UNIVERSITÀ DEGLI STUDI DI PADOVA

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# Growth Comparison of Black Pines and Scots Pines in the German Region of Westphalia

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**Abstract**

Climate change pushes foresters to rethink which trees are fit for the future. This gave black pines increasing attention as a possible candidate to fill the gaps. But until now, this species is not classified in Germany in contrast to Belgium, Great Britain or the Netherlands in an own yield table to evaluate its productivity. It is common practice to use yield tables of Scots pine even though first publications showed a difference in growth (e.g. Šeho et al., 2010) – a break of oath to the concept of sustainability for scholars like Assmann (1964).

This work compares growth of Scots and black pine using dendrochronology to address this issue and contrasts the growth pattern with climate data and forest management activities in the stands. 12 Scots and black pines are sampled randomly in two near-by stands using dendrochronology. The sample selection is limited on silvicultural pre-selected definitive trees. The sample size is a compromise between economic devaluation of sampled trees (damaging the tree by boring holes) and scientific considerations (increasing sample size increases insights). Measurements of tree ring width and crossdating are followed by a two-step test: visually in TSAP and statistically with COFECHA.

The results show a stronger radial growth of black pines than Scots pines in Westphalia. Drought, precipitation and thinnings in the stands were the main influencing factors. These findings contribute to an introduction of a black pine yield table in Germany.

**Acknowledgements**

The work is dedicated to my grandfather Forstmeister Johannes Baron Twickel who introduced the black pine to our forests in Westphalia and to my father Ferdinand Graf Merveldt who endlessly continues taking care of these stands. Both have shown an open eye for the given inside and outside of forest stands addressing opportunities and challenges equally. It is my honour to value and analyse the work of the last three generations with this thesis.

My thank goes to Professor Pividori and Professor Marcolin giving me the chance to write on a Mediterranean species in a continental context. They share the passion for silviculture – a science yet art of forestry that proves making the forest more prepared for future generations. Further I like to express my gratitude to my family, friends, and my uncle Dr. rer. pol. Andreas Graf Ballestrem repeatedly supporting me in studies.

Padova, 31 July 2021

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# 1. Introduction

## 1.1. Role of Scots and black pines in Westphalia

The black pine's (*Pinus nigra*) natural habitat stretches across the Mediterranean Area up to Austria (Mayer, 1984). In Germany this species plays only a minor role (Seho, 2020). But as climate changes, calls for more resistant species become louder. First publications on the black pine in Germany support the idea to include it in the tree portfolio (Stratmann, 2019, 2021). It resists longer droughts, demands only low level of soil nutrients and still produces superior growth (Klemmt et al., 2012).

Discussions on the suitability of black pines in Germany are ongoing. Should this species gain in importance, silviculturist will raise the question how strong it can grow on German soils. This thesis will contribute to give an answer to this.

## 1.2. Missing data for own yield table for black pine.

Germany does not have own yield tables to assess the productivity of its black pines unlike its neighbours in the Netherlands (Jansen et al., 2018), Belgium (Delevoy, 1949) or Austria (Frauendorfer, 1954). The forest owners and timber producers have not given yet the black pines greater attention: less than one percent cover German forests. Calls to introduce own yield tables have been ignored so far (Stratmann, 2019, 2021). Besides limited market interest (Seho, 2020), insufficient growth data of black pines can be the reason. Collecting such data contributes to fill this gap serving as basis for yield tables.

Yield tables are essential for sustainable forestry. They assess the productivity of the species to set an annual harvesting allowance preventing overcutting. In practice foresters choose the yield tables of the Scots pines (*Pinus sylvestris L.*) – the pines commonly found in German forests. But black pines seem to grow differently than predicted in the yield table of its German relative (Šeho et al., 2010). Using the wrong yield table can result in overcutting putting sustainability at risk (Assmann, 1964).

Past research on black pines focused on southern and eastern areas of Germany and younger stands below 60 years (Huber & Šeho, 2016; Reichert et al., 2011; Šeho et al., 2010). Although black pine is also present farther north, such as over 60-year-old stands in Westphalia, research has not collected data there. The past findings were mainly published in German technical journals. Dedicating a thesis on this issue contributes to an increasing scientific and practical interest.

## 1.3. Research objectives

The purpose of this study is to demonstrate the different growth pattern of black pines compared to Scots pines in Westphalia. This would support the introduction of a separate yield table for black pines in as a basis for sustainable forest management. This work provides data for future research to build on to set up a yield table for black pines in Germany.

**Specific objectives are:**

- To quantify and compare the annual growth of black pines and Scots pines in Westphalia using a dendrochronological analysis.
- To identify the growth components (including environmental impacts, e.g. stand tending treatments and climate) to make the collected data comparable.

**Hypothesis**

The black pine dominates the Scots pine in terms of growth. Previous publications have mainly proven this hypothesis (Huber & Šeho, 2016; Šeho et al., 2010), though not universally (Fischer et al., 2019; Reichert et al., 2011).

**Limitations**

This study focuses on stands in the region of Westphalia. General statements on a national level from this analysis is limited due to varying environmental and silvicultural differences. Please also note the limitations in the methodology section.

To clarify, the black pine species covered by this research is the Corsican black pine (*Pinus nigra subsp. laricio* or also named *Pinus nigra subsp. salzmannii var. Corsicana* – referred to as "black pine" in this research). This subspecies varies in terms of needle length and growth pattern compared to other subspecies, such as the Austrian black pine (*Pinus nigra var. austriaca* or also named *Pinus nigra subsp. nigra var. nigra*) (Scotti-Saintagne et al., 2019; Seho, 2020).

# 2. Study area

## 2.1. Stand description

The sampled Corsican black pines (65 years old) and Scots pines (84 years old) are growing in Westphalia in the north-west of Germany. Past research on black pines has focused on southern and eastern parts of Germany. Choosing this area in the north-west increases the spatial coverage of research on this species. The two sampled stands are comparable being similar in terms of soil (brown earth) and location (12 kilometres in a beeline apart): the black pines in Berghaltern (51.738525, 7.145063 - Haltern am See) and the Scots pines in Wessendorf (51.784313, 6.995150 - Lembeck).

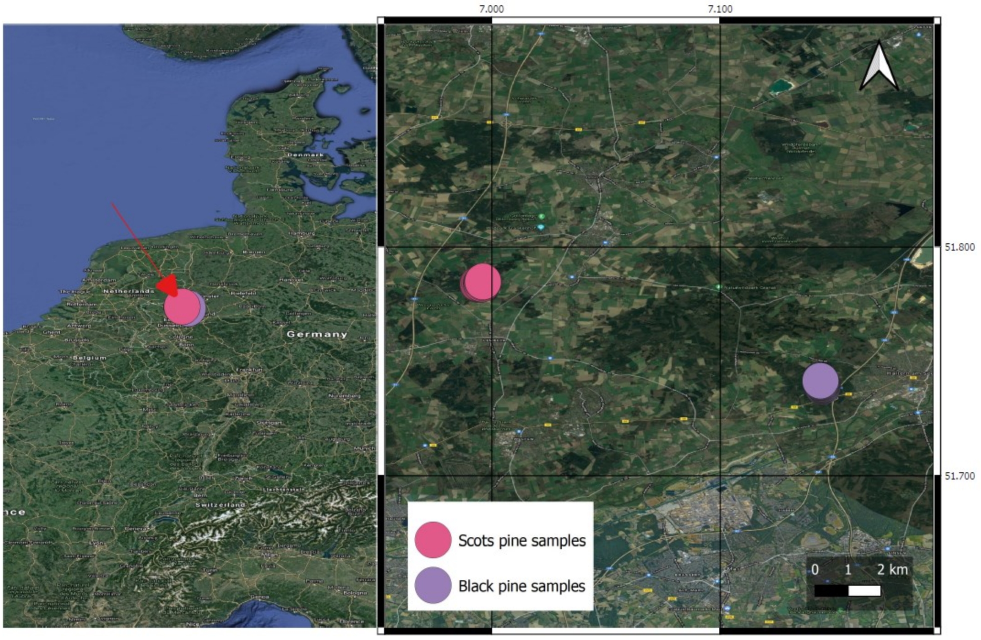



*Figure 1: Mapping of stands in Germany*

| Stand description | Scots pine | Black pine |
|---|---|---|
| Year of sowing/plantation | 1936 | 1955 |
| Forest management compartment | 82 A3 | 107 A1 |
| Growing area | Westphalian Bay | Westphalian Bay |
| Growing district | Westmünsterland | Westmünsterland |
| Elevation | 80 m asl | 70 m asl |
| Altitude zone | Plain | Plain |
| Terrain | Rocky plain | Undulating plain |
| Slope | Flat to slightly inclined | Flat to slightly inclined |
| Water balance | Medium fresh to medium dry | Medium fresh to fresh |
| Nutrient balance | Low | Low |
| Soil type | Clayey sand | Clayey sand |
| Location | 51.784313, 6.995150 | 51.738525, 7.145063 |
| Number of trees | 6 | 6 |
| Number of cores | 12 | 12 |

*Table 1: Stand description following Atalay (1990)*

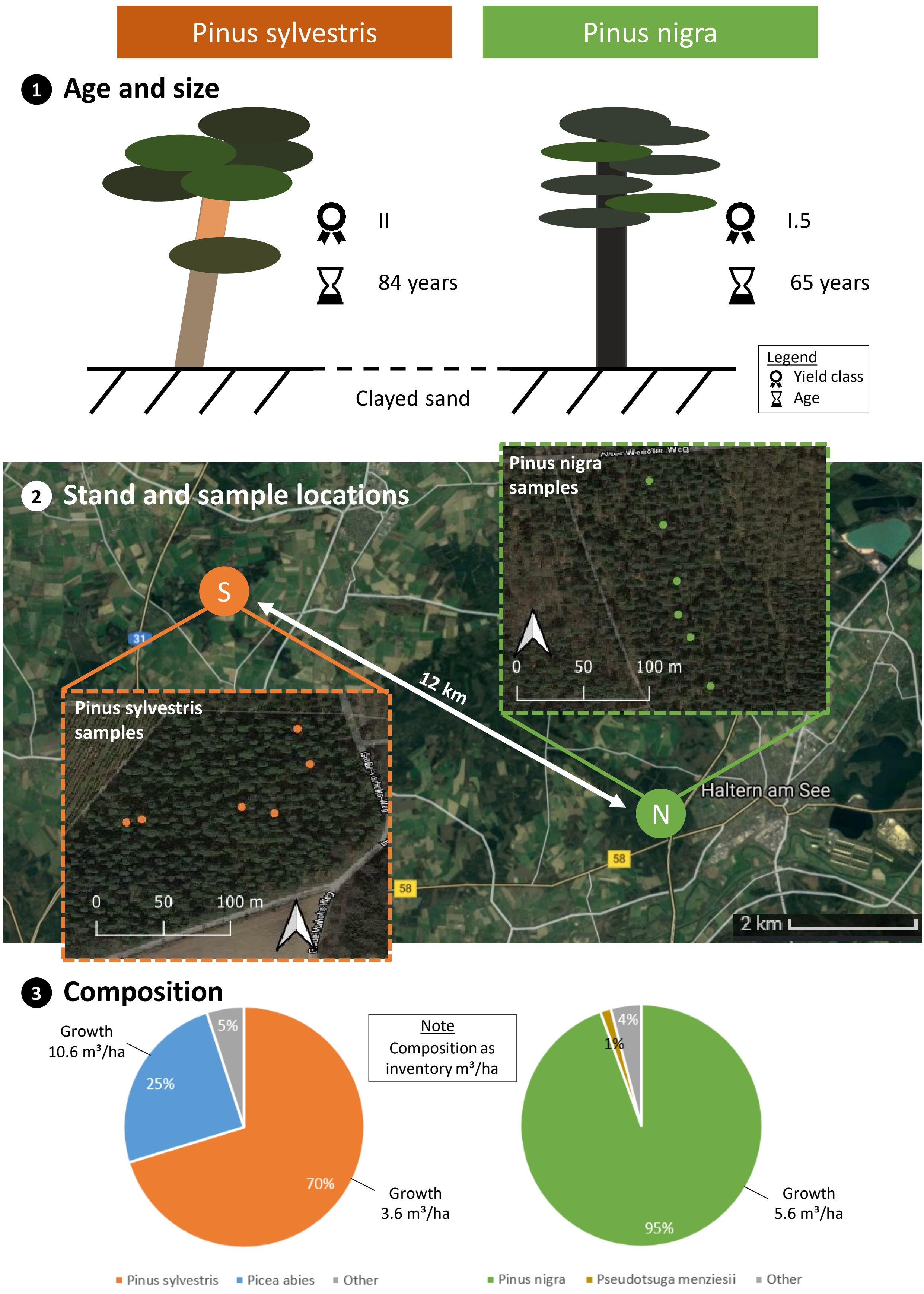



*Figure 2: Stand description and mapping*

## 2.2. Surface structure and geology

The stands are at comparable elevation of 70 to 80 meters above sea level and mostly flat, though shallow hills alter the landscape of the Scots pines (Spoddek, 1953). Both are in the plain of the Westphalian Basin that forms together with the Lower Rhine Bay the North German Plain (Glässer, 2003). The basin is mostly flat with its highest point is 100 meters above sea level (Glässer, 2003).

