Pests and diseases in the native and European range of Douglas-fir. 3.5

Alain Roques, Marie-Anne Auger-Rozenberg, Paolo Capretti, Daniel Sauvard, Nicola La Porta, Alberto Santini

What Science
Can Tell Us

Douglas-fir

– an option for Europe

Heinrich Spiecker, Marcus Lindner and Johanna Schuler (editors)

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Preface

It is expected that European forests provide renewable resources for the bioeconomy, ensure biodiversity and other ecosystem services while help us to mitigate and adapt to and mitigate climate change. Choosing the adequate tree species is one tool to reach this aim. Not only native but also non-native tree species may serve these purposes. However, non-native tree species are associated with less experience, higher risk and uncertainty and potentially invasive harming of the native ecosystem. Therefore, European forest policy makers and practitioners require science-based knowledge in order to make better informed decisions regarding the future use of fast-growing, valuable but non-native tree species with uncertain consequences for indigenous ecosystems while having a better understanding of the role some non-native tree species can play in providing different ecosystem services, including biomass in a context of rapidly changing environment. This book provides science-based support for decision-making by synthesizing relevant research results on various aspects of growing non-native tree species in Europe using Douglas-fir as an example.

Marc Palahí
Director, European Forest Institute

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Heinrich Spiecker

Executive summary

Heinrich Spiecker

History

In western North America, Douglas-fir covers an area of almost 20 million hectares across a huge climatic range that generally features rather dry summers. In Europe, Douglas-fir has been introduced as an ornamental tree in arboreta and parks since 1827. From the end of the 19^{th} century it was planted at a progressive rate in the forests of various European countries, especially after the second world war. This has led to the current relatively high representation of trees up to an age of 60 years. Today Douglas-fir is the second most common non-native tree species in European forests where it covers more than 800,000 hectares (see Chapter 2). The largest area of Douglas-fir is found in France, followed by Germany where it has rapidly become the most widespread non-native tree species. In other European countries, Douglas-fir is still grown to a considerable extent: In the UK it covers 45,000 hectares, in Spain 25,000 hectares, in Belgium 23,000 hectares, in the Netherlands 19,000 hectares and Slovenia 18,000 hectares; whereas in northern and eastern European countries the extent of Douglas-fir is smaller. The main reason for growing Douglas-fir is its high productivity and desirable wood properties. The value chain of Douglas-fir provides thousands of jobs and tens of millions of euros worth of income and employment. Today, other factors have to be considered as well. These may be positive, such as Douglas-fir's capacity to adapt and mitigate to climate change, or negative, such as public perceptions concerning detrimental effects on native ecosystems and their biodiversity.

Experience up to now

In its natural habitat Douglas-fir grows well on a wide range of site conditions and, accordingly, displays high adaptive genetic variability. A major challenge for European forestry is therefore to target the most appropriate genetic material for selected site conditions and / or expected environmental changes. Out of the wide natural range of Douglas-fir the coastal provenances have proven to be best suited for most European conditions (Chapter 3.2).

Douglas-fir grows best on well-drained, deep soils, whereas on poorly drained and dense soils the root system does not develop well (Chapter 3.1). It has an impressive growth potential. Douglas-fir exhibits the tallest trees, e.g. in the Netherlands, Ireland, Britain, Germany and Czech Republic, and these trees have the potential to grow for much longer and get even taller. The volume growth per hectare generally exceeds that of native European tree species, even surpassing the growth of Norway spruce, which has been planted far beyond its natural range because of its high volume yield.

The technical wood properties generally equal or exceed the quality of timber from native softwood species as well as from other widespread exotic species, except the juvenile core and sapwood. The heartwood of Douglas-fir is of exceptional durability and suitable for many uses (Chapter 4.3). The proportion of valuable construction wood is – as with most other softwood species – much larger than that of hardwood species. Douglas-fir timber sells in many countries at higher prices than European softwood species of similar size and quality. However, planting cost are relatively high, because the young plants are susceptible to drought, grow slowly and face competition from weeds, as well as being exposed to deer browsing and rubbing. In addition, to achieve high wood quality, pruning is necessary when wide spacing is applied. In most cases, the economic outcome is outstanding when the market for this species is developed (Chapter 5.1). This market is developed differently in European countries.

Douglas-fir is less vulnerable to summer drought than Norway spruce. Douglas-fir in Europe has not yet been subject to major species-threatening pests and diseases. An exception is the threat posed by infestation with the needle blight *Rhabdocline pseudotsugae*, which can be avoided by exclusively planting coastal varieties of Douglas-fir. It is less susceptible to the attacks of annosum root rot (*Heterobasidium annosum*) than many other conifers. The woolly aphid *Adelges cooleyi* causes yellowing and deformity of the needles and can severely reduce growth when the trees are young. An emerging concern is the large pine weevil (*Hylobius abietis* L.), which damages young plants. Recently a needle midge, *Contarinia pseudotsugae*, has been recorded as damaging young Douglas-fir needles. New infestations of pests and diseases are difficult to predict (Chapter 3.5).

The impact on ecosystems of introducing Douglas-fir is not yet fully understood. Compared to other European coniferous tree species, except for larch, Douglas-fir litter decomposes more easily and does not lead to soil degradation. Douglas-fir is sometimes considered to be a potentially invasive species in several European countries as it may occasionally regenerate outside its cultivation areas. Habitats on poor, shallow and dry sites, or block fields, are particularly prone to Douglas-fir invasion with negative effects on the respective plant communities (Chapter 3.4).

The large-scale cultivation of Douglas-fir outside its natural range has been the subject of controversy in wider society as more people have become interested in nature, its conservation and its management. European forestry has increasingly adapted "close-to-nature" management principles. In public perception, the cultivation of non-native species carries a variety of risks (Chapter 5.2). Public perception varies substantially between European countries. There is a gradient from open in the west to restrictive in the east of Europe. In some countries the planting of non-native tree species in forests is forbidden. Legal restrictions on its cultivation are formulated with respect to management planning in Natura 2000 sites. Certification schemes also try to limit the extent of Douglas-fir forests (Chapter 5.4). Additionally, several NGOs have launched media campaigns to raise people's awareness of Douglas-fir. In 2012, for instance, Greenpeace activists removed nearly 2000 Douglas-fir saplings from a plantation in southern Germany and replaced them with beech saplings to protest against the industrialisation of German forestry and the destruction of old-growth beech forests. In public discourse, Douglas-fir is used as a symbol for manmade changes to nature (Chapter 5.3). The debate about Douglas-fir is controversial because of its high biomass supply, its contribution to the income of forest owners and, on the other hand, the risks and uncertainties and its potential negative impact on ecosystems. Indeed, there are still many unanswered questions relating to the cultivation of Douglas-fir in Europe.

Recommendations

As a consequence of the high productivity, the technical wood properties, the economic attractiveness and the climate mitigation potential of Douglas-fir, supporters are enthusiastically promoting the species. It is recommended for use as a substitute for the increasingly instable or less productive Norway spruce or Scots pine, and it is also touted as the most important biomass producer of the future. The rapidly changing climate raises the question of whether the current tree species composition needs to be artificially adjusted. Non-native tree species may provide additional options to cope with future challenges. Douglas-fir is quite often considered to be a great hope for European forests in the face of climate change. One of the most important ecosystem services provided by Douglas-fir – particularly in the context of climate change mitigation – is the substantial contribution to long-term carbon sequestration in European forests, which is even higher than that of Norway spruce (Chapter 4.2).

The expected climate change makes the species attractive to forest managers who are concerned about the future drought resistance of their current spruce-dominated stands. While other tree species may grow under climate change conditions, none of them has comparable wood quality to meet the demand from existing industries. In this context, the addition of appropriate Douglas-fir provenances to the tree-species portfolio is valued as a good "insurance" against future droughts. For these reasons, Douglas-fir is occasionally celebrated as the "new dry spruce". The logic is obvious: it provides not only an opportunity to increase wood production, even on decreasing commercial forest areas, and income in large parts of Europe; it may also enhance forest resilience in a changing environment.

Management of Douglas-fir is still in a dynamic phase of development (Chapter 4.1). While planting was up to now the most common establishment technique, causing high planting cost, in the future more efforts will be undertaken to use natural regeneration. When regenerating Douglas-fir under shelter, the shelter should be removed early in order to give the young plants enough light. To keep the proportion of lower quality juvenile wood small, a longer lifespan combined with larger dimensions would be favourable. Wood quality can be further improved by crop-tree selection and pruning. Higher age, on the other hand, may increase the risk of storm damage as the trees get taller. Diameter growth can be controlled through appropriate spacing, thinning, pruning and timing of final cuts. Establishment and management of mixed stands will gain importance.

