

**Effects of drought, pathogens and insects on pine mortality –
case Kemiönsaari, Finland.**

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Tiivistelmä/Referat – Abstract			
<p>Overall warming of climate, causing drought and sometimes co-occurring with insect outbreaks poses a risk to tree health and has been linked to tree mortality in many areas. The drought of 2003 was particularly severe in many regions in Europe, including Finland. It exceeded many previous drought years in its severity and intensity. Also, in the summer of 2006, 25% of the permanent forest sample plots of Finland National Forestry Inventory showed symptoms of drought damages. The Finnish south-west archipelago is high-risk drought area, and dry summers becoming more frequent and severe may cause severe forest damages in the area.</p> <p>In this study we investigated forest damages in Kemiönsaari, South-West Finland, approximately 60° 11'N, 22° 33'E. The forest damages there were first discovered in 2009, by local forest society, and has been spreading in the area. The crowns of Scots Pines (<i>Pinus sylvestris</i>) in the area were partially or completely defoliated. The defoliation started from the top of the canopy and spread evenly downwards. The central research questions of this study were: 1. Has the past drought years affected the growth of <i>Pinus sylvestris</i> in Kemiönsaari? 2. How is the Pine bark bug, <i>Aradus cinnamomeus</i>, affecting the trees hydraulic conductivity? 3. How is the <i>Crumenulopsis sororia</i> affecting the trees hydraulic conductivity?</p> <p>The findings provide support for the first research question stating that there has been a notable reduction in growth of the trees in the study area. The superposed epoch analysis revealed that droughts occurred in the past 20 years, reduced the radial growth of Scots pines. However, the results from this were within the lower 95% bootstrapped confidence limit and are not statistically significant. The results indicated that the most limiting factor to radial growth of <i>Pinus sylvestris</i> was precipitation in June, and last year July. Water shortage during the growing season decreases photosynthetic production and causes physiological stress to tree and is known to promote outbreaks of many insect.</p> <p>This study showed that the hydraulic conductivity of Scots pines in this area is not decreased by the pathogen <i>Crumenulopsis sororia</i> or <i>Aradus cinnamomeus</i>, in contrary, there was a clear correlation with higher hydraulic conductivity in the top of the crown of Scots pine's where <i>Crumenulopsis sororia</i> or <i>Aradus cinnamomeus</i> were present.</p>			
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<p><i>Pinus sylvestris</i>, <i>Aradus cinnamomeus</i>, <i>Crumenulopsis sororia</i>, dendrology, dendroecology, dendroclimatology, hydraulic conductivity, carbon starvation</p>			
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<p>Ilmaston lämpenemisen aiheuttamat kuivuusjaksot yhdessä mahdollisten hyönteistuhojen kanssa lisäävät puiden kuolleisuutta. Vuoden 2003 kuivuus oli erittäin ankara monilla alueilla Euroopassa, myös Suomessa. Se oli ankarampi ja pidempi kuin aikaisemmat kuivuudet. Vuonna 2006 kohdatun kuivuusjakson aikana 25% valtion metsien inventoinnin oli löydettävissä kuivuuden aiheuttamia vahinkoja. Suomen lounaisalueiden saaristo on korkean kuivuusriskin aluetta, ilmastonmuutoksen myötä entistä kuumemmat ja kuivemmat kesät voivat aiheuttaa alueella vakaviakin metsätuhoja.</p> <p>Tässä tutkielmassa tutkittiin metsätuhoja Kemiönsaarella, lounais-Suomessa (60° 11'N, 22° 33'E). Metsätuhot havaittiin ensikertaa 2009 paikallisen metsänhoitoyhdistyksen toimesta ja ovat levinneet alueella. Mäntyjen (<i>Pinus sylvestris</i>) latvukset alueella ovat osittain, tai kokonaan harsuuntuneet. Harsuuntuminen alkaa latvuksesta ja leviää tasaisesti alaspäin. Keskeisimmät tutkimuskysymykset olivat: 1. Ovatko viimeaikojen kuivat vuodet vaikuttaneet mäntyjen (<i>Pinus sylvestris</i>) kasvuun Kemiönsaarella? 2. Miten punalatikka (<i>Aradus cinnamomeus</i>) vaikuttaa puiden vedenkuljetuskykyyn? 3. Miten sorokka (<i>Crumenulopsis sororia</i>) vaikuttaa puiden vedenkuljetuskykyyn?</p> <p>Tulokset antavat tukea ensimmäiselle tutkimuskysymykselle. Alueen männyissä (<i>Pinus sylvestris</i>) on havaittavissa kasvun heikkenemistä kuivien vuosien aikana. SEA-analyysi paljasti että viimeisen 20 vuoden aikana tapahtuneet kuivat kesät ovat heikentäneet puiden paksuuskasvua. Tulokset eivät kuitenkaan olleet tilastollisesti merkittäviä. Tuloksien mukaan kasvua merkittävimmin rajoittava tekijä on sadanta kesäkuussa ja viime vuoden kesällä. Vedenpuutos kasvukaudella vähentää fotosynteesistä tuotosta ja aiheuttaa fysiologista stressiä puulle ja tutkitusti edesauttaa monien tuhohyönteisten menestymistä.</p> <p>Tämä tutkimus osoitti että alueen mäntyjen (<i>Pinus sylvestris</i>) vedenkuljetuskyky ei heikentynyt niissä puissa missä oli sorokkaa (<i>Crumenulopsis sororia</i>) tai punalatikkaa (<i>Aradus cinnamomeus</i>). Päinvastoin, tässä tutkimuksessa löydettiin selkeä korrelaatio korkeampaan vedenkuljetuskykyyn niiden mäntyjen latvuksissa joista löytyi punalatikkaa ja sorokkaa.</p>			
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1. Introduction

1.1 Preface

In 2009 the local forestry society, Kemiönseudun metsänhoitoyhdistys ry., contacted the Natural Resource Institute Finland about the undecipherable mortality of Scots pine (*Pinus sylvestris*) in Kemiönsaari. The crown of trees were partially or completely defoliated (Figure 1). The defoliation started from the top of the canopy and spread evenly downwards.



Figure 1 Defoliated canopy of Scots Pine (*Pinus sylvestris*) in Kemiönsaari, summer 2017.

During their first examination in 2009, the Natural Resource Institute Finland noticed the sporadic dying of Scots pines and spotted typical fungus and fauna in the base of the pines (*Armillaria* sp. and *Tomicus piniperda*). Healthy junipers (*Juniper communis*) are common in the area, which indicated that *Heterobasidion annosum* is not the cause of the symptoms and the tree mortality because all of our domestic conifers are susceptible for this fungus (Piri et al. 2017).

In the spring of 2010, the Natural Resource Institute Finland fell a single partially defoliated Scots pine, from which they could not find a clear cause of the symptoms. In the canopy however, at low incidence, they found skins of *Aradus cinnamomeus*. In addition, stains of resin bleeding were found in the branches. No traces of reproduction of *Pissodes pini* or *Tomicus piniperda* or traces of *Armillaria* sp. were found. The amount of partially, or completely defoliated Scots pines had increased from the previous year. In the fall of 2010, the Finnish Food Safety Authority looked for *Bursaphelenchus* sp., but could not find any traces of the nematodes.

Four forest damage scientists from the Natural Resource Institute Finland felled two larger defoliated Scots pine for closer inspection in the summer of 2014 and isolated a number of fungi for DNA identification. *Diplodia pinea* was suspected as a cause of defoliation, but it was not identified. Moreover, the cultivations also revealed an unknown fungus as well as pine shoot disease *Gremmeniella abietina* and *Sarea*

resinae, which do not fully explain the defoliation pattern of the Scots pine in the area. Natural Resource Institute Finland could not make a prognosis, because the source of defoliation was not clear (Heino & Pouttu 2015).

In the summer of 2015, three forest damage specialists from the University of Helsinki, Risto Kasanen, Kari Heliövaara and Antti Uotila visited the area and made the presumption that there might be signs of drought induced damages in the Scots pines. However, spruces and birches did not show any symptoms of suffering from drought.

1.2 Drought

The drought of 2003 was particularly severe in many regions in Europe, including Finland. It exceeded many previous drought years in its severity and intensity (Rebetez et.al. 2006). Also, in the summer of 2006, 25% of the permanent forest sample plots of Finland National Forestry Inventory showed symptoms of drought damages (Muukkonen et al. 2015). In their study, Muukkonen et al. (2015), showed that the south-west archipelago area, where the study area is located, is a high-risk drought area where during a dry growing season there is over 50% probability of detecting drought symptoms, such as defoliation, decreased carbon and nutrient assimilation or breakdown of the photosynthetic process through the loss of hydraulic conductivity (Figure 2). The drought symptoms are usually visible in the drought areas the year after the drought, due to natural delay in plant allocation processes (Solberg 2004).

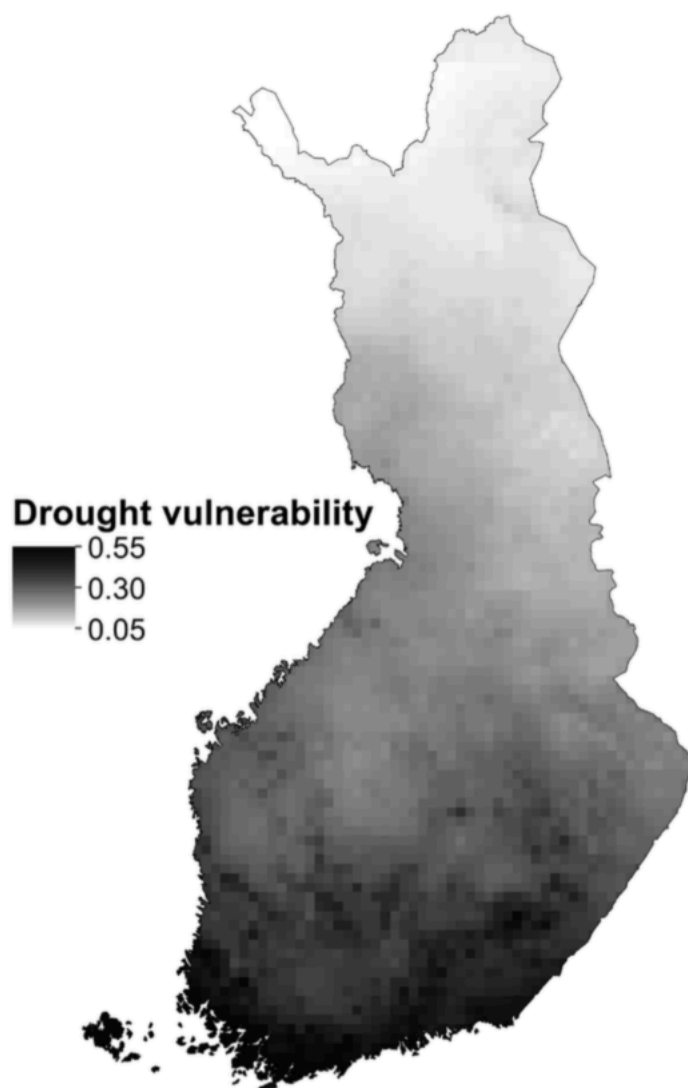


Figure 2 Predicted drought vulnerability in Finland showing that the southwest archipelago area is a high-risk zone. Vulnerability is the probability (0-1) of detecting drought symptoms in a forest during a dry growing season (Muukkonen et al. 2015)

Overall warming of climate, causing drought and sometimes co-occurring with insect outbreaks poses a risk to tree health and has been linked to tree mortality in many areas (Allen et al. 2010). In their study, Allen et al. (2010) addressed that the future changes in climate drives to more extensive, severe, or frequent tree mortality events. The ecosystem functions and services and possible feedbacks to climate change caused by biophysical effects and loss of carbon sinks are at risk due to increased forest mortality (Adams et al. 2010, Anderegg et al. 2014).

The low soil water content causes trees to limit their evapotranspiration, and that is when drought takes place (Bréda et al. 2006). There are several factors effecting the severity of drought in the forest stand, such as soil texture, depth, exposure to sun,

species composition, and life stage. However, the major influence and the most variability are caused by frequency, duration and severity of drought (Dale et al. 2001).

In an average year, the soil water content is adequate for trees in the boreal zone, and the actual evapotranspiration of trees does not fall below the potential evapotranspiration (Lockwood et al. 1979). However, the trees have been adapted and acclimated to certain climatic conditions, and inter- and intra-annual changes in that may cause a problem to all trees that within one species may be nearly equally sensitive to drought (Muukkonen et al. 2015).

The increasing amount of summer droughts and decline in precipitation in northern Europe, and in Finnish archipelago may be causing soil water deficits and thus lead into increasing tree mortality (Innes 1993, Muukkonen et al. 2015). There is also evidence that severe soil water deficits may cause hydraulic as well as physiological stress and responses which may be carried over into subsequent years (Innes 1993).