Looking at the geologic profile, the stands are on a up to 300-meter-thick sand layer (Münsterländer Oberkreidemulde). This is a reminiscent sand cliff at the shores of a sea over 100 million years ago during the Late Cretaceous. Though origins of sedimentary sands are unknown until today, they provide important functions to store and filter the water table important for the surrounding region. The landscape was shaped further until the early Holocene: Pleistocene glaciers brought in stripes of ground moraine; later during the Holocene wind regimes produced the shallow hills in the Scots pine stand (Spoddek, 1953). Further information can be found in Drozdzewski (1995).

## 2.3. Soil and hydrology

The soils of both stands are sandy composed of brown earth with a soil ph of about 4.5 and low on base nutrients. Looking at the different soil horizons, the surface of six to ten centimetres depth includes slightly silty, slightly loamy sands (A horizon) over the subsoil of sandy loan to strongly loamy sand and sandy silt (B horizon). This soil was formed from redeposited Pleistocene cover sands on top of the ground moraine (C horizon). (AVH, 2020; Spoddek, 1953)

The sandy soils of both stands are permeable to water. This demands deep rooting of trees to reach the water table.

## 2.4. Climate

The oceanic sub-climate prevailing in the Westphalian Basin is connected to its surface structure. From above it resembles to a triangle with an open side to the west inviting winds from the Atlantic Ocean. Natural barriers close the two remaining sides of the triangle with the Rhennish Massif to the south and hills of the Teutoburg Forest and the Egge to the east. These regular west winds bring humid and fresh weather allowing mild winter and fresh summer. The precipitation lays between 650 to 900 millimetres. The vegetation period endures 150-190 days with average temperatures above 10°C. The temperatures are 7.5°C to 10.5°C. (Wald und Holz NRW, n.d.)

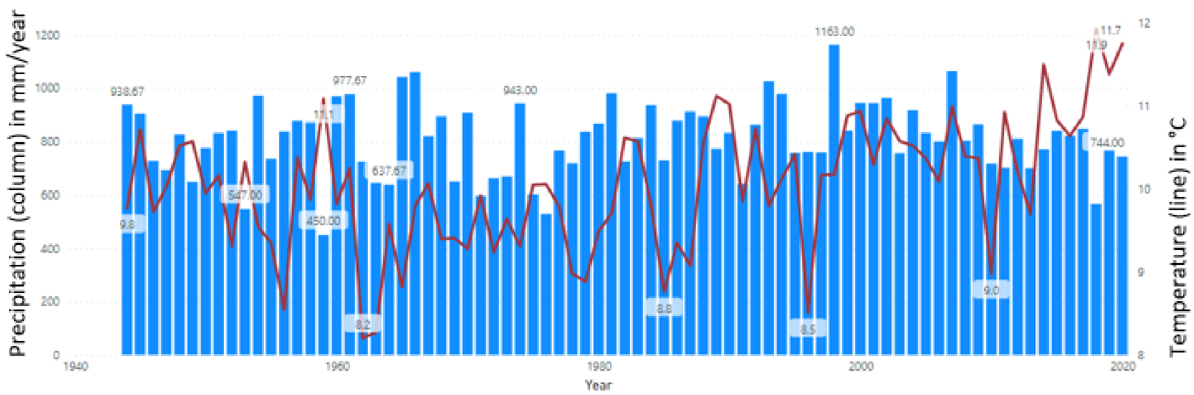



*Figure 3: Precipitation and temperature around the stands* (Deutscher Wetterdienst, n.d.)

## 2.5. Vegetation

On regional level the dominant tree species is the pine. The tree mix in the forests of the Westphalian Basin covering 16 percent of its surface (173,700 ha):

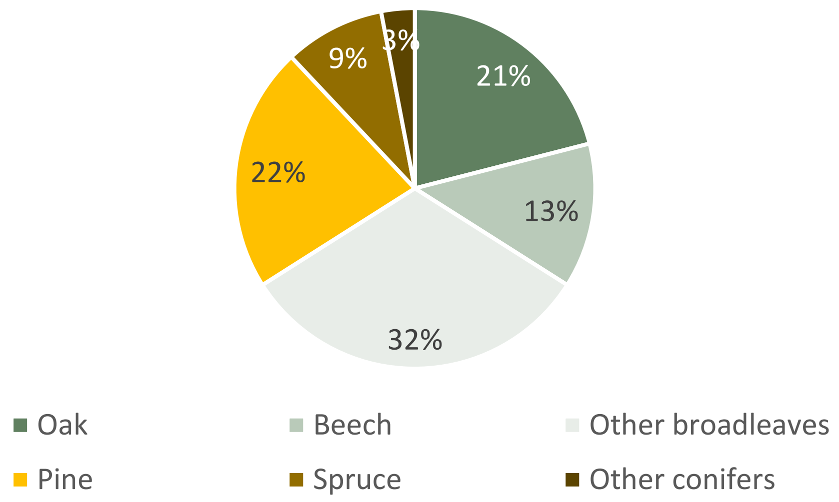



*Figure 4: Species composition of trees in the forests of the Westphalian Basin* (Wald und Holz NRW, n.d.)

On stand level the vegetation above ground differs. Following the vertical structure from top to ground, the 65-year-old Corsican black pines (*Pinus nigra var. corsicana*) in Haltern are the dominant species forming an even-aged canopy layer. According to the latest forest management plan from 2020, Douglas fir (*Pseudotsuga menziesii*) and European beech (*Fagus sylvatica*) planted 18 years ago form the lower canopy. Natural regeneration of English Oak (*Quercus robur*), European larch (*Larix decidua*), European beech (*Fagus sylvatica*), northern red oak (*Quercus rubra*), and Scots pine (*Pinus sylvestris L.*) enriching the intermediate layer. (AVH, 2020)

The shrubs and ground cover below the black pines was not described in the latest management plan. During the field work the owner mentioned presence of ilex (*Ilex*), mountain-ash (*Sorbus aucuparia*), raspberry (*Rubus idaeus*), blueberry (*Vaccinium myrtillus*), nettle (*Urtica dioica*), gorse (*Ulex europaeus*), thistle (*Cirsium palustre*), rushes (*Juncus effusus*), male fern (*Dryopteris filix-mas*), bracken fern (*Pteridium*), wavy hair-grass (*Deschampsia flexuosa*), and other.

The Scots pines (*Pinus sylvestris L.*) near Lembeck form the even-aged canopy (84 years old). Norway spruce (*Picea abies*) planted 30 years ago form the lower canopy. European beech (*Fagus sylvatica*) and Weymouth pine (*Pinus strobus*) complete understory. (AVH, 2020)

Also, the management plan did not include the shrub and ground cover. The owner listed mountain black cherry (*Prunus serotina*), European white birch (*Betula pendula*), Scots pines (*Pinus sylvestris L.*), English Oak (*Quercus robur*) in the understory. Different blackberries and grasses complete the ground cover.

## 2.6. Forest management

Here the history of silviculture is listed from the beginning to the present composition of the stand.

Three generations of the longstanding owner, the family Graf von Merveldt, have formed the two stands. The current owner and manager is Ferdinand Graf von Merveldt (referred to Graf von Merveldt) has developed its today's structure. A large share of information for this thesis comes from discussions in the field with the owner. His grandfather regenerated artificially the Scots pine in 1936;

his father sowed the Corsican pines in 1955. The following section describes the stand history including the stand tending treatments. (Personal communications, 2021)

The Scots pines are the elder stand founded between the two World Wars in 1936. No detailed records survived to unveil the considerations behind this artificial regeneration. According to Ferdinand Graf von Merveldt the management plans were lost in the turbulences of the wars. Nonetheless it seems that these Scots pine were the second generation of pines at this stand. A brief history of pines in Lembeck helps to understanding the development. (Personal communications, 2021)

The history of pines in Lembeck is strongly tied to the rising coal mining in the neighbouring Ruhr area in the 19th century. The mining industry had a strong demand for timber to stabilise their tunnel systems. This fell into a time when in Lembeck large areas of uneconomic heather areas were available for afforestation. Heather previously served as feeding ground for the sheep farming. With its fall in the mid-19th century these lands were afforested with pines to supply nearby mines. The pine as pioneer species could grow on these less fertile lands. (Personal communications, 2021)

The low fertility of these soils was natural, but also human made. Agriculture not only took the fertile soils, but also made the forest and heather soils poorer. As artificial fertilisers were not yet developed, natural ones were valuable making heather and forest lands an important supplier. Residues were taken from the forests and the heather cut in the winter to feed the animals or used as underlay in the cattle stables. Later this manure was brought out on the fields as organic fertiliser. This cycle meant that less biomass was left in the forest and on heather grounds for humus formation leading to reduced fertility of the already poor soils. (Personal communications, 2021)

Coming back to the mining supply, pine timber served as stabilisation of tunnels. The first plantations began around 1860. Its main advantage is the slow lout cracking that alarmed the mine workers before the tunnel broke. The rotation time was around 70 years. The Scots pine sample stand of 1936 are thought to be the second generation. (Personal communications, 2021)

The origin of the Scots pine is not recorded. Graf von Merveldt assumes that the seeds could originated from forests outside of Lembeck. His explanation is that the large demand in seeds in Germany for mining afforestation exceeded local supply. Nurseries only started producing at that time. The mother trees for seed collection were easily accessible along the roads according to his assumption. The quality of those trees did not necessarily match the silvicultural demands of straight growing trunks. In Lembeck this becomes evident: the quality of the afforested pine stands on the former heather grounds are worse than the older pine stands (over 170 years old). (Personal communications, 2021)

The technique of sewing is also not recorded. At the time sewing and planting were common with low labour costs allowing a higher degree of manual work than today. Also, technology was not sufficiently developed. Plants were raised in own nurseries as external providers did not exist. (Personal communications, 2021)

| | Scots pine | Black pine |
|---|---|---|
| Year of sowing/plantation | 1936 | 1955 |
| Technique | Sowing or plantation | Sowing of pine seeds |
| Origin | Not recorded; probably from surrounding forest | 12.5 kg from Rossi in Albertacce, Corsica<br>4.0 kg from Liciani in Tomino, Corsica |
| Preparation of soil | Not recorded; manual | Clear-cut and ploughing, mechanised |

*Table 2: Characteristics of pine plantations in 1936 and 1955 (Personal communications, 2021)*

The younger plantation of Corsican black pine came 19 years later in 1955. Sources of information are richer: they include forest management plans and memories of Ferdinand Graf von Merveldt, born in 1951, passed from his father.