The future susceptibility of Douglas-fir to pests and diseases is still uncertain, but this is also true for native tree species. As previously mentioned, the cultivation of Douglas-fir in Europe has so far been unburdened with major pest-related risks. However, this comfortable situation might change in the future as neither the risk of future introductions of pests from the origin of Douglas-fir, nor new adaptations of European pest organisms to Douglas-fir, can be excluded. The latter has already occurred with the eastern pine processionary moth (Chapter 3.5).

The impact of Douglas-fir on native systems is still not fully understood. As the oldest Douglas-fir stands currently growing in Europe have only reached approximately a fifth of the species' maximum lifespan in its natural habitat, growth and interaction dynamics of mature, old-growth stands in Europe are still unknown. Silvicultural practices suffer from a lack of knowledge of potential interactions between species in older stand development stages, especially with respect to mixtures of Douglas-fir with indigenous tree species. Furthermore, knowledge about the long-term effects of Douglas-fir cultivation on ecosystems is fragmented, particularly with respect to aspects of site characteristics or biodiversity in stands of different age classes and silvicultural treatments. Regarding storm damage, Douglas-fir has been considered to be relatively resistant by forest practitioners. However, recent analyses indicate that the storm resistance of Douglas-fir has been overrated on some sites. Future developments should be carefully monitored in order to reduce the uncertainties around growing Douglas-fir.

Recognising the EU's "20-20-20" energy targets, and assuming that forest industry production will continue along the same trend as the last decade, the demand for forest biomass will increase. However, at the same time, biodiversity policies at both the EU and national levels could unintentionally threaten the EU's wood supply. As substantial timberlands have been, and are still being, segregated for nature conservation purposes, the industry is increasingly forced to cover their construction wood demand from a shrinking area or from imports. Under these conditions, the traits of Douglas-fir are becoming even more valuable for the European wood industry, because they offer high quality wood in large quantities and with a higher ecosystem resilience at a time when native softwood species are increasingly projected to be suffering from pest and diseases. Accepting a non-native species in some parts of the forest may enable supporting other ecosystem services in other parts of the forests. Rational decision-making is needed to best satisfy society's desires for numerous ecosystem services from forests.

In conclusion, the reputation of Douglas-fir and the question of the continued growth of this species in Europe is loaded with hope, prejudice, reservation and scepticism. The current debates among numerous stakeholders often vary from enthusiastic to emotional, and can benefit from an evidence-based, sound scientific knowledge.

To set the course for the future, European forest policies must find a balance between supporting a fast-growing but non-native tree species with not yet fully understood consequences for native ecosystems and, on the other hand, promoting native tree species but thereby likely missing opportunities for increasing future sustainable construction wood supply.

1.

Introduction

Heinrich Spiecker and Johanna Schuler

In Europe, forest ecosystems play a prominent role in wood production, nature protection, water conservation, soil conservation and recreation as well as in carbon sequestration. These ecosystems have been shaped by humans since prehistoric times. For centuries forests in Europe have been affected by over-exploitation and soil degradation. Severe wood shortages resulted, which have been addressed in the last 150 years by countermeasures, including regenerating and tending highly productive forests. The high growth rates, increasing growing stocks and improved wood quality of many of those forests indicate the success of those actions. Coniferous species were often favoured because they are easy to establish and manage, show high volume growth and provide a range of valuable timber such as construction wood. Today coniferous forests expand far beyond the limits of their natural ranges. These changes have been accompanied by a shift to less site-adapted tree species, increasing the susceptibility to storms, snow, ice, droughts, insects and fungi. Some of these hazards are further intensified by the increasing average stand age. Climatic fluctuations, especially changes in the frequency and intensity of extremely warm and dry conditions and heavy storms, have a considerable impact on forest ecosystems. Therefore, the question arises of whether the current, rather artificial, species and provenance composition needs adjusting. For example, Norway spruce has grown surprisingly well outside its natural range. However, bark beetle outbreaks and storms stimulated a substantial decrease in its area during the last decades, especially in low elevations in Central Europe where it has been frequently substituted by broadleaved tree species over the last decades. On the one hand, society is asking for sustainable forestry that emphasises biodiversity and close-to-nature forest management. On the other hand, increasing worldwide demand for wood and rising interest in a green economy as well as the need to sequestrate carbon to support climate change mitigation also calls for adjustments in forest management. These changing demands require a widened scope of forest management. Tree species selection can help to cope with these challenges and this includes the selection of non-native tree species.

The interest in non-native tree species has a long history. Their introduction to Europe dates back to the 17th and 18th centuries. Currently, the proportion of European forests consisting of non-native tree species amounts to about 5% of the total forest area, and most prominently includes Sitka spruce (*Picea sitchensis* (*Bong.*) Carr.), Douglas-fir (*Pseudotsuga menziesii* (*Mirb.*), Franco), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Japanese larch (*Larix kaempferi* (*Lamb.*) Carrière), lodgepole pine (*Pinus contorta* (Douglas ex Loudon)), eucalyptus (*Eucalyptus sp.*), black locust (*Robinia pseudoacacia* L. (Fabaceae)), and red oak (*Quercus rubra* L.). Among these species, Douglas-fir is believed to have a high economic potential in large parts of European forests. Growing Douglas-fir in Europe is the subject of controversy and debate, raising questions of future sustainable biomass supply and the income of forest owners, as well as nature conservation issues, about which the public is increasing aware. In addition, experience with growing non-native tree species is limited and possible impacts on the existing ecosystem are not yet fully understood. This leads to uncertainties, which have to be taken into account when selecting tree species. In order to determine the full potential of non-native tree species, as well as to assess associated risks and challenges, this book investigates the options and consequences of growing these species using Douglas-fir as an example.

Douglas-fir's importance for forest management is not restricted to North America, where it is ranked among the most important tree species. The species has been successfully introduced in many forests around the world, including Europe and New Zealand. Since the introduction of the first Douglas-firs in Europe in the 19th century, the species has received increasing interest as a forest tree. It has rapidly developed into the most widespread non-native tree species of major economic importance in Germany and France. The main reason for this development is that Douglas-fir is considered by various European forest stakeholders to serve as a reliable future biomass source, even under changing climatic conditions. In its natural habitat, Douglas-fir grows well on an extremely wide range of site conditions and accordingly displays high adaptive genetic variability. A major challenge for European forestry is therefore to target the most appropriate genetic material for selected site conditions and/or expected environmental change. Since the two varieties of Douglas-fir were not initially differentiated when introduced to Europe, hybridisation of coastal and interior varieties is not uncommon in European seed orchards. As not only the growth performance but also the susceptibility to pests and diseases differs between varieties, the genetic properties of the seed material is highly relevant.

Douglas-fir has a high growth potential, exceeding that of indigenous European tree species. In fact, it even exceeds the growth potential of Norway spruce, which is still considered the most popular high-yielding tree species of central Europe and forms the economic base for many forest enterprises in Europe. However, when evaluating a tree species' value, it is also important to consider factors other than growth and timber value such as adaptation to climate change and mitigation of climate change effects, concerns about detrimental effects on native ecosystems and their biodiversity, and unpredictable infestations of pests and diseases.

Douglas-fir is considered to be more drought resistant than alternative timber-providing tree species in Europe. In some areas of its natural range it is adapted to severe annual summer droughts. Given climate change, this fact makes the species attractive to forest managers who are concerned about the future drought resistance of their current spruce-dominated stands. In this context, the addition of appropriate Douglas-fir provenances to the tree-species portfolio is valued as a good "insurance" against the future droughts expected under changing climates.

To evaluate the opportunities and risks of growing Douglas fir in Europe various questions have to be considered:

- Which Douglas-fir provenances should be selected for which site conditions?
- What are the site requirements of Douglas-fir?
- What is the impact of Douglas fir on native ecosystems? Is Douglas-fir invasive?
- How does Douglas-fir litter decompose?

- What pests and diseases may threaten the ecosystem?
- How much biomass can Douglas-fir produce compared with native tree species?
- What are the technical wood properties of Douglas-fir?
- What is the current and future value of the wood compared with native species?
- How should pure and mixed Doulas-fir forests be managed?
- How does the economic performance of Douglas-fir compare with native tree species?
- What is the public perception of Douglas-fir?
- Can Douglas-fir help to mitigate climate change effects?

Many European forest managers have high expectations of Douglas-fir. It is recommended as a substitute for increasingly unstable or less productive spruce or pine, and it is also touted as an important biomass producer in the future. Douglas-fir is quite often considered as a great hope for European forests in the face of climate change. However, not everyone appreciates the idea of advocating so strongly for this non-native, fast-growing tree species. The large-scale cultivation of Douglas-fir outside its natural range is therefore subject to social controversy. As the term "sustainability" has become accepted in society over recent decades, more and more people have gained an interest in nature, its conservation and its management. Additionally, NGO campaigns have raised people's awareness. In public perception, the cultivation of non-native species is therefore considered to be fraught with a variety of considerable risks. This may result in legal restrictions on its cultivation. Indeed, there are still many unanswered questions relating to the cultivation of Douglas-fir in Europe. Knowledge about the long-term effects of Douglas-fir cultivation on ecosystems is fragmented, particularly with respect to aspects of site characteristics, or biodiversity in stands of different age classes and silvicultural treatments. An additional "known unknown" is Douglas-fir's future susceptibility to pests and diseases as the risk of future introductions of pests can be neither excluded, nor new adaptations of European pest organisms to Douglas-fir.