Tree growth and survival are directly linked to severe and prolonged droughts, but they have also been triggering outbreaks of forest insects and pathogens (Ayres & Lombardero, 2000, Breshears et al., 2005, Logan et al., 2003, Moore & Allard, 2008, Netherer & Schopf, 2010). Climate change causing increased summer droughts globally and in northern Europe may cause the forests to a state where the droughts trigger insect and pathogen epidemics growth losses and mortality (McDowell et al. 2008)

In their study McDowell et al. (2008) suggest that there are two main physiological mechanism leading to drought-induced mortality of trees. The mechanisms are hydraulic failure and carbon starvation. The hydraulic-failure hypothesis suggests that intense drought will lead to the loss of hydraulic conductivity due to cavitation of xylem conduits and rhizosphere, because of low soil water content and high evaporative demand. This will eventually cause the tree to die, due to cellular death. Second hypothesis from McDowell et al. (2008) suggests, is the carbon-starvation hypothesis. The carbon-starvation hypothesis suggests that long lasting low-intensity drought will eventually lead to a state where tree prevents hydraulic failure by stomatal closure, which causes the photosynthetic uptake of carbon to diminish. Eventually the tree will starve due to continued metabolic demand for carbohydrates. Moreover, these mechanisms may lead to a reduced resistance to biotic agents.

1.3 Dendroecology

Dendrochronology is a useful tool for determining the impacts of drought to tree-ring growth. Combined with accurate weather data, the exact drought years and their impact and distribution can be studied (Speer 2010).

Dendrochronology is an important and accurate environmental recording technique for observing different occurrences, which are recorded in the tree-ring structure. One application of the dendrochronology is dendroecology, which focuses on the interactions between tree growth and the environment, e.g. insect outbreaks. Other subfield closely attached to this study is dendroclimatology, which reveals the growth-response of temperature, precipitation and drought (Speer 2010).

In the seasonal climate, coniferous and deciduous trees produce one ring in a year, and this annual ring is divided into earlywood and latewood. Earlywood is produced in spring and early summer, whereas latewood is produced in late summer. The latewood is thick due to compact lumen relative to cell walls whereas earlywood has large lumen relative to cell walls. This makes detecting the ring boundaries of coniferous trees possible by examining the size and cell wall thickness of the tracheids (Speer 2010).

The influence of droughts on tree growth have been widely studied. As an example, Cook et al. (1999) used the Palmer Drought Severity Index (PDSI) and grid network reaching throughout the United States of America and showed that the past droughts can be examined reliably through the tree-ring data.

1.4.1 Hydraulic conductivity

To assess the impact of drought on the increased mortality of Scots pines in the area, the hydraulic conductivity of trees should be analyzed. Stem xylem hydraulic properties provide fundamental information of trees vitality, i.e. capacity to supply water to photosynthetic and growing tissues (Tyree & Zimmermann 2002, Brodribb 2009).

Stem xylem and phloem are the two transport systems that vascular plants, such as trees use to move and distribute sugar, water and nutrients. Phloem is a positive pressure system, up to 3 MPa, moving sugar from leaves to growing meristems and all other

cells. In xylem, the water from soil is distributed throughout the whole tree. Contrary to the phloem, in the xylem conduits the water is under negative pressure. Typically, this negative pressure in the xylem is between -1 to -2 MPa, but in some cases even as low as -10 MPa (Tyree & Sperry 1989).

Transporting water through stem xylem and photosynthetic production are tightly linked processes. Leaves lose vast quantity of water transported through xylem in exchange for CO₂ in photosynthetic process (Brodribb 2009). The cohesion theory by Dixon (1914) reveals the mechanism of xylem transport. Water in the cell wall surfaces in the leaf evaporates, causing air-water interface to retreat into the finely porous spaces between cellulose fibers in the wall. The air-water interface is sustained by capillarity, under negative pressure. This negative pressure is a result of tension. This tension is transmitted to soil water by a continuous water column. Any breakage, or loss of continuity, disrupts water flow.

Xylem transport can sustain the water column because of the properties of water and structure of the xylem. Cohesion between water molecules is promoted by hydrogen bonding which allows water not to vaporize at pressures well below its vapor pressure and remain liquid, in a metastable state. Xylem tissue is a network of conduits; vessels in deciduous trees and tracheid's in coniferous trees. Conduits have rigid walls, which do not collapse when water is under negative pressure (Tyree & Sperry 1989).

The metastable state of water in the xylem flows means that the xylem must prevent nucleation of vaporization, or cavitation. Cavitation leads to a state, where the conduit is primarily vapor-filled, and eventually fills with air. When a conduit is in this air-filled state, it is embolized, and no longer available for water conduction. (Tyree & Sperry 1989). Water fills the xylem conduits from the inception, and they contain no entrapped air bubbles that could nucleate cavitation. In addition, the xylem conduits walls are extremely hydrophilic, which decreases the occurrence of cavitation at the wall-water interface. However, if cavitation occurs, or a conduit is punctured, a pit membrane between conduits prevents the vapor, or air bubble expanding to following conduits (Bailey 1916).

1.4.2 Embolism by water stress, cavitation and loss of hydraulic conductivity

The ability of xylem conduits (vessels and tracheids) to maintain water transport by water tension is limited by their ability to withstand embolism. As the soil dries, the hydraulic soil-leaf tension increases in the xylem. This leads to a higher risk of xylem cavitation. Embolism by water stress is caused by air seeding at pit membranes between xylem conduits, in the intervessels/ -tracheids. This can only occur when there are some vessels or tracheids that are already embolized. But embolism happens in frequent basis by herbivory, or mechanical damage to stems and leaves (Tyree & Sperry 1989).

The tracheid-type conduit of conifers (e.g. *Pinus sylvestris*) are usually about 3mm long with a pit membrane between conduits. This pit membrane has an ability to minimize air seeding between conduits. If a tracheid is embolizing, capillary forces cause the torus to cover the pit aperture, thus minimizing air seeding to following conduits (Dixon 1914). This sealing action has its limits. For instance, Stamm (1964) has shown that the air can penetrate the inter-tracheid pit membranes, when the water-tension afflicted pressure difference grows.

Mechanism behind the drought-induced cavitation is not yet fully understood. However, when cavitating, the pit membrane which allows inter-vessel connections may release slight air bubbles when the drought induced tension overcomes the threshold allowed by membrane capillarity. This mechanism causes the vessel to empty, allowing the diffusion of ambient air into the cavitating vessel, which leads to embolism (Bréda et al. 2006).

1.4.3 Recovery of hydraulic conductivity

Some deciduous trees, such as *Acer platanoides* or *Fagus sylvatica*, can form positive xylem sap pressure during spring, and flush embolized vessels (Sperry et al. 1988, Cochard et al. 2001). However, for coniferous trees, the recovery of xylem conductivity is achieved by the formation of a new ring with functional xylem in a following year (Bréda et al. 2006). As cavitation itself, the recovery from it remains under debate. There is evidence that the trees may recover their hydraulic conductivity even under transpiration (Salleo et al. 1996), though this mechanism is still not fully accepted

(Clearwater et al. 2005).

In addition to drought, there are also pathogens and pests that may affect the hydraulic conductivity, and furthermore the vitality of trees. Drought has also been indirectly linked to increased tree-mortality, increasing the severity of insect or pathogen outbreaks (Ferrell et al. 1994, Ferrell 1996, Speer et al. 2001). Interestingly, the pine bark bug (*Aradus cinnamomeus*) and pine canker pathogen, (*Crumenulopsis sororia*) were commonly found in affected trees on Kemiönsaari, on sites which were suspected to experience severe drought in the past.

1.5 Pine bark bug, *Aradus cinnamomeus*

Pine bark bug (*Aradus cinnamomeus*) is an insect pest of young pine stands (*Pinus sylvestris*) (Brammanis 1975). It has been identified as a harmful insect for forests in the mid-twentieth century due to new methods of forestry. Currently the pine bark bug damages have been associated with young, sparsely stocked pine stands located in low-fertile soil (Hokkanen, 1987).



Figure 3 Pine bark bug (*Aradus cinnamomeus*) nymphs.

The external symptoms caused by the pine bark bug consist of rapid reduction in height growth and yellowing of the needles in the top part of the crown. Later, the whole top of

the tree dies (Brammanis 1975, Heliövaara 1984.) The current understanding is that the pine bark bug adults and nymphs suck the sap from the tree (Heliövaara & Väisänen 1988), but the mechanism is yet unknown. In addition, there is evidence that the Pine bark bug injures the phloem, cambium and xylem tissues in the process, and possibly extracting substances in the tree (Brammanis 1975, Heliövaara & Laurema 1988, Raitio, 1990a). The studies made by Raitio (1990a) show that pines which the pine bark bugs were feeding, were suffering from the deficiency of calcium, magnesium, nitrogen and phosphorus, and magnesium in the top part of the crown.

There is also indication that the pine bark bug might be a vector of a common pine canker pathogen, *Crumenulopsis sororia* (Doom 1976).

1.6 *Crumenulopsis sororia*

Crumenulopsis sororia was first described in Finland as early as 1871 by Karsten. It causes irregular cankers in the stem and branches of Scots pine. Infection can be identified from resin flow and blackish staining on the bark. The infected wood has blue or blackish staining (Vuorinen 2000).

In Britain, *Crumenulopsis sororia* was found associating cankers of Corsican pine (*Pinus nigra* ssp. *laricio*) and Scots pine in large areas in England, Ringwood forest (Batko et al. 1964). The soil was poorly drained and had extreme nutrient deficiency which had led to poor growth of 30 years stand. At the same time *Crumenulopsis sororia* were found on young Corsican and Scots pine stand, where the poor growth was more associated to nutrient deficiencies.

In fertile rich sites, such as abandoned field, *Crumenulopsis sororia* can be a quite common pathogen of *Pinus sylvestris* as shown in the studies of Vuorinen (2000). In his studies at Suonenjoki field station, Vuorinen (2000) showed that the Scots pines planted in 1972, 48% of the pines felled down in the first thinning were infected by *Crumenulopsis sororia*. In 1997 when the site was clear-cut, altogether 78% of Scots pine were infected by the fungus.

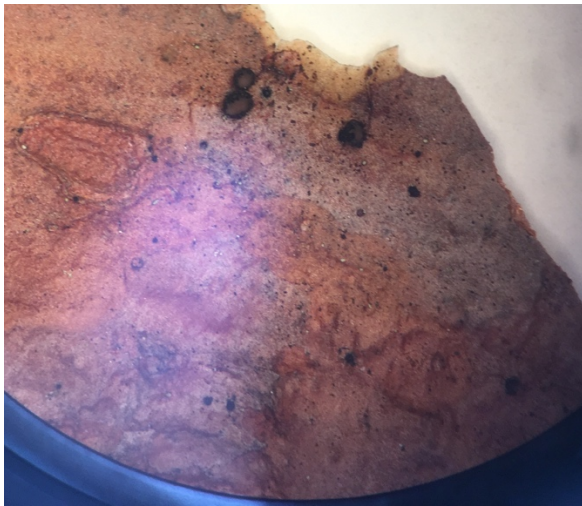


Figure 4 Moist apothecia of *Crumenulopsis sororia* are irregularly round or oval, the hymenium is grey or brown and the excipulum margin slightly raised.

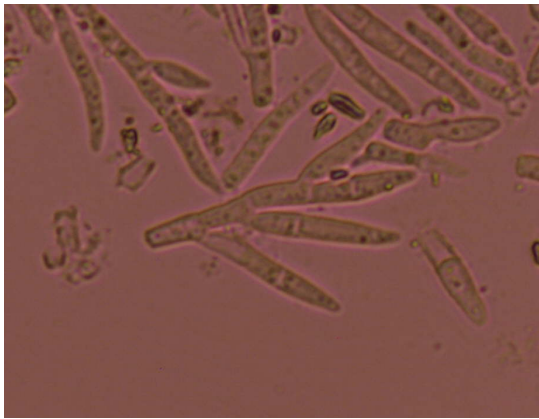


Figure 5 Characteristic branched multicellular conidia of *Crumenulopsis sororia*.

2. Objectives of this work

The aim of this study was to identify the main reason or reasons behind the tree mortality in Kemiönsaari. We approached this question by conducting a random sample plot inventory in the area to get a comprehensive look of the amount and severity of the damage. Furthermore, 37 trees were subjectively selected from the area, from which all the harmful insects and pathogens were identified and quantified. In addition, from the selected trees, the hydraulic conductivity was measured from the top of the crown and just below the living crown. To identify the effect of past drought to radial-growth a sample disks were collected from each tree at the height of 1.3m.

Central research questions and hypotheses of the study are:

1. Has the past drought years affected the growth of *Pinus sylvestris* in the case area?

Hypothesis: The trees have suffered from severe droughts that are visible in tree rings as reduced radial growth.