The main motivation to plant black pine was a reaction to a distress situation: the Scots pines in Lembeck were low in quality and started to die. After the war, the iron production industry in the Ruhr area increased sharply (e.g. Duisburger Kupferhütte). This led to an increase of emissions which caused damages to the forest (later in 1980s called in public "Waldsterben"). But Johannes Freiherr von Twickel observed already 30 years prior dying Scots pine. Black pine was suggested to sustain these emissions. (Personal communications, 2021)

The origin of the plantation was from Corsica. In total he planted over 80 hectares of black pine, thereof 77 hectares with the Corsican subspecies and 3 hectares with Calabrian and Austrian. The silvicultural advantage of the Corsican subspecies were straighter trunk and fine-branched crown structure. (Personal communications, 2021)

Prior to plantation the previous stand was clear-cut in the winter of 1954/1955 to prepare it for sowing. According to the forest management plan of 1953 the stand was of low-quality timber including birch, European aspen, mountain ash, Scots pine and oak. The north part of the stand was victim of a fire in 1945 as forester Cordel remembers. The stand overall was badly formed and slow in growth. The author of the management plan, forester Spoddek, did not see any future value ("kein Zukunftswert"). This conclusion might have contributed to the decision to choose this stand for the black pine. (Personal communications, 2021)

In February 1955, the stand soil was prepared with a forest plough. This sort of plough is two-sided and thus different than its one-sided agricultural sibling. The earth is opened to both sides leaving space in the middle to lay the seeds. Between 8 and 10 May 1955 in total 16.5 kilogram of Corsican pine seeds were sowed. (Personal communications, 2021)

The seeds are from the Corsican nurseries Rossi in Albertacce and Liciani in Tomino. The father of Graf von Merveldt drove down personally to Corsica to find the appropriate nursery and see examples of mature black pine stands on the island. He was accompanied by his wife Josepha and a local nursery manager. (Personal communications, 2021)

In the beginning of the 1980s Diplodia tip blight spread across the black pine stand. Management reacted by performing consecutive thinnings to open up the stand and increase air circulation to stop this spread.

For a first overview, the treatments are summarised as following:

| Year | Activities in the Scots pine stand |
|---|---|
| 1936 | Sowing of pine seeds |
| 1956 | Removal of competing broadleaves |
| 1958 | Thinning of Scots pine |
| 1965 | Thinning of Scots pine |
| 1975 | Thinning of Scots pine |
| 1987 | Thinning of Scots pine |
| 1990 | Thinning of Scots pine |
| 1991 | Autumn: liming with 3 t/ha slaked lime via helicopter |
| 1992 | Spring: pruning of selected trunks (7 m, partly 10 m high) |
| 1992 | Thinning of Scots pine |
| 1994 | Thinning of Scots pine |
| 1995 | Autumn: spraying of black cherry (*Prunus serotina*) und understory-plantation of 5.200 Norway spruce (nursed 4 years, 40-70 cm) |
| 1995 | Thinning of Scots pine |
| 1996 | Autumn: selective spraying of black cherry |
| 1997 | Spring: understory-plantation of 300 European beech (nursed 4 years, 120-150 cm) and 200 sessile oak (nursed 4 years, 120-150 cm) |
| 1997 | Summer: spraying of gras |
| 1997 | Autumn: replantation of 200 Norway spruce (5 years, 60-100 cm) and selective spraying of black cherry |
| 1998 | Thinning of Scots pine |
| 2000 | Spring: Partly fertilisation of understory |
| 2001 | Winter: mulching and opening of skid trails. Manual cutting of strong black cherry branches |
| 2002 | Manual cutting of black cherry and spraying of cut stumps |
| 2003 | Winter: mulching of skid trails. |
| 2003 | Spring: manual cutting of black cherry and spraying of cut stumps |
| 2005 | Summer: manual cutting of birch and black cherry and spraying of cut stumps |
| 2005 | Winter: snow breaks in crowns |
| 2007 | Winter: storm Kyrill felled one tree (#16) and broke crowns on sample #4 |
| 2007 | Autumn: felling of damaged trees (#5, #6, #12, #14, three trees around #15) |
| 2014 | Prunning of young beech and spruce |
| 2015 | Summer: manual cutting of birch and black cherry and spraying of cut stumps |
| 2018 | Winter: storm Friederike causes only crown break (5-20%) |

*Table 3: Treatment history of Scots pine stand (Atalay, 1990; AVH, 2000, 2010, 2020; Bork, 1980; Ransch, 1967; Spoddek, 1953, Personal communications, 2021)*

The thinning approach of management follows the concept of definitive selection. The definitive pines are selected and managed following silvicultural criteria to produce quality timber following a positive selection. These trees represent the expected best trees in terms of quality and are prioritised; competitors around are thinned out. (Personal communications, 2021)

| Year | Activities in the black pine stand |
|---|---|
| 1955 | Sowing of pine seeds |
| 1965 | Pruning of every 5th row and removal of invasive Scots pine (10% of cover surface) and birch (5%) - (no precise amount - "1 qm/ha" as fictional marker) |
| 1967 | First thinning of bent and small pines (no precise amount - "1 qm/ha" as fictional marker) |
| 1973 | Pruning of pines to 2 m |
| 1979 | Thinning of black pines |
| 1980 | Strong thinning after tip blight of pines |
| 1983 | Thinning |
| 1986 | Pruning of selected pines (thereof 70% up to 4 m and 30% to 7 m) |
| 1987 | Thinning |
| 1991 | Thinning |
| 1995 | Thinning |
| 1998 | Thinning of black pines |
| 2002 | Third light thinning (positive selection) |
| 2003 | Higher pruning to 9 m of selected pines |
| 2005 | Understory-plantation of Douglas fir and red beech |
| 2006 | Thinning of black pines |
| 2007 | Windthrow Kyrill: 6 trees in sample stand |
| 2011 | Pruning of Douglas fir and common beech |
| 2014 | Pruning of Douglas fir and European beech |
| 2017 | Thinning of black pines |

*Table 4: Treatment history of Corsican black pine stand (Atalay, 1990; AVH, 2000, 2010, 2020; Bork, 1980; Ransch, 1967; Spoddek, 1953, Personal communications, 2021)*

# 3. Methodology

## 3.1. General methodology

To show the differences in growth of black pine and Scots pine in Westphalia this study:

(i) Collects primary (raw) data in the field before producing and analysing growth data in the laboratory using statistical programmes.
(ii) Identifies major impacting environmental factors.

## 3.2. Specific methodology 1: dendrochronological sample analysis

### 3.2.1. Data collection methodology in the field

To identify the growth of the pines core samples are taken with an increment borer of selected dominant (definitive) trees. The tree rings of core samples show the annual growth of the tree. The samples are chosen following a random selection technique to show a representation of the stand (Speer, 2010). However, it is only partly random as the sample pool limits on pre-selected definitive pine trees in the stands.

For each stand six definitive trees are selected. The sample areas focus on a 20-meter-wide corridor in each stand where the present 30 definitive trees are numbered. For this thesis, every 5th of the 30 definitive trees were chosen.

Two core samples are taken per tree evaluating at a later stage in the laboratory an average growth per tree of both samples. The borer was applied at a height of 30 cm above ground. Each core was taken for the entire stand in the same direction – in a right angle to each other.

The instruments used in the field include a 5 mm increment borer to extract the core samples from the trees. These are then fixed on grooved wood strips with tapes and labelled to store the cores safely after extraction. To dry the samples slowly and avoid cracking, they were left for a week at room temperature.


*Figure 5: Sample taking in the field at the height of 30 cm above ground*

### 3.2.2. Laboratory analysis

The samples are prepared for the measurement and analysis in the laboratory. The preparation involves mounting the core samples on the wood strips using water-soluble white glue with standing fibres. In the next step the samples are grinded using abrasive paper.

The tree rings of the prepared samples are then measured based on dendrochronology standards: the tree rings are dated with the support of computer programmes producing a tree ring width dataset (Speer, 2010). Dendrochronology is using the natural characteristics of trees forming a tree ring per calendar year. The tree produces smaller cells in autumn and winter and larger early wood cells during the vegetation period. The border between both forms a line to the naked eye. It allows a counting of lines to identify the calendar year in which it was formed. Measuring the width between these two lines produces the radial growth of the tree in the specified calendar year.

Measurements are done at the laboratory of the University of Padova. The workplace consists of the PC using the tree ring analysis software TSAP-Win connected to the measurement instruments. These instruments are a moveable stage equipped with an optical encoder and a microscope to identify the borders of tree rings, i.e. the transition of late wood to early wood. The stage with the sample is moved from one border to the next resulting in the tree ring width in 1/100 mm which is communicated to the PC programme. The measurement of the entire core samples results in the desired time series with growth data.


*Figure 6: Sample preparation (A) and measurement (B) in the laboraty*

The analysis programme TSAP-Win (Time Series Analysis and Presentation for Dendrochronology and Related Applications) at the laboratory is the version 0.53 for Microsoft Windows developed by Rinntech, Heidelberg in Germany (Rinntech, n.d.). It allows cross-dating to record an entire time series dating each ring width to the corresponding calendar year. In addition to the time series produced per core sample, an average time series per tree (mean) is calculated in TSAP-Win. The file format is Tucson (.rwl).

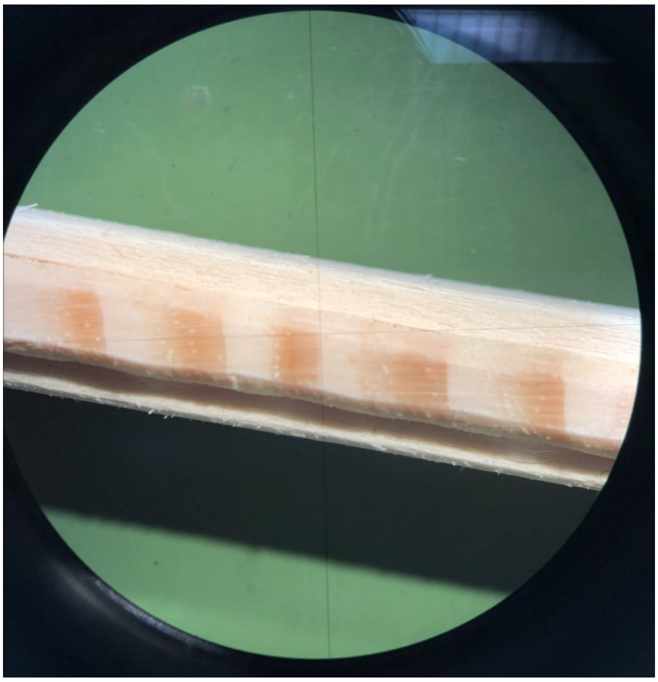


*Figure 7: Tree ring width measurement detecting early and late wood of core samples*

After the initial measurement, a two-step crossdating check is applied before further evaluation: (i) visually in TSAP-win and (ii) statistically with COFECHA (Holmes, 1983). The first check in TSAP-Win contrasts the two time series of both core samples taken per tree to check the quality of accordance between both (Rinntech, 2005). A helpful indicator is the Gleichläufigkeit parameter that looks at the overall accordance of the two times series and rates the quality in four levels (Rinntech, 2005).

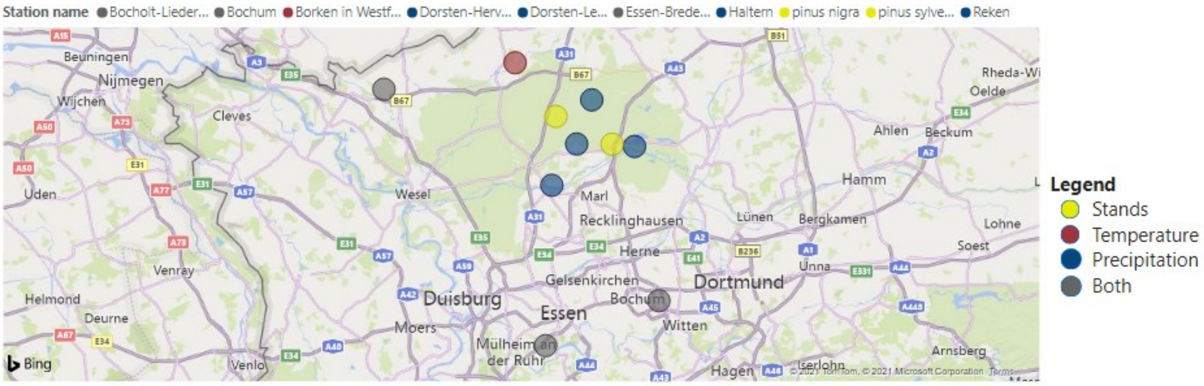
The second check in COFECHA enhances the reliability of the data by running all the time series (single sample and mean per tree) against the created master chronology (Speer, 2010). The programme is Windows based evaluating the correlation level between the core samples.

| Programme | Version | Application |
|---|---|---|
| TSAP | 3.0 | Measurement and crossdating (first check) |
| COFECHA | n/a | Crossdating (second check) |
| Tricycle | 0.3.1 | File conversion (TSAP to Excel) |
| Microsoft Excel | 2015 | Data handling |
| Microsoft Power BI | 2.93.981.0 | Data visualisation |

