853 by Lobb from Oregon and Columbia River, mainly for ornamental purposes but also as edge tree to forest plantations. Further on, around 283 ha, were present at 1947 (MacDonald et al., 1957). Since the 1950s, more than 5000 ha have been established (Aldhous and Low, 1974). *Thuja plicata* has recently been considered as forest tree again, due to climate change, pathogen outbreaks, continuous cover transformation and timber preservative regulations (Wilson et al., 2016).

There are more than 400 provenance trials of exotic tree species in Britain and provenance choice recommendations have been made by Lines (1987). However, those trials are rather a mixed group of origins than organised and well-established experiments. Yet, in 1962/1963, 13 provenances of *Thuja plicata* were tested in seven experiments covering a wide range of growing conditions in Great Britain. Seed material originated mainly from the coastal region, whereas only one inland provenance from the Sushwap Lake, close to Kamloops in British Columbia was tested (Lines, 1987). After evaluating these experiments, the first choice for introducing seed material to Great Britain should be from the northern slope of the Olympic Mountains in Washington, US zone 221, less than 150 m elevation. Second choice then should be seed material from Vancouver Island. Except for one site, Sushwap lake provenances grew well, too.

In addition, *Thuja plicata* from Shushwap Lake has been found “extraordinary tall” in the Tulliallan nursery in the Devilla forest trail in Scotland. Another good provenance proved to be from the Terrace on Skeena River in British Columbia, originating, where the inland and coastal distribution´s part come together. In total, 90 % of the planted *Thuja plicata* seedlings in this nursery survived (Lines and Aldhous, 1962). In the arboretum in Kennington, Oxford, no significant differences between provenances have been observed.

Generally, it has been found that seed material from America is suitable up to ten degrees south of the latitude in which it would be established in Great Britain, if site and climate conditions match the species’ requirements (Samuel, 2003). For example, if climate is oceanic with high rainfall, origins from Oregon shall be used. Yet, if climate is colder and drier, hence not matching the species requirements anymore, no relation between latitude and choice of provenance could be observed, because the site effect on growth becomes stronger compared to the origin´s impact. In Britain however, seedlings from British

Thuja plicata seeds grow better than from directly imported seeds, due to selection and favouring of the best adapted individuals through thinnings (Samuel, 2003).

1.7.2 Ireland

Ireland´s forestry highly depends on Sitka spruce, which is why other fast growing conifers are increasingly considered. *Thuja plicata* test trials in Avondale estate and Co. Wicklow, established in 1906 with *Larix decidua* as a nurse crop, have shown promising results. Unfortunately, exact provenance information are not available (Bothwell, 1998). Due to the good results, Coillte stated the aim of afforesting at least 200 ha per year with *Thuja plicata* on sheltered, low elevation and fertile soils from 1993 onwards. In 1995, 119 ha of state owned forest planted with *Thuja plicata* could be found (Anon., 1990 see Bothwell, 1998). Moreover, *Thuja plicata* has proven to be a suitable choice for afforestation projects on cutaway peat lands (Renou et al., 2006).

1.7.3 Denmark

Thuja plicata was introduced to Denmark in 1855 as garden and park tree (Bornebusch,1936) and has been used as forest tree the first time around 1860 on the island Funen (Larsen, 1943a; Larsen 1943b). Provenance records are first available from plantations established in 1933. Seeds were taken from Washington, the Ranier National Forest and the area around Ashford Spirit Lake, 122 ° west and 47 ° north. Later on, provenances from the Shuswap Lake Area in British Columbia, 119 ° west and 51° north were taken (Bornebusch, 1936; Olesen, 1962). These provenances were planted, among others in Drebygaard, Hvedholm, Gjorslev, Ringsted and Frijsenborg. On the most suitable sites in Denmark, hence on damp, low and clayey coastal areas, *Thuja plicata* reached production levels comparable to the best growing Norway spruce. *Thuja plicata* developed best on the mildest sites, because of higher mean annual temperatures up to 2° C as well as less severe winters in their natural range. Conversely, *Thuja plicata* from the Sushwap lake area is supposed to be hardier due to shorter vegetation periods and more severe winters. However, this difference was inconsiderable.

1908-1919, an exotic conifer trial with 14 species was established in the Giesegaard estate in Denmark. Whereas most species were successfully established, “only the plantation of *Thuja plicata* was considered a complete failure and was replanted with Norway spruce” (Madsen, 1975). However, the exact provenance used, is unknown.

Moreover, *Thuja plicata* stands are found in Oreby, Knuthenborg, Skjoldenaesholm, Soro/ II, Tinghuus and in Holstenshuus. *Thuja plicata* grew especially in Oreby and

Knuthenborg better than the best growing Norway spruce (Olesen, 1962). In addition there is a trial in Holsteinborg, Ludvigskoven, which was established 1964/1965 (Bang, 1966). However, no provenance information is available for these plantations. Besides the presented plantations, there exist several additional *Thuja plicata* stands in Denmark (e.g. Madsen, 1977).

1.7.4 Germany

Exotic forest trees, have been in focus in Germany for a long time. Due to Germany´s history in the last century and reorganisations, a lot of information is lost and serious provenance experiments have only been considered after the Second World War (Fox, 1984). However, 1881 to 1900, 220 kg of seeds were ordered by the Prussian forest administration to plant around 22 ha on 26 test sites with *Thuja plicata* (Schober, 1956; Trauboth, 2006; Schwappach, 2013). 1910, 71 stands covering 27 ha in total have been present in Prussia (Panka, 2014). In the same area, today partly Brandenburg, growth in youth was much less compared to Sitka spruce and Japanese larch. However, total volume production was around 300 m^3/ha more than the best Scots pine. Seed material was assumed to be from California, although the exact provenance was unknown and seeds from the northern parts of *Thuja plicata*´s distribution are supposed to be the best growing ones (Panka, 2014).

There are some examples all over Germany, where *Thuja plicata* has been established. Seed source information is only available in some cases. Besides the presented stands in the following, there exist several additional stands of *Thuja plicata* in Germany, about which no information has been published (Anon., 2009). The first example covers a stand of 0.5 ha in the north west of Germany, in Aurich. Mean heights were around 25 m and mean diameter of 32 cm at the age of 67 years (Borchers, 1952). In the "Forstgarten" in Munich, mean height of *Thuja plicata* was 20-22 m at the age of 38 years and overtopping Norway spruce at the same age (Spellmann and Schober, 2001). In Homburg, 23 m tall *Thuja plicata* could be observed at the age of 105. In this case, they have been established under shelter from Japanese larch, which was 12 m higher than *Thuja plicata* (Spellmann and Schober, 2001). In east Prussia, *Thuja plicata* has shown poor establishment and growth (Schenck, 1939). Another stand has been established 1873 in Weinheim, under mild climate and frost-absent springs (Beyse, 1997). The stand, 0.27 ha, has been planted with 465 seedlings, which showed good early growth and sufficient natural regeneration in older stages, but was strongly damaged by wind 1997. This stand was also included in a comparative study by Fox (1984) which has shown similar height and volume development of five *Thuja plicata* stands in South west Germany. Moreover, the stands developed similar to *Thuja plicata* stands in its natural range.

In today´s South West Thuringia, only a few plantations of *Thuja plicata*, covering in total 11 ha, have been established since 1869 (Trauboth, 2006). However, those plantations are not really experimental trials, since *Thuja plicata* was still widely seen as park or cemetery tree, so that almost no measurements were carried out. Initial spacing however, was 1.25 m x 1.25 m, mixed with Douglas fir. Already at the age of 16, a two storied stand has developed with Douglas fir in the overstorey and *Thuja plicata* in the understorey. Site index for Norway spruce in mean was one, hence corresponding to a mean annual increment of around 12 m^3/ha at the age of 100 (Schober, 1975). Niefnecker (1989) states that seeds for later plantations were partly used from the well-grown *Thuja plicata* established from Schwappach (Lembcke, 1973), while other material has been directly imported from coastal regions and western Cascadian mountains.

The plantations, trials and experiments have shown that *Thuja plicata* is worth planting, considering the good development of the species in German forests (Beyse, 1997). Yet, there has been (Schober, 1956) and still is little information regarding *Thuja plicata*, and the choice of provenance available. Hence, more trials need to be established to be able to find the fitting provenances.

1.7.5 Austria

Kristöfel (2003) evaluated *Thuja plicata* stands in Austria. Provenances have been imported from "somewhere in Montana". Generally, the growth potential of these trees was impossible to show due to a lack of data. However, at the age of 72, trees were 22 m high. Stem number was counted to 1678 per ha at the age of 56. At the age of 105, 30 metres were reached. The total volume production was 1059 m^3/ha, corresponding to a mean annual increment of 10 m^3/ha. In the 60s, the stand was opened up, which led to sufficient natural regeneration. The same study has shown that diameter increment culminates at the age of 30, whereas height increment climaxes at the age of 70.

1.7.6 Switzerland

Diez and Bürgi (1991) recommended, to not establish any more *Thuja plicata* plantations in Switzerland due to the increased risk of *Heterobasidion annosum* and *Armillaria mellea* infections. Moreover, too little experiences and information with this tree species and right choice of provenance until 1991 justifies their conclusion. If *Thuja plicata* shall be established, then for experimental and research purposes only.

Having this in mind, a project called “guest tree species” in relation to climate change was started in Switzerland. In combination with this project, 867 containerized *Thuja plicata* seedlings together with other species, were planted from 2012 to 2015. Seed material came from Oregon City to Salem, seed zones 261-05, 45° 00´ 52´´ to 123° 16´03´´ (Nikolova et al., 2016). 16 seedlings were planted as supplements in spring 2014. 0.7 % of the seedlings planted in autumn 2012 and 12.5 % of the seedlings planted in spring 2014 died after establishment. Among all tested species, *Thuja plicata* established as one of the best with annual height increments between 0.4 to 0.5 m/year and only little damage.

2. Materials and Methods

2.1 Sites

This thesis contains data from four experiments on three sites in South Sweden (Figure 3).

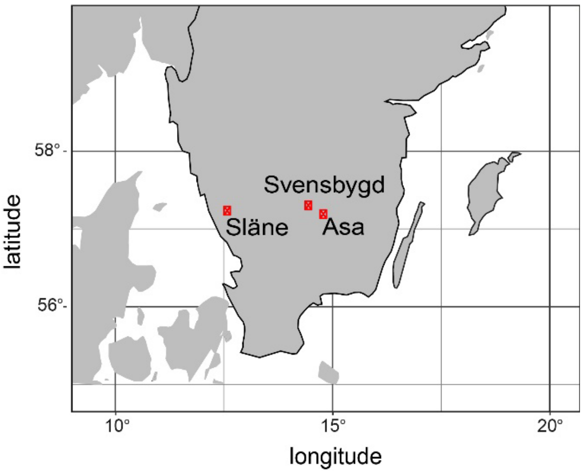

Figure 4: Experimental sites located in South Sweden.