2. How is the Pine bark bug, *Aradus cinnamomeus*, affecting the trees hydraulic conductivity?

*Hypothesis: The *Aradus cinnamomeus* decreases the hydraulic conductivity of the *Pinus sylvestris*,*

3. How is the *Crumenulopsis sororia* affecting the trees hydraulic conductivity?

*Hypothesis: The pathogen *Crumenulopsis sororia* decreases the hydraulic conductivity of the *Pinus sylvestris*.*

3. Material and methods

3.1 Study area

The study was carried out in six plots at Kemiönsaari, South-West Finland, approximately 60° 11'N, 22° 33'E (Figure 6). Phytogeographically, it belongs to the hemiboreal zone which is the intermediate zone between temperate and boreal zone (Ahti et al. 1968). Mean annual temperature varies between 2,9° C and 7,3° C the



Figure 6 Location of the study area.

average being 5.5° C (1961-2015) and the total annual precipitation varies between 1017mm and 360mm the average being 612mm (1961-2015). The coldest month is February (mean temperature 1961-2015 -2,2° C) and the warmest is July (the mean temperature 1961-2015 21,3° C). A climate diagram characterizing the annual precipitation and temperature (Figure 7) shows that precipitation sums are highest in the late-summer and fall. There can be seen a clear trend in rising temperatures and rising precipitation sums in the late twentieth-century and early twenty-first century (Figure 8).

The plots have been managed as private owned economical forest, dominant tree species being Scots pine (*Pinus sylvestris*). In all six plots, the site type, according to the classification of Cajander (1949), is Vaccinium type. The soil type was coarse or mid-coarse moraine. The age of the dominant canopy layer varied from 25-65 years, whilst the size of plots varied from 1 to 8,1 hectares. The site information was provided by the local forestry society, Kemiönseudun metsänhoitoyhdistys ry. The monthly temperature and precipitation records for the area were available from nearby Lövböle meteorological station, 60° 09'N, 22° 33'E.

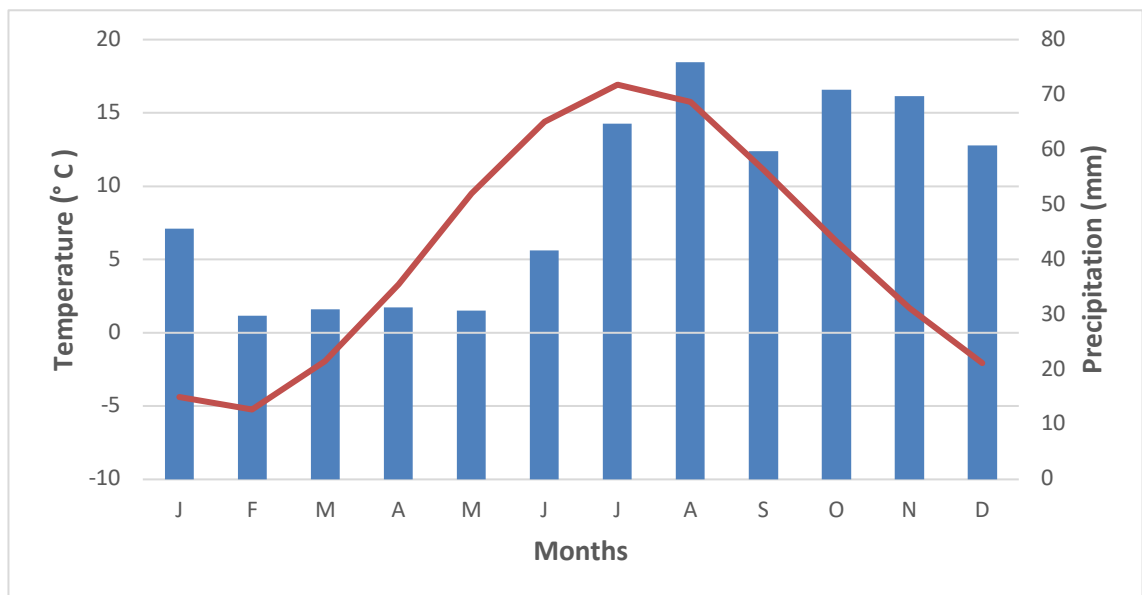


Figure 7 Climate diagram for the Lövböle meteorological station, 60° 09'N, 22° 33'E, for the period 1961-2015. Mean temperature(line) = 5,5° C, mean annual precipitation(columns) = 612mm.

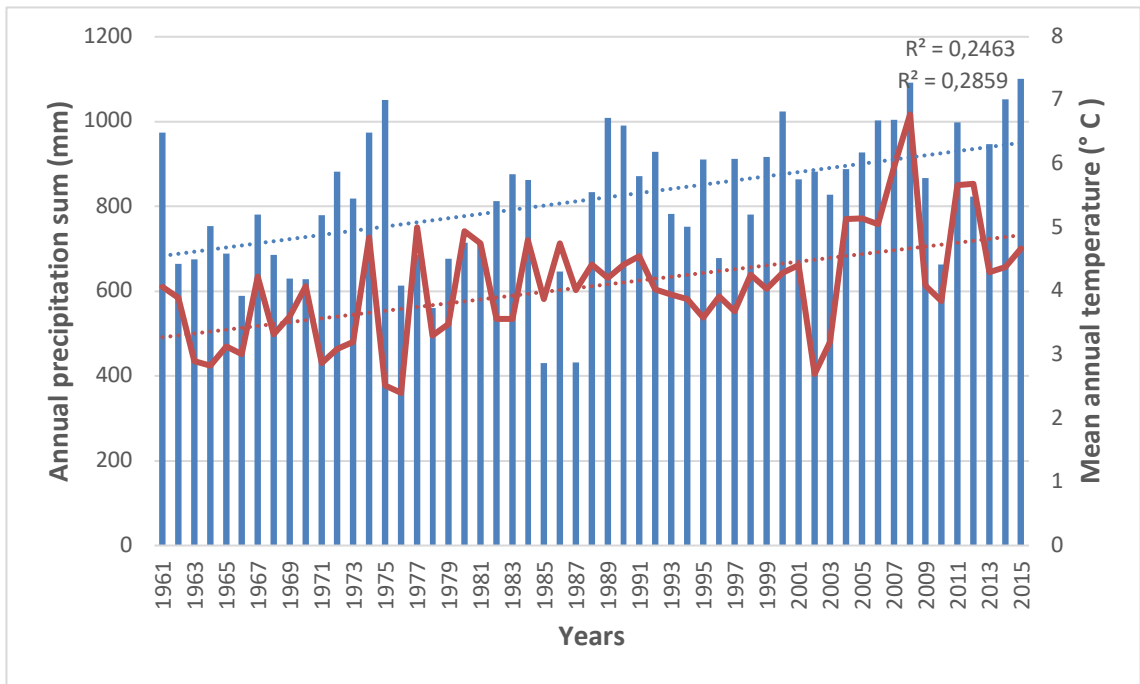


Figure 8 Annual time series for Lövböle meteorological station, 60° 09'N, 22° 33'E, for the period 1961-2015. Mean annual temperature (line) and annual precipitation (columns).

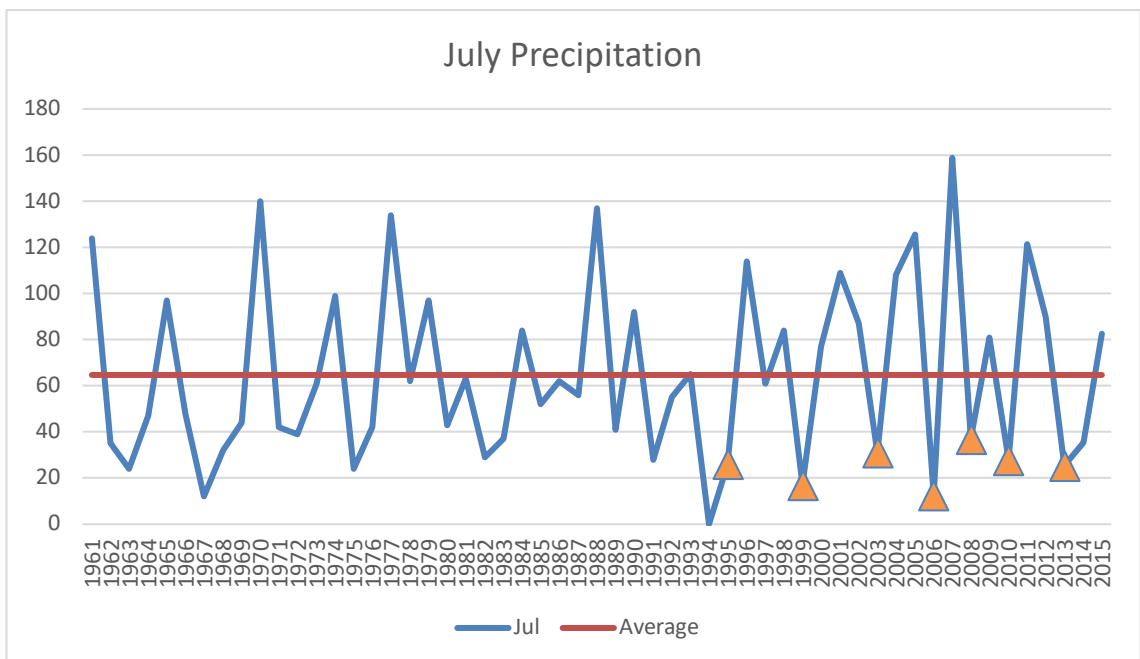


Figure 9 Annual July precipitation. The solid thin line is average (64.7mm), and the solid thick line each year July precipitation. Triangles mark the years with least precipitation during the past 20 years. (1995, 1999, 2003, 2006, 2008, 2010, and 2013).

Site	Size (ha)	Number of plots	Total basal area	Age (y)	Mean DBH (mm)	Mean height (m)
309	8,20	13	24	65	236,9	17,5
302	1,50	5	22,4	60	178,4	13,9
107	1,00	5	10	60	262,4	12,8
106	1,60	6	9,5	30	175,3	10,3
116	1,10	4	13,5	40	191,1	16,1
117	1,00	5	9	25	121,6	8,6
Average	2,40	6,33	14,73	46,67	194,28	13,20
SD	2,60	3,04	6,18	15,72	45,39	3,09

Table 1 Site characteristics (BA = basal area, DBH = diameter at breast height, SD = standard deviation).

3.2 Materials used for this study

The measurements in the study area were carried out in July 2017 on six forest compartments assigned by the local forest association. Circular sample plots with 5-meter radius were measured along a transect through the compartment. From the circular sample plots, basal area, breast height diameter and height of the median tree was measured (Table 1). The defoliation class of pines was estimated by the guidelines of ICP Forests (Nevalainen et al. 2011) and divided it into 5 classes by the foliation percentage; 0-19, 20-39%, 40-59%, 60-79%, 80-100%, where a tree with 0% is completely defoliated and a tree with 100% has all its needles, respectively (Figure 10).

In total 37 Scots pine were felled for closer examination, of which 34 trees were used for dendroecological studies, and 35 for hydraulic conductivity measures. For tree-ring analyses we only selected tree-ring series that could be properly cross-dated. Two trees were excluded from the hydraulic conductivity measurements because of the size of trees and the lack of sufficient research equipment. Trees were selected subjectively by disturbed crown condition, according to modified instruction by ICP Forests (Nevalainen et al. 2011). We used the upper one quarter crown condition classification and divided it into 5 classes by the foliation percentage; 0-19, 20-39%, 40-59%, 60-

79%, 80-100%. A tree with 0% is completely defoliated and a tree with 100% has all its needles.

From the sample trees, all insect pest *Aradus cinnamomeus* nymphs and adults and fungi, *Crumenulopsis sororia* were surveyed. All other insect pests, and common fungi causing forest damages (*Gremmeniella abietina*, *Diplodia pinea*, *Cronartium flaccidum* and *Peridermium pini*) were also surveyed. However, only few other insects or fungi were found from trees, and therefore we concentrated mainly on *Aradus cinnamomeus* and *Crumenulopsis sororia*.