*Table 5: IT programmes employed*

## 3.3. Specific methodology 2: climate and stand tending treament data

To understand the growth patterns, the times series are compared with climate data and management activities in the stands. The climate data for local precipitation and temperature is sourced from weather stations run by the German weather service surrounding the stands (Deutscher Wetterdienst, n.d.). Further, the Standardised Precipitation-Evapotranspiration Index (SPEI) is included in the analysis to address the evapotranspiration effect showing the drought severity in the region (Vicente-Serrano et al., 2010). A SPEI database spanning the period 1901-2018 with monthly temporal resolution and 0.5° gridded lat./long. spatial resolution is freely available (https://spei.csic.es/database.html, last access: 03 July 2021).




| Station name | Data provided | Temporal coverage | Elevation (m asl) |
|---|---|---|---|
| Reken | Precipitation | Jan00-Dec45 and Jan47-Jan85 and Jan90-Feb21 | 59 |
| Essen-Bredeney | Temperature | Jan01-Dec44 and Jan48-Feb21 | 150 |
| Dorsten-Hervest | Precipitation | Jan01-Jan44 and Jan46-Oct10 | 33 |
| Bochum | Temperature | Jan25-Dec59 and Jan79-Dec18 | 101 |
| Haltern | Precipitation | Jan37-Dec44 and Jan47-Dec09 | 40 |
| Bocholt-Liedern (Wasserwerk) | Temperature | Jan46-Dec53 and Oct76-Feb06 | 23 |
| Borken in Westfalen | Temperature | Jun04-Feb21 | 47 |
| Dorsten-Lembeck | Precipitation | Nov10-Feb21 | 51 |

*Figure 8: Weather station data used around the two stands*

Besides climatic indicators the stand tending treatments and natural disturbances in the stands are drawn from forest management plans and discussions with the management.

### 3.4. Limitations

The limitations of this work include:

- The **type and size** of sampling may limit the validity of this work. The selection type follows a random approach to draw conclusions for a larger region (Speer, 2010), but includes only pre-selected definitive trees. The stands are managed selecting the strongest trees of the stand based on silvicultural considerations. The sample selection is therefore showing the result of the strongest growing trees. The result may show higher growth yields than in unmanaged stands.
- Also, management prescriptions **limit the sample size**. The prime function of the stand is to produce timber. The collection of samples injures the trees that reduce the timber value. The sample size is a compromise between scientific and economic considerations. However, to achieve the objective this is regarded as sufficient.
- The **comparability of core samples** can be limited as the height of sample taking can be prone to deviations. The height was aimed at 30 cm; however, minor surface differences may lead to an estimated delta of height of +/- 5 cm.
- The results of this work do **not allow a general statement for black pines**. This thesis is focused on Corsican black pine that behaves differently compared to other provenances (Fischer et al., 2019).
- The drought index SPEI is only available for the period 1900-2018. This impairs the analysis for the last two years of times series.
- According to management local **microclimates differ** in both stands. Due to the lack of data supporting this differentiation, the same average of weather stations (precipitation and temperature) is applied.

# 4. Results

## 4.1. Dendrochronological analysis

### 4.1.1. Descriptive statistics of time series

All 24 samples taken have sufficient quality for analysis:

- the first cross-dating check visually in TSAP resulted in three measurement adjustments within the Scots pine samples.
- the second check in Cofecha contrasted the samples with the master of each stand. The results from this statistical test confirm the first check and allow further analysis with the samples (see Table 6: COFECHA statistical table.

| **Species** | **Scots pine** | **Black pine** |
|---|---|---|
| Cubic smoothing spline | 32 years | |
| Examined segments | 50 years lagged successively by 25 years | |
| Correlation | Pearson | |
| 99% confidence level | 0.3281 | |
| Time span | 76 years | 61 years |
| Mean length of series | 66.3 years | 49.8 years |
| Number of samples | 12 | 12 |
| Number of sampled trees | 6 | 6 |
| Total dated rings | 795 | 598 |
| Series intercorrelation | 0.333 | 0.494 |
| Average mean sensitivity | 0.237 | 0.222 |
| Mean measurement (mm/year) | 3.32 | 4.09 |
| Max measurement (mm/year) | 9.32 | 10.24 |
| Standard deviation (mm/year) | 1.478 | 1.730 |

*Table 6: COFECHA statistical table*

### 4.1.2. Growth of stands

The sampled trees represent the stands well. The difference in diameter of the Scots pine sample to the forest management plan evaluation is 0.4 cm (for black pine 2.8 cm). The comparison can be found in the annex.

The Scots pine is the older of the two stands following the time series data by 15 years. The overall growth of Scots pine is inferior to black pine. This contrasts, however, with the current growth – based on the past decade – where the Scots pine is more dominant. The largest average growth is recorded in 1990 in the black pine stand with 0.70 cm; the lowest also in black pine in 2013 with 0.18 cm. Further, the growth of Scots is less extreme: the spread between minimum and maximum is 0.36 cm (vs. 0.52 cm). The period between the minimum and maximum in Scots pine is longer (42 years) than in black pine (23 years). Note that these are stand averages with of the six sample trees that are based on the two borer sample data taken per tree. On tree level please find further details in the following section.

| Stand average (in cm) | **Scots pine** | **Black pine** |
|---|---|---|
| *Earliest time series* | *1945* | *1960* |
| Time series average | 0.34 | 0.40 |
| Current growth* | 0.30 | 0.27 |
| **Extremes:** | | |
| Min growth | 0.19 | 0.18 |
| *Min year* | *1989* | *2013* |
| Max growth | 0.56 | 0.70 |
| *Max year* | *1947* | *1990* |
| *average of last decade (2011-2020) | | |

*Table 7: Key radial growth information of the two stands*

In the visual comparison of the stand averages show common (1960-1976 and 2000-2017) and diverting trends (1977-1999 and 2018-2020). The highest delta with 0.21 cm between the two stands in terms of growth was in 1989: here the black pine grew by 0.56 cm (vs Scots pine 0.19 cm).

On tree sample level the black pine could show the strongest growth with 0.91 cm in 1990 (Scots pine 0.74 cm in 2014). The least growth was a Scots pine in the 2000s with 0.02 cm.

| Tree average (in cm) | Scots pine | Black pine |
|---|---|---|
| Min | 0.02 | 0.06 |
| *Min year* | *2004, 2008, 2009* | *2018* |
| *Min sample* | *82S04M* | *17N03M* |
| Max | 0.74 | 0.91 |
| *Max year* | *2014* | *1990* |
| *Max sample* | *82S19M* | *17N23M* |
| Min/Max delta | 0.72 | 0.85 |

*Table 8: Tree averages in Scots and black pine stands*

Overall, the sampled black pines within the same stand show a more similar growth pattern than the Scots pine. Comparing the sample average and the tree average the tree samples are tighter together. The higher series intercorrelation in the black pine also confirms this.

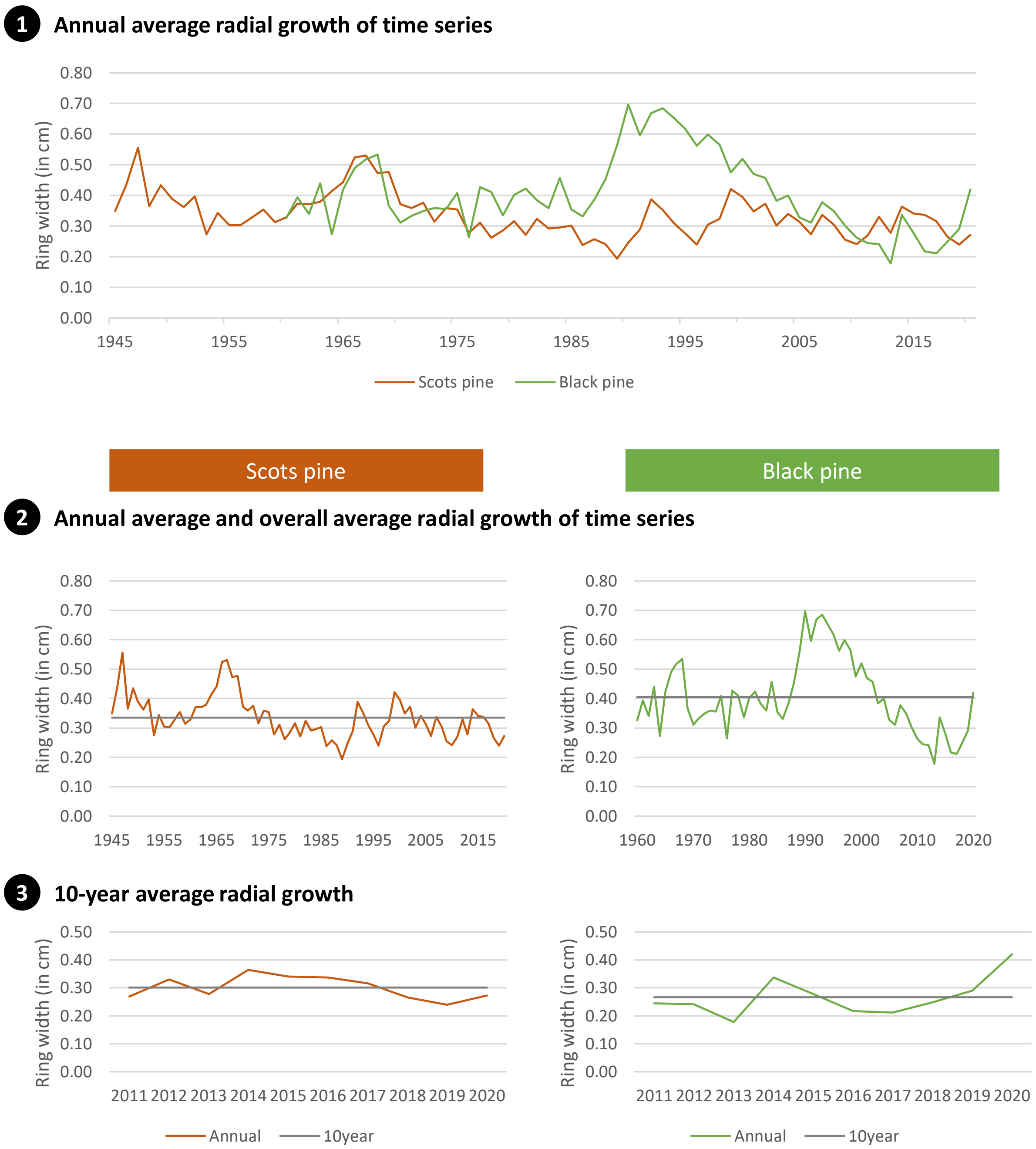
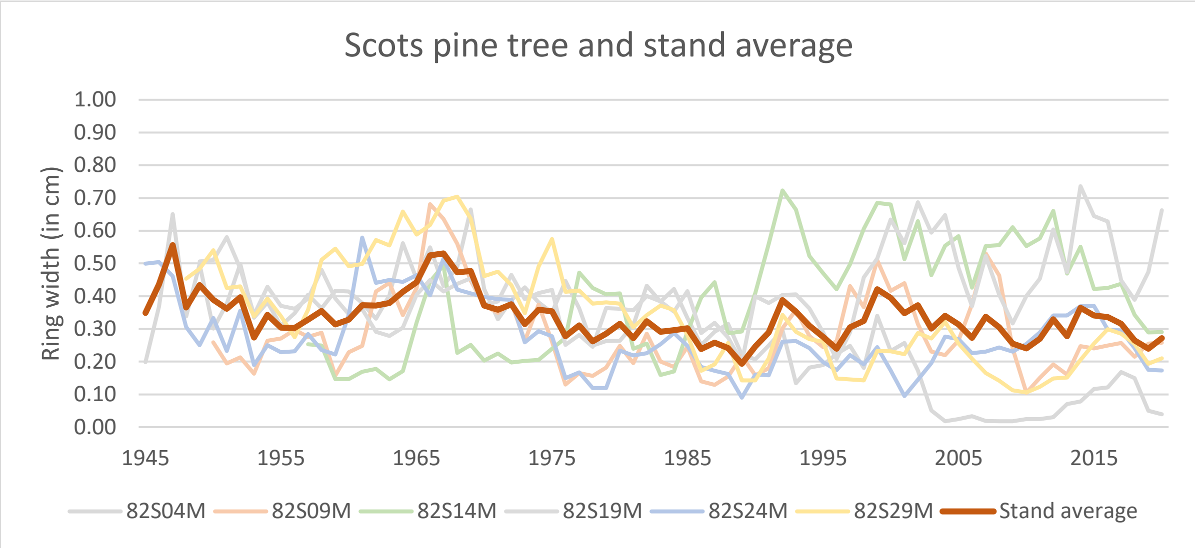