In conclusion, the reputation of Douglas-fir and the issue of continuing to grow this species in Europe are loaded with hope, prejudice, reservation and scepticism. The current debates among the many stakeholders often vary from enthusiastic to emotional and could benefit from sound scientific knowledge. This book is therefore intended to give science-based, objective information by synthesising relevant research results on the options and consequences of growing Douglas-fir in Europe.

2.

Douglas-fir distribution in Europe

Chapter editor: Marcela van Loo

2.1 History of introducing Douglas-fir to Europe

Marcela van Loo and Dorota Dobrowolska

Douglas-fir (*Pseudotsuga menziesii* (Mirb.), Franco), the second most cultivated non-native conifer tree species in Europe (0.8 million hectares) after Sitka spruce (1.2 million hectares), was first described in the scientific context in 1792 by Archibald Menzies on the west coast of Vancouver Island (British Columbia, Canada). The first seeds were introduced to Europe in 1827 by the Scottish botanist David Douglas and the first trees were planted at Scone Palace, Perthshire, Scotland. David Douglas probably collected the seed near Fort Vancouver on the Washington side of the Columbia River.

In the following years, plantings in other European countries followed a comparable pattern with solitary or small groups of Douglas-fir trees introduced for ornamental reasons in arboreta or parks. Around the end of the 19^{th} century and beginning of the 20^{th} century Douglas-fir was introduced into European forests. But compared to other non-native forest species (e.g., *Robinia pseudoacacia, Pinus strobus*), Douglas-fir planting remained modest until the middle of the 20^{th} century. After the second world war, the tree was planted widely, even in monocultures, and became a major reforestation species in Western Europe (Table 1, Figure 1).

It is all the more astonishing that the success of the introduction of Douglas-fir in European forests results primarily from a coincidental and lucky choice of appropriate seed sources in the majority of initial introductions. Douglas-fir is universally accepted to be represented by two geographically distinct varieties. *Pseudotsuga menziesii* var. *menziesii* or *viridis* (coastal variety) extends from central British Columbia south along the Pacific coast ranges into central California. *P. menziesii* var. *glauca* (interior variety) grows along the spine of the Rocky Mountains to as far south as Mexico.

The coastal and interior varieties are morphologically, physiologically, chemically and also genetically distinct with the coastal variety enjoying higher growth rates and lower

Table 1. History of introducing Douglas-fir to countries in Europe: first introduction to parks/arboreta and forests

Period	Date	Country	How Douglas-fir was introduced into Europe
1827–1850	**First introduction of Douglas-fir in various European countries**		
	1827	UK	Seeds collected by David Douglas in 1826, probably near Fort Vancouver. The seeds were distributed by the London Society of Horticulture's nursery and trees were planted in various parks in UK. They grew well and UK landowners became interested in Douglas-fir. Denmark, Germany, Netherlands, and Portugal also received plants from this society.
	1828–42	France	The date of first introduction is still under debate. Single trees of Douglas-fir were planted in forests.
	1830–40	Russia	Douglas-fir planted at Nikitsky Botanical Garden on the Crimean Peninsula.
	1831	Germany	John Richmond Booth planted two-year-old Douglas-fir that had been distributed by the London Society of Horticulture in his Arboretum. His nursery near Hamburg later provided plants for many European countries.
	1833	Poland	Douglas-fir planted near Krakow.
	Late 1840s to early 1850s	UK	Seeds collected by Sir William Douglas Stewart, Karl Theodor Hartweg, William Lobb and John Jeffrey.
	1843	Czech Republic	A seedling from the Booth nursery planted in Chudenice Arboretum near Klatovy.
	1844–49	Portugal	First plantation in Sintra (Castelo dos Mouros), most probably progeny of David Douglas's collection.
	1848	Netherlands	Probably one of the first introductions of Douglas-fir.
	1850	Ireland	First introduction and planting on old woodland sites.
	1850	Luxemburg	Introduction of Douglas-fir in Luxembourg-Limpertsberg.
1851–1900	**First introduction of Douglas-fir in the majority of European countries and first forest plantations**		
	After 1850	Luxemburg	Douglas-fir stands planted near Meysenburg.
	Since 1850s	Latvia	Douglas-fir planted in parks.
	1851	Denmark	Douglas-fir trees planted from seeds imported from German nurseries.
	1858, 1885–90	Italy	Single trees planted in Brolio (one tree), Moncioni (one to two trees) in Tuscany, later forest plantation in Valombrosa, Masseto and Bivigliano.
	1858/60	UK	First forest plantation at Buchanan and Taymount using David Douglas's seeds.
	1866	Denmark	Forest plantations with seeds from Scotland, probably from trees introduced by David Douglas.
	Late 1860s	Czech Republic	First forest plantations.
	1884 and 1889	Slovakia	First trial plantings in the forest of the Academy of Mining and Forestry in Banská Štiavnica.
	1863–77	Switzerland	Probably first planting in field trials by the Swiss Forestry Association.
	1879, turn of 19th century	Norway	First planting of solitary trees, later forest plantations.
	1872	Belgium	Pre-1872, plantations in parks and gardens then, in 1872, first forest plantation at Sibret near Bastogne.
	End of 1870s to 1880s	Germany	Large plantations in Prussia by private forest owners Count Wichard von Wilamowitz-Moellendorff and chancellor Otto von Bismarck.

Table 1. continued.

Period	Date	Country	How Douglas-fir was introduced into Europe
1851–1900	**First introduction of Douglas-fir in the majority of European countries and first forest plantations**		
	1876 and 1886	Austria	Douglas-fir was planted near Bregenz (Vorarlberg) and forest plantations were later established.
	Middle of 19th century, 1880	Sweden	First Douglas-firs planted and first Douglas-fir stand was planted in the Rössjöholms state.
	1880	Estonia	First attempt to grow Douglas-fir failed – probably due to inappropriate provenance.
	Since 1880	Russia	Plantations were established in European Russia.
	1879-80 and 1891-95	Poland	First forest plantations, probably by seeds from Schwappach collected in British Columbia, Washington and from UK.
	1880-82	Hungary	Seed purchased by the Hungarian National Forest Association for trial plantation.
	1888-90	Romania	Douglas-fir introduced in parks and forests (sometimes seedlings from Austria and France).
	Around 1888	Spain	Single Douglas-fir trees planted in Vizcaya (Basque country).
	End 19th century	Ukraine	Small groups of Douglas-fir planted.
	1892	Croatia	First forest Douglas-fir plantings.
	End 19th century	Slovenia	Tree forest planting, seeds were obtained from Belgium and Germany (from John Booth´s nursery).
1901–1950	**Period of establishing forest plantations of Douglas-fir at larger scale in Europe**		
	1900–02	Latvia	First forest plantations.
	1903–05 1906	Bulgaria	Douglas-fir was planted in Vrana park near Sofia. Forest plantation with seedlings of coastal variety imported from Austria.
	Starting 1904	Portugal	Forest plantations established.
	1905 1924 and 1942	Finland	First forest plantation at the Mustila Arboretum near Elimäki (seeds from British Columbia - intermediate); later trial plantations with seeds from interior British Columbia and Alberta with low-growth performance.
	1905–06	Bosnia and Herzegovina	Douglas-fir plantation near Olovo.
	1908 and 1913	Lithuania	Planting of first the intermediate and interior varieties at Radviliškis forest, later the costal variety at Pagėgiai and Rambynas forest.
	1911–12	Serbia	Plantation of 0.4 hectares of coastal Douglas-fir in the Avala mountains.
	1912 and 1914	France	Douglas-fir plantations in Normandy, Tarn, Ardennes and Vosges mountains.
	1907–10	Poland	More forest plantations, probably using seeds from Schwappach collected in British Columbia, Washington and from UK.
	1919	Greece	Douglas-fir planted at the Arboretum of Vytina (central Peloponnese).
	1926	Spain	Forest plantation of Douglas-fir.
	1940	Iceland	First forest stand planted.
	1950	Macedonia	Douglas-fir seedlings from Slovenian nursery introduced and planted.
	Early 19th century	Estonia	Small plantations were established.

Table 1. continued.