2.1.1 Asa

Asa (57.153122, 14.756700) is the furthest east of the three sites in this study and lays 222 m above sea level. The site index for Norway spruce is G32, indicating a top height of 32 m for Norway spruce at a total age of 100 years, on a sandy-silty glacial till and mesic soil type. Vegetation type has been determined as "låg-ört" (Appendix, p. 60), "low-herb", indicating a rather fertile soil in Sweden (Hägglund and Lundmark, 1982).

Mean annual temperature between 2011 and 2018 was 7.5 °C with a mean annual precipitation of 613.8 mm (Sveriges meterologiska och hydrologiska institut, 2019). Mean temperature for the coldest month in this period was -1.5 °C in January, whereas the mean temperature for the warmest month was 17.2 °C in July.

2.1.2 Släne

Släne (57.199233, 12.545120) is located close to the west coast of Sweden. It is around 62 m above sea level. The site index for Norway spruce is G32 on mesic, sandy-silty glacial till, on which the vegetation type has been determined as "smalbladig grästyp", "thin-leaved grass type", indicating medium soil fertility in Sweden (Hägglund and Lundmark, 1982).

Mean annual precipitation for the period between 2011 and 2018, was 1186.6 mm, whereas the mean annual temperature was 7.4 °C. Mean temperature for the coldest month in this period was -1.2 °C in February and 16.4 °C were recorded in mean for the warmest month in July (Sveriges meterologiska och hydrologiska institut, 2019).

2.1.3 Svensbygd

Svensbygd (57.267490, 14.413840) is located 213 m above sea level between the experiments Asa and Släne. Site index in Svensbygd is G30 for Norway spruce on dry to mesic soil with sandy glacial till and vegetation type has been inventoried as "smalbladig grästyp", "thin-leaved grass type", indicating medium soil fertility for Swedish conditions (Hägglund and Lundmark, 1982).

Mean annual precipitation was 724.7 mm, during the period between 2011 and 2018 and mean annual temperature was 7 °C. The coldest month during this period was January with a mean temperature of -2.1 °C, whereas July was recorded as the warmest month with a mean of 17 °C (Sveriges meterologiska och hydrologiska institut, 2019).

2.2 Experiments

In 2011, three experiments were established in Asa, Släne and Svensbygd. 2014, an additional experiment was planted in Släne on a clear-cut area, close to the older experiment. In all experiments, four provenances of *Thuja plicata* were chosen to study growth and vitality (Table 1 and Figure 4). As a reference, genetically improved Norway spruce from the seed orchard in Bredinge, in the following also referred to as "Bredinge spruce", was planted in all experiments. Norway spruce from this seed orchard in the south west of Öland was chosen, because it is considered hardy against spring frost and shows high production on the experimental sites (Hällgren, 2015). Norway spruce, as well genetically improved, from the seed orchard in Södergärde, "Södergärde spruce", was planted additionally in the experiment from 2014 in Släne.

Table 1: Provenances used in the experiments. Climate data was taken from the closest available weather station in Canada between the years 1981 and 2010 (Government of Canada, 2019a). [I] and [C] stands for interior, respective coastal provenance. Treatment signifies the choice of provenance and was used to simplify the visualisation of the experiments.

Provenance	**Treatment**	**Latitude/ longitude**	**Elevation [m]**	**Mean annual precipitation [mm/year]**	**Mean annual temperature [°C]**
Horsey Creek	1 / yellow	53.06/-119.41 [I]	800	1069.8	2.8
Yola Creek	2 / orange	49.13/-121.25 [C]	700	1220.4	6.4
Bench Road	3 / red	51.48/ -118.39 [I]	800	1070.9	5.1
Pyramid Creek	4 / blue	52.23/ -119.10 [I]	800	1024.3	4.8
Norway Spruce, seed orchard in Bredinge	5 / dark-grey				
Norway Spruce, seed orchard in Södergärde	6 / light-grey				

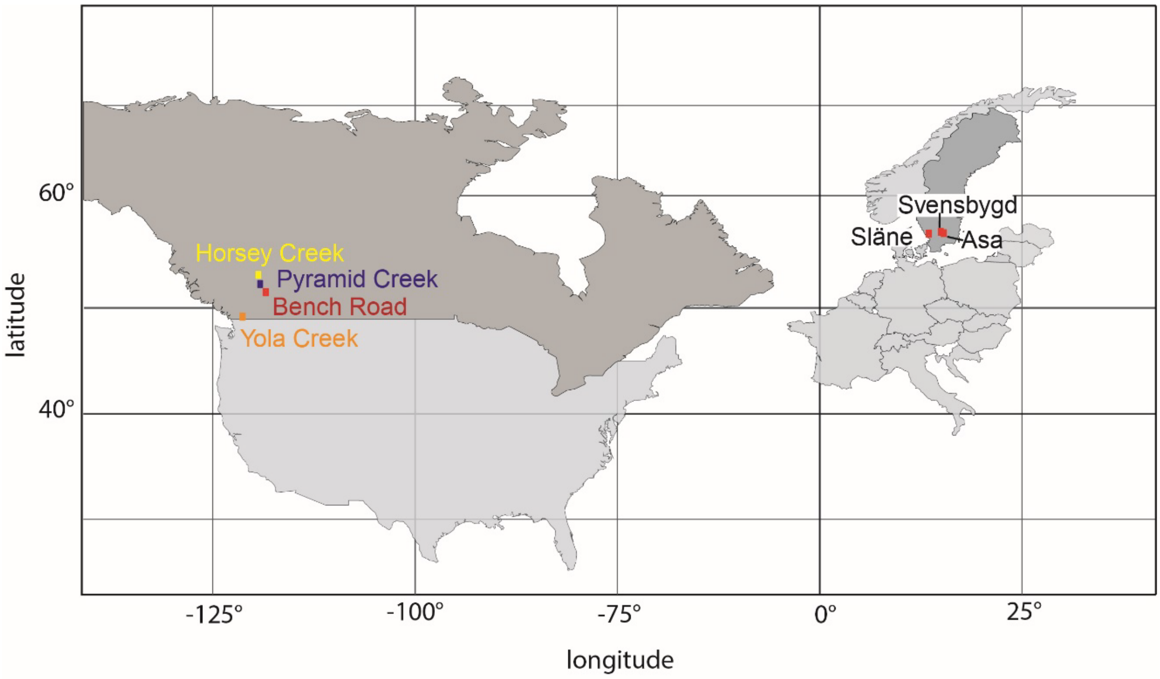

Figure 5: Provenances´ sites in Canada and location of the experiments in Sweden.

2.2.1 Asa

The experiment in Asa is a randomized block design with three blocks, in which each treatment is represented once. The plot size for each treatment is 31.62 m x 31.62 m, hence 0.1 ha (Figure 5). *Thuja plicata* was planted in a row-wise mixture with hybrid larch in treatment one to four, with initial spacing of 2 m x 2 m. Norway spruce was planted in treatment five without hybrid larch. The purpose of mixing larch and *Thuja plicata* was mainly to improve microclimatic conditions, due to the relatively high frost sensitivity of *Thuja plicata* (Hällgren, 2015). *Thuja plicata* was one and a half years old, when planted in spring 2011. Norway spruce was planted as large one year old seedlings, whereas hybrid larch was planted at the age of two. Containerized plants were used. Moreover, treatment against pine weevil (*Hylobius abietis*) was carried out with insecticides, the first two years after planting.

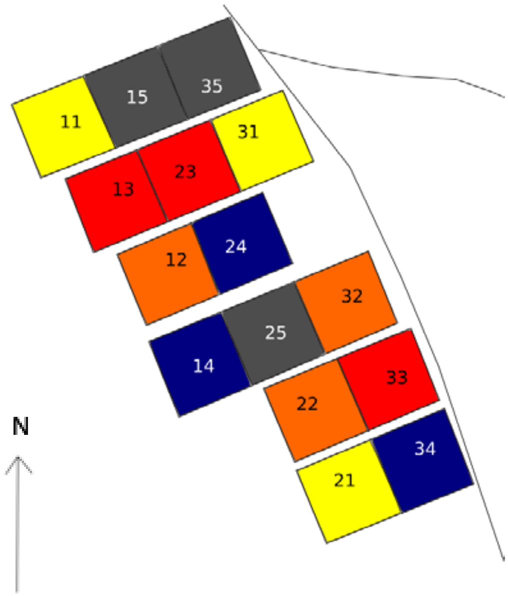

Figure 6: Experimental design in Asa. The first number is the block, the second number represents the treatment. Colours represent the provenances as well, according to table one.

2018, two rows of 15 saplings were measured in each plot. Hence, 30 saplings per block and 450 saplings in total were measured in the experiment in Asa. Before the 2018 inventory, several measurements were done. Height and damage were measured in autumn 2011 and 2013 as well as in spring 2016. Additionally, damage was assessed in spring 2012 and 2013.

2.2.2 Släne_2011

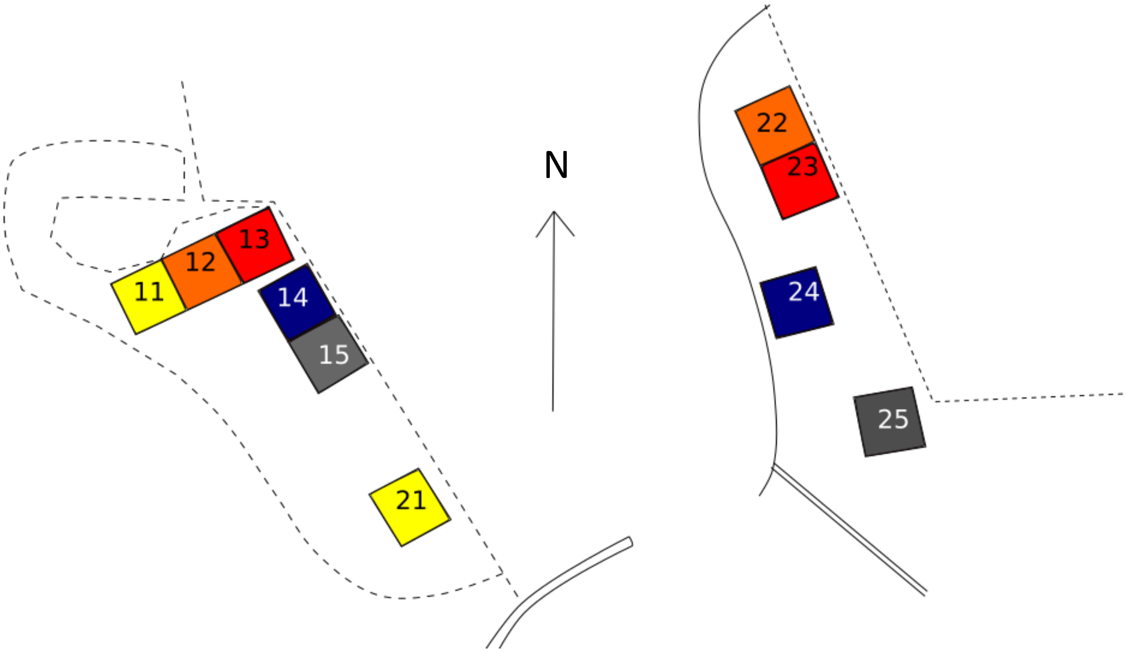

Figure 7: Experimental design in Släne, established in 2011. The first number represents the block, the second the treatment. Colours represent the provenance as well, according to table one.