*Figure 9: Radial growth of Scots pine (1945-2020) and black pine (1960-2020)*



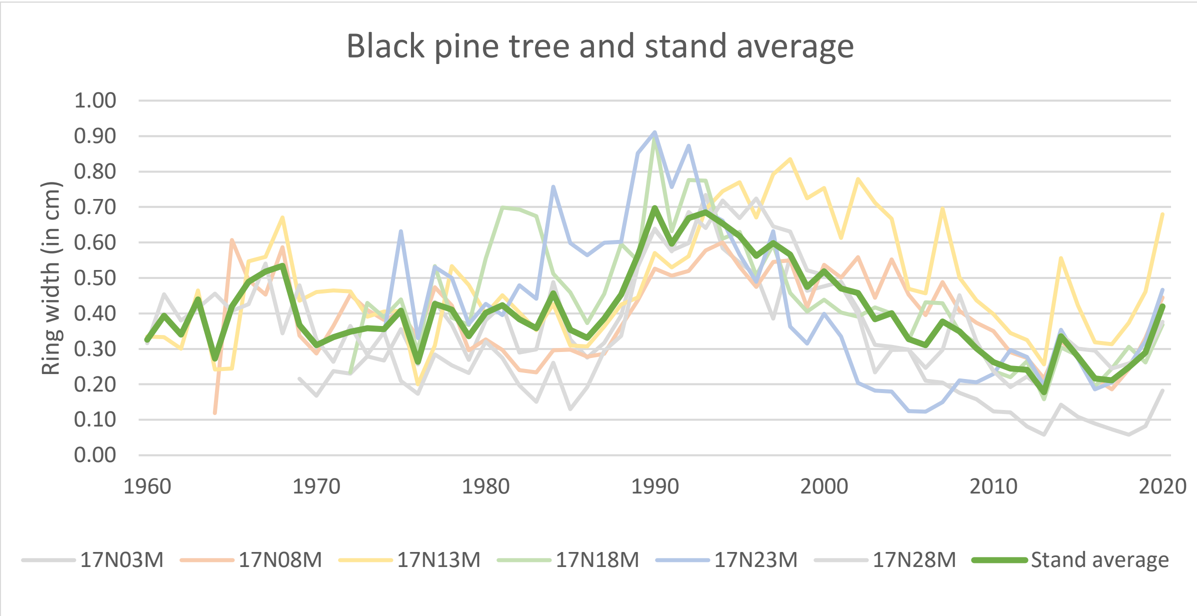




*Figure 10: Radial growth of samples of Scots pine (1945-2020) and black pine (1960-2020) with stand average*

## 4.2. External impacts

### 4.2.1. Effects of climate

In this section the tree growth is compared to climate data. One would expect increase in growth with increasing precipitation (positive correlation) and decreasing temperature (negative correlation). But results show only a limited relationship between growth and climatic factors: the Pearson correlation between the growth and different climate data is low (closer to 0 than 1). Throughout the black pine growth shows higher correlation than the Scots pine. Does this show that black pines can adapt their growth to stress situations, such as drought, to increase the changes of survival?

| Correlation with stand growth | Scots pine | Black pine |
|---|---:|---:|
| SPEI 3m | 0.1959 | 0.2628 |
| SPEI 6m | 0.2066 | 0.2610 |
| SPEI 12m | 0.2182 | 0.2408 |
| Temperature | -0.1396 | 0.0602 |
| Precipitation | 0.1001 | 0.3200 |

*Table 9: Correlation of climate data with stand average growth*

Looking at the visual analysis of climate data, only precipitation and SPEI are useful factors of influence on growth (comparable results as in the statistics above). **SPEI** 12 months gives to some extent a good representation. Black pine seems more sensitive to SPEI when the index is moving below the drought threshold of -0.500. For instance, the growth decline in the black pine stand in the 2000s is in line with the droughts preceding around 1990/1991 and 1996. On the other hand, Scots pine has a more resistant attitude towards drought.

**Precipitation** is showing a (low) positive correlation. The average annual amount of rain decreased in the region around the stands from 842 mm in the 1960s to 768 mm in the 2010s (drop of 8.8%). Growth in the Scots pine decreased by 30.9% comparing these two decades (0.43 cm in 1960s vs 0.30 cm in 2010s). Black pines growth reduced in the same period by 38.9%. Scots pine stands profits from rain exceeding the annual 1,000 mm-mark and growths in 1965 and 1966 at 0.44 cm and 0.52 cm (average 0.34 cm). Whereas the overall correlation of growth-precipitation in Scots pine is low, the picture looks different when focusing on the period after 1990: here the growth trend follows the precipitation curve.

**Temperature** is on an annual comparison not showing the expected negative relationship in both stands. However, the comparison of decade averages could support the argument. The temperature increased from 9.4°C in the 1960s by 1.3°C to the 2010s (10.7°C). Using the decreasing growth trends in these two decades in Scots pine and black pine the correlation is negative.

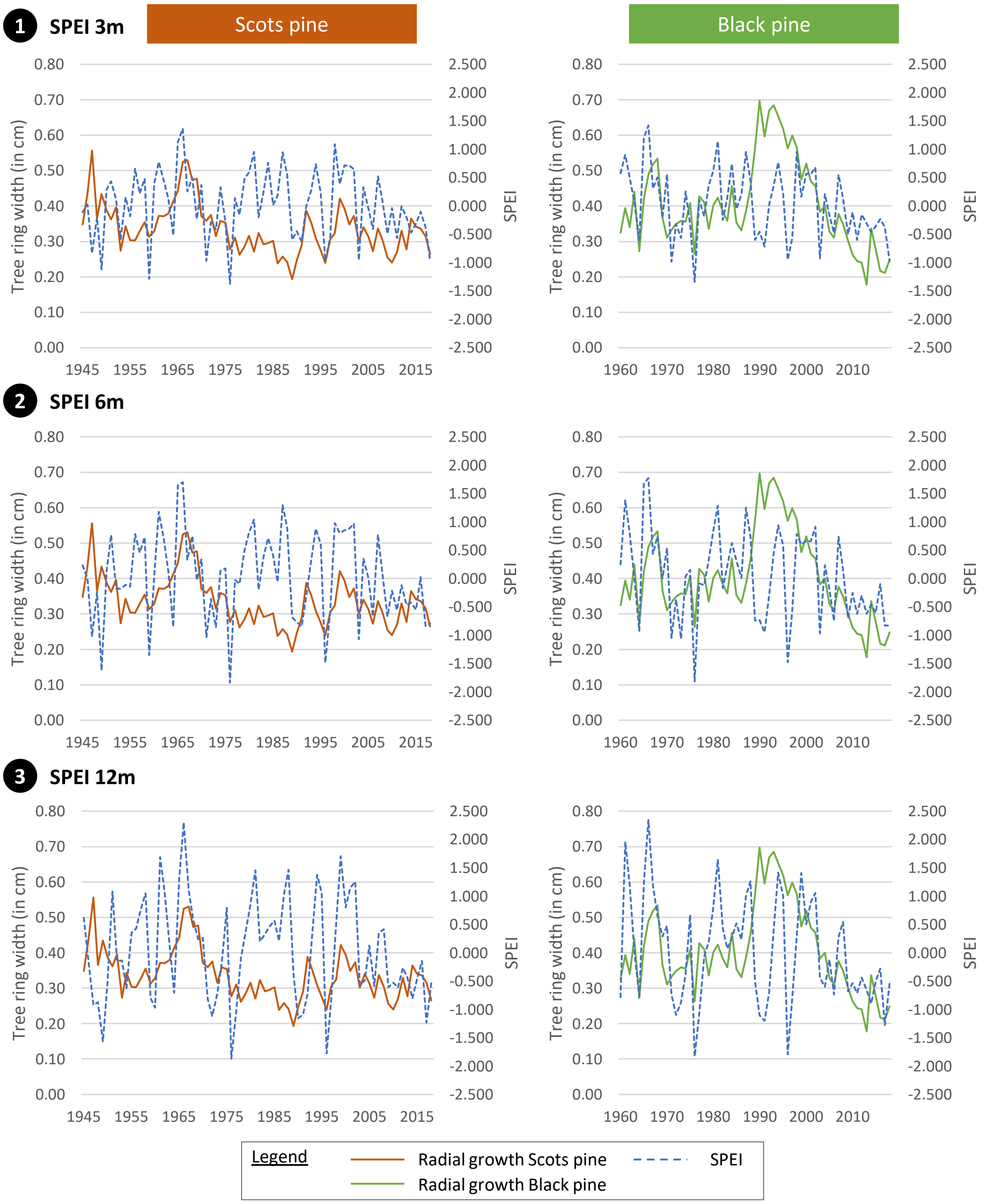



*Figure 11: Radial growth and SPEI*

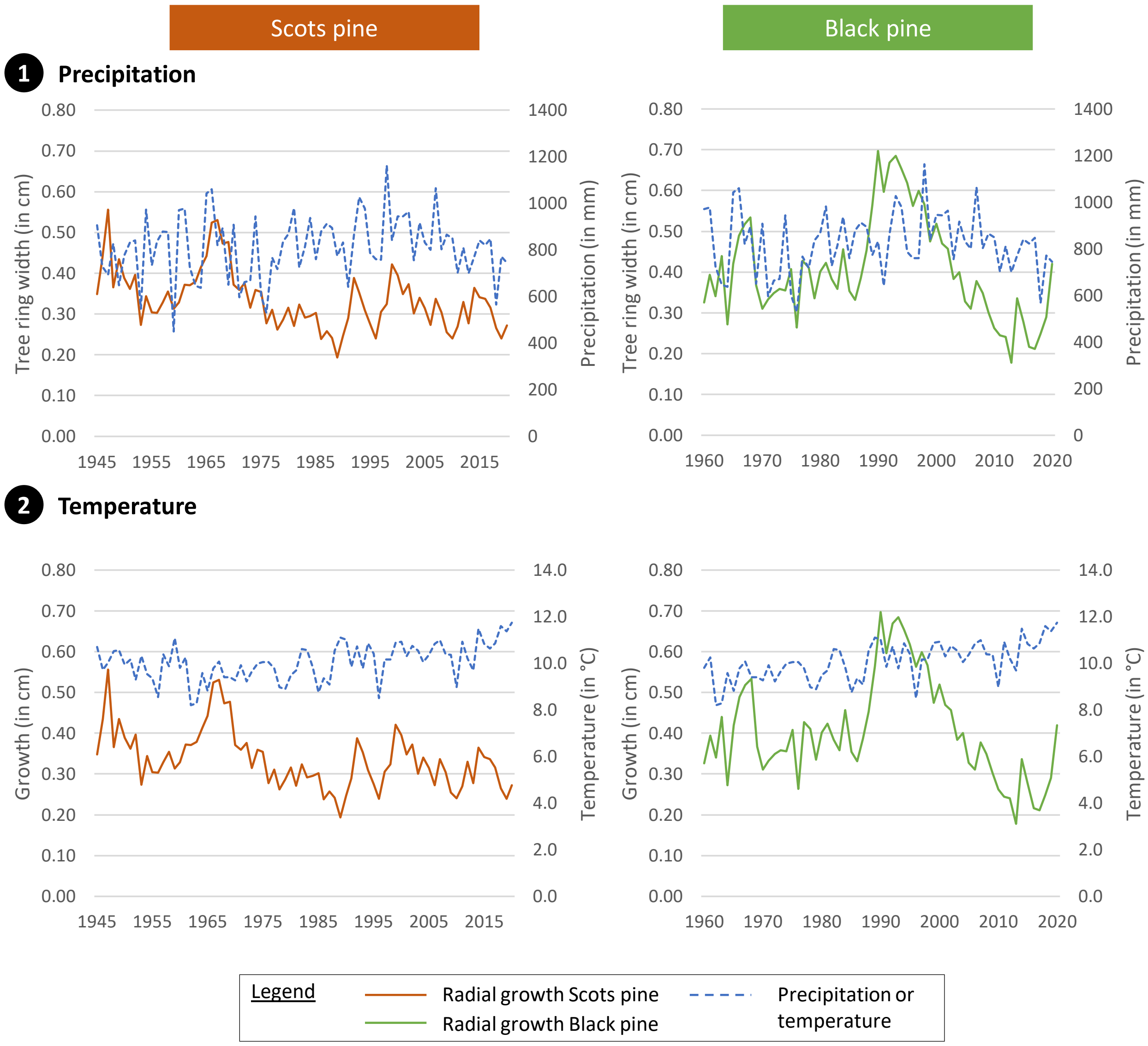
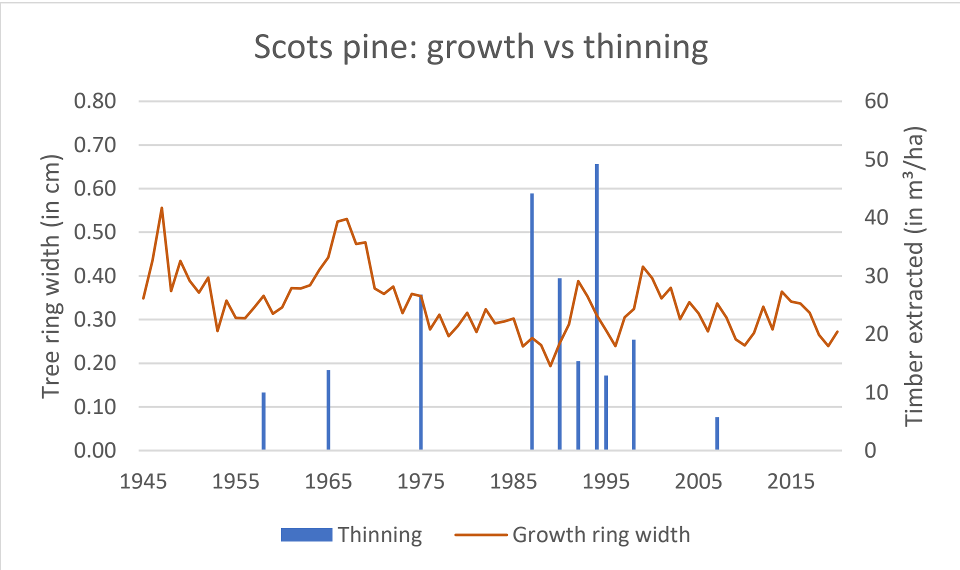