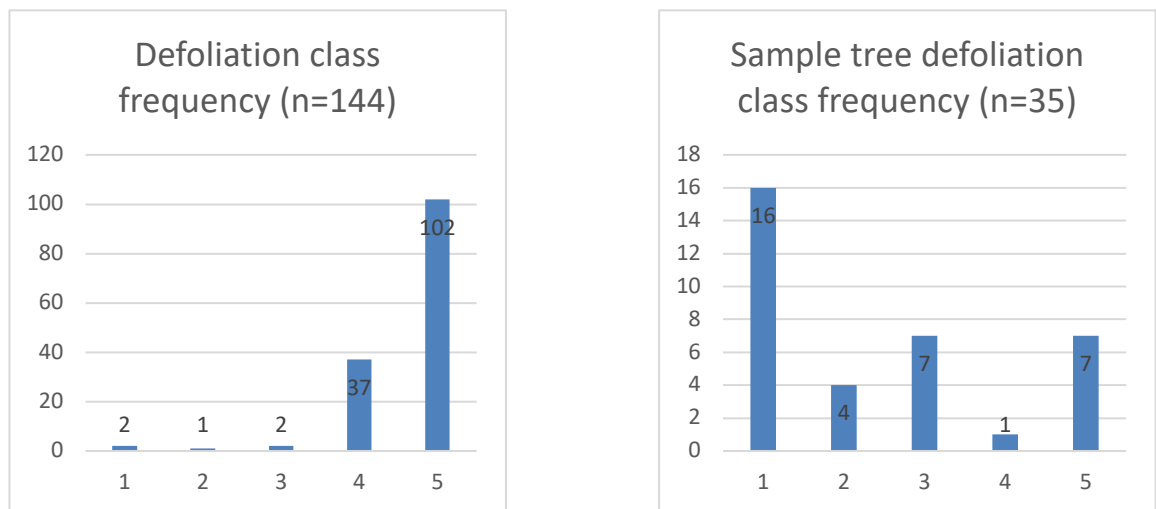


Figure 10 Defoliation class frequencies of whole area (n=144) and sample trees (n=35)

3.3 Dendroecological analyses

To examine the climate response to tree growth in the study area, we used the dendroecological approach to examine the climate response of radial growth of trees. We analyzed, in monthly and seasonal scale, how the changes in precipitation and temperature affect the radial growth on trees. Furthermore, we were able to focus on the critical months, in which the changes in climatic conditions affect the most to the radial growth of trees. Additionally, we examined the effect of drought years to trees radial-growth the current, three years prior and three years after the drought event using superposed epoch analysis.

3.3.1 Cross-dating and measuring the sample disks

To examine the relationship between tree growth and climate, sample disks were cut with a chainsaw from 35 trees at 1.3m height. From these sample disks, a high-frequency chronology was created, which combined with the climatic data revealed us the months, seasons and certain years when the climate has been a limiting factor for the growth.

Usually, in the favorable conditions, trees produce wide and easily detectable annual rings which reflects fast growth of the trees. However, during stressful years, such as in times of drought or during insect outbreaks, the growth hormone production of trees is limited, which may lead to narrow, or missing annual rings (Speer 2010). The tool for determining the exact year for a certain tree ring is cross-dating. No matter what aspect is studied in the field of dendrochronology, the cross-dating is a necessity in determining the right year for certain tree rings. Without this tool, the sample ring count may produce errors due to locally absent or false rings (Speer 2010).

By cross-dating the samples we can match the pattern of wide and narrow rings and determine the location of real ring boundaries. The ring width patterns from a single tree sample can be listed, and then matched to other tree sample ring widths to determine that all the rings are present in a sample (Speer 2010). There are several ways for visual cross-dating. In this study, we used the list method (Yamaguchi 1991), which is a fast way for samples which have clear pattern, such as *Pinus sylvestris*. In this method, the narrow rings which are present in each sample disk are recorded and then simply compared to other disks narrow rings (Yamaguchi 1991). This way we can dismiss the false-rings, determine if we are missing any rings or if there are two or more rings in one year. Thus, a reliable tree ring chronology is created.

In this study, the goal of crossdating was to place verified calendar years to each annual ring of the live tree samples so that the changes in growth during annual years could be determined. After crossdating the samples from trees, the rings widths were measured with the WinDENDRO software (Regent Instruments Inc. 2015). The precisely cross-dated ring widths were then used with the climatic variabilities to pinpoint the drought years for superposed epoch analysis.

The dried sample disks were sanded with 1000 grit to 600 grit until the structure of tree-ring widths were clearly visible. The disks were scanned, and the widths of tree-ring sections were measured to the nearest 0.01mm with Win-Dendro software using two radii with a 90 degrees angle. The radii were selected so that they contained a minimum amount of reaction wood or other irregularities.

3.3.2 Dendrochronological analyses

For the climate-growth analysis, a dataset of tree ring widths were created covering the years from 1961 to 2015, the years of accurate precipitation and temperature data gathered at nearby Lövböle meteorological station, 60° 09'N, 22° 33'E.

For the climate-growth analyses, a high-frequency chronology was created to examine the climate-growth relationship at inter-annual scale. For high-frequency chronology, the age-related growth trends and the possible influence of stand dynamics were removed from the ring-width series by detrending them, using a spline function with a 50% frequency response of 30 years (Cook et al. 1990). For detrending the series, a dendrochronology program library in R (dplR) was used (Bunn 2008). After the detrending, the ring-width series were then averaged using the chron function, which uses Tukey's biweight robust mean, and pre-whitened by autoregressive modelling to enhance the common signal and correlation with the climate signal (Andrew 2008) (Figure 11).

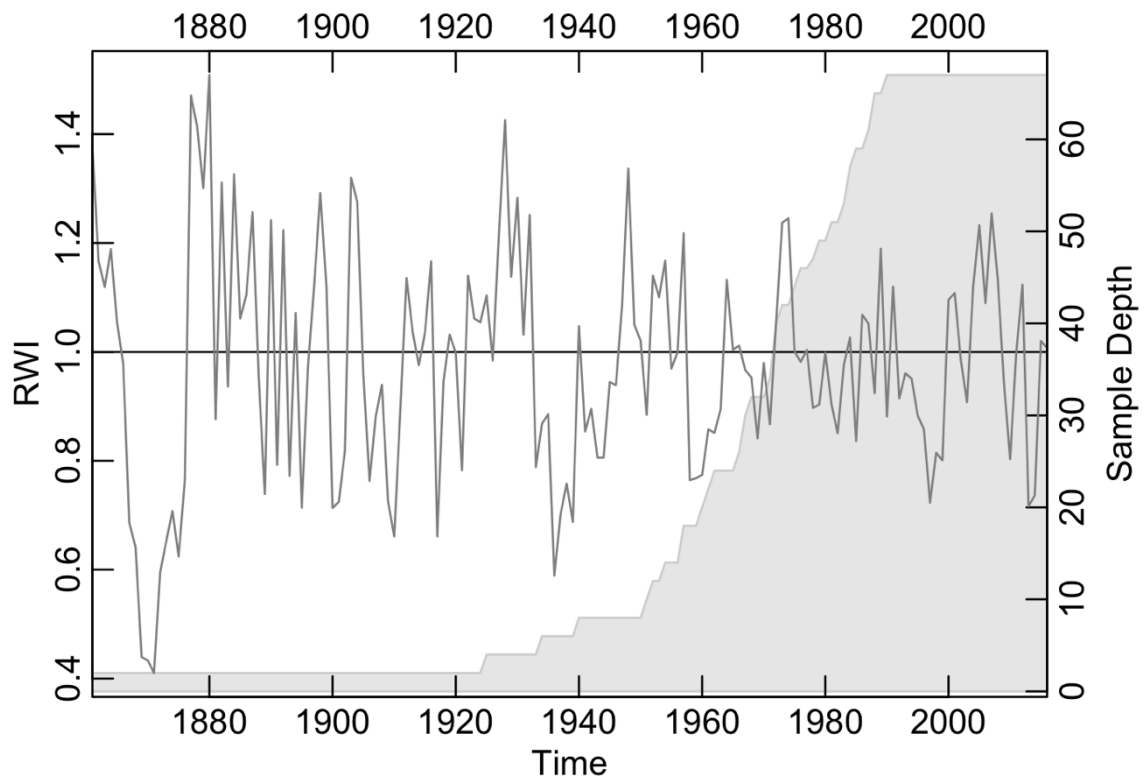


Figure 11 Detrended, averaged and pre-whitened ring width indices of all 34 sample trees.

For dendroclimatic analyses, the treeclim package in R by Zang & Biondi (2015) were used. The treeclim package uses correlation and response function bootstrapped error estimates which allows to identify the climatic conditions that limits the wood growth (Fritts 1976). In this study, the correlation and response function bootstrapped error estimates were used at monthly, and at seasonal scale.

3.3.3 Superposed epoch analysis

To identify if the tree ring growth showed punctual responses to drought, we used superposed epoch analysis (Martín-Benito et al. 2007), which shows the decreased growth from the mean indexed values from the high frequency chronology. We analyzed the tree ring growth 3 years prior, and 3 years after the drought event. Superposed epoch analysis overlays the drought year and examines the current, previous and subsequent year's radial growth (Haurwitz & Brier 1981). The dplR package in R was used in analysis (Bunn 2008).

3.3.4 Marker years for superposed epoch analysis

In this study, drought events were calculated from the temperatures and precipitation of early summer (June and July average), which were the most significant predictors for tree-ring growth in the bootstrapped response functions (figure 14). We created a simple drought index of the temperature and precipitation data available from Lövböle weather station. The drought index (DI) was calculated for every year (1961-2015) from the monthly average of June and July temperatures and monthly sums of June and July precipitation by creating index value for temperature and precipitation by subtracting the average temperature or precipitation from current year temperature (t_y) or precipitation (p_y) from the average temperature ($\frac{1}{n}\sum_{i=1}^n t_i$) or precipitation ($\frac{1}{n}\sum_{i=1}^n p_i$) and dividing it with standard deviation of temperature ($\sqrt{\frac{\sum(t_i - \bar{t})}{(n-1)}}$) or precipitation ($\sqrt{\frac{\sum(p_i - \bar{p})}{(n-1)}}$). Then the index value of precipitation was subtracted from the index value of temperature. The complete equation shows as following.

$$DI = \left(\frac{t_y - \frac{1}{n}\sum_{i=1}^n t_i}{\sqrt{\frac{\sum(t_i - \bar{t})}{(n-1)}}} \right) - \left(\frac{p_y - \frac{1}{n}\sum_{i=1}^n p_i}{\sqrt{\frac{\sum(p_i - \bar{p})}{(n-1)}}} \right)$$

Based on the drought index, we selected the marker years indicating drought within past twenty years, when the temperature was considerably high, and in addition, the precipitation was low. The drought years are shown as high index value, and the selected years were 1999, 2003, 2006, 2010 and 2013 (Figure 12).

The years 2003 and 2006 corresponded with previous studies which pointed out extreme drought. In the year 2003, the drought was particularly severe in many regions in Europe, including Finland and it exceeded many previous drought years (Rebetez M. et.al. 2006). Second marker year pointed out by the previous studies was 2006, when 25% of the permanent forest sample plots of Finland National Forest Inventory sample plots showed symptoms of drought damages (Muukkonen, P. et.al. 2015). In addition, in their study, Muukkonen, P. et.al. (2015) showed that 65.5% of pine-dominated forests showed symptoms in 2006 and the damages were more frequent in the southern part of Finland where the temperature sum is higher. Especially in areas of bare rock formations and shallow soils affecting the acclimation of root distribution the vulnerability for drought is increased.

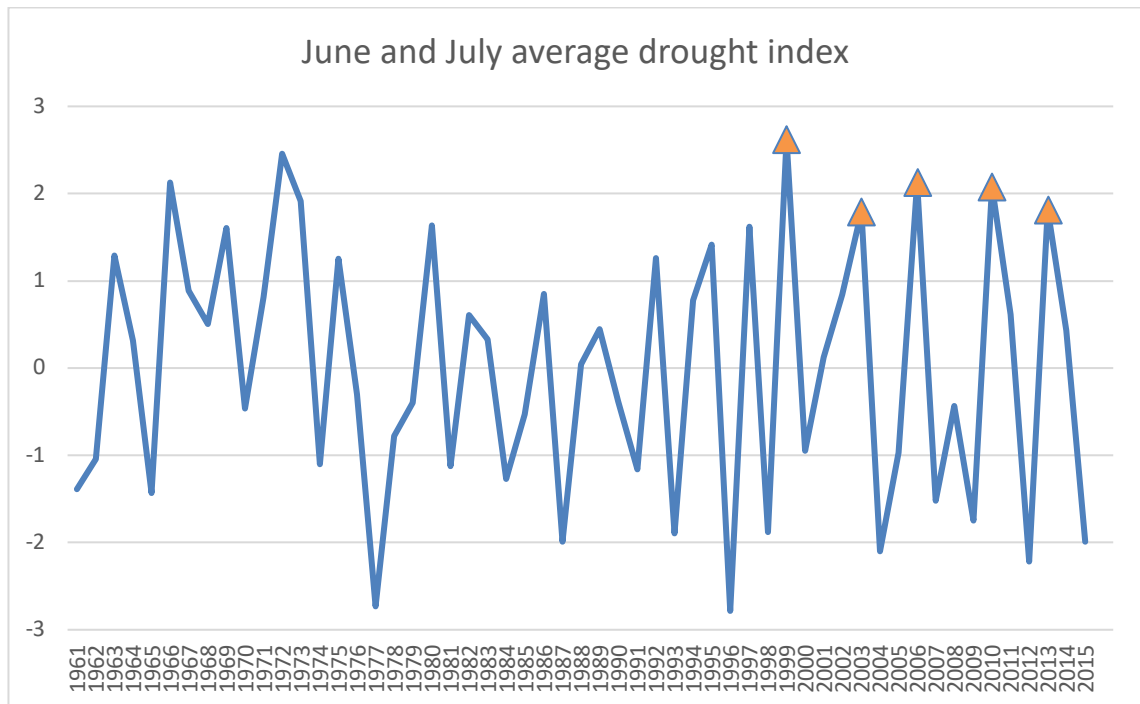


Figure 12 June and July average drought index from the years 1961 to 2015. Triangles mark the years with highest drought index in the past 20 years. (1999, 2003, 2006, 2010, and 2013).