Period	Date	Country	How Douglas-fir was introduced into Europe
After 1951–	**High interest in establishing additional forest plantations of Douglas-fir in Europe**		
	1951, 1953	Turkey	Seeds introduced and Douglas-fir planted at the Arboretum of Istanbul and in forests.
	1960	Macedonia	Forest plantations at several locations with seed from Oregon distributed by the International Union of Forest Research Organisations (IUFRO).
	After 1960s	Greece	Trial plantations with Douglas-fir originating from Germany (intermediates from Oregon).
	1962	Cyprus	In this year Douglas-fir was already growing in an arboretum at an elevation of 800m.
	1970s	Portugal	Forest Development Fund supported large afforestation of Douglas-fir.
	1970–90	Montenegro	Douglas-fir introduced.
	Around 1980	Armenia	introduced and planted in botanical gardens.

susceptibility to fungi. The coastal variety that was first introduced into Europe originated from a few areas, most likely around the Columbia River mouth between Washington and Oregon. The first plantations were quite successful and resulted in excellent growing and healthy trees. At the beginning of the 20th century, the first problems resulted from the introduction of seed from the interior variety. This led Schwappach, head of the Prussian Forest Research Institute, to initiate the first European provenance test in Chorin, to the east of Berlin, in 1910. He was convinced that within the huge native distribution range of Douglas-fir with very different ecological conditions, natural selection had formed locally adapted races (provenances) which could differ in growth performance. Other provenance tests followed in the Netherlands (1923) and in Germany (1932 and 1954). In 1965 the International Union of Forest Research Organisations (IUFRO) organised a Douglas-fir seed collection in America led by H. Barner from the Danish State Forestry Tree Improvement Station in Humlebaek, Denmark. 182 seed lots were collected and distributed to 36 countries across the world (15 of them situated in Europe). This was the first seed collection performed by European scientists, which covered the entire native distribution range and where seeds of exactly known origin were collected. Provenance research based on this collection confirmed the importance of the origin of planted forest reproductive material (FRM) for cultivation success. Furthermore, it provided essential knowledge about Douglas-fir´s growth, frost sensitivity, and tolerance to diseases as well as provenance recommendations for European countries. The Douglas-fir provenances from the coastal zone (*Pseudotsuga menziesii var. menziesii)* of the North American Pacific region seem to be the best for European conditions, especially for Western European countries. In Europe, provenance trials proved that the provenances from lower elevation from the coastal and Cascade range in Washington State were superior in growth.

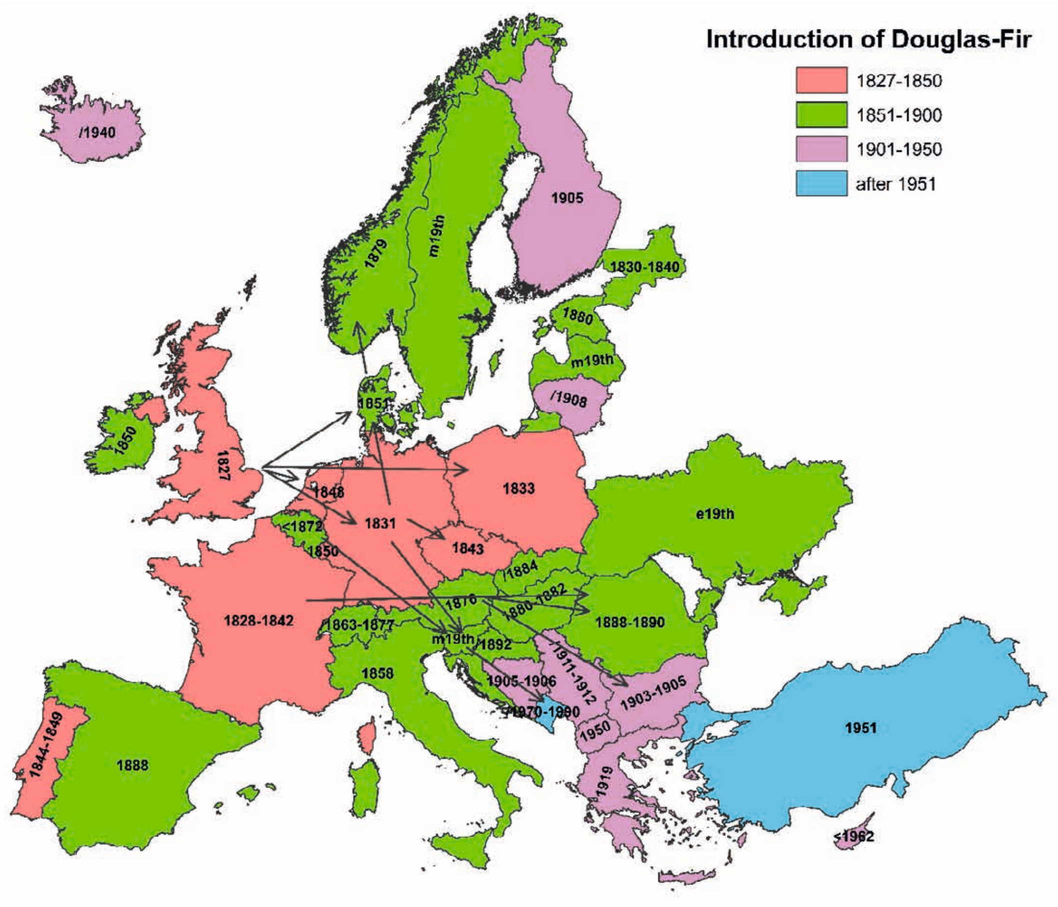

Figure 1. The first introduction of Douglas-fir into parks and arboreta throughout Europe and pathways of Douglas-fir seed distribution until the end of the 19th century (arrows). When not known, first forest plantation was depicted (year behind /). Abbreviations 'e', and 'm' mark the end and the middle of the century (by T. Eckhart).

Box 1. Lessons learnt about Douglas-fir from the past

- First introduction in Europe in 1827 as an ornamental tree.
- First forest plantations were established across majority of European countries in the 19th century. Some of the first forest plantations still exist.
- The common age of Douglas-fir (green variety) is 750 years. Thus, the oldest "European" Douglas-firs are only in adulthood age at the present.
- A major reforestation species in Western Europe after the second world war.
- Planting experiences were mixed, depending on site and variety.
- Importance of the origin of forest reproductive material was acknowledged and scientifically confirmed.
- For first forest plantations, reproductive material (mainly seed) was imported from North America. Later seeds and plants were often transferred between European countries.

2.2

Current situation

Marcela van Loo and Dorota Dobrowolska

Douglas-fir covers, in total, more than 823,534 hectares in forests of 35 European countries, occupying around 0.40 % of the European forest area. There are huge differences between countries. France (420,000 hectares) and Germany (217,604 hectares) have the largest areas of Douglas-fir and more than 75 % (two-thirds) of the total European Douglas-fir area (Figure 2, Table 2). In both countries, Douglas-fir is *the most planted introduced tree species*. The production concentrates on saw logs for sale. In France these are produced mainly in monocultures with 40-year rotation period, whereas in Germany silvicultural guidelines ask for Douglas-fir mixed forest with structural diversity and selection cuts of diameters larger than 50 cm and trees older than 60 years. France is well known for promotion and enhancement activities for Douglas-fir, including breeding. A professional association, *France Douglas* (www.france-douglas.com) was established in 1993 on the initiative of Douglas-fir producers. The present *France Douglas* represents various professionals (foresters, sawyers, industrial producers, etc.) that decided, in close cooperation with research, to coordinate and develop favourable market conditions for this specific wood. In Germany, the perception of Douglas-fir, as with other exotic species, is more critical, especially by nature conservationists (Chapter 5.3).

In order of size of the planted Douglas-fir area, France and Germany are followed by the UK, Belgium, Spain and the Netherlands with areas between 18,000 hectares and 45,000 hectares. In the majority of other European countries, the area covered by Douglas-fir is less than 10,000 hectares and, in some countries, even less than 1,000 hectares (Table 2).

As for the growing stock, France (with 100 million m^3) and Germany (72.7 million m^3) are followed by the UK, with over 15 million m^3 and then the Netherlands (> 6.5 million m^3), Belgium (> 4 million m^3), Bulgaria and Denmark with growing stock over 2 million m^3 each (Table 2).

Douglas-fir is common in many West European countries, such as the BENELUX countries, Germany, France, Ireland, the UK and Denmark, where it dominates more than 1% of the forests (Figure 3). In the Czech Republic, Austria, Bulgaria, Romania and the Mediterranean countries Croatia, Portugal and Spain the area covered by this species is far below 0.5% but still higher than 0.1% (Table 2). In all remaining European countries Douglas-fir covers less than 0.1% of forests and plays a marginal role in forestry or is, to date, not important at all.

Table 2. Today´s coverage (ha) of Douglas-fir in individual European countries.