The experiment in Släne from 2011 consists of two blocks, in which each treatment is represented once (Figure 6). Plots in the randomized block design are 40 m x 40 m, hence 0.16 ha. *Thuja plicata* was established in a row wise mixture with hybrid larch in treatment one to four. Initial spacing between the rows was 2 m, spacing within the rows of *Thuja plicata* was 2 m and within the rows of hybrid larch 2.5 m. Norway spruce was planted 2 m x 2 m without any shelter in treatment five. Soil scarification was carried out in spring 2011, before *Thuja plicata* was planted the same spring at the age of one and a half years. Hybrid larch was planted at the age of two, while Norway spruce was planted as large one year old seedlings. Generally, containerized plants were used and treated against pine weevil with insecticides the first two years after planting.

In autumn 2018, each third row of 15-18 saplings, was measured in every plot. In total, 168 saplings were measured. Previous measurements of height and damage were carried out in autumn 2011, 2013 and spring 2017.

2.2.3 Svensbygd

The experiment in Svensbygd is a randomized block design, consisting of two blocks with five treatments (Figure 7). However, Norway spruce was not established in a separate plot due to lack of space. Therefore, Norway spruce was planted around and inbetween the plots. Despite the experiments in Asa and Släne_2011, *Thuja plicata* was established without hybrid larch as shelter.

Thuja plicata was planted the 21st and 22nd of May 2011 at the age of one and a half years. Norway spruce was planted at the same time as *Thuja plicata* as large one year old seedlings. All plants were treated against pine weevil the first two years after planting, applying insecticides.

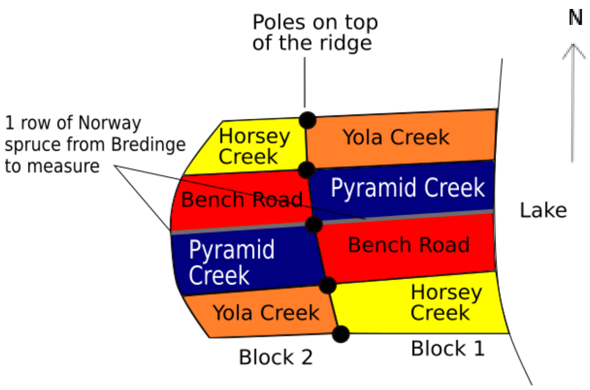

Figure 8: Experimental design in Svensbygd. Colours according to table one.

In autumn 2018, each middle row of 20 saplings per plot was measured. To get the reference of Norway spruce, the row between the plots of Bench Road and Pyramid Creek was marked to be measured. Hence, 200 saplings were measured in total. One previous measurement of height and damage was done in autumn 2012.

2.2.4 Släne_2014

The experiment from 2014 in Släne has been established as a randomized block design with two replicates (Figure 8). Among six treatments, four *Thuja plicata* provenances and two provenances of Norway spruce are represented once in every block. The plots are 40 m x 40 m, hence 0.16 ha with initial spacing of 2 m x 2 m.

Before planting in spring 2014, soil scarification was carried out in autumn 2013. At the time of planting, *Thuja plicata* seedlings were one and a half years old, whereas Norway spruce was planted as large one year old seedlings. For both species, containerized plants were used. No shelter of hybrid larch

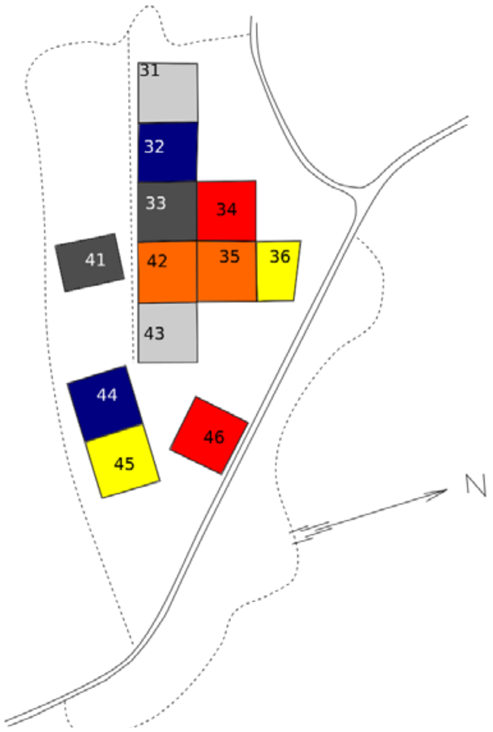

Figure 9: Experimental design in Släne, established in 2014. The first number represents the block, the colours represent the provenance according to table one. The second number cannot be seen as the treatment reference, since the number dispersal in 2014 was done differently than in 2011.

was established. The first two years after planting, all plants were treated with insecticides against pine weevil.

In the inventory in autumn 2018, measurement was done in two circular plots with a radius of 3.99 m, 50 m², in each treatment plot. The number of measured saplings in each circular plot varied between 17 and 28. In the end, 266 saplings were measured in total in this experiment. Before 2018, height, leading shoot and damage was measured in spring 2016 and spring 2017.

2.3 Measurement

2.3.1 Height

To get an indication of growth of the different provenances, height was measured by a height measurement rod with a scale from zero to four metres. In those plots, in which *Thuja plicata* was established in mixture with hybrid larch, the height of hybrid larch was estimated and a mean was taken for each plot.

2.3.2 Damage assessment

Damage was assessed for each measured sapling. The cause of damage was subdivided into ten possible reasons and damage severity was judged on a scale from zero to six (Table 2). In case of dead saplings, it was often impossible to say, what cause led to death, since many saplings have been dead for a long time.

Table 2: Possible reasons that caused damage and scale of damage severity.

	Damage cause
0	No damage
1	Fungi
2	Frost
3	Drought
4	Winter desiccation
5	Vegetation
6	Game
7	Insect, other than pine weevil
8	Pine weevil
9	Other/Unknown

	Damage severity
0	No damage
1	Insignificant
2	Somewhat
3	Severe
4	Life-threatening
5	Dead
6	Missing

2.4 Statistical analysis

The statistical analysis was carried out by the software R, version 3.5.2. Significance was tested for the experiments in Asa, Släne_2011 and Svensbygd, because they were established the same year. Since the experiment in Släne_2014 was established three years later and includes one more tested provenance, it was not considered in the statistical analysis. Moreover, it was not analysed separately, due to an insufficient number of degrees of freedom. However, means for each block and provenance were taken as well for this experiment. Hence, trends are still observable.

Due to the design of a randomized block, means for height 2018 and damage severity of each block and provenance were taken, before any analysis was implemented. Afterwards, an analysis of variance type III, using the Satterthwaite's method ("package lme4"), was carried out according to the following nested model, in which block is nested within site (Bolin, 2017):

$$Ypijk = \mu + \alpha_p + b_i + d_{j(i)} + \varepsilon_{pijk}$$

where, $Ypijk$ is the dependent target variable as height in 2018 or damage severity, μ is the overall mean, α_p is the fixed effect of provenance, b_i is the site effect, $d_{j(i)}$ is the block effect nested within site and ε_{pijk} is the error. In case of p-values smaller than 0.05, Tukey´s test with $p < 0.05$, was applied to identify exact differences.

3. Results

3.1 Height 2018

Saplings´ mean height 2018 from all the sites included in the statistical analysis reached from 204 cm (Yola Creek) to 263 cm (Bredinge spruce). Highest *Thuja plicata* provenance proved to be Pyramid Creek with 226 cm, followed by Bench Road and Horsey Creek (Table 3). The analysis of variance indicated a significant influence of provenance on height in 2018. Yola Creek saplings were significantly smaller than Norway spruce saplings from Bredinge. However, other *Thuja plicata* provenances did not differ significantly from Norway spruce and no significant difference in height has been shown between the *Thuja plicata* provenances.

Table 3: Results of the ANOVA with height as dependent variable, including both Norway spruce and Thuja plicata. Släne_2011, Svensbygd and Asa are included in the analysis. "NumDF" is the number of degrees of freedom in the numerator and "DenDF" is the number of degrees of freedom in the denominator. The full results of the statistical analysis are attached in the appendix, p. 65.

Height in cm					
		NumDF	**DenDF**	**F-value**	**P-Value**
	Provenance	4	28	3.42	0.021
Provenance		**Mean [cm]**	**Grouping**		
	Horsey Creek	219	ab		
	Yola Creek	204	a		
	Bench Road	220	ab		
	Pyramid Creek	226	ab		
	Bredinge Spruce	263	b		

Comparing all experiments, saplings in Släne_2011 were taller than on the other sites (Figure 9). Moreover, saplings in Släne_2014 were almost as tall as saplings in Svensbygd, although established three years later. In addition, Yola Creek saplings in Asa were similar tall as saplings from all provenances in Släne_2014. Furthermore, variation in height within the provenances as well as between them tended to be less in Släne_2014.

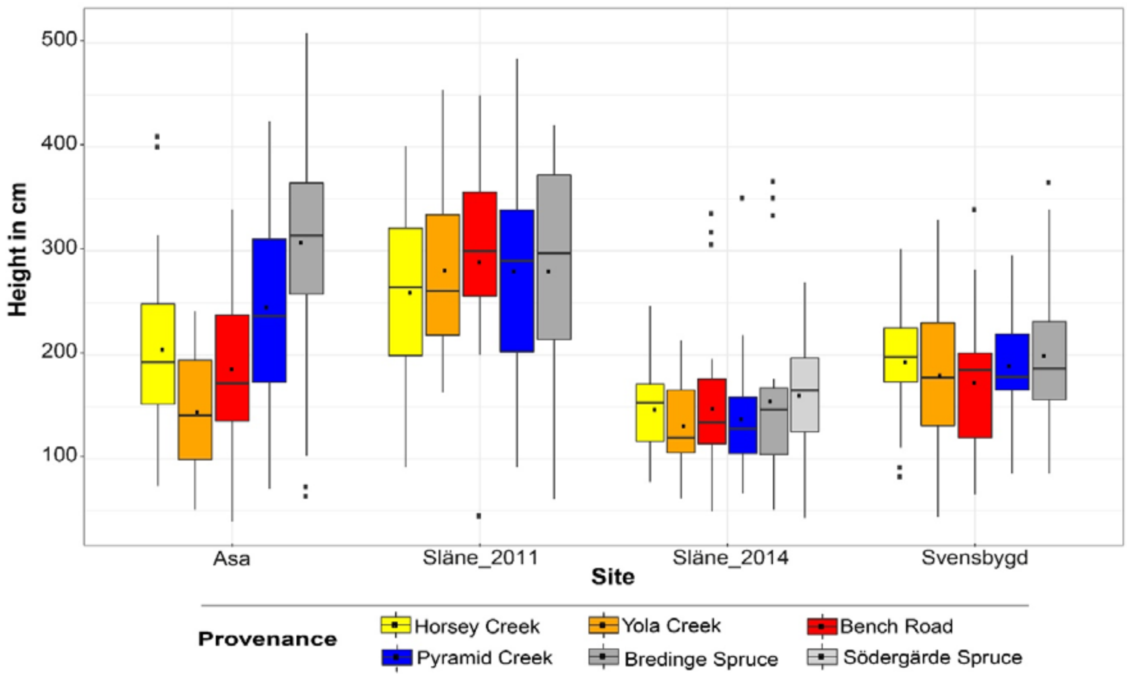

Figure 10: Height 2018, divided by provenance on each site, all measurements included. The boxes represent the upper, respective lower 25 % limit of all the heights measured. The whiskers spread to the lowest, respective highest value of all the heights measured in 2018. Unusual high, respective low values are represented by the outliers. The dot in the boxes represents the mean value, whereas the horizontal line equals the median.