3.4 Measuring hydraulic conductivity

Measurements of stem xylem hydraulic conductivity were also conducted in the area. Of a total of 35 trees, 22 were selected for this analysis. From these trees, stem xylem hydraulic conductivity was measured from the top of the crown, and just below the living crown.

Measuring stem xylem hydraulic conductivity provides information of trees capability to transport water for photosynthesis and growing tissues (Brodribb 2009). Melcher et al. (2012) provide an extensive review on the set of methods and theory in the field of measuring hydraulic conductivity.

Water is transported in the xylem conduits in a nonturbulent flow. The hydraulic conductivity, which is calculated by the volumetric flow rate per pressure gradient, is proportional to 4th power of conduit radius (Hagen-Poiseuille equation) (Lewis & Boose 1995). However, the internal anatomy of xylem and their interconnections is not just a parallel straight walled tube. Thus, measurements of xylem hydraulic conductance calculated from measurements of conduit radii overestimates measured conductivity

(Tyree & Zimmermann 2002).

Xylem conduits are dead at maturity. However, the tissues in which they function contain living cells. For this, the hydraulic conductivity measurements made for stem trunks has to be made within few days, or preferably on field. Shortly after logging, wounding reactions or clogging of vessels by fungal and bacterial growth might affect measured flow rates (Sperry et al. 1988, Melcher et al. 2012). In this study the measurement from crown were made on field, within same day. The measurements of stem samples below living canopy were made in laboratory within five days and samples were kept in black plastic bag and in cold to prevent drying and clogging.

From the stems, the xylem specific conductivity (K_s) was measured. Hydraulic conductivity, which is the hydraulic conductance, or the flux for a given driving force ($Q/\Delta P$) normalized by the length of the segment and referenced to the cross-sectional area of the xylem (Sperry, et.al. 1988). The equation by Sperry et.al. 1988 shows as following:

$$K_s = QL/(\Delta P A_{sw})$$

Where Q is the recorded flux, L is the length of the measured stem, ΔP is the pressure drop across the segment, in this case caused by the height of the water pillar. A_{sw} is the cross-sectional area of the conducting sapwood.

There are numerous ways to measure the fluid flow in a stem. In this study, we used the pressure from water column height and measured the change in mass with time with a computer interface, as described in the study of Sperry et al. (1988). The segment of stem was attached to a tube, which was then filled with water. The volume flow rate of water, Q in the equation, was then measured with a digital scale for 20-40 minutes in order to get steady flow rate. The flow rate was then measured at regular intervals and logged into a data file automatically with stems from living crown and manually with stems from top of the crown.

The effect of evaporation in the measurement container was minimized with a relatively short (20-40min) measurement time. Even though the measurement time was rather short, the flow rate was steady and stabilized.

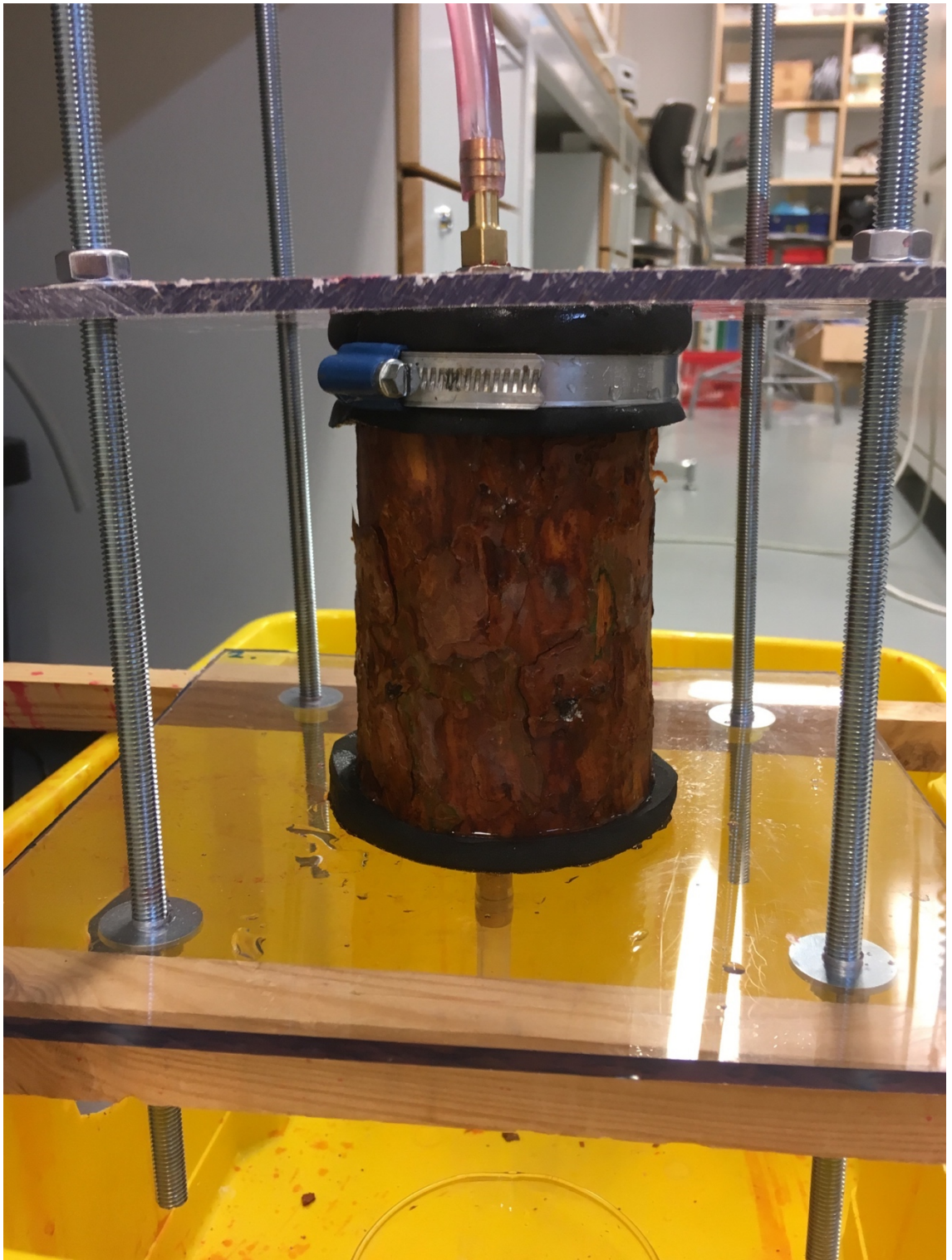


Figure 13 Measuring hydraulic conductivity

3.5 *Aradus cinnamomeus* and hydraulic conductivity

For analyzing the effect of *Aradus cinnamomeus* and make the data comparable, we calculated the volume of each tree and created an index which takes account the size of the tree, and the amount of *Aradus cinnamomeus* in the tree. To calculate the volume of tree, we used the volume functions created by Laasasenaho (1982). The equation was as following:

$$V = 0,036089 \times d^{2,01395} \times (0,99676)^d \times h^{2,07025} \times (h - 1,3)^{-1,07209}$$

Where V is the volume of tree, d is the diameter of tree from breast height (1,3m) and h is the height of the tree. To create the index, the number of insects in a certain tree was derived by the volume of the tree.

4 Results

4.1 Climatic influence on tree-ring growth

The Pearson correlation coefficients between the detrended 30-years spline chronologies and monthly climatic variabilities revealed a significant negative relationship (Figure 14) with the precipitation of previous year June (Pearson's $r = -0.32$) and a positive relationship with the precipitation of previous year December ($r = 0.297$). In addition, the previous year July temperature were also a significant positive predictor ($r = 0.416$). Of the current year climatic variabilities, the precipitation in July ($r = 0.333$), temperature in January ($r = 0.323$) and April ($r = 0.266$) were also significant positive predictors.

When the response function coefficients were applied, the climatic conditions of only some months appeared to have significance on growth. The precipitation of previous year June's and current year July's had significant relationship (Figure 15). Effect of precipitation during previous July was negative ($r = -0.34$) and effect of current year's July was positive ($r = 0.24$). Temperature in the previous year July showed a significant positive relationship ($r = 0,274$).

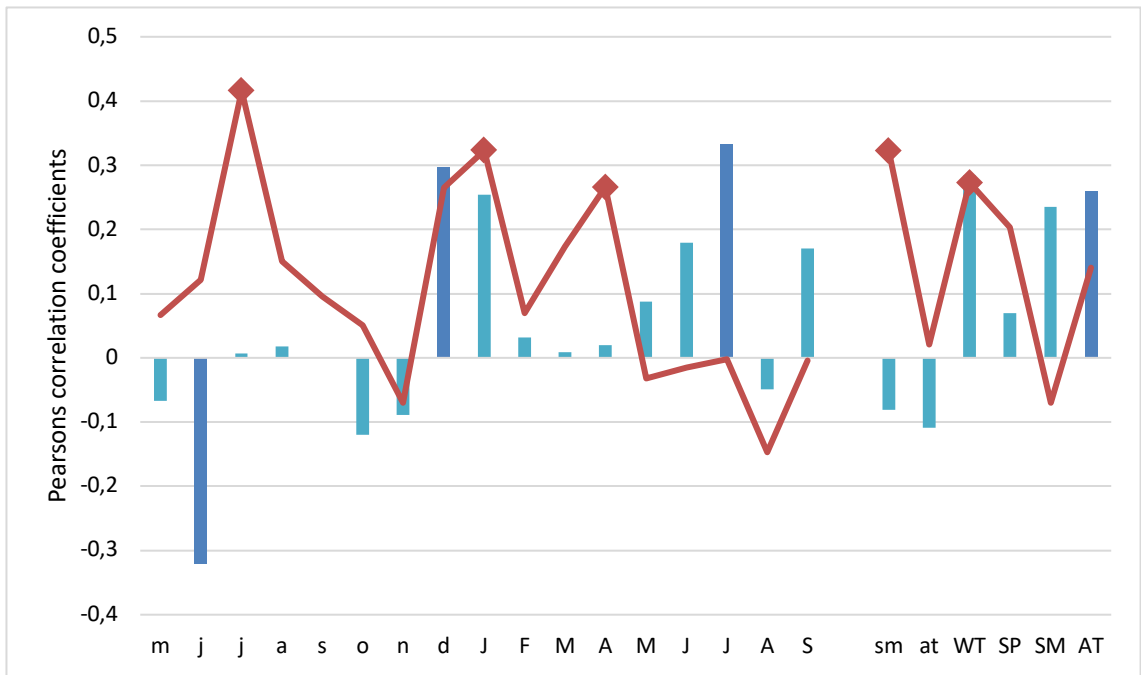


Figure 14 Results of bootstrapped correlation analysis between the detrended 30-years spline chronologies and monthly and seasonal climate data during the period 1962-2015. Bars indicate correlation between precipitation and lines for temperature. Months and seasons are abbreviated with small letters (previous year) and capital letters (current year). SM = Summer (June-August) AT = Autumn (September-November) WT = Winter (December (previous year) – February) SP = Spring (March-May). Statistically significant relationships ($p < 0.05$) are indicated as darker bars for precipitation and asterixis for temperature.