*Figure 12: Radial growth with temperature and precipitations in the stands*

### 4.2.2. Effects of stand tending treatments

Thinnings were performed in both stands at young stages. But the interval of operations differed: black pine was thinned more regularly from a young age (every 5 years on average over time series) than Scots pine (every 7 years).

The analysis of management activities is limited to thinning on a visual basis (no statistical methods applied). Overall, there is no consistent relationship between thinning and growth. Both reacted positively to thinnings at the end of 1980s. But this is not a pattern recognisable after each thinning. The Scots pine's growth accelerated after the first major thinnings. In 1975 the thinning limited the decreasing growth trend for a decade at around 0.30 cm per year. Growth jumped up above 0.40 cm-mark after strong thinnings in the late 1980s and early 1990s (up to more than 40 m³ per ha). In the Black pine stand thinning in the 1980s doubled growth rates up to 0.70 cm. However, they could not prevent the decrease in the 1990s. Only after 2017 the Black pine saw an important increase.



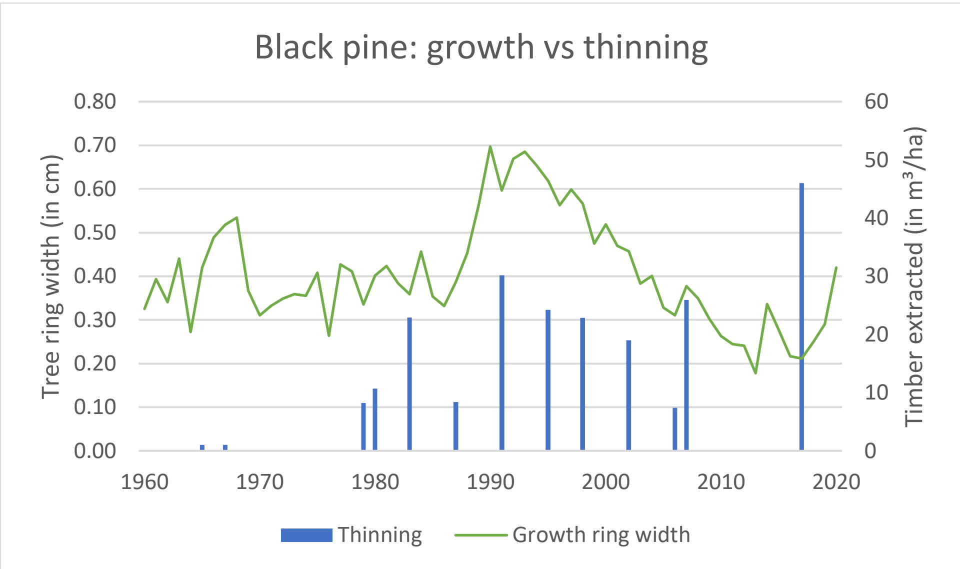




*Figure 13: Radial growth and stand tending operations (thinning)*

## 5. Discussion

### 5.1. Interpretation of results

This thesis compared the growth of black pine and Scots pine in Westphalia, Germany. Black pine shows a different growth pattern than the Scots pine. This puts the practice in Germany in question to apply the yield tables of Scots pine for black pine when conducting the forest management planning.

The black pine **growths overall stronger** than the Scots pine. This is also in line with other research in Germany (Šeho et al., 2010; Stratmann, 2019, 2021). Stratmann (2021) analysed the growth performance measuring the height of the same black pine stand in Haltern and compared the results with the existing Dutch and British yield tables for the species. He concludes that the Corsican black pine outperforms the Scots pine on these sandy stands and even compares its growth to that of an average spruce or Douglas fir. This supports the call to increase the use of black pine as more resistant species to climate change (Huber & Šeho, 2016). The dominance becomes apparent only after the age of 30 confirming that this species needs more time to show its potential compared to the Scots pine (Reichert et al., 2011; Seho, 2020). A possible explanation is a focus of black pine in the youth on root development instead of height growth.

Contrasting to the overall growth, the growth of black pine **in the last decade** (2011-2020) is inferior. The main factors are drought and diseases as discussed below:

**Drought** had a stronger effect on black pine reducing growth. SPEI with a value $\leq -1$ was defined according to Potop et al. (2014) as a a drought episode. The SPEI index showed droughts in 1990/1991 and 1996 that affected the black pine growth. This supports the idea of higher sensitivity of black pine at the edge of its habitat to drought (Camarero et al., 2013). This research team compared the growth response to droughts on the Southern edge of black pine distribution. This thesis speculates a similar pattern to its Northern edge. The Scots pine present in this area for many generations is more resilient to these extremes. For example, the Scots pine grew strongly in the late 1940s though drought hit the stand in four consecutive years. But this could be also connected to the observation that young trees produce larger tree rings than the average (Speer, 2010). Moreover, pine as a pioneer species tends to grow strongly in youth aiming to dominate the conquered site (Huss, 1983).

**Precipitation** and black pine growth in Westphalia also show a strong correlation. The results agree with Heinze (1996) that observed a higher susceptibility of black pines to reduced precipitation – it dropped here below 800 mm in the last decade. But this is still enough to grow – even though at lower rates. The necessary precipitation for the oceanic species black pine is between 600 to 1,000 mm (Seho, 2020).

Looking at the Scots pine stand, the analysis indicates a low correlation with precipitation. This is also related to its broad climatic adaption: the Scots pine grows in areas with annual precipitation of 400-2,500 mm (Mayer, 1984). Also it requires low water storage capacity of the soil (Walentowski et al., 2007). But in the past thirty years this research showed an increased dependency on precipitation. With decreasing annual precipitation this will negatively affect its growth. Putting Scots pine on the high risk alert list based on climatic predictions, is a comprehensive consequence (Kölling & Zimmermann, 2007).

This research raises the question if the black pine should play a more important part in the strategy for German forests to survive facing climate change? The characteristics of reducing growth during drought could be interpreted as tool for survival. This loss in growth is compensated by dominant growth outside drought periods. As shown, the black pine growths stronger overall than the Scots pine. This means uniting the capability of survival with overall dominant growth in one tree species. Of course, this is ignoring other factors such as biotic disturbances. But something German foresters could consider when looking for a way out of Waldsterben 2.0. This would be in line with the German ministry for agriculture demanding a development of climate resilient forests in its latest Forest Strategy 2050 publication in September 2021 (BMEL, 2021).

This research found no correlation between annual **temperature** and growth. The mild climate in Westphalia is suggested to reduce the effect. As Scandinavian research on Scots pine showed, the temperature effect is lower on rich soils and mild climates (Fries et al., 1998). Moreover, both pines species are heat-resistant (Seho, 2020; Spellmann, 2008). The limiting factor according to management information for black pine, however, is that it is not late-frost tolerant which is commonly found in May in Westphalia. In field experiments this could not be confirmed so far (Huber et al., 2011; Larsen & Suner, 1984).

A further factor of growth reduction is the disease of **Diplodia tip blight** on black pine that causes damages to the needles (Budin, 2019). It slowly spread in the 1980s affecting the reduced growth in the 1990s. Management reaction to thin and open the stand stopped the decline in 2014.

Next to climatic factors, **forest management activities** have a strong impact on growth (e.g. Mäkinen & Isomäki, 2004; Martín-Benito et al., 2010). The aim defined by management for the stands is timber production. In line with Huss (1983) thinnings at a young stage were performed to increase the volume in the stands. Overall, both stands were treated from a young stage onwards and increased growth after thinning including a time lag. But our graphical evaluation suggests that Scots pine shows a more positive response in the following years compared to black pine. This result is standing against the findings of Navarro-Cerrillo et al. (2019). They carried out a field experiment in Spain comparing the growth of black pine and Scots pine to understand the effect of thinning on drought resistance. Here the black pine showed a prompt growth reaction after the thinning. The black pine overall outgrew the Scots pine after the thinning. The Spanish paper is not entirely comparable to this thesis as the number of thinnings (one vs multiple) and the climate (dry vs temperate climate) differ (Spanish and this study site respectively). The provenance of black pine in that paper may also differ, but was not described.

As the previous research in Spain has concluded (Navarro-Cerrillo et al., 2019), also this thesis indicates that thinning in the black pine produces growth against unfavourable climatic conditions. After thinnings in the 1980s the peak in growth followed in 1990 although drought prevailed that year (SPEI 12m of < -1.0). Furthermore, the strongest thinning in the black pine stand history in 2017 stimulated an immediate growth response also against unfavourable climatic conditions (SPEI 12m of -1.280).

## 5.2. Critical review on attained objectives

The thesis fulfilled its objectives showing a dominance of black pine with drought, precipitation and thinning having the greatest impact on radial growth. The background effect of climate on growth and the overlap of anomalous climatic events makes it difficult to identify the changes induced over time by thinning on the growth of the stand. The critical view on the results sees the limited accuracy on the relationship between thinning and growth. The conclusions were based on graphical analysis that inhibits a level of observation error. More data on thinning density expressed in percentages, for instance, could give a sharper view on this relationship. Furthermore, a greater number of trees sampled would probably have allowed to have more chances in capturing individuals who have enjoyed the thinning of the closest competitors.

Then the precipitation and temperature data may not represent well the local (micro-)climate and, therefore, be biased for the correlation with radial growth of trees. The data is an average of surrounding weather stations aiming to come close to the local (micro-)climatic variations prevailing in the two stands according to management information. This thesis supports its decision due to the lack of data (no full coverage since 1945 for microclimate) and proximity (distance 12 km) of the two stands.