Country	Dg-fir area (ha)	Forest total area (ha)	Dg-fir % national forest area	Dg-fir % European forest area[a]	Growing stock (m^3) of Dg-fir
Albania	0.5	776,000	> 0.000	0	
Armenia	0	4,590,900	0.000	0	
Austria	8,000[b]	3,887,000	0.206[b]	1	635,000
Azerbaijan	0	1,021,880	0.000	0	
Belgium	22,800[c]	703,421	3.241	2.8	> 4,389,268[d]
Belorussia	25	8,630,000	0.000	0	
Bosnia and Herzegovina	2,500	2,904,000	0.086	0.3	342,000
Bulgaria	7,372	3,686,000	0.200	0.9	2,781,465
Croatia	393	2,688,687	0.015	0	
the Czech Republic	5,800	2,636,394	0.220	0.7	1,436,000
Cyprus	0	171,615	0.000	0	
Denmark	6,742	544,000	1,239	0.8	2,166,470
Estonia	25	2,284,600	0.001	0	
Finland	500	26,200 000	0.002	0.1	
France	420,000	15,954 000	2.633	51.0	100,000,000
Germany	217,604	11,419 124	1.906	26.4	72,731,000
Georgia	0	2,997,100	0.000	0	
Greece	6	3,903,000	> 0.000	0	
Hungary	353	2,000,000	0.018	0	
Iceland	10	46,000	0.022	0	
Ireland	10,200	680,000	1.500	1.2	
Italy	2,598	10,467 533	0.025	0.3	
Latvia	47	3,354,000	0.001	0	
Liechtenstein	0	7,000	0.000	0	
Lithuania	20	1,800,000	0.001	0	
Luxembourg	2,650	88,500	2.994	0.3	986,000
Macedonia	671	900,875	0.074	0.1	
Moldova	0	467,700	0.000	0	
Montenegro	78	826,782	0.009	0	
the Netherlands	18,933	373,480	5.069	2.3	6,691,000
Norway	150	11,538 461	0.001	0	
Poland	5,062	9,160,000	0.055	0.6	24,367
Portugal	4,200	3,153,800	0.133	0.5	
Romania	7,307[e]	6,249,000	0.117	0.9	
Serbia	1,690	2,252,400	0.075	0.2	511,151
Slovakia	1,353	1,933,000	0.070	0.2	
Slovenia	18,066[f]	1,094,000	0.020	0.1	170,980
Spain	25,400	18,372 700	0.138	3.1	
Sweden	1,000	23,200 000	0.004	0.1	
Switzerland	17	1,310,000	0.001	0	
UK	45,000	3,100,000	1.452	5.5	15,055.000
Ukraine	4,427	9,705,000	0.046	0.5	900,980
Total	823,534	204,080 852	0.404		

Malta, Monaco, Vatican and San Marino – no forests according to UN FAO definition of forests
a Total forest area of listed countries
b Based on growing stock, Douglas-fir covers ≈ 1 800 ha and 0.06 % of Austrian forests
c Douglas-fir in Wallonia, which covers 80% of Belgian forests
d Douglas-fir of Wallonian pure stands only, Douglas-fir of mixed stands is not included
e ± 40% ha
f Area of subcompartments with species presence (ha)

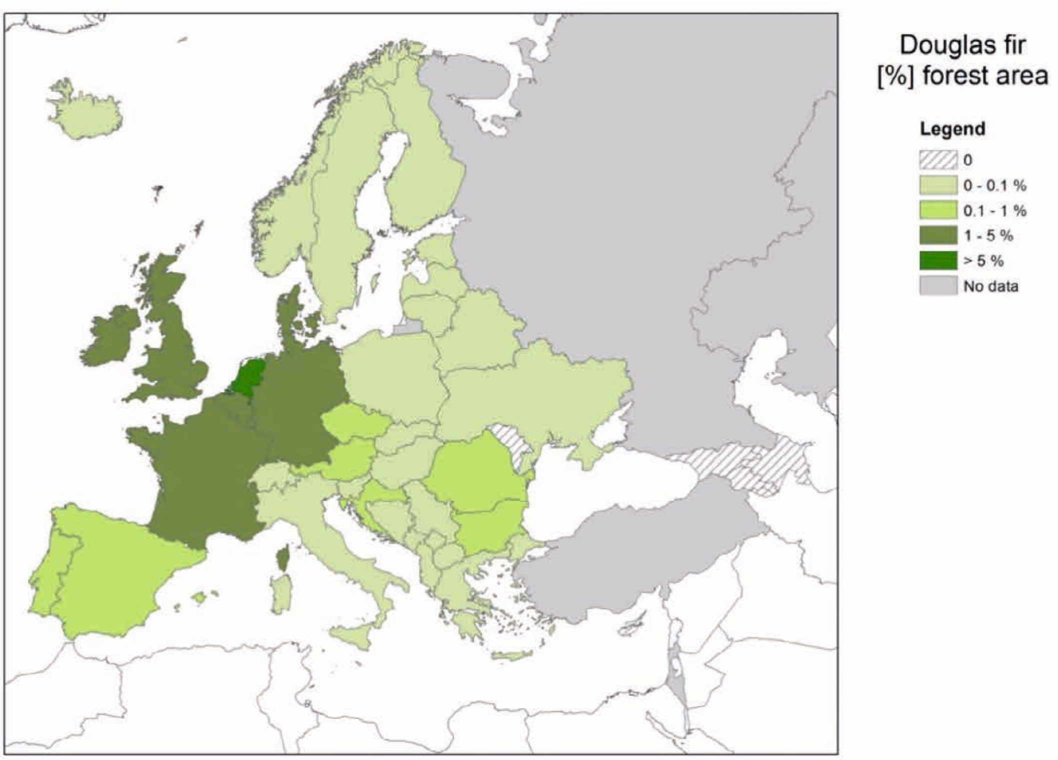

Figure 2. Douglas-fir in Europe (in % of forest area of individual countries) (by M Westergren). Transcontinental countries (Russia, Kazakhstan and Turkey) are not displayed.

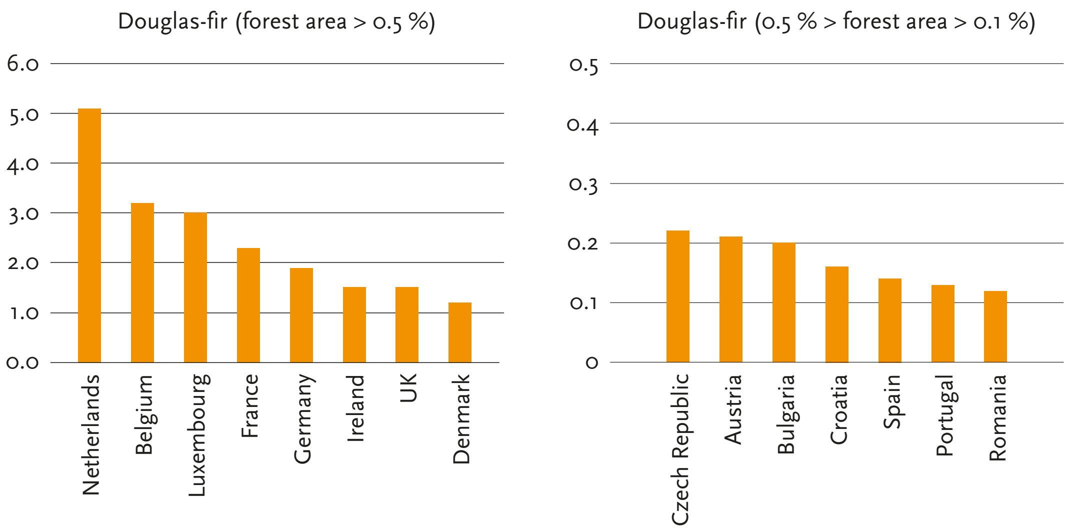

Figure 3. Douglas-fir in Europe (in % of forest land area of a country).

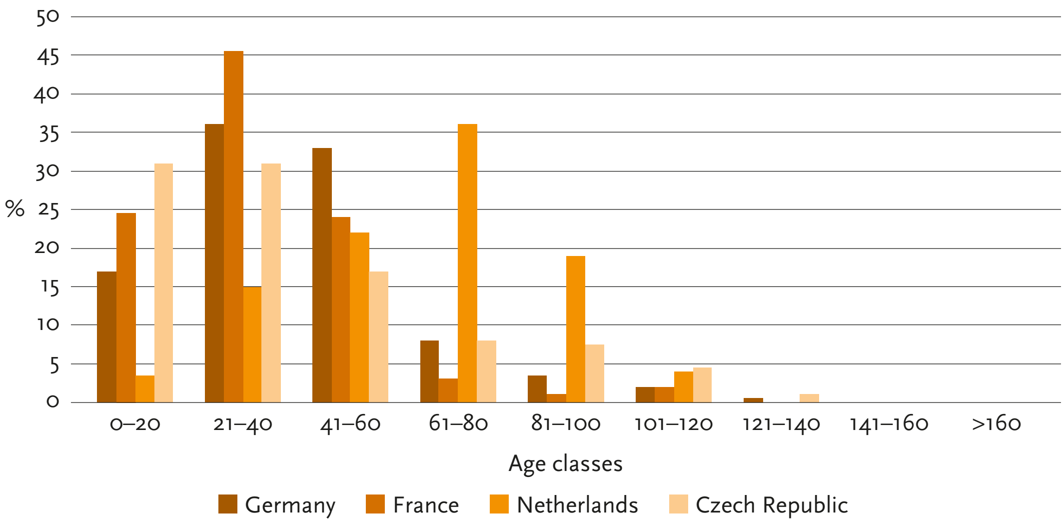

Figure 4. Age class distribution (in % ha). (Data provided by H Spiecker, J Ch Bastien, F Mohren, V Podrazsky; original sources are not listed here.)