After **ranking** the provenances according to their mean height in 2018 on each site, Horsey Creek and Bench Road saplings were the tallest *Thuja plicata* provenances (Table 4). It must be mentioned that Horsey Creek was the better growing provenance in Sweden´s inland away from the coast, whereas Bench Road seemed to grow better along the coast. Norway spruce was in almost all cases the tallest species, with the exception in Släne_2011. In this experiment, Bench Road saplings grew taller than any other provenance.

Table 4: Ranking of mean heights 2018, divided by site and provenance, with "R" for ranking and "MR" for mean ranking. Number 1 as the tallest provenance, 5 as the shortest. Södergärde spruce was not considered in the ranking, since it is only represented in Släne_2014.

Mean height									
	Asa		**Släne_2011**		**Svensbygd**		**Släne_2014**		
	[cm]	**R**	**[cm]**	**R**	**[cm]**	**R**	**[cm]**	**R**	**MR**
Horsey Creek	202	3	261	4	193	2	147	3	3
Yola Creek	148	5	281	2	181	4	132	5	4
Bench Road	184	4	306	1	172	5	149	2	**3**
Pyramid Creek	228	2	258	5	192	3	135	4	**3.5**
Bredinge Spruce	308	1	281	3	200	1	165	1	**1.5**
Södergärde Spruce							161		

3.2 Height development

Norway spruce was the fastest growing species in all experiments, apart from Släne_2011 (Figure 10). Horsey Creek and Pyramid Creek developed best in Asa and Svensbygd, whereas Bench Road grew faster compared to all other provenances in Släne_2011 and faster than the *Thuja plicata* provenances in Släne_2014. Yet, Bench Road was the poorest growing provenance in Svensbygd. Yola Creek was growing more slowly than the other provenances in Asa and Släne_2014. In Släne_2011 however, it grew similar well as Bench Road.

During the first three vegetation periods, *Thuja plicata* saplings in Släne_2014 and Svensbygd grew faster than saplings in Släne_2011 and Asa. After that, saplings´ height increment in Asa and Släne_2011 increased more than in Svensbygd and Släne_2014. Hence, similar tall saplings could be found after five vegetation periods in both experiments in Släne. Norway spruce however, has to be considered separately, since the saplings were half a year younger than *Thuja plicata* saplings.

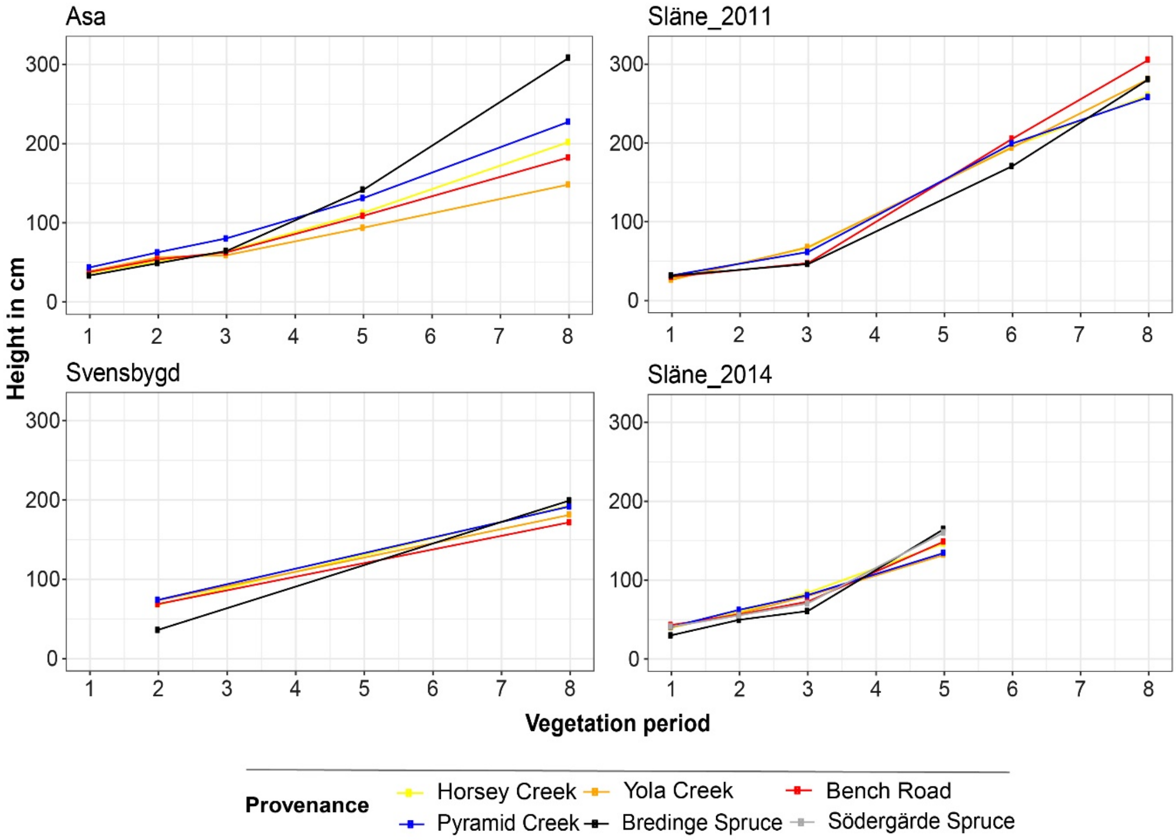

Figure 11: Height development in relation to vegetation period. The time, the inventory was carried out was converted to vegetation periods, counted after planting. An overview of inventory years, number of vegetation periods and related seedling ages can be found in the appendix, page 60.

3.3 Hybrid larch - height 2018

Hybrid larch reached heights between 450 and 750 cm (Figure 11). In all cases, hybrid larch was taller than *Thuja plicata* (Appendix, p.63). The smallest difference between heights of *Thuja plicata* and hybrid larch was found in Släne_2011 in block one, whereas larches in Asa, block two were much taller compared to *Thuja plicata* in the same block.

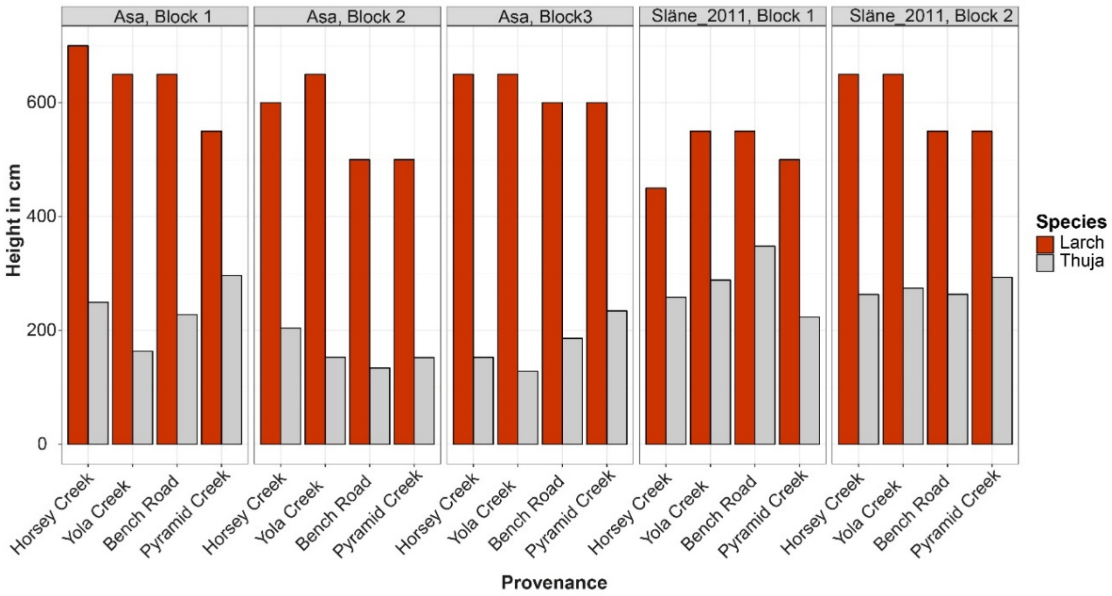

Figure 12: Height of Hybrid larch compared to height of Thuja plicata in Asa and Släne_2011 in cm, in autumn 2018, divided into blocks and provenance plots.

3.4 Survival and damage

Mean damage severity of the sites included in the statistical analysis varied for *Thuja plicata* between 1.18 (Horsey Creek) and 1.79 (Bench Road) in the range from zero to six and was 0.29 for Bredinge spruce (Table 5). Horsey Creek was the least damaged *Thuja plicata* provenance, followed by Yola Creek and Pyramid Creek. On average for all sites, mortality between the *Thuja plicata* provenances was between 19.8 % (Horsey Creek) and 29 % (Bench Road), whereas 19 % from Norway spruce saplings from Bredinge had died before 2018 (Table 6).

The analysis of variance indicated a significant influence of provenance on damage severity in the 2018 inventory. Tukey's test determined significantly less damaged saplings of Norway spruce compared to all *Thuja plicata* provenances, whereas no significant difference has been indicated between the *Thuja plicata* provenances. Taking all sites into consideration, saplings were more damaged in Släne_2014 compared to Släne_2011 as well as more damaged in Svensbygd compared to Asa (Table 6). Generally, saplings in Släne_2011 were the least damaged.