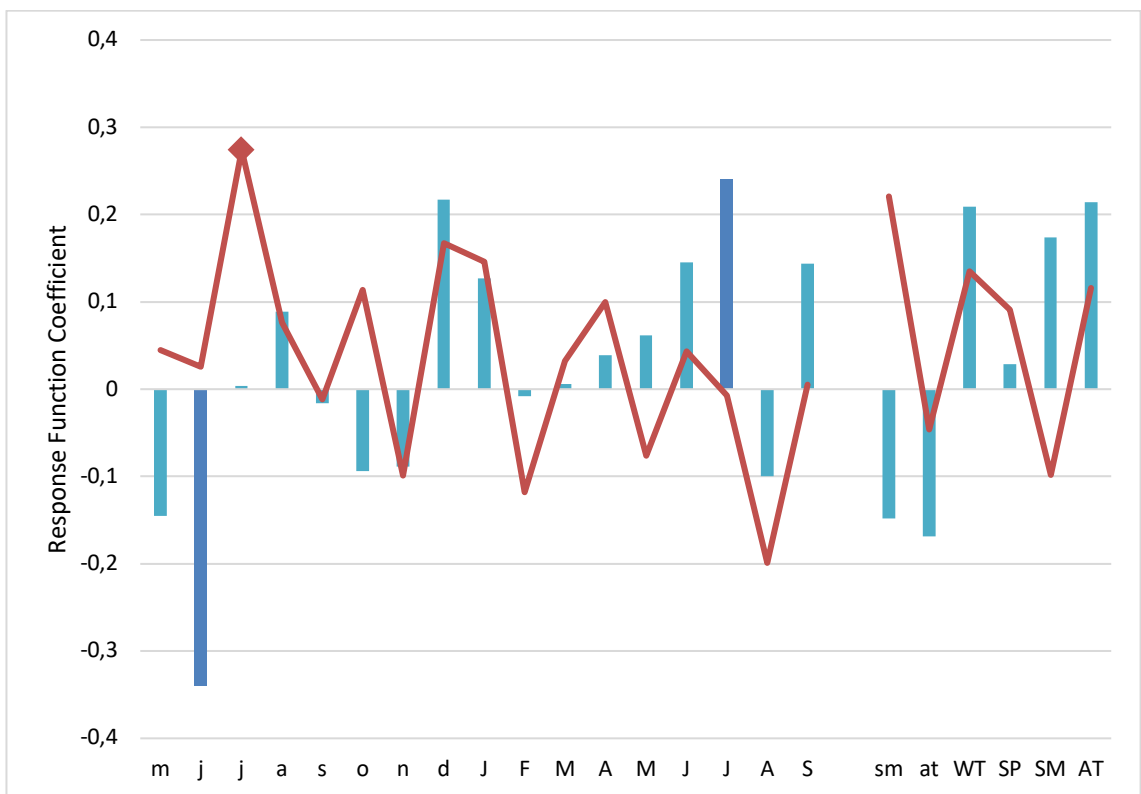


Figure 15 Results of response function analysis between the detrended 30-years spline chronologies and monthly and seasonal climate data during the period 1962-2015. Bars indicate correlation between

precipitation and lines for temperature. Months and seasons are abbreviated with small letters (previous year) and capital letters (current year). SM = Summer (June-August) AT = Autumn (September-November) WT = Winter (December (previous year) – February) SP = Spring (March-May). Statistically significant relationships ($p < 0.05$) are indicated as darker bars for precipitation and asterix for temperature.

	Pearsons Correlation Coefficient		Response Function Coefficient	
	Temperature	Precipitation	Temperature	Precipitation
may	0.067	-0.067	0.045	-0.145
jun	0.121	-0.32	0.026	-0.34
jul	0.416	0.007	0.274	0.004
aug	0.15	0.018	0.076	0.089
sep	0.096	0	-0.012	-0.016
oct	0.051	-0.12	0.114	-0.094
nov	-0.07	-0.089	-0.099	-0.089
dec	0.265	0.297	0.167	0.217
JAN	0.323	0.254	0.146	0.127
FEB	0.07	0.032	-0.118	-0.008
MAR	0.173	0.009	0.032	0.006
APR	0.266	0.02	0.1	0.039
MAY	-0.032	0.088	-0.076	0.062
JUN	-0.015	0.179	0.043	0.145
JUL	-0.002	0.333	-0.007	0.24
AUG	-0.147	-0.049	-0.199	-0.1
SEP	-0.004	0.17	0.005	0.144
sm	0.322	-0.081	0.221	-0.148
at	0.021	-0.109	-0.046	-0.169
WT	0.273	0.284	0.135	0.209
SP	0.203	0.07	0.091	0.029
SM	-0.07	0.235	-0.098	0.174
AT	0.14	0.259	0.116	0.214

Table 2 Results of bootstrapped correlation and response function analysis between the detrended 30-years spline chronologies and monthly and seasonal climate data during the period 1962-2015. Months and seasons are abbreviated with small letters (previous year) and capital letters (current year). SM = Summer (June-August) AT = Autumn (September-November) WT = Winter (December (previous year) – February) SP = Spring (March-May). Statistically significant relationships ($p < 0.05$) are showed in bold.

4.2 Impact of drought pointer years to growth

Applying the driest years, 1966, 1972, 1973, 1999, 2003, 2006, 2010 and 2013 to the superposed epoch analysis, the results show a small response for the radial growth on the drought year, and a significant positive response for the growth one and two years after the drought year (figure 16). However, when applying only the driest years for the

past 20 years to the superposed epoch analysis, the response of the drought year to the current year growth is clear (figure 17).

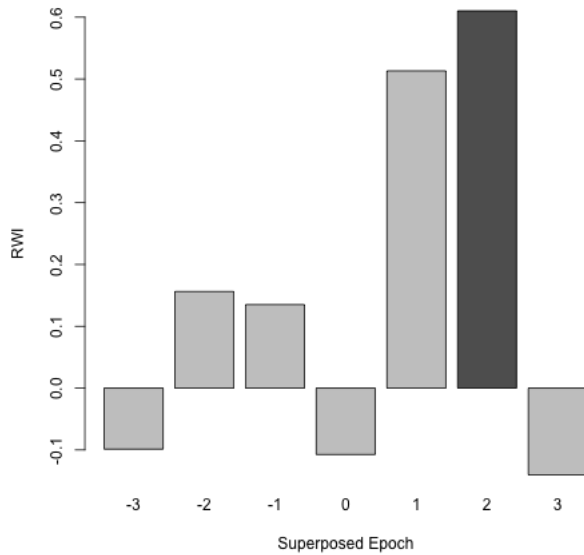


Figure 16 Mean ring width growth departures shown in the superposed epoch analysis 3 years prior, and 3 years after the drought (1966, 1973, 1974, 1999, 2003, 2006, 2010,2013). Values were averaged for the 5 drought years considered. Dark black bar shows a departure greater than wo

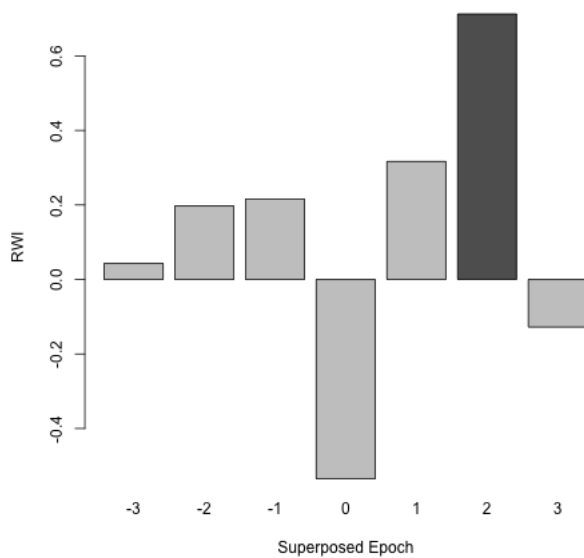


Figure 17 Mean ring width growth departures shown in the superposed epoch analysis 3 years prior, and 3 years after the drought (1999, 2003, 2006, 2010, 2013). Values were averaged for the 5 drought years considered. Dark black bar shows a departure greater than would have occurred by chance as determined from 10000 random simulations ($P < 0.05$)

4.3 Hydraulic conductivity and damage agents

The hydraulic measurements of Scots pine from the top of the crown, and the pine bark bug index revealed us a small, but significant correlation. The tree's hydraulic conductivity in the upper part was higher when there were more pine bark bugs in the tree ($r = 0,1815$) (Figure 18). In comparison to the measurements taken just below the living crown, no significant relation was found ($r = 0,0277$) (Figure 19).

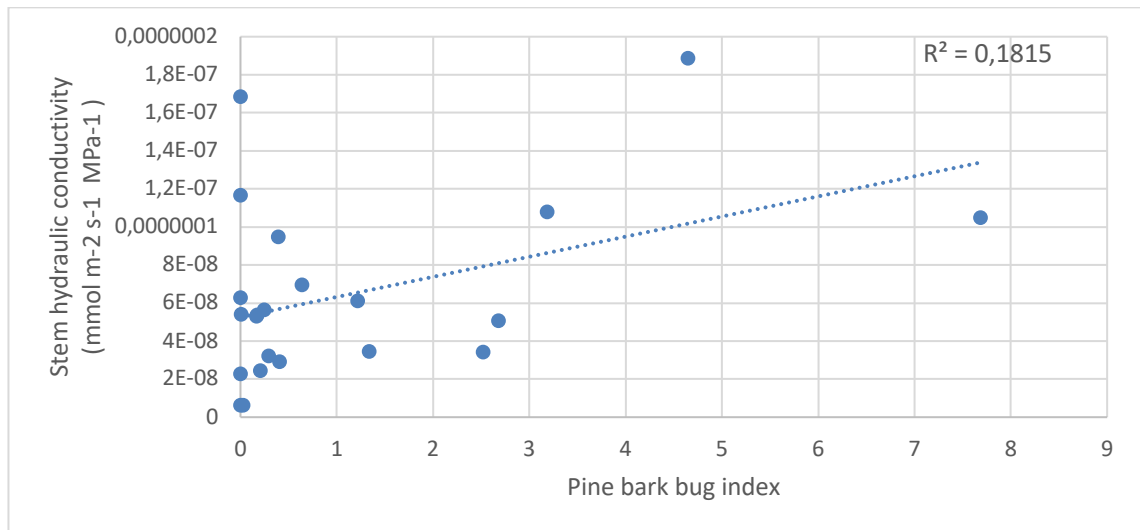
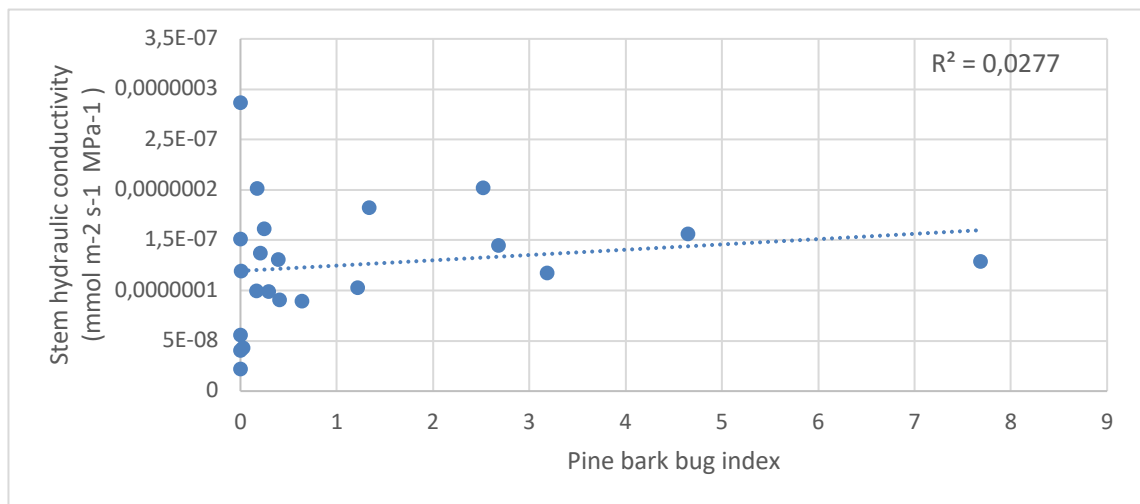


Figure 18 Hydraulic conductivity of stem from the top of the crown (x-axis) and *Aradus cinnamomeus* index (y-axis).



the *Crumenulopsis sororia* were identified microscopically.

Hydraulic conductivity below the living crown was normally distributed (Figure 20). In addition, the Leven's test for equality of variances showed that there is quite significant variance in the two groups (Sig. value 0.027). Moreover, the Shapiro-Wilk test showed that sample values were normally distributed (Sig. value 0.598) (Figure 21), therefore the test is statistically reliable. This study showed that below the living crown the pathogen *Crumenulopsis sororia* had no statistically significant effect on stem hydraulic conductivity ($p=0.458$) (Figure 25).