Age class distribution varies among European countries and even among the leading countries France, Germany and the Netherlands. As Figure 4 shows, in France and Germany Douglas-fir is largely represented by the age class of 21–40 years. This means that the growing stock, as well as the supply of Douglas-fir wood, will increase substantially. In France, in order to increase the annual timber production from current three million m^3 to the planned six million m^3, the reforestation rate has to increase from 4,000 hectares/year towards 10,000 hectares/year. This quantitative challenge is intended to be accompanied by a specific quality of genetically improved material, which is climate resilient and possesses good wood technological properties and a high productivity.

On the other hand, in the Netherlands older Douglas-fir trees, largely in age class 61–80 years, dominate forests. The sharp decline of Douglas-fir in younger classes in the Netherlands follows a general pattern noticeable in Dutch forests, which are older with an average age of 67 years in conifers.

In the Czech Republic, in contrast to the Netherlands and as result of larger plantings of Douglas-fir in the last 50 years, forests are dominated by trees younger than 40 years. In the Czech Republic, where Douglas-fir was the tree species of the year 2014 and is projected to be a suitable alternative to Norway spruce, comprehensive research confirmed its position as a very promising non-native tree species.

2.3

Douglas-fir's role in European forests in the 21st century

Marcela van Loo and Dorota Dobrowolska

Today, Douglas-fir planting is often discussed in relation to the expected adaptations of forest management to climate change. With climate change scenarios predicting higher mean annual temperatures and increased summer drought, Douglas-fir may serve as an alternative tree species even in those countries where the wood market for this tree species is not yet developed. For Douglas-fir to be introduced in new areas adequate seed material is essential. Thus, in both France and Germany, around eight million Douglas-fir seedlings are needed each year for afforestation and reforestation. In recent years, huge efforts were made to establish a basis for suitable reproductive material production of Douglas-fir. By harmonising the European regulations for marketing of forest reproductive material (FRM) with the Organisation for Economic Cooperation and Development (OECD) scheme regulating the production of FRM in non-EU countries, import of FRM with known origin from the native distribution range is allowed. In addition, at present in Europe more than 2,200 Douglas-fir stands are selected for seed production and around 70 seed orchards covering 400 hectares produce up to 2.5 tons of seed each year.

The increase of areas covered by Douglas-fir (by both natural regeneration and afforestation) and adverse effects of Douglas-fir on biodiversity and habitats are both associated with another important topic: the invasiveness of this species. In some European countries Douglas-fir is considered to be invasive, whereas in others it is not (see Chapter 3). Nevertheless, it should be highlighted that, despite the fact that Douglas-fir was shown to have an effect on forest species composition and habitats, none of the investigating authors argues for an absolute ban of Douglas-fir in silviculture. In the recently published "List of Invasive Alien Species of Union Concern" for implementation of the Regulation (EU) no 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species, Douglas-fir is not included.

In addition to social and political issues (such as trade barriers, war, political discussion about the introduction of non-native species or preference for natives), silvicultural and biological factors also affect the current distribution of Douglas-fir in European forests. These include growing experiences with this species (also in mixtures with others) and preferences for other non-natives but also the possible physiological and biological limits of this species. Occurrence of diseases, in general, have led to setbacks in Douglas-fir's cultivation. For example, in Germany, where as a consequence of the rapid spread of the Swiss needle cast in Württemberg, cultivation of Douglas-fir in the state forest was prohibited by a directive in 1940. This directive was moderated seven years later when increasing knowledge about biology of the fungus revealed that, with selection of suitable genetic varieties, planting sites and appropriate silvicultural treatments, the risks associated to this pathogen could be limited. Afterwards Douglas-fir was allowed to be used for forest mixed cultures and was planted on a larger scale than before.

At the national level, there is a lack of knowledge in most countries of the ecological demands and the growth potential of Douglas-fir, as well as the technological and economic aspects associated with cultivation of this tree, that makes the economic evaluation of Douglas-fir in relationship to other tree species very difficult. Furthermore, certain European countries have still not passed the "arboretum" and "provenance trial" stage in cultivating Douglas-fir.

It is obvious that both further research into the associated risks and challenges in growing this species within European forests and a European multidisciplinary platform for a state-of-the-art knowledge transfer on Douglas-fir are needed. The latter is being established within the COST Action FP1403 NNEXT (www.nnext.boku.ac.at).

European countries differ not only in their histories but also in their present realities relating to Douglas-fir planting and cultivation. As a consequence, the distribution of Douglas-fir across Europe is as diverse as the European countries in which it grows. Nevertheless, if further cultivation trends are identical to those existing at present, and no new danger comes from pest and pathogens, we can assume that this fast-growing tree species, which also regenerates naturally in European forests, will be a relevant part of the European forest landscape.

Key messages

- Douglas-fir occupies an area of more than 823,534 hectares in 35 European countries, which accounts for 0.40% of the European forest area.
- Douglas-fir is present in nearly all European countries, but is more common in Western Europe (8 Western European countries occupy 94% of total Douglas-fir area).
- France and Germany are leading countries in size of planted areas (75% of European Douglas-fir area).
- BENELUX countries (BE, NL and LU) are the countries with the highest proportion of Douglas-fir in their forests.
- The two most important factors for broader Douglas-fir use in Europe are geographic origin and availability of forest reproductive materials (seeds and seedlings). These factors affect growth rates of Douglas-fir and its susceptibility to biotic and abiotic factors.
- High quality- and fast- growing timber led to successful Douglas-fir establishment in Western Europe.
- Adaptation of forest to changing environment and mitigation of climate change are the most important topics in Douglas-fir studies.
- Invasiveness and public perception of the non-native Douglas-fir are the two most controversial issues discussed across European countries.

Recommended reading

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Hasenauer, H., Gazda, A., Konnert, M., Mohren, G., Pötzelsberger, E., Spiecker, H. and van Loo, M. 2016. Non-Native Tree Species for European Forests: Experiences, Risks and Opportunities. COST Action FP1403 NNEXT Country Reports, Joint Volume. Vienna (BOKU), Vienna, Austria. 370 p.

3.

Douglas-fir ecology

Chapter editor: Valeriu-Norocel Nicolescu

3.1 Natural range, site requirements and shade tolerance

Valeriu-Norocel Nicolescu

3.1.1 Natural range

Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco*)* is the most commercially important tree species in western North America and one of the most important and valuable timber trees worldwide.

Two geographic varieties of the species are now recognised in North America: the coastal variety or green Douglas-fir (*P. menziesii* var. *menziesii*), and the interior variety (*P. menziesii* var. *glauca* (Beissn.) Franco) also called Rocky Mountain or blue Douglas-fir. The coastal variety grows quicker and is much larger, while the interior variety is both more shade tolerant and significantly more cold hardy. The two varieties also differ in morphological, anatomical, cytological, physiological and genetic characteristics. The existence of a third variety, grey Douglas-fir (*Pseudotsuga menziesii* var. *caesia* (Schwerin) Franco), considered *intermediate* between the green and blue Douglas-firs, with the highest frequency in the northern part of Rocky Mountains (British Columbia) is also acknowledged.

Douglas-fir covers an area of about 14.4 million hectares in the USA and 4.5 million hectares in Canada and the species has the greatest latitudinal range of all the commercial conifers of western North America. It extends from latitude 19° to 55° N, and this range resembles an inverted V with uneven sites (Figure 5).

The range of coastal variety (*menziesii*) extends from the apex in central British Columbia south along the Pacific coast ranges for about 2,200 km to latitude 34° 44’ N. The interior variety (*glauca*) range extends from the Rocky Mountains into the mountains of central Mexico over a distance of nearly 4,500 km.