Table 5: Results of the ANOVA with damage severity as dependent variable for both species Norway spruce and Thuja plicata. Experiments in Asa, Släne_2011 and Svensbygd were included in this analysis. "NumDF" is the number of degrees of freedom in the numerator and "DenDF" is the number of degrees of freedom in the denominator. The full results of the statistical analysis are attached in the appendix, p. 66.

Damage severity					
		NumDF	**DenDF**	**F-value**	**p-Value**
	Provenance	4	28	23.25	8.305E-06
Provenance		**Mean**	**Grouping**		
	Horsey Creek	1.18	b		
	Yola Creek	1.67	b		
	Bench Road	1.79	b		
	Pyramid Creek	1.61	b		
	Bredinge Spruce	0.29	a		

3.4.1 Asa

Before the inventory in autumn 2018, already 42.2 % of Bench Road saplings had died (Table 6). In comparison, only 25.6 % of Pyramid Creek and 13.3 % of Norway spruce saplings died before 2018. The least damaged provenance in Asa 2018 was Bredinge spruce (Figure 12). The most vital *Thuja plicata* provenance was found to be Horsey Creek, followed by Pyramid Creek, Yola Creek and Bench Road as the least vital.

It is noteworthy that many saplings, damaged in severity classes one and two, were infected by fungi. The few times game was present, damage was not caused by browsing but by fraying. Drought was the main factor for the small number of damaged saplings in Norway spruce.

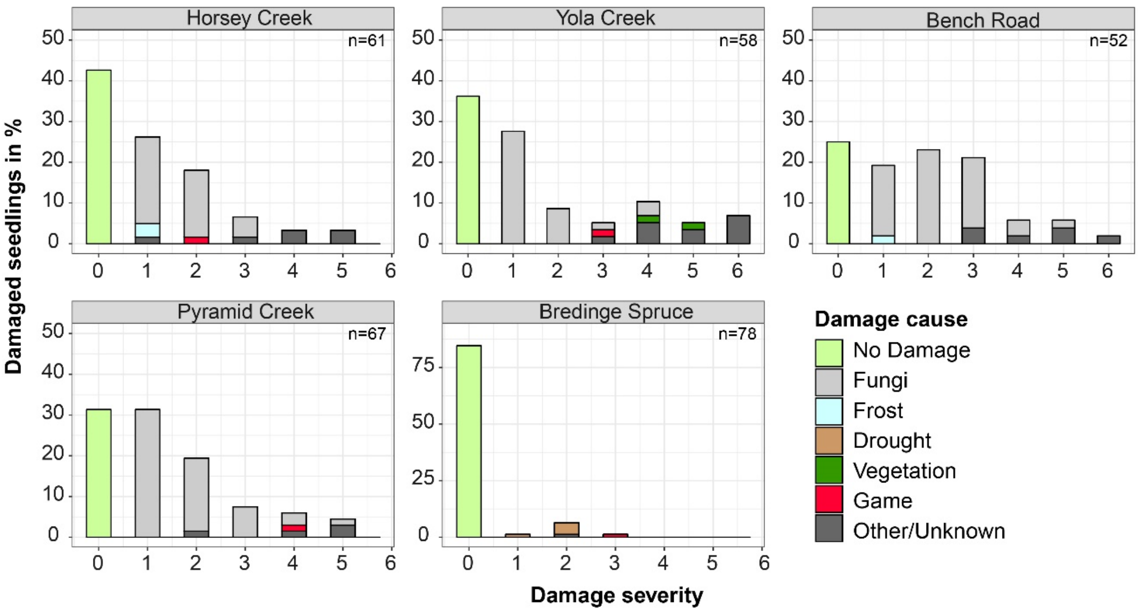

Figure 13: Damage 2018 in Asa. Damage severity is listed according to table 2. The y-axis represents damaged seedlings in percent of all the seedlings of one provenance. Damage cause is represented by colours seen in the legend. It is shown in percentage of each severity class of the respective provenance.

3.4.2 Släne_2011

Mortality in the provenances Bench Road and Yola Creek was 68.8 % and 65.7 % respectively (Table 6). Half of the Pyramid Creek saplings died before the inventory in autumn 2018, whereas, 37.8 % of Bredinge spruce saplings and only 28.1 % of Horsey Creek saplings died before 2018. The same ranking pattern can be seen in the damage distribution in 2018 (Figure 13). Bench Road was the most damaged provenance, followed by Pyramid and Yola Creek. Horsey Creek as most vital *Thuja plicata* provenance, was mostly damaged in severity classes one and two. Norway spruce from Bredinge was mainly undamaged. However, two Norway spruce saplings were damaged by game and drought.

As well as in Asa, damage in severity classes one and two was mostly caused by fungal infection. Seedlings were damaged more severely through fraying instead of browsing, if game was the cause. Compared to Asa, game damaged more saplings at this site.

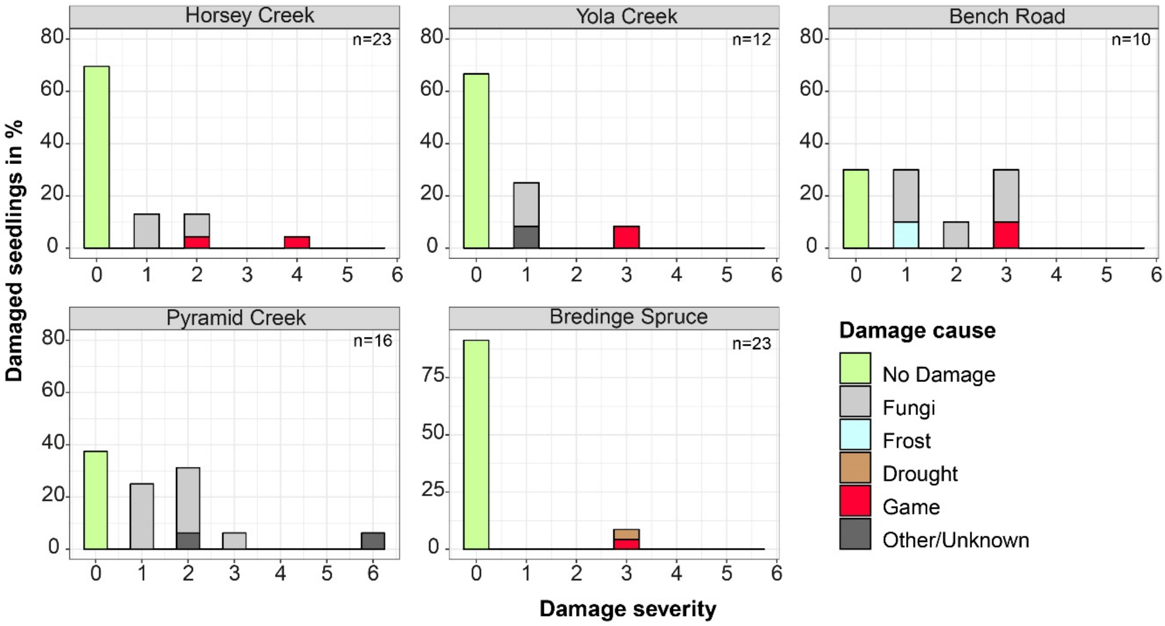

Figure 14: Damage 2018 in Släne_2011. Damage severity is listed according to table 2. The y-axis represents damaged seedlings in percent of all the seedlings of one provenance. Damage cause is represented by colours seen in the legend. It is shown in percentage of each severity class of the respective provenance.

3.4.3 Svensbygd

In Svensbygd, only 2.5 % of Horsey Creek saplings died before 2018 (Table 6), while all other saplings survived. Yet, the previous inventory was done in autumn 2012. The least damaged provenance 2018 was Bredinge spruce, in which only 7.5 % of the saplings were dead by unknown reason (Figure 14). Horsey Creek was the most vital *Thuja plicata* provenance, followed by Pyramid Creek, Bench Road and Yola Creek.

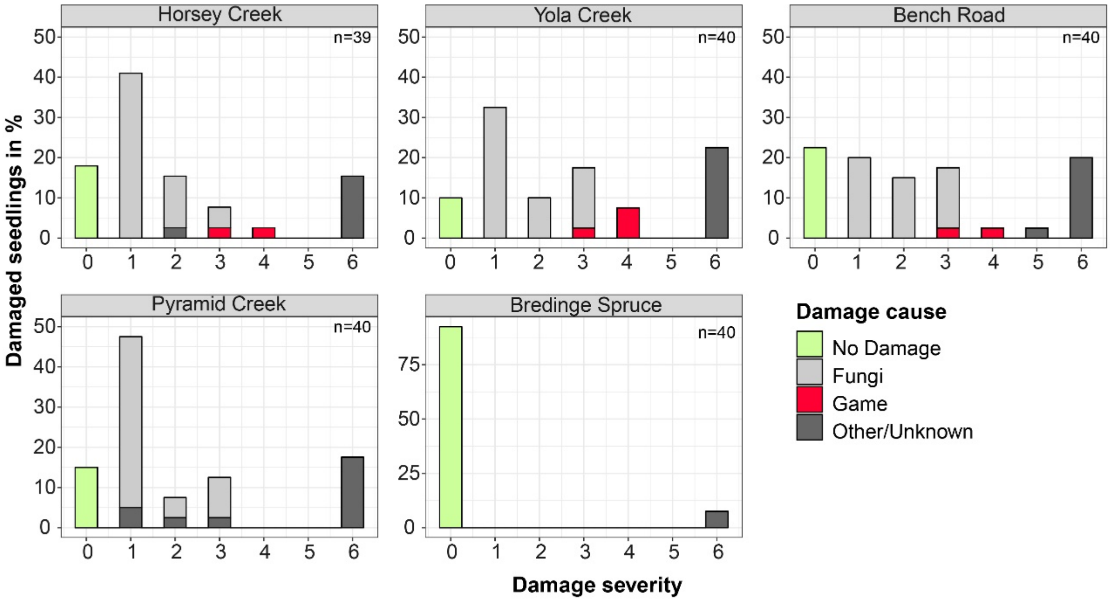

Figure 14: Damage 2018 in Svensbygd. Damage severity is listed according to table 2. The y-axis represents damaged seedlings in percent of all the seedlings of one provenance. Damage cause is represented by colours seen in the legend. It is shown in percentage of each severity class of the respective provenance.

Most saplings in severity classes one to three were infected by fungi. Game had a stronger impact on saplings´ vitality which led to strong or life-threatening severity. However, game did mostly fray the saplings or bend them over without browsing them (Appendix, p.62). In Svensbygd, more saplings were found dead and more severely damaged in block two compared to block one (Figure 15), although, the reason was unknown. Additionally, more saplings were damaged by game in block two than in block one.