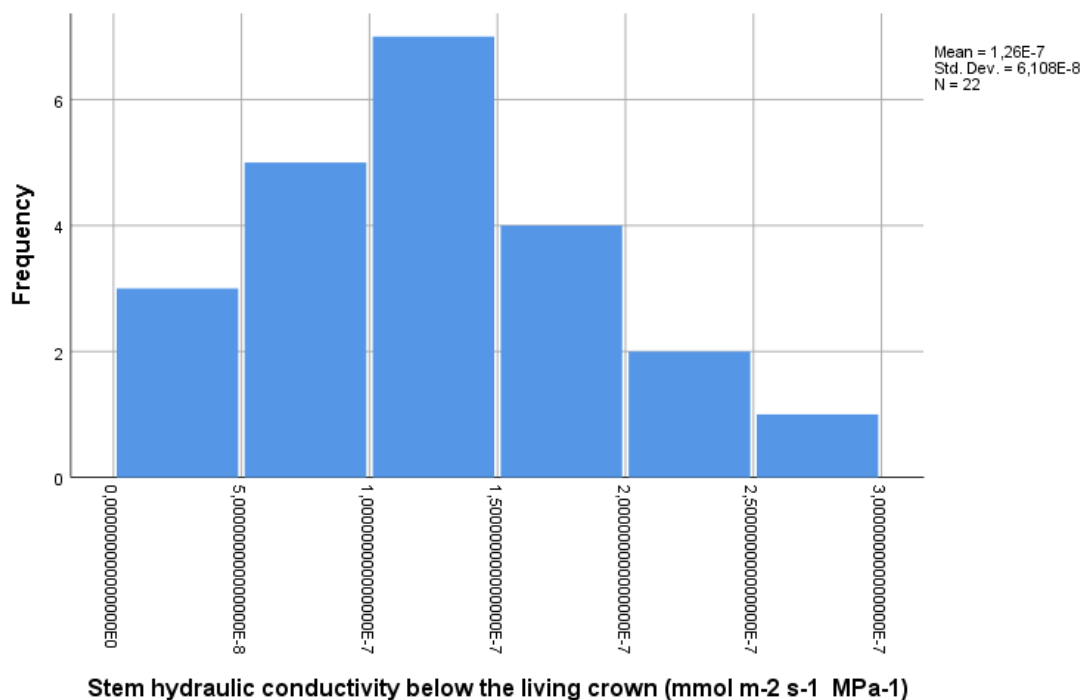


Figure 20 Histogram of stem hydraulic conductivity below the living crown showing that the sample is normally distributed.

Tests of Normality						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Stem hydraulic conductivity below the living crown (mmol m-2 s-1 MPa-1)	,097	22	,200*	,965	22	,598

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Figure 21 Test of normality of stem hydraulic conductivity below the living crown.

In the top of the crown, the hydraulic conductivity were not normally distributed (Figure 22) and the Shapiro-Wilk test of the hydraulic conductivity in the top of the crown (Sig. value 0.015) (Figure 23) showed that the hydraulic conductivity in trees are not normally distributed. Therefore, we used the non-parametric Kruskal-Wallis H test (Figure 24). The Kruskal-Wallis H test showed that there is statistically significant difference in hydraulic conductivity between the two groups $p = 0.018$, with a mean rank of 15.10 for pathogen and 8.5 for non-pathogen (Figure 24).

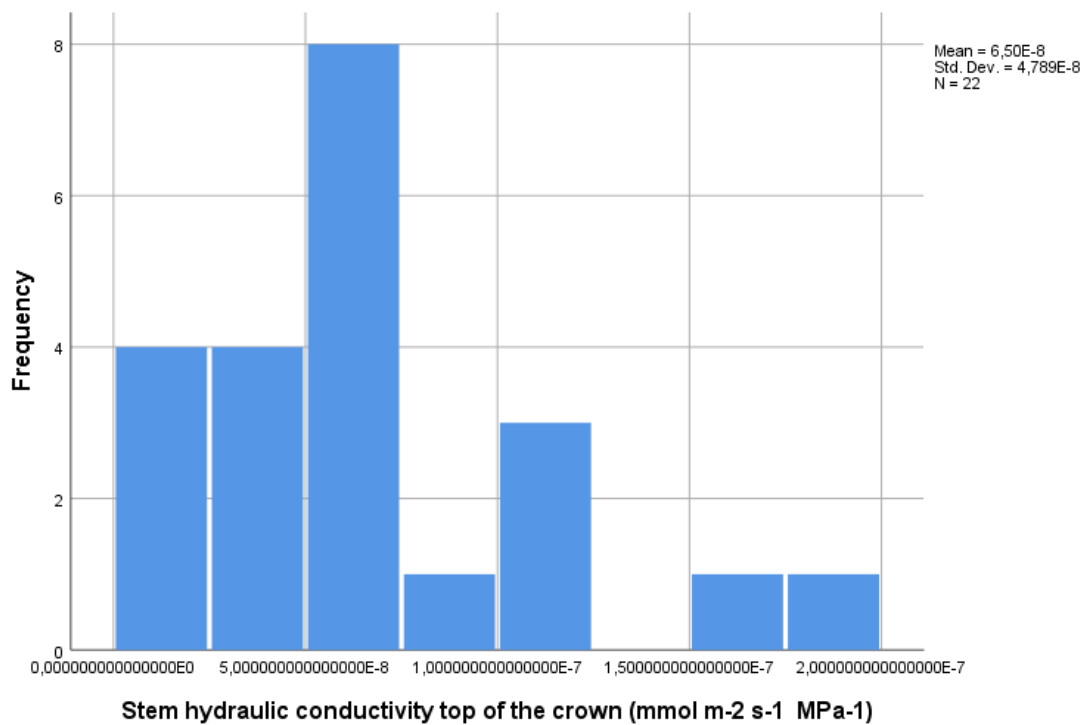


Figure 22 Histogram of stem hydraulic conductivity top of the crown showing that the sample is normally distributed.

Tests of Normality						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Stem hydraulic conductivity top of the crown (mmol m-2 s-1 MPa-1)	,201	22	,021	,885	22	,015
a. Lilliefors Significance Correction						

Figure 23 Test of normality of stem hydraulic conductivity top of the crown.

Kruskal-Wallis Test

Ranks			
	Sorokkaa (1 = Kyllä, 0 = ei)	N	Mean Rank
Stem hydraulic conductivity top of the crown (mmol m ⁻² s ⁻¹ MPa ⁻¹)	ei	12	8,50
	kyllä	10	15,10
	Total	22	

Test Statistics^{a,b}

	Stem hydraulic conductivity top of the crown (mmol m ⁻² s ⁻¹ MPa ⁻¹)
Kruskal-Wallis H	5,635
df	1
Asymp. Sig.	,018

a. Kruskal Wallis Test

b. Grouping Variable:
Sorokkaa (1 = Kyllä, 0 = ei)

Figure 24 Kruskal-Wallis H test of stem hydraulic conductivity top of the crown.

The averages from the group from which the pathogen, *Crumenulopsis sororia*, were microscopically identified and from which the pathogen were not identified revealed that the stem hydraulic conductivity was 64,9% higher in the group from which the pathogen were identified (figure 25).

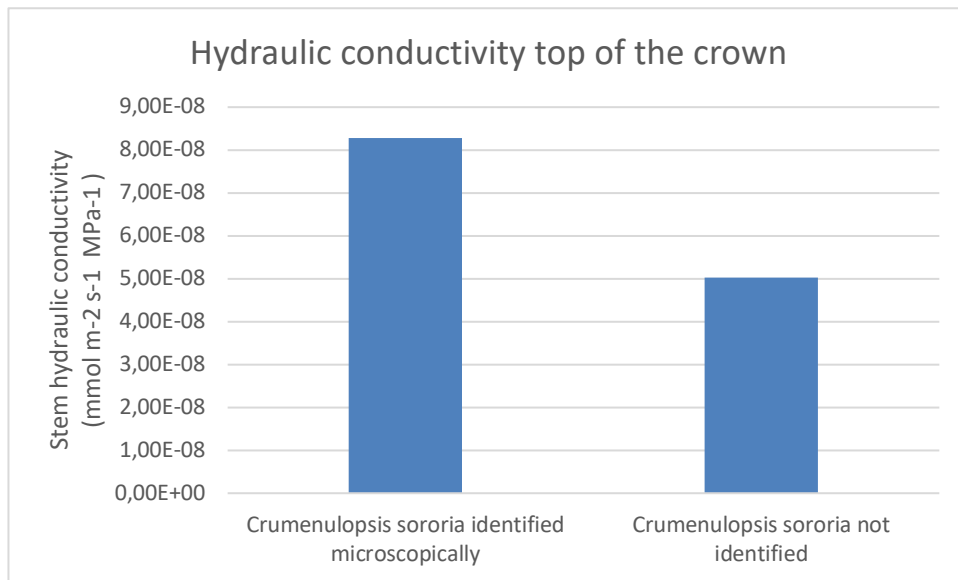


Figure 25 Hydraulic conductivity of stem from the top of the crown (x-axis) and averages of hydraulic conductivity of the group from which *Crumenulopsis sororia* were microscopically identified and the group from which *Crumenulopsis sororia* were not identified.

4.4 Hydraulic conductivity and defoliation

The hydraulic measurements of Scots pine from the top of the crown, and the upper one quarter defoliation index revealed that the hydraulic conductivity was significantly higher, if the tree crown was not defoliated. The trend was clear ($r = 0,39$) (Figure 26). The hydraulic conductivity in the top of the crown and the defoliation index revealed also a small trend showing similar results ($r = 0,063$) (Figure 28). Below the living crown, the upper one quarter defoliation index and hydraulic conductivity ($r = 0,043$) and the defoliation index and hydraulic conductivity ($r = 0,01$) showed no clear trend (Figure 27 and Figure 29).

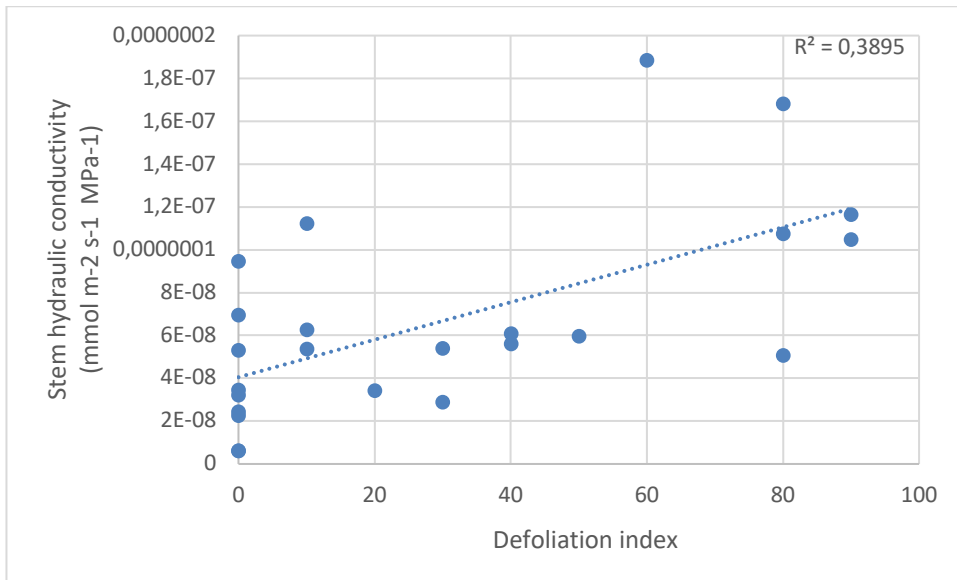


Figure 26 Hydraulic conductivity of stem from top of the crown (x-axis) and defoliation index of upper one quarter (y-axis).

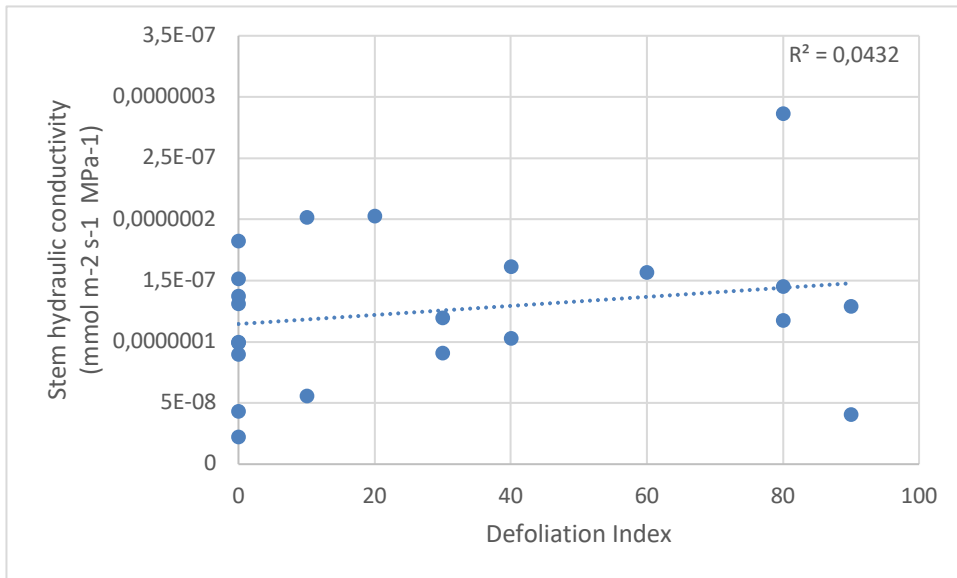


Figure 27 Hydraulic conductivity of stem just below the living crown (x-axis) and defoliation index of upper one quarter (y-axis).