Figure 5. The natural range of Douglas-fir; in black: coastal variety; green: interior variety (after Little 1971, from Miller and Knowles 1994, with permission)

Table 3. Climatic data for five subdivisions of the range of Douglas-fir (from Lavender and Hermann 2014, with permission)

Climatic data	Pacific Northwest		Rocky Mountains		
	Coastal	Mountainous	Northern	Central	Southern
Mean temperatures					
July (C°)	20–27	22–30	14–20	14–21	7–11
January (C°)	-2.5 to 2.5	-9.0 to -2.5	-7 to -2.5	-9.0 to -6.0	0 to 2.0
Frost-free period (days)	195–260	80–180	60–120	65–130	50–110
Precipitation					
Mean annual (mm)	760–3000	600–3000	560–1020	360–610	410–760
Snowfall (cm)	0–60	10–300	41–584	50–460	180–300

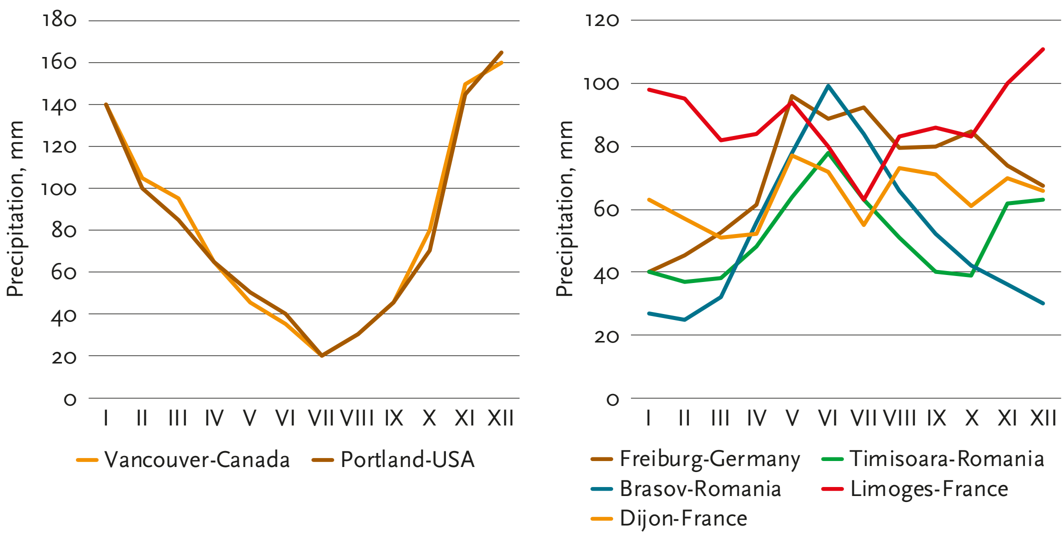

Figure 6. Monthly precipitations in the coastal region of Pacific Northwest (Vancouver, British Columbia and Portland, Oregon) (left) and in Europe (western Europe: Freiburg, Germany; Limoges and Dijon, France and eastern Europe: Timisoara and Brasov, Romania) (right).

3.1.2 Site requirements

3.1.2.1 Climate requirements

In the *natural range*, Douglas-fir grows under a wide variety of climatic conditions (Table 3).

These conditions are as follows:

a. *Coastal region of the Pacific Northwest*: the climate is *maritime (oceanic)*, characterised by mild, wet winters (Figure 6), cool, relatively dry summers, and long frost-free (growing) seasons.

b. *Northern Rocky Mountains*: the climate becomes markedly *maritime (oceanic)*. Precipitation is evenly distributed throughout the year, except for a dry period in mid-summer (July and August).

c. *Central Rocky Mountains*: the climate is *continental*, with long and severe winters, hot summers and, in some parts of the region, it is very dry. Annual precipitation, higher on the western sides of the mountains, is mainly snow.

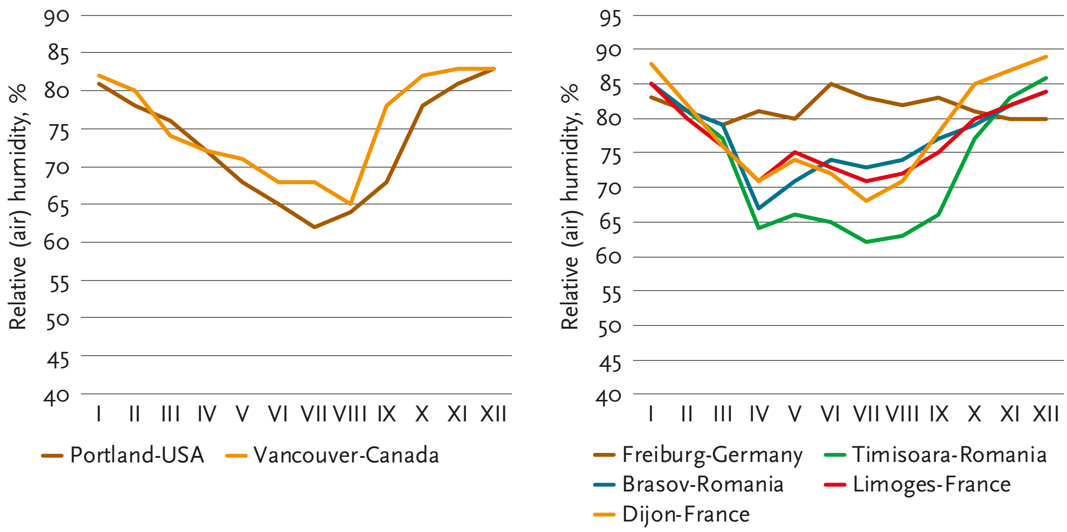

Figure 7. Monthly air relative humidity in the coastal region of Pacific Northwest (Vancouver, British Columbia and Portland, Oregon) (left) and in Europe (western Europe: Freiburg, Germany; Limoges and Dijon, France and eastern Europe: Timisoara and Brasov, Romania) (right).

d. *Southern Rocky Mountains*: rainfall patterns show two different situations:
   - East of the *Continental Divide of the Americas* (it separates the watersheds of the Pacific Ocean from those of the Atlantic and Arctic Oceans): low winter precipitation but high precipitation during the growing season.
   - West of the Continental Divide: the rainfall is more evenly divided between winter and summer.

In the natural range, Douglas-fir suffers from some important climatic factors such as: *mid-winter and spring frosts* (harmful for needles, buds, trunks and roots, mostly in nurseries, young plantations and natural regenerations), heavy *snows* (produces leaning, bent, fractured stems and broken branches), *freezing rain* (breaks stems and branches), *summer droughts* (especially affects natural and artificial regeneration of Douglas-fir, the death of older trees appearing to be rare), *wildfires* (especially surface fires, affecting mostly young trees), *wind* (provokes breakage of trunks or blowdown) etc. However, *frost* is the most harmful abiotic factor for Douglas-fir; the coastal variety is considerably less frost resistant than the interior one.

In **Europe**, Douglas-fir was introduced in different climatic conditions. The species is best adapted to *humid temperate climate* or *Atlantic climate*, with higher relative air humidity during the summer months than in its natural range (Figure 7).

In Europe, the distribution of precipitation is quite different (Figure 6). During the growing season precipitation is relatively high compared to the extreme dry summer conditions in the Pacific Northwest but, even so, there is quite some variation. As Douglas-fir is adapted to dry summers in its natural range it uses water very efficiently in dry conditions and can adapt to dry summers in Europe.

The mean annual precipitation should be at least 700–800 mm for high wood production but Douglas-fir can tolerate lower amounts of rainfall (even less than 600 mm/yr).

The species tolerates *mid-winter frosts* but the mid-winter cold hardiness is weakly inherited. However, in the first two years, Douglas-fir cannot withstand temperatures below – 25° Celsius, as they can harm the terminal shoot.

Douglas-fir trees, especially when young, can be damaged by *late (spring) frosts* in low-lying places, on the forest borders and on south-facing slopes. These frosts are often the cause of forking. In this respect, in order to avoid the harmful effects of spring frosts, the use of Douglas-fir provenances or genotypes with a late bud burst (showing spring cold hardiness) is highly advisable.

Douglas-fir seedlings and young trees (up to 25 years) are sensitive to evapotranspiration so prolonged *summer droughts* may lead to dieback, although old trees are able to tolerate dry periods. The species can withstand the summer drought periods if the soil water reserve is high. In different parts of western (Germany, Switzerland, Belgium), central (Czech Republic) or eastern Europe (Romania), Douglas-fir is less sensitive to increased summer drought conditions than Norway spruce, silver fir, Scots pine, larch, oaks, European beech. This high potential to resist drier conditions and cope with projected climate changes makes Douglas-fir an alternative to Norway spruce in future drought-prone protection forests, or mixed European beech-Norway spruce forests.

In Europe, the tolerance to low temperatures and drought periods depends on the Douglas-fir varieties or provenances. In this context, it is acknowledged that provenances of Douglas-fir from the northern part of the species-distribution range are generally more productive than provenances from the south. In contrast, drought tolerance increases towards the south. Consequently, as summer droughts are expected to be more frequent in the future, if one is considering replacing Norway spruce with Douglas-fir one might take into account the trade-off between the adaptation to extreme drought periods and the long-term growth performance.