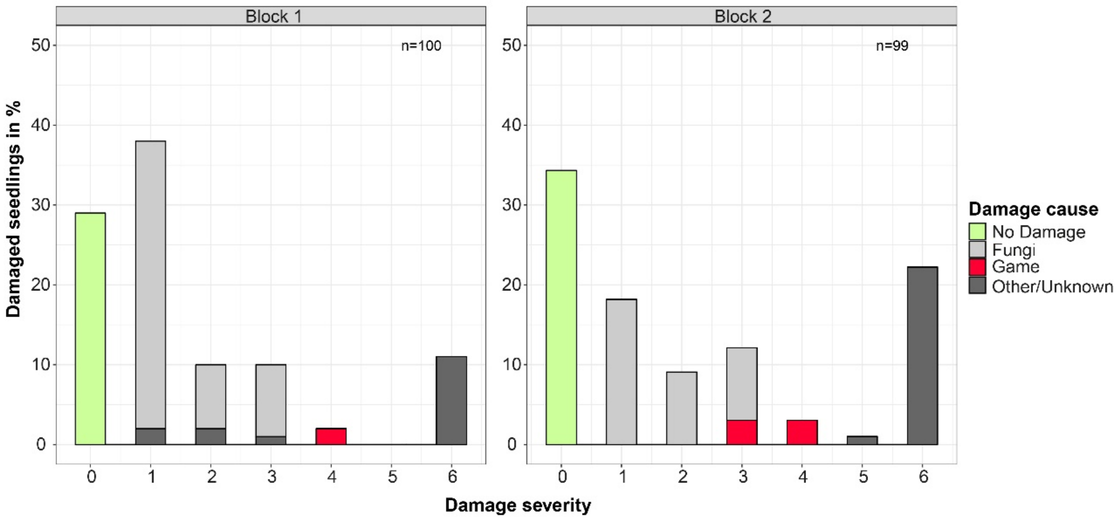

Figure 15: Damage 2018 divided into blocks in Svensbygd. Damage severity is listed according to table 2. The y-axis represents damaged seedlings in percent of all the seedlings in one block. Damage cause is represented by colours seen in the legend. It is shown in percentage of each severity class of the respective block.

3.4.4 Släne_2014

Most dead saplings before 2018 were found in Norway spruce, Bredinge provenance with 25 %. 18.2 % of Pyramid Creek saplings had died before 2018, followed by Horsey Creek and Yola Creek. The lowest mortality was recorded in Bench Road with 5.1 % (Table 6). Controversy to these results, Bredinge spruce and Södergärde spruce were the least damaged provenances in 2018 (Figure 16). The most vital *Thuja plicata* provenance was Yola Creek, followed by Horsey Creek and Bench Road, whereas Pyramid Creek was the most damaged provenance. Severity classes between one and three were mainly caused by fungal infection. The proportion of game damage was rather small, although it led to "somewhat" and "strong" damage severity of the saplings.

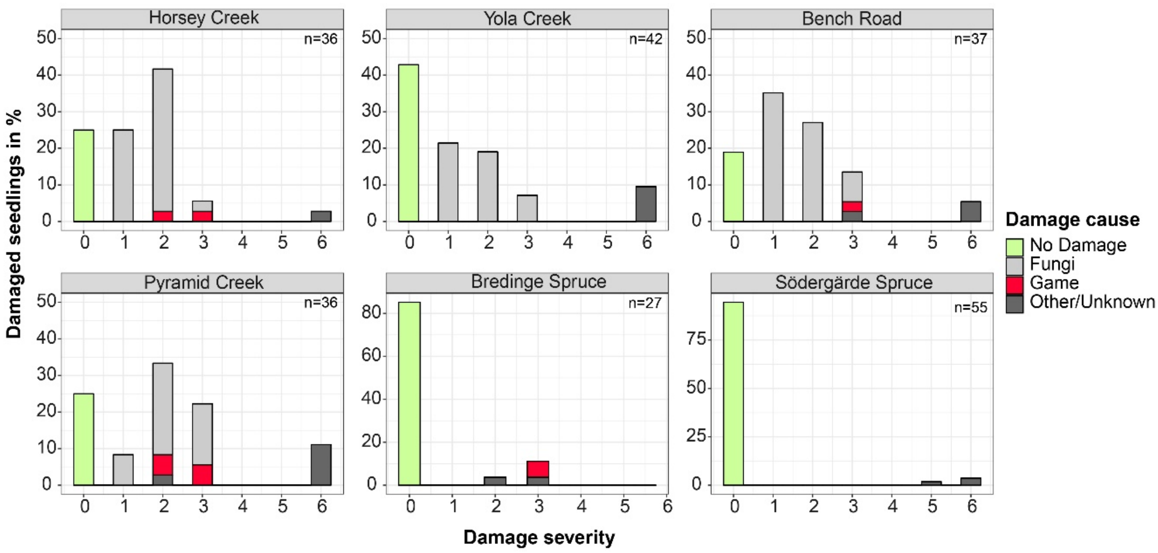

Figure 16: Damage 2018 in Släne_2014. Damage severity is listed according to table 2. The y-axis represents damaged seedlings in percent of all the seedlings of one provenance. Damage cause is represented by colours seen in the legend. It is shown in percentage of each severity class of the respective provenance.

3.4.5 Ranking

Ranking all provenances on each site according to the mean of damage severity, Horsey Creek was the least damaged *Thuja plicata* provenance, followed by Yola Creek, Pyramid Creek and Bench Road as the most damaged (Table 6). However, Norway spruce was much less damaged than *Thuja plicata* in all cases.

Table 6: Overview and Ranking of damage severity, divided by provenances and sites, with "M" for the mean of damage severity and "R" for ranking. 1 represents the least and 5 the most damaged provenance. Södergärde spruce is not included in the ranking, since it is only represented in Släne_2014.

Mean damage severity													
	Asa			Släne_2011			Svensbygd			Släne_2014			
	M	Dead before 2018	R	M	Dead before 2018	R	M	Dead before 2018	R	M	Dead before 2018	R	Mean of Ranking
Horsey Creek	1.13	32.2 %	2	0.66	28.1 %	3	1.98	2.5%	2	1.41	16.3 %	3	2.50
Yola Creek	1.67	35.6 %	4	0.51	65.7 %	2	2.70	0.0 %	5	1.38	14.3 %	2	3.25
Bench Road	1.88	42.2 %	5	1.34	68.8 %	5	2.45	0.0 %	4	1.61	5.1 %	4	4.50
Pyramid Creek	1.41	25.6 %	3	0.96	50.0 %	4	2.05	0.0 %	3	2.06	18.2 %	5	3.75
Bredinge Spruce	0.19	13.3 %	1	0.26	37.8 %	1	0.45	0.0 %	1	0.45	25.0 %	1	1.00
Södergärde Spruce										0.33	0.0 %		

4. Discussion

4.1 Height 2018

4.1.1 Height differences between the provenances

The results found in this study are consistent with those found by Hällgren (2015) for the same experiments in Asa and Släne_2011. However, no significant differences have been found between *Thuja plicata* provenances regarding height growth.

Besides the limited number of tested provenances in this thesis, one reason for the lack of significance might be an overall low genetic variation in *Thuja plicata*. Sakai and Weiser (1973) describe trees with unexpectedly similar forms and growth rates, when they are grown at the same site although originating from different regions. Therefore, less genetic variation, as compared to other North West American tree species may be the cause, although some differences between provenances from the coastal and inland distribution have been found (Rudloff et al., 1988; Minore, 1990). In addition, only little adaptation in response to environmental selection pressures has been detected in this species (Fan et al., 2008). Furthermore, O'Connell et al. (2008) have clustered 23 *Thuja plicata* populations into three groups in relation to their genetic variation. Besides, two southern populations with the genetically highest differences have been regarded separately. The groups were sorted into a northern-coastal, a central and a southern-interior part of the species´ range. Both the coastal provenance Yola Creek as well as the three inland provenances tested in this thesis, would belong to the southern-interior group, which reflects the missing significance in height differences.

Conversely, Cherry (1995) has found significant levels of genetic variation in *Thuja plicata* concerning growth and survival. The same study states the hypothesis of *Thuja plicata* being in permanent genetic change, hence contradicting to the previously stated conclusions. In addition, significant levels of height growth variation and resistance to *Didymascella thujina* have been found in provenance studies made in Great Britain (Rollinson, 1988 see Klinka and Brisco, 2009). Moreover, Rehfeldt (1994) has determined genetic variation in growth and winter hardiness in inland provenances, south of those tested in this thesis. Nonetheless, no significance could be shown.

In brief, it cannot be said for sure, whether the absent significance is a cause of low genetic variation exclusively in the limited number of tested provenances, or if it is due to an overall low genetic variation in this species.

Yola Creek, as the only coastal origin, was the poorest growing *Thuja plicata* provenance tested, which is supported by Tukey´s test that indicated significantly smaller saplings of Yola Creek compared to saplings of Norway spruce. In line with this, Radwan and Harrington (1986) found significantly higher growth of the terminal shoot in populations growing in the interior compared to those in the coastal zone on sites with the same site index ($p < 0.01$). Moreover, precipitation is higher in the natural range of coastal origins compared to inland origins (Krajina, 1969), which makes inland provenances better suited for Swedish climate conditions.

On the contrary, Fan et al. (2008) have not found significant differences between southern coastal and interior provenances regarding growth. However, populations from Vancouver island´s northern and western coast grew significantly less, "especially when weather became drier and hotter". In addition, the highest precipitation has been found in the natural range of these poorer growing populations from Vancouver island´s northern and western coast, which is consistent with the results of this thesis. Compared to the other provenances tested, the highest precipitation with 1220 mm/year and 6.4 °C mean temperature was recorded in Yola Creek´s natural range (Government of Canada, 2019a). Neither in Släne, nor in Svensbygd or Asa, is this precipitation reached, whereas the mean temperature on all sites is higher than 6.4 °C (Sveriges meterologiska och hydrologiska institut, 2019). It has also been found that growth of Yola Creek was much smaller in Asa compared to Släne. Hence, this provenance grew less "especially when weather became drier and hotter".

In addition, **Horsey Creek** and **Bench Road** proved to be the best growing provenances, whereas Horsey Creek grew better in Sweden´s inland and Bench Road along the coast. Horsey Creek is the provenance from the furthest north, while Bench Road comes from the southernmost inland region tested. Consistent with this result, Panka (2014) considers seed material from the northern parts of *Thuja plicata*´s natural distribution as the best growing provenances for sites in continental Germany. Hence, it would explain Horsey Creek´s better growth compared to Bench Road in Sweden´s drier, more continental climate in Asa.

Furthermore, Bench Road experiences in its natural distribution 2.3 °C more in mean temperature compared to Horsey Creek with the same annual precipitation of around 1070 mm/ year (Government of Canada, 2019a). Temperatures are almost the same in Asa (7.5°C) and Släne (7.4°C) (Sveriges meterologiska och hydrologiska institut, 2019).