## 5.3. Recommendation for future research in this field

The future research for pines in the region of Westphalia could quantify the impact of factors excluded from this research, such as diseases or pollution, or extent beyond radial growth on other measures, such as intrinsic water-use efficiency (Navarro-Cerrillo et al., 2019). Also, the impact of thinning on the climate resistance on pines in Westphalia could further enrich science. Field experiments in Spain (e.g. Ameztegui et al., 2017; Martín-Benito et al., 2010; Navarro-Cerrillo et al., 2019) have shown a positive effect of thinning on water status and an increased resilience to warmer and drier conditions as thinnings reduced competition for water. Moreover, comparing different thinning methods and its effect on growth would give forest manager better information to choose the appropriate solution (Pividori et al., 2015).

Different views on climate could enrich the understanding its relationship with growth. Researchers (e.g. Martin-Benito et al., 2013) have compared climate data from previous periods with the current year growth to understand its relationship in a broader context beyond the analysis of this thesis on same year basis. Also the role of frost, especially late frost, was identified in the past as factor influencing growth (e.g. Xenakis et al., 2012); its impact on black pines in Westphalia needs further analysis.

At last, the discussion on assisted migration should continue as solution to adapt forests facing climate change (e.g. Leech et al., 2011). The introduction of the oceanic black pine in the sub-oceanic Westphalia shows us two sides on the same medal: the economic feasibility (dominant growth compared to Scots pine) and ecological risk (susceptible to climate and diseases). Categorised as non-invasive species (Seho, 2020), this research supports taking the risk to increase the species portfolio facing the challenges from climate change. The fact that other species as spruce have difficulties in Germany make trees that survive as the black pine more valuable. Also the Scots pine should be kept within the scope of management, thus, no becoming an obsolescent model (Spellmann, 2008).

## 6. Conclusion

The aim of this thesis was to show the difference in growth patterns between Scots pine and black pine in Westphalia using dendrochronology and identifying growth drivers based on climate data and forest management information. The results of this thesis confirm the hypothesis that the growth differs and the black pine – looking at the entire time series– dominates in terms of radial growth. This supports the call to introduce a separate yield table for black pines in Westphalia for more appropriate forest management planning.

Besides demonstrating altering growth strengths, two key findings resulted from this work:

(i) Black pine in Westphalia is more sensitive to drought than Scots pine.
(ii) Scots and black pine respond positively to thinnings.

The drought sensitivity of black pine became especially evident, when radial growth strongly decreased following two consecutive droughts in the 1990s (indicated by drought index SPEI). The Scots pine shields itself responding more resilient. This response to climate in Northern Europe confirms a behaviour of the black pine observed at its Southern edge of its natural habitat.

Thinning promoted radial growth confirming its role as crucial silvicultural method. Management’s approach to perform regular thinnings from the youth onwards paid off pushing growth against deteriorating climatic conditions. The difficulty remains though to set up a clear action-response relationship of a single thinning activity and immediate growth response. The interaction of the multitude of growth influencing factors make the analysis complex.

At last, the recommendation for management arising from these findings is to apply regular strong thinning on pine stands increasing its strength against disturbances including droughts and diseases.

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# 8. Appendix

## 8.1. Appendix A – Research matrix

The overall objective was to show a difference in growth of Black pines and Scots pines in Westphalia to contribute to the introduction of a separate yield table for Black pines in Germany.

| Specific objective | Hypothesis | Data required | Data collection method | Data analysis |
|---|---|---|---|---|
| 1 To show that growth of Black pines differs from Scots pines | Black pine dominates Scots pine in terms of growth | Tree ring width data series of Black and Scots pine | 1.1 Collect corer samples with increment borer in the field | 1.1 Dendro-chronological tools (including TSAP) |
| | | | 1.2 Measure ring width with Aniol System and TSAP software in the laboratory | 1.2 Statistical evaluation to be discussed (e.g. Mann-Whitney-Test) |
| 2 To identify the most influencing external factors to growth of both species | Drought reduces growth though Black pines manage to grow more than Scots pine | 2.1 Climate data (precipitation, temperature) | 2.1 Download from DWD – German Weather Service | 2.1 Statistical evaluation to be discussed (e.g. correlation ring width and temperature/ precipitation) |
| | | 2.2 Stand tending treatments | 2.2 Extract from forest management plans of forest owner | 2.2 Evaluation to be discussed (e.g. qualitative analysis) |

## 8.2. Appendix B – Data collection instruments

Data entry form (*example*)

| Stand | Sample number | GPS latitude | GPS longitude | *Comments* |
|---|---|---|---|---|
| Pinus nigra | 07N23A | 51.7393255 | 7.1440962 | *Light crown* |
| Pinus nigra | 07N23B | 51.7393255 | 7.1440962 | *Core broke* |
| […] | […] | […] | […] | *[…]* |
| […] | […] | […] | […] | *[…]* |
| […] | […] | […] | […] | *[…]* |

## 8.3. Appendix C – Stand representation of samples

### Scots pine

1 Forest management plan

| | | |
|---|---|---|
| Excerpt | German | *Baumart: SKi, Alter: 62 Jahre, EKL: I,5, BG: 0,8, WZ: 2, ha: 11,33, Vorrat: 200 Efm o.R. je ha, Zuwachs: 5,6 Efm o.R. je ha.* |
| | English translation | Tree species: black pine, age: 62 years, yield table I.5, [...] |

Excerpt Yield table after Wiedemann (1943) for Scots pine (EKL I und EKL II - strong thinning)

| Diameter after strong thinning (in cm) | **Age 60** EKL I | EKL II | calculated EKL I.5 (?) | **Age 70** EKL I | EKL II | calculated EKL I.5 (?) | *interpolated* **Age 62** EKL I | EKL II | calculated EKL I.5 (?) |
|---|---|---|---|---|---|---|---|---|---|
| Diameter middle of tree length | 24.7 | 21.0 | 22.9 | 28.1 | 24.1 | 26.1 | 25.4 | 21.6 | 23.5 |
| Height middle of tree length | 22.2 | 18.6 | 20.4 | 24.4 | 20.6 | 22.5 | 22.6 | 19.0 | 20.8 |
| *Adjust height with tapering coefficient 0.1 cm per m** | | | | | | | | | |
| DBH (@H=130 cm) | 45.6 | 38.3 | 42.0 | 51.2 | 43.4 | 47.3 | 46.7 | 39.3 | 43.0 |
| Diameter (@H=40 cm) | 46.5 | 39.2 | 42.9 | 52.1 | 44.3 | 48.2 | 47.6 | 40.2 | 43.9 ← |

<u>*Formula tapering coefficient</u>
(Diameter middle) + (Height middle) - (Height desired, e.g. DBH 1.3) * (tapering coefficient, e.g. 0.1 cm per m)

2 Sample stand diameter

Diameter (@H=40cm) 44.3 ←

Delta 0.3 ←

## Black pine

1 Forest management plan

| | | |
|---|---|---|
| Excerpt | German | *Baumart: Ki 84j. EKL: II.0, BG: 0,6, WZ:3, ha: (5,10), Vorrat: 162 Efm o.R. je ha, Zuwachs: 3,6 Efm o.R. je ha.* |
| | English translation | Tree species: Scots pine, age: 84 years, yield table II, [...] |

Excerpt Yield table after Wiedemann (1943) for Scots pine (EKL II - strong thinning)

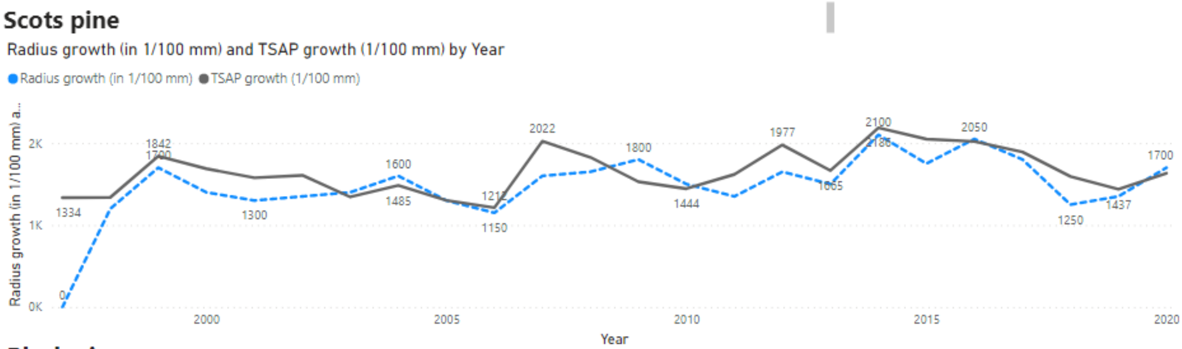
| Diameter after strong thinning (in cm) | **Age 80** EKL II | **Age 90** EKL II | *interpolated* **Age 84** EKL II | |
|---|---|---|---|---|
| Diameter middle of tree length | 27.1 | 29.9 | 28.2 | |
| Height middle of tree length | 22.2 | 23.4 | 22.7 | |
| *Adjust height with tapering coefficient 0.1 cm per m** | | | | |
| DBH (@H=130 cm) | 48.0 | 52.0 | 49.6 | |
| Diameter (@H=40 cm) | 48.9 | 52.9 | 50.5 | ← |

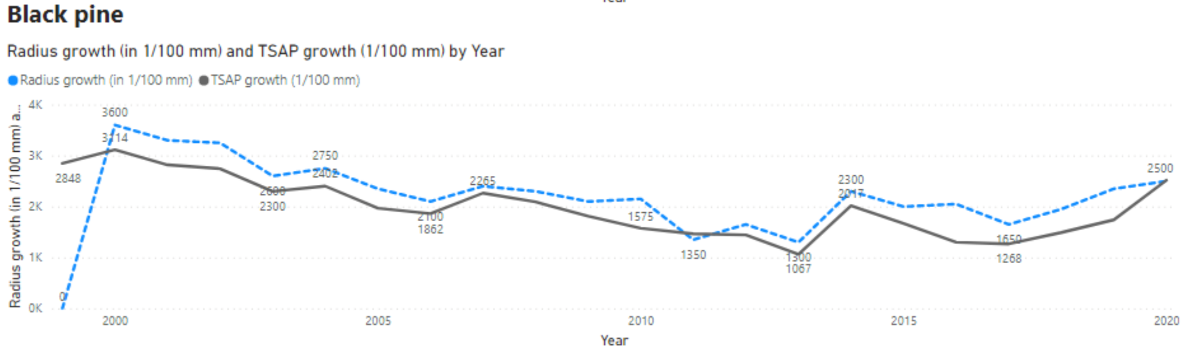
*Formula tapering coefficient
(Diameter middle) + (Height middle) - (Height desired, e.g. DBH 1.3) * (tapering coefficient, e.g. 0.1 cm per m)

2 Sample stand diameter

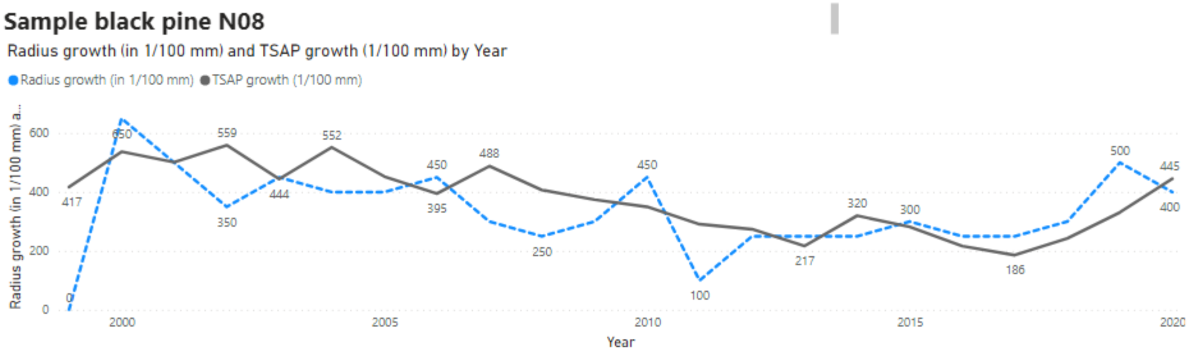
| | | |
|---|---|---|
| Diameter (@H=40cm) | 47.7 | ← |
| Delta | -2.8 | ← |