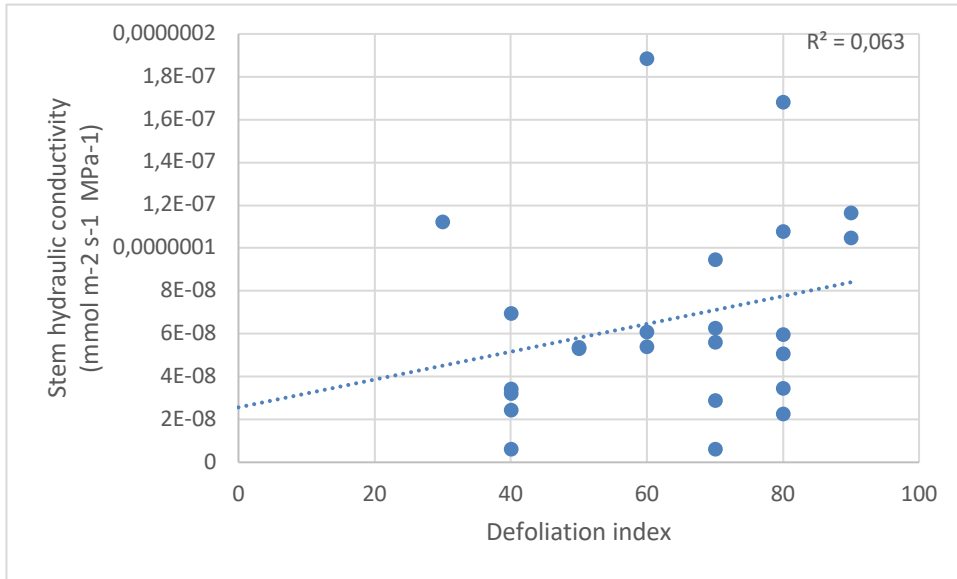


Figure 28 Hydraulic conductivity of stem from top of the crown (x-axis) and defoliation index of the whole tree (y-axis).

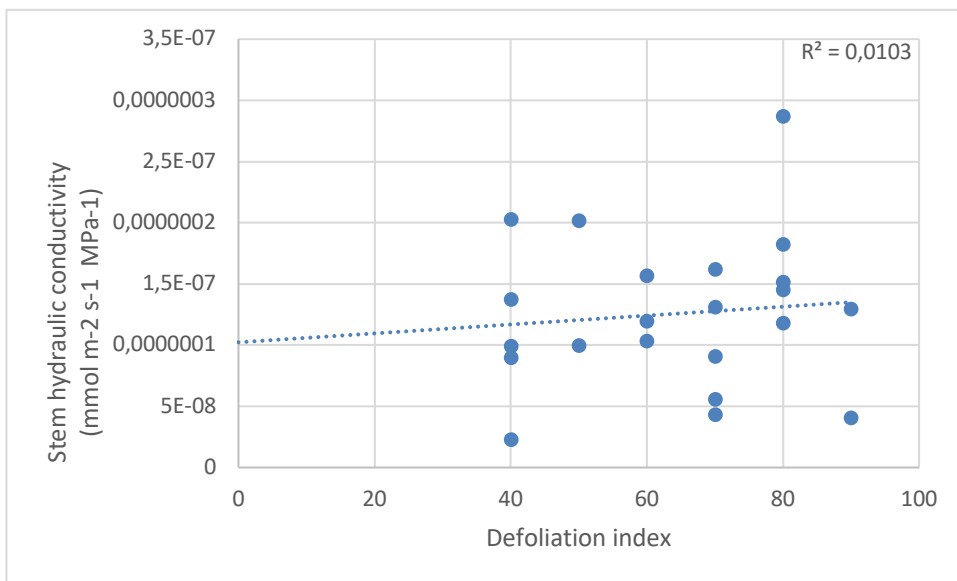


Figure 29 Hydraulic conductivity of stem just below the living crown (x-axis) and defoliation index of the whole tree (y-axis).

5 Discussion

5.1 Dendroclimatology

The findings provide support for the first hypothesis stating that there has been a notable reduction in growth of the trees in the study area. This goes well along with another dendroclimatological study about drought affecting to radial growth of the Scots pine in Finland (Nöjd et al. 2017). The superposed epoch analysis revealed that droughts occurred in the past 20 years, reduced the radial growth of Scots pines (Figure 17). However, the results from this were within the lower 95% bootstrapped confidence limit and are not statistically significant. Similar and statistically significant observations have also been made previously (Eilmann et al. 2006, Martín-Benito et al. 2007, Pichler & Oberhuber 2007). Two years after the drought, trees showed a statistically increased growth, larger than in an average year (Figure 17). Bansal et al. (2013) studied the effect of growth response of *Pinus sylvestris* seedlings to drought and showed that the seedlings which had more severe drought, recovered more rapidly. Bansal et al. (2013) suggest that the reason for this is that severe drought induces acclimation by activating signaling pathways and gene regulation (Hare et al. 1999) which allow rapid recovery after suitable conditions returns. In the study made by Pichler & Oberhuber (2007), the growth recovery of Scots pine was not as rapid, although the Pichler & Oberhuber study examined only the extreme drought year 2003 and located Switzerland Alpine dry valley, while our superposed epoch analysis covers the years 1999, 2003, 2006, 2010, 2013 in the present study area.

The findings of this study shows that there was a significant positive relationship between the tree-ring growth and precipitation in July in the response function (Figure 15). In addition, the Pearson correlation coefficient (Figure 14) showed a significant positive relationship between tree ring growth and precipitation in autumn (September–November) which goes along with a study by Henttonen et al. (2014) where a correlation between soil water content of previous year late summer and autumn was discovered. In this study, only previous years July's temperature had a positive significance in the response function. Previous studies show a clear correlation between tree-ring growth and temperatures in July. However, the connection is stronger in northern Finland than in southern Finland (Helama et al. 2005).

Previous dendroclimatological studies in Finland indicate that precipitation in May and

June and previous year late summer precipitation has a relationship in the growth of Scots pine in northern and southern Finland (Lindholm 1996, Helama et al. 2005, Henttonen et al. 2014, Nöjd et al. 2017).

5.2 Biotic agents

McDowell et al. (2008) suggest that there are two main physiological mechanisms leading to drought-induced mortality of trees. The mechanisms are hydraulic failure and carbon starvation. The carbon-starvation hypothesis predicts that the trees starve as a result of continued metabolic demand for carbohydrates. Therefore, the carbon-starvation takes effect when the drought is long, and it lasts longer than the equivalent amount of plant carbon reserves (McDowell et al. 2008). The other theory, hydraulic-failure hypothesis takes place when the drought is extremely severe, and the tree's evaporative demand remains high during reduced soil water content, causing the embolism of water filled conduits (McDowell et al. 2008). The biotic agents may benefit from warmer seasons and decreased winter mortality because of the warming of winter months. In addition, the biotic agents may amplify or be amplified by the drought-induced physiological stress (McDowell et al. 2008).

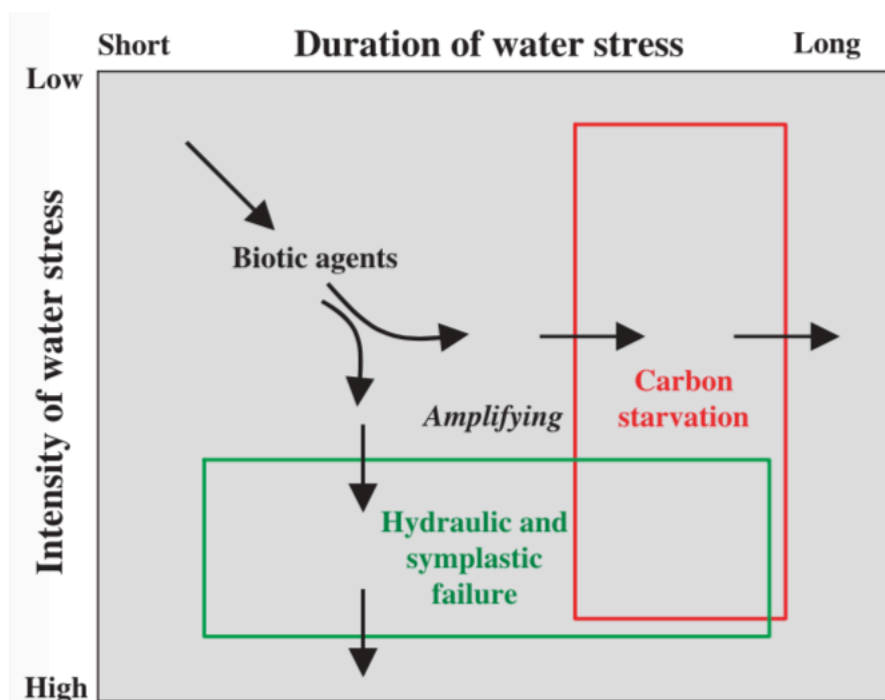


Figure 30 Hydraulic framework between the duration and intensity of drought leading to either carbon starvation or hydraulic and symplastic failure. McDowell et al. 2008.

The results indicated that the most limiting factor to radial growth of *Pinus sylvestris* was precipitation in June, and last year July. Water shortage during the growing season decreases photosynthetic production and causes physiological stress to trees and is known to promote outbreaks of many insect (Mattson and Haack, 1987). In drought-stressed *Pinus sylvestris* the induced resin flow has shown to decrease (Croise and Lieutier, 1993), which might affect the trees ability to defend against biotic agents. Severe droughts have been found benefitting bark beetles and wood borers (Koricheva et al., 1998; Huberty & Denno, 2004), also generally sap sucking insects such as *Aradus cinnamomeus* performs better on water-stressed trees (Koricheva et al., 1998; Björkman & Larsson, 1999).

Aradus cinnamomeus and *Crumenulopsis sororia* may both be benefitting from increased physiological stress caused by drought years, leading the trees to be more vulnerable. 32 out of 35 tree in this study showed resin stains, which may indicate that the tree is using resin against *Aradus cinnamomeus* or *Crumenulopsis sororia* or both of them. The increased resin production depletes the carbon reserves of tree, and this may lead to increasing carbon loss and eventually to carbon starvation (Wallin et al. 2003). There is also evidence that biotic agents may amplify hydraulic failure of tree by beetles inoculating sapwood with xylem-occluding halting the water transport (Larsson et al. 1983, Waring & Pitman 1985, Wullschlegel et al. 2004). There are previous findings that the *Crumenulopsis sororia* and *Aradus cinnamomeus* are co-occurring together (Doom 1976) and this might be the cause of dying of trees in Kemiönsaari.

This study showed that the hydraulic conductivity of Scots pines in this area is not decreased by the pathogen *Crumenulopsis sororia* or *Aradus cinnamomeus*, in contrary, there was a clear correlation with higher hydraulic conductivity in the top of the crown of Scots pine's where *Crumenulopsis sororia* or *Aradus cinnamomeus* were present. (Figure 18 and Figure 25). The reason of this might be that neither the *Crumenulopsis sororia*, nor the *Aradus cinnamomeus* inhabits trees that has a low hydraulic conductivity. The *Crumenulopsis sororia* might not get enough nutrients from a tree that has low hydraulic conductivity, and *Aradus cinnamomeus* might abandon the tree which is not vigorous enough and work as a vector for the *Crumenulopsis sororia* and spread is across the forest. Moreover, these results are consistent with meta-analysis by Jactel et al. (2011), suggesting that the effect of drought on sucking insects and bark pathogens would be negative. The effect is probably due to the decreasing

concentrations of carbohydrates and nitrogen in the stem of trees under moderate water stress. This would limit the performance and consequently the damage caused by the pests of woody organs (Jactel et al. 2011).

Therefore, the hypothesis two and three can be partially declined, thus according to this study, these biotic agents do not decrease the hydraulic conductivity of Scots pine.

6 Conclusion

The aim of this study was to examine the main reason or reasons behind the tree mortality in Kemiönsaari. The focus of this study was on drought, and biotic agents *Crumenulopsis sororia* and *Aradus cinnamomeus*.

The climatic and dendroecological evidences in this study showed that there have been several severe drought summers in Kemiönsaari during the past twenty years, and the drought has decreased the growth of *Pinus sylvestris*. The results indicated that the most limiting factor to radial growth of *Pinus sylvestris* was precipitation in last year June, and temperature in last year July. This result was shown both in Pearson's correlation and response function correlation. South-west archipelago area is a high-risk drought area (Muukkonen et al.2015), and it is likely that there will be drought summers in the future. Increased frequency and severity in droughts will lead to more declined growth and possibly enhance the occurrence of some biotic agents in the area.

Another interesting finding in this study was that the trees where the *Aradus cinnamomeus* index were highest and which had *Crumenulopsis sororia*, had higher hydraulic conductivity. It might be that the drought had increased the number of these biotic agents in the study area, but the biotic agents prefer trees that are in better condition. Also, the co-occurrence of *Aradus cinnamomeus* and *Crumenulopsis sororia* is notable, there are previous evidence of *Aradus cinnamomeus* working as a vector to *Crumenulopsis sororia* (Doom 1976).

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