However, mean annual precipitation is around 600 mm higher in Släne than in Asa. Hence, the deciding factor concerning growth differences in Bench Road and Horsey Creek seems to be precipitation in Sweden. While Horsey Creek does not benefit from higher precipitation along the coast, Bench Road takes advantage of the additional water, which results in faster growth. This hypothesis can be explained by observations made by Wright (1976) in provenance testing. He states that southern seed origins or origins from warmer regions, grow faster than provenances from further north. However, being able to reveal these differences is dependent on experimental site conditions, which can also be seen from provenance experiments made in Great Britain (Samuel, 2003). If the climate is oceanic and mild, provenances up to 10° south in latitude from where they are planted in Britain, are recommended. This general recommendation however is not valid anymore, if climate becomes colder and drier. Therefore, in this thesis, water is limiting Bench Road´s higher growth potential in Asa, while the same is revealed through higher precipitation in Släne.

Summing up, although no significance between *Thuja plicata* provenances has neither been identified in this thesis nor in many other studies, trends in height growth variation can still be seen. The coastal provenance Yola Creek seems to be the least suitable provenance for Swedish climate and site conditions. Bench Road, as the southernmost tested provenance discloses its full growth potential under sufficient precipitation, while Horsey Creek grows well on drier sites, too. Therefore, Bench Road seems to be the better choice for coastal areas in Sweden, while Horsey Creek would be the choice for all other, especially drier sites. Yet, sufficient precipitation and soil moisture is essential for a successful cultivation of *Thuja plicata*.

4.1.2 Height differences between the sites

Additionally, the results have shown that the trees were taller in Släne compared to Asa and Svensbygd. This can be explained by higher annual precipitation along the coast compared to the sites in Sweden´s inland, which leads to better soil moisture availability. Several publications support this conclusion. As such, water is seen as the limiting factor for *Thuja plicata´s* growth (Olesen, 1962; Trauboth, 2006). Hence, *Thuja plicata* grows better with increasing soil moisture, and stagnating height growth in older ages was observed in response to limited water access instead of nutrient limitations (Lembcke, 1973). The same study has shown the possibility of *Thuja plicata* outgrowing Norway spruce on moist sites, which explains that *Thuja plicata* saplings were exceptionally taller than Norway spruce in Släne_2011. Moreover, Correia et al. (2018) have proven decreasing height growth with decreasing precipitation and increasing temperature. In addition, Fan et al. (2008) have demonstrated *Thuja plicata* being intolerant to water stress. Hence, moist sites and humid environments result in better growth.

In addition, elevation has been found the most important geographical element that is limiting *Thuja plicata´s* growth in Canada (Cherry, 1995). 167 m increase in elevation results in one centimetre loss in height growth, with all other factors being equal. This relation might partly explain the taller saplings in Släne compared to Asa and Svensbygd, since Släne lays around 160 m lower above sea level than the other sites. Moreover, if saplings were planted along the coast, a longer vegetation period benefits growth (Cherry, 1995), which effects faster increment.

In conclusion, a longer growing season, higher precipitation and lower elevation leads to taller *Thuja plicata* saplings in Släne.

4.2 Effect of hybrid larch on height development of *Thuja plicata*

This thesis has shown faster initial height increment in Släne_2014 and Svensbygd, which leads to the conclusion that the mixture of hybrid larch and *Thuja plicata* results in reduced growth of *Thuja plicata*. However, this effect could mainly be observed the first three years after planting, which is supported by Weber et al. (2003), who have shown that *Thuja plicata* seems to behave like a shade-intolerant species especially in the early establishment phase.

In addition, several authors have shown best height development without any shelter and mixture on various sites, although total stand volume production increases (Spellmann and Schober, 2001; Trauboth, 2006; Panka, 2013). Furthermore, the strong shade-tolerance of *Thuja plicata*, has been stated in numerous studies, but as soon as the canopy opens, a strong reaction in terms of growth can be seen (Lines, 1987; Stratmann, 1988; Weber et al., 2003; O'Callaghan et al., 2012). This is due to *Thuja plicata´s* traits as an "opportunist" (El-Kassaby, 1999). Hence, if the species encounters favourable conditions, it takes advantage of these and responds immediately. Moreover, *Thuja plicata* tolerates shade, but it does not require it, since maximum growth rates have been recorded without any shelter (Wang et al., 1994; Panka, 2013).

Contrarily, Kennedy et al. (2007) could observe faster growth in all shade levels compared to the open, in the first and second year after planting in Ireland. Though, shade-tolerance for *Thuja plicata* has proven to be highly dependent on the nutrient regime and decreases with increasing soil moisture (Carter and Klinka, 1992; Weber et al., 2017). Hence, in Ireland, site conditions, others than insolation, may have had a stronger impact on growth. However, this effect could not be shown in this thesis, since the height differences between saplings in Asa and Svensbygd, respectively Släne_2011 and Släne_2014 were similar.

In summation, although *Thuja plicata* tended to grow faster without hybrid larch, especially the first years after planting, the difference was small. Additionally, the original purpose of planting this admixture needs to be remembered, which was to provide a shelter from frost and therefore reducing damage and mortality.

4.3 Survival and damage

Damage assessment has shown Horsey Creek as the least and Bench Road as the most damaged provenance. However, the damage did not affect growth very much, but led mainly to mortality, which can be seen through good growth of the survived Bench Road saplings in Släne_2011. Moreover, saplings were more damaged in Släne_2014 compared to Släne_2011 as well as more damaged in Svensbygd compared to Asa. This can be explained by the improved microclimate through the shelter of hybrid larch. Several studies have proven higher survival underneath shelter, than without (Aldhous and Low, 1974; Niefnecker, 1989; Bothwell, 1998; Wilson et al., 2016). As *Thuja plicata* is known for its frost sensitivity (Krajina, 1969; Sakai and Weiser, 1973; Aldhous and Low, 1974; Minore, 1990; Wilson et al., 2016), the higher amount of dead and damaged saplings in Släne_2014 and Svensbygd may result from the exposed growing conditions towards climate. Moreover, Olesen (1962) emphasizes *Thuja plicata´s* establishment under shelter in its natural habitat, which is considered one main reason for frost sensitivity if the same species is grown without shelter. Additionally, many saplings in Svensbygd were dead in block two. During the inventory, it became clear that vegetation, mainly *Pteridium aquilinum*, spread in this block. However, it cannot be said, if the vegetation led to the saplings´ death or if it appeared when saplings have already been dead before 2018.

4.3.1 Fungal infection

Seedlings were mainly damaged by fungal infection. The fungus is assumed to be *Didymascella thujina* (Appendix, p. 61), also called cedar leaf blight. However, this can only be said for sure after analysing the fruit body, which was no part of this thesis. Furthermore, it could be observed that fungal infection led to damage severity in classes one to three. Hence, the fungus was in most cases not life-threatening. In line with this, Søgaard (1969) and Gray et al. (2013) could show that *Didymascella thujina* leads to death on young seedlings and saplings but to growth loss and branch death on plants older than six years.

Resistance to cedar leaf blight is highly dependent on the population´s origin and a higher variation among provenances could be observed in resistance to *Didymascella thujina* than in growth (Russell et al., 2007). If populations originate from wetter and milder climates, these show significantly higher resistance to the fungus at the same site (Søgaard, 1969; Russell et al., 2007; Russell and Yanchuk, 2012; Gray et al., 2013). Hence, Yola Creek saplings, originating in a milder and wetter climate along the coast, compared to the other provenances used in this thesis, should show higher resistance to this fungus. However, this was only the case in Asa and Släne_2011 which can possibly be explained by the transfer of this species to Sweden. It has been stated before that *Didymascella thujina* has a more severe impact in Europe as it has in America (Søgaard, 1969; Minore, 1990). Therefore, the resistance pattern of *Thuja plicata* is very likely to behave differently in Europe.

In addition, studies have shown higher infection rates on coastal, warm and moist as well as on low elevation sites (Russell and Yanchuk, 2012; Gray et al., 2013). Therefore, more infection should be observed in Släne compared to Asa and Svensbygd, due to lower elevation and moister climate. This could only be shown in the experiment from 2014 in Släne, in which slightly more saplings were damaged by the fungus compared to Asa and Svensbygd. In Släne_2011, however, not only the smallest number of saplings was damaged in general, but also the smallest number was infected by the fungus compared to the other experiments. This may be very likely due to the fact that many saplings had died in Släne_2011 already. Hence, the survived saplings show higher resistance to cedar leaf blight, whereas saplings in Släne_2014 were three years younger so that selection has not taken place, yet. Another explanation for this might be the shelter from hybrid larch which led to an improved microclimate, hence to less damage in general. However, a shelter also leads to a warmer microclimate and increased humidity (Aldhous and Low, 1974), which would favour the fungus. This would support the hypothesis that many saplings have already died before the inventory in 2018 and the remaining saplings show higher resistance towards cedar leaf blight.

To sum up, *Didymascella thujina* infects *Thuja plicata* with slight preferences in site and provenance and decreasing severity with increasing age of the saplings. Several factors may impact these observations, but too few studies of cedar leaf blight resistance have been carried out in Europe, to draw meaningful and comparable conclusions for the experiments in Sweden.

4.3.2 Game

If game damaged the saplings, it had a more severe impact on saplings´ vitality than fungal infections. However, none of the saplings was browsed but mostly frayed and sometimes broken or bent over. *Thuja plicata* has been found as a preferred species for fraying if it is present, compared to other species, which is partly explained by the soft texture of the bark (Gill, 1992; Vila et al., 2004). Moreover, in Sweden, a whole plantation of *Thuja plicata*, established in the 1930s, failed due to strong fraying damages (Svensson, 2008).

The observation of the absent browsing damage is supported by some studies and experiences made in Europe, which state that game is fraying *Thuja plicata* only (MacDonald et al., 1957; Kristöfel, 2003; Trauboth, 2006; Guba, 2019). Nonetheless, other authors, from Europe and North America, describe browsing by deer, elk and rodents as one of the main threats on *Thuja plicata* plantations (Curran and Dunsworth, 1988; Niefnecker, 1989; Bothwell, 1998; Brodie and DeBell, 2013). In Canada, browsing by black tailed deer led to the failure of whole plantations (Russell and Yanchuk, 2012). However, Oliver et al. (1988) have found only little browsing damage in some cases, though elk populations were high. Explanations for this have not been found.

The absence of browsing damage and therefore the discrepancy to several studies that observed browsing damage could be explained by three hypotheses: The first logical explanation would be that saplings were already too tall for browsing. This would support the observation from 2013 in Svensbygd, when saplings were heavily browsed. However, several saplings were still below the browsing threshold in 2018 (Gill, 1992), especially in the experiment from 2014 in Släne. Hence, those saplings could have been browsed in particular by moose. Moreover, Hällgren (2015) has only shown little damages by game in Asa and Släne_2011, which calls for other explanations than too tall saplings.

Secondly, Vourc'h et al. (2002) have shown higher monoterpene concentrations in less browsed saplings, while heavier browsed ones showed lower concentrations of these components. It has also been shown that the amount of monoterpene is dependent on genetic origin (Vourc'h et al., 2001; Vourc'h et al., 2002; Russell, 2008). Consequently, a variation in monoterpene concentration in provenances used in this study compared to other studies could be an explanation for the observed discrepancy.