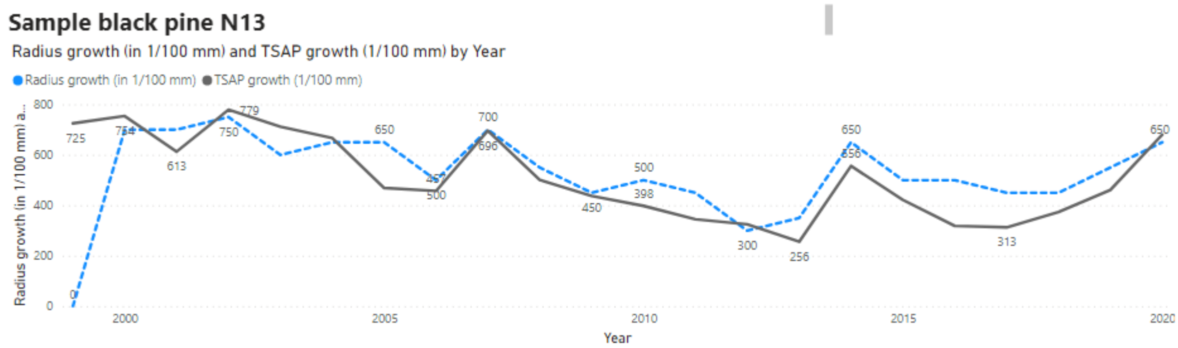
## 8.4. Appendix D – Comparison of Annual Radial Growth: Increment Borer vs Circle Measurements

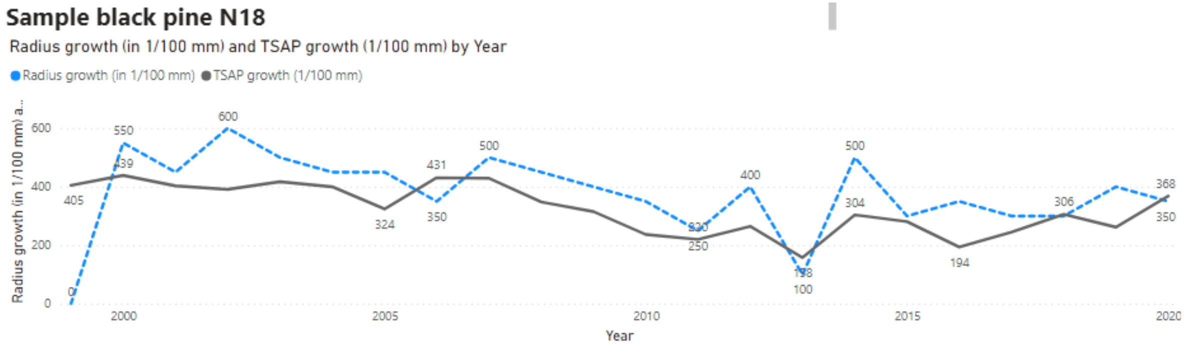


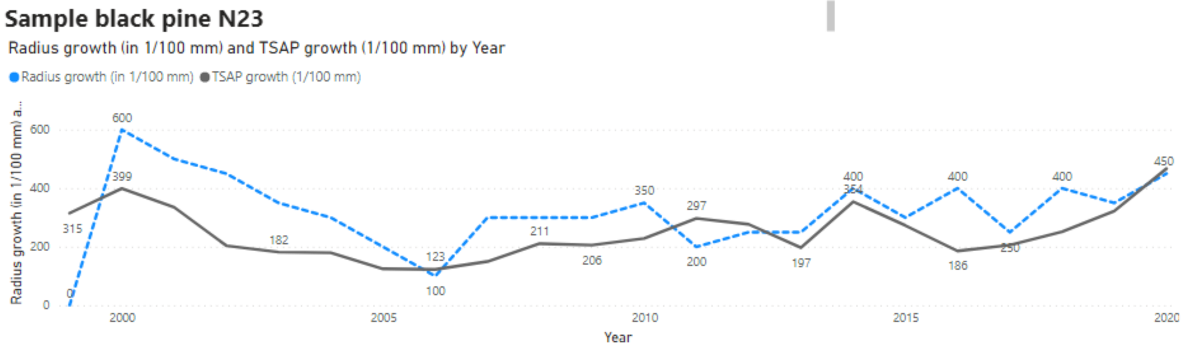




The management conducted circle measurements in the stands (Scots pine from 1997 onwards; black pine from 1999 onwards). In the following the comparison on tree level:

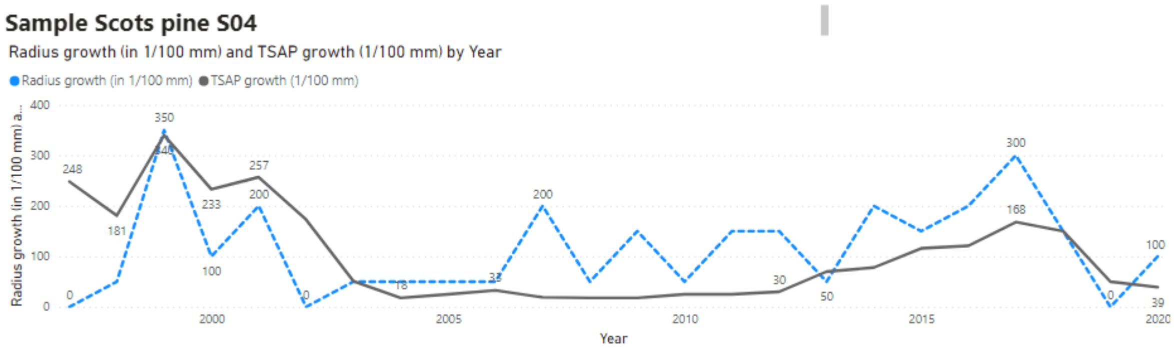




Sample black pine N13
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
Year


Sample black pine N18
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
Year

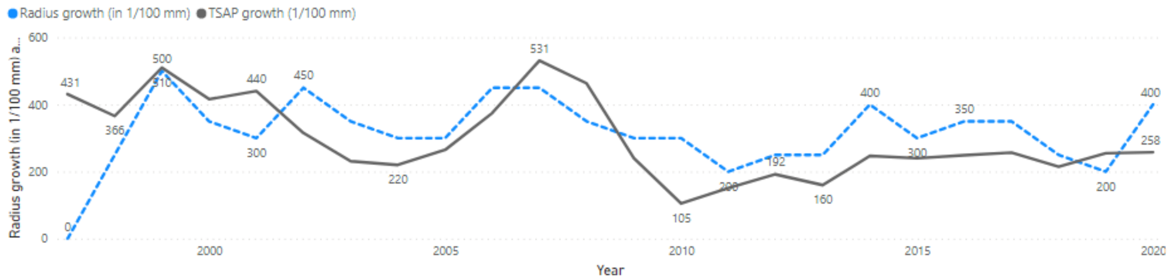

Sample black pine N23
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
Year


Sample black pine N28
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
Year


Sample Scots pine S04
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
Year

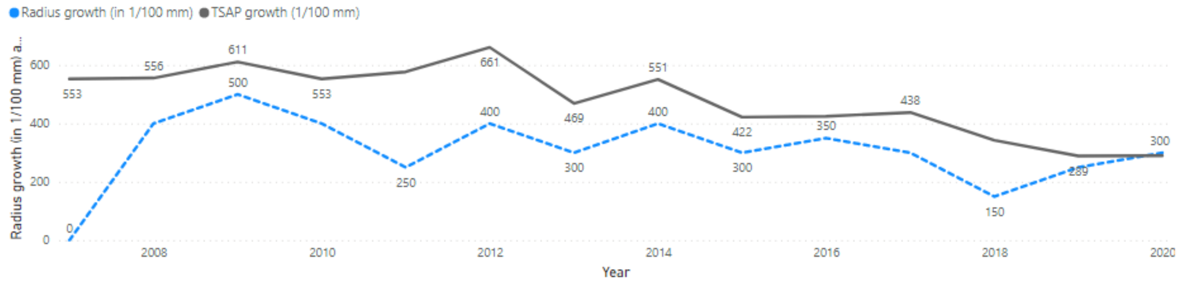
**Sample Scots pine S09**

Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year



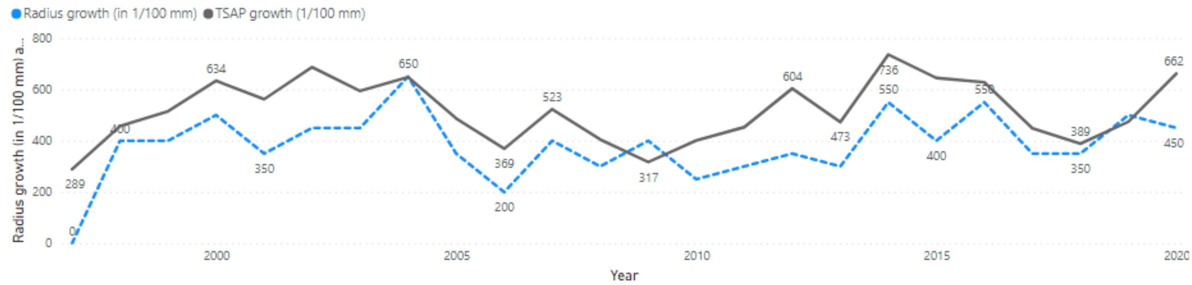

**Sample Scots pine S14**

Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year



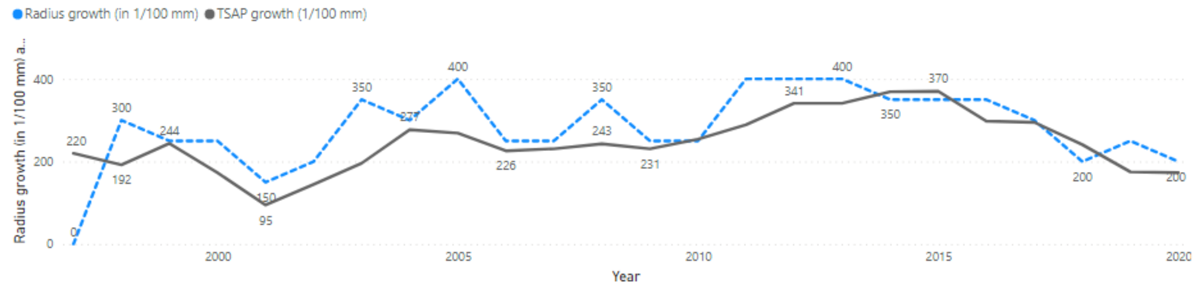

**Sample Scots pine S19**

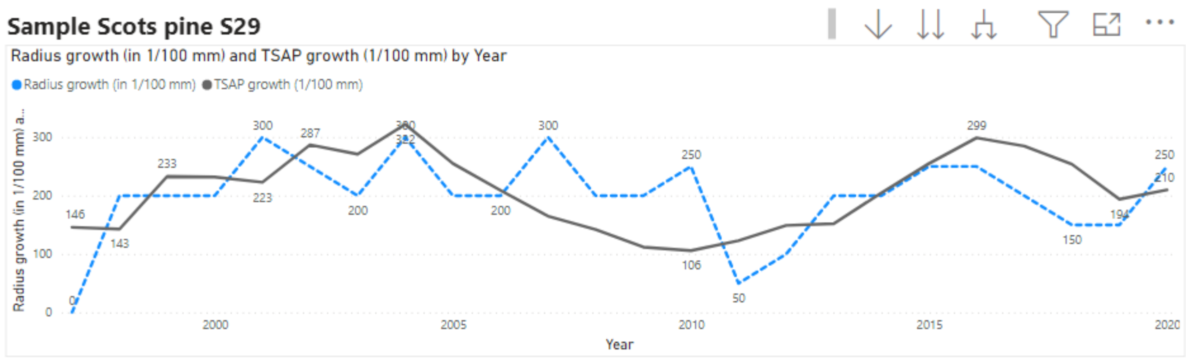
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year




**Sample Scots pine S24**

Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year




Sample Scots pine S29
Radius growth (in 1/100 mm) and TSAP growth (1/100 mm) by Year
Radius growth (in 1/100 mm)
TSAP growth (1/100 mm)
Radius growth (in 1/100 mm) a...
0
100
200
300
2000
2005
2010
2015
2020
Year
146
143
233
300
223
287
200
300
200
250
106
50
299
150
250