A third explanation might be that other food sources than *Thuja plicata*, more preferred by deer, were available close to the experiments in this thesis, whereas these food sources were missing in studies that observed browsing damage. While all experimental sites, except Svensbygd, had sufficient complements for ungulate´s food requirements, the lack of these food sources may be the reason why *Thuja plicata* saplings were heavily browsed in 2013 in Svensbygd, regardless of possible high monoterpene concentrations. Therefore, no browsing pressure was shown for *Thuja plicata* in Sweden. In consistence, Kimball and Provenza (2003) as well as Felton et al. (2016) have shown that ungulates select their food source depending on energy input and detoxification to reach a nutritional balance. Hence, if *Thuja plicata* is the only available food source fitting the deer's nutrient requirements at the current situation, browsing pressure will be higher.

4.3.3 Conclusion of survival and damage

Concluding damage and survival, this thesis has shown that several factors combined, including site, shelter, the resistance to fungal infection and the influence of game, determine the observed variations in damage severity and mortality between the provenances. However, it cannot be said for sure, why exactly Bench Road was the most damaged and Horsey Creek the least damaged *Thuja plicata* provenance, especially since the cause of death was in most cases unknown. Nonetheless, it is very likely that variation in resistance to frost and *Didymascella thujina* led to the difference in mortality among the provenances. On the one hand, inland provenances are supposed to be more tolerant to frost (Sakai and Weiser, 1973) but more susceptible to fungal infection. On the other hand, coastal provenances are more tolerant to fungal infection, though more frost sensitive. Hence, all provenances would have the same risk of being damaged. Nonetheless, Bench Road was more damaged and showed high mortality compared to the other provenances, which is very likely due to higher frost sensitivity and simultaneously high susceptibility to *Didymascella thujina* because of the southernmost inland origin (Wright, 1976). Horsey Creek however, was the least damaged *Thuja plicata* provenance, possibly due to higher frost resistance and the same sensitivity to fungal infection as Bench Road. Since Yola Creek was less susceptible towards cedar leaf blight only on some sites, but more sensitive towards frost than the inland provenances, it was neither the most nor the least damaged *Thuja plicata* provenance tested in this thesis. Hence, regarding low damage risk I would recommend to plant Horsey Creek.

5. Critical appraisal

The difficulty of explaining the results can be traced back to the little experiences with *Thuja plicata* in Europe. Not much literature regarding variations in growth and survival is available about this tree species in Europe. Moreover, no other provenance experiments in Sweden regarding *Thuja plicata* have been established so far. Since other countries will use other provenances due to differing soil and climate conditions, it is difficult to compare the results to non-Swedish experiments and draw meaningful conclusions. If *Thuja plicata* was planted, information and data on the exact origin and choice of provenance is often lost due to reorganisations or historical events. The literature study for further experiences of adequate provenance choices was additionally limited by language barriers. Many publications have been written in the native language. Hence, it was impossible to include Italy, France, Belgium and Poland in chapter 1.7, although experiences with *Thuja plicata* have been stated in these countries.

Moreover, this thesis includes only four *Thuja plicata* provenances, from which three origin from the species´ inland population. Additionally, all tested provenances occur in higher elevations from 700 to 800 metres with annual precipitation more than 1000 mm. Therefore, the tested provenances represent only a small part of *Thuja plicata´s* population.

Hence, for future provenance trials with *Thuja plicata* it is advisable to create plots with a shelter from hybrid larch as well as plots without, to be able to draw meaningful conclusions with regard to shelter effects. Furthermore, a higher variety of provenances to test should be considered: First, provenances from the coastal as well as from the inlands distribution are recommendable to investigate, to be able to see possible impacts on coastal, respectively inland sites in Sweden. Secondly, provenances from drier areas in their natural range should be taken into account, to test a possible suitability for Sweden´s drier sites. Finally, provenances from lower elevations should be tested due to better growth in their natural range (Cherry, 1995).

In summary, it is important to keep varying conditions in Europe as well as between North America and Sweden in mind, when interpreting the results. For future provenance experiments, a wider choice of provenances to test should be considered.

6. Conclusion

Promising experiences with *Thuja plicata* in other European countries in combination with no severely damaging insects, high storm resistance, fairly low browsing pressure as well as a higher tolerance towards drought stress than Norway spruce, make *Thuja plicata* an interesting potential tree species for South Sweden.

Besides growth and production, it is important to consider vitality as well as stem quality in later stages. All factors combined determine whether to choose coastal or inland, northern or southern provenances. Moreover, vitality has an influence on growth, as more severely damaged trees grow more slowly. Therefore, in some cases, less production needs to be accepted for better health conditions.

Consequently, the recommendable choice of *Thuja plicata* would be Horsey Creek as the most suitable provenance for Swedish growing conditions among the ones tested in this thesis. It was the least damaged provenance, and grew well, both on wet and drier sites.

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IV. Appendix

Overview of inventories made in the experiments

Table 7: Summarizing overview of implemented inventories in the experiments, including respective ages of the seedlings and number of vegetation periods after planting. "S" stands for spring, "A" for autumn depending on when the inventory was carried out.

	Establishment year	Inventory year	Vegetation periods after planting	Age of *Thuja plicata* [years]	Age of Norway spruce [years]
Asa	2011	A-2011	1	2	1.5
		A-2012	2	3	2.5
		A-2013	3	4	3.5
		S-2016	5	6.5	6
		A-2018	8	9	8.5
Släne_2011	2011	A-2011	1	2	1.5
		A-2013	3	4	3.5
		S-2017	6	7.5	7
		A-2018	8	9	8.5
Svensbygd	2011	A-2012	2	3	2.5
		A-2018	8	9	8.5
Släne_2014	2014	S-2016	2	3	2.5
		S-2017	3	4.5	4
		A-2018	5	6	5.5

Overview of vegetation types

Table 8: Summarizing overview of vegetation types in Sweden according to Hägglund and Lundmark (1982).

Vegetation type	Translation	Nutrient availability
Hög-ört	high-herb	HIGH
Låg-ört	low-herb	
Mark utan fältskikt	soil without field layer	
Bredbladig grästyp	wide-leaved grass type	
Smalbladig grästyp	thin-leaved grass type	MEDIUM
Starr-Fräkentyp	?	
Blåbärstyp	blueberry type	
Lingontyp	lingonberry type	
Kråkbär-Ljungtyp	crowberry type	
Fattigristyp	?	LOW

Disease pattern

Fungal infection

The irregular and sporadic pattern of dark spots and brown leaves must be noticed. This is a typical sign for the fungus *Didymascella thujina (Søgaard, 1969).*

Figure 17: Infected Thuja plicata by fungi, which is assumed to be Didymascella thujina. Picture: Author, Asa 2018.

Figure 18: Infected Thuja plicata seedling by very likely Didymascella thujina. Picture: Author, Asa 2018.

Game damage

Most seedlings damaged by game have been found frayed or bend over. No seedling was browsed.

Figure 19: Thuja plicata seedling bend over and rubbed by game. Picture: Author, Svensbygd, 2018.

Figure 20: Thuja plicata seedling broken due to game. Picture: Author, Svensbygd 2018.

Hybrid larch

It can clearly be seen that hybrid larch is growing faster than *Thuja plicata*.

Figure 21: Thuja plicata planted in between rows of Hybrid larch. Picture: Author, Asa 2018.

Figure 22: Relation between height of Thuja plicata and height of Hybrid larch. Picture: Author, Asa 2018

Natural regeneration of *Thuja plicata*

Figure 23: Stand 1403c, 26 year-old natural Thuja plicata regeneration in a 55 year old mixed stand of Thuja plicata and Douglas fir. Picture: Author, 22nd February 2019, Harpstedt, Germany.

Figure 24: Natural regeneration of Thuja plicata in a gap in a mixed stand of 55 year old Thuja plicata and 50 year old Japanese larch. Stand 2419. Picture: Author, 22nd February, 2019, Harpstedt, Germany.

Full results of the statistical analysis for height 2018 as dependent variable

Nested model fit by maximum likelihood . t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: Height18 ~ Provenance + (1 | Site/Block)
Data: all

AIC	BIC	logLik	deviance	df.resid
382.9	395.3	-183.4	366.9	27

Scaled residuals:

Min	1Q	Median	3Q	Max
-1.45842	-0.66269	0.08571	0.64090	2.10282

Random effects:

Groups	Name	Variance	Std.Dev.
Block:Site	(Intercept)	480.2	21.91
Site	(Intercept)	988.4	31.44
Residual		1540.1	39.24

Number of obs: 35, groups: Block:Site, 7; Site, 3

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	217.727	24.925	5.353	8.735	0.00023 ***
Provenance2	-20.603	20.977	28.000	-0.982	0.33443
Provenance3	-1.592	20.977	28.000	-0.076	0.94006
Provenance4	9.879	20.977	28.000	0.471	0.64132
Provenance5	53.147	20.977	28.000	2.534	0.01717 *

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	(Intr)	Prvnn2	Prvnn3	Prvnn4
Provenance2	-0.421			
Provenance3	-0.421	0.500		
Provenance4	-0.421	0.500	0.500	
Provenance5	-0.421	0.500	0.500	0.500

ANOVA

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Provenance	21111	5277.7	4	28	3.4268	0.02116 *

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Full results of the statistical analysis for damage severity as dependent variable

Nested model fit by maximum likelihood . t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: Damage.severity ~ Provenance + (1 | Site/Block)
Data: all

AIC	BIC	logLik	deviance	df.resid
71.0	83.5	-27.5	55.0	27

Scaled residuals:

Min	1Q	Median	3Q	Max
-2.02770	-0.62793	-0.00932	0.80873	1.57288

Random effects:

Groups	Name	Variance	Std.Dev.
Block:Site	(Intercept)	0.00801	0.0895
Site	(Intercept)	0.20219	0.4497
Residual		0.22456	0.4739

Number of obs: 35, groups: Block:Site, 7; Site, 3

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	1.1668	0.3176	5.1850	3.674	0.01349	*
Provenance2	0.5350	0.2533	28.0000	2.112	0.04371	*
Provenance3	0.6365	0.2533	28.0000	2.513	0.01802	*
Provenance4	0.4122	0.2533	28.0000	1.627	0.11489	
Provenance5	-0.8821	0.2533	28.0000	-3.482	0.00165	**

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	(Intr)	Prvnn2	Prvnn3	Prvnn4
Provenance2	-0.399			
Provenance3	-0.399	0.500		
Provenance4	-0.399	0.500	0.500	
Provenance5	-0.399	0.500	0.500	0.500

ANOVA

Type III Analysis of Variance Table with Satterthwaite's method

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	
Provenance	10.786	2.6966	4	28	12.008	8.305e-06	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1