In Europe, Douglas-fir is also subject to *frost-induced drought* (frost dryness, winter desiccation) in early spring. This phenomenon happens when the soil is frozen (so no water uptake) and trees lose more water through transpiration on sunny days than they can take up. This leads to the brown-red discolouration of the foliage beginning at the tip of the needles, affecting mostly the young trees which may even die.

Douglas-fir is sometimes affected by heavy *snowfalls*, producing snow breaks particularly in densely stocked stands that are between 20 and 40 years old.

Damage caused by *hail* is rare in Europe but can be disastrous. A hail storm near Angers, France caused so much damage to the trees in young Douglas-fir plantations that they had to be replanted.

3.1.2.2 Soils and Topography

In the **natural range**, the *coastal* variety of Douglas-fir reaches its best growth on moist, well-aerated, deep, nutrient-rich soils with a pH range from 5 to 5.5. It does not thrive on poorly drained or compacted soils. The soils in this area originate from a considerable array of parent materials (eg sedimentary, including limestone, igneous rocks, formations of volcanic origin, etc). They are, in general, moderately acid, high in organic matter and total nitrogen, and low in base saturation. The soil depth ranges from shallow, on steep slopes and ridge-tops, to deep, where deposits of volcanic origin, residual and colluvial materials are found. Texture varies from gravely sands to clays.

Soils within the range of the *interior* variety of Douglas-fir also originated from a wide array of parent materials. Soils derived from non-calcareous substrates are variable in texture but are consistently gravely and acidic. A significant portion of the sedimentary rock is limestone, which gives rise to neutral or alkaline soils (pH between 7.0 and 8.5) ranging in texture from gravely loams to gravely silts. Limestones often weather into soils that are excessively well drained.

Altitudinal distribution of both varieties of Douglas-fir *(menziesii* and *glauca*) in the natural range increases from north to south, reflecting the effect of climate on the distribution of the species. The principal limiting factors are temperature in the north of the range and moisture in the south. The interior variety grows at considerably higher altitudes than the coastal variety of comparable latitude. In this respect, the coastal variety grows from the sea level (Oregon and Washington) to elevations as high as 2,286 m (Sierra Nevada). The interior variety occurs at altitudes ranging between 549m (northern part of its range) and 3,264 m (south-eastern Arizona).

In **Europe**, Douglas-fir shows a high adaptability and grows on different soil types, at least of moderate fertility. However, it grows best and produces a high volume of wood on deep (at least 50 cm depth), fresh to moist, well-drained soils, where it develops a good root system. It is unsuited to alkaline (calcareous) soils, so they should be moderately acid, with a pH of 5 to 6. However, the species can grow on soils with calcareous subsoil if the thickness of mineral horizons is at least 40 cm and there is no free lime/carbonates in the upper 20 cm of topsoil to negatively affect the availability of several nutrients (e.g., iron, phosphorus, zinc, copper, boron, manganese, etc), increase the rates of nitrification/soil nitrate levels and lead to severe growth reduction or even dieback.

The soil aeration is essential to Douglas-fir as it is very intolerant to the anaerobic conditions. Therefore it does not tolerate shallow, compact and heavy (clayey, with pseudogley), waterlogged soils, where rooting is restricted. If planted on such sites Douglas-fir trees become unstable and are prone to windfalls/uprooting as they are plate-like (without any taproot) and shallow root systems develop.

The summer water deficit (especially cumulated over several years) in the soil leads to either the dieback of mature Douglas-fir trees or the reduction of their diameter increment; the water deficit can be partially compensated by the nitrogen availability in the soil.

Douglas-fir has a positive effect on forest soils as, compared to other conifer species such as Norway spruce, its litter acidifies the upper soil layers to a lesser extent, it is easily decomposed, transforms better and produces more favourable forms of humus.

3.1.3 Shade tolerance

In the natural range, except in its youth, when Douglas-fir is considered *reasonably tolerant to shade*, both coastal and interior varieties are classed as *intermediate* in overall shade tolerance.

If not released after a maximum of four to six years, shade from the side and especially from above is harmful to Douglas-fir trees. It causes deformations of the tree trunk and crown, impedes root development and even leads to mortality due to competition with other species.

In Europe, Douglas-fir is often considered a *moderate shade-bearing* species that is more light-demanding than Norway spruce and silver fir. As pointed out by Savill (2013), ”Douglas-fir is sufficiently shade-bearing to be useful for planting beneath well-thinned canopies, especially for enriching scrub and in neglected woodland, but it is not so shade-bearing that it will form a lower storey to another species, unless it has a very light canopy”.

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3.2

Potential of Douglas-fir under climate change

Jean-Charles Bastien

3.2.1 Impacts and risks of climate change on temperate forests

Recent climate change is a reality. Over the past 30 years, temperatures increased by 1.2°C in Europe. Droughts have also dramatically increased in number and intensity. In Europe, a possible increase of mean annual air temperature by 2 to 4.5°C is foreseen by the end of the century, depending on greenhouse gas emissions scenarios. A 10 to 30% decrease in annual precipitation is also estimated in the southern part of Europe. In this context, the consequences and risks associated with climate change for forest trees, and Douglas-fir in particular, are many. Climate change is projected to lead to increased water scarcity, higher temperatures and increased CO_2 concentration, which all directly affect tree physiology and the behaviour of other plant or animal species that make up forest ecosystems.

Bud burst phenology is strongly dependent on temperature. Observations made on Douglas-fir over the last 35-year period in France show an average advance in the bud flushing period of five days per decade. The main risk associated with this phenomenon is an increased sensitivity to late spring frosts.

Summer drought is considered to be the greatest risk Douglas-fir will face. Drought affects growth, survival and even regeneration due to its impact on several physiological processes, including gas exchanges and carbon allocation. In the case of water deficit, stomatal regulation is a protection mechanism used by Douglas-fir to limit its transpiration. When the water deficit is too intense or lasts too long, stomatal regulation may not be enough. In that situation, loss of the hydraulic continuity of the tree may occur. It is linked to air bubbles appearing in the sap-conducting vessels, caused by an imbalance between the demand for water (transpiration) and its availability. This phenomenon, called *cavitation*, can cause damage ranging from simple leaf fall to tree death, through the mortality of branches or a significant portion of the crown. In periods of high temperatures, leaf temperature can reach a lethal threshold resulting in the partial or total loss of the tree foliage.

In addition to these examples of the direct damage caused by drought, the reduced assimilation may also have an impact on the amount of carbon reserves that the tree will produce during the year. These reserves are important for cold resistance, growth and the vitality of the tree.

3.2.2 Consequences and forecasts for Douglas-fir in its natural range

Douglas-fir is an ecologically and economically important species in North America (Hermann and Lavender, 1999). Over the past few years, several studies have been conducted to determine the impact of climate change on this species in its area of origin. This section presents the available knowledge on the impact of climate change on different aspects, such as change of distribution range (Rehfeldt et al., 2006; Weiskittel et al., 2010), changes in radial growth (Chen et al., 2010), changes in productivity (Weiskittel et al., 2010), changes in wood density (Stoehr et al., 2009) and the risk of genetic maladaptation (St Clair and Howe, 2007). The results can be partially contradictory depending on the methods used.

To assess the possible changes in radial growth with increasing drought, in 2010, Chen et al. used the time series data of 179 Douglas-fir obtained in the natural area through increment core readings. They studied the response of radial growth to past climate variations and projected future climate scenarios. Their results showed that coastal and interior Douglas-fir growth was limited by summer drought (Palmer drought index; Palmer, 1965). The significant relationships established between this drought index and growth made it possible to establish growth projections for three regional groups and for different climate scenarios. Growth response was found to be more pronounced in the north than in the south of the study area. The authors hypothesise that populations in the southern part of the area are genetically more adapted to drought and therefore less affected by adverse water conditions. These results suggest that climate change may not necessarily affect the southernmost populations and margin areas of the natural distribution so quickly. The results contradict the projections of many models of range distribution, based on bioclimatic envelopes established for different species (see for example Rehfeldt et al., 2006; Weiskittel et al., 2019).

Rehfeldt et al. (2006) and Weiskittel et al. (2010) proposed maps of the future Douglas-fir range in 2030, 2060 and 2090 by transposing a bioclimatic model (mainly based on growing season precipitation, drought index) to a future climate. For the majority of stands, the results show no change or a slight site index increase between 2030 and 2090. However, even if Douglas-fir seems less affected than seven other tree species, this model forecasts a strong decline of the southern populations (southwest Rocky Mountains) and of the most coastal populations in Washington and Oregon. On the other hand, an extension of central populations (central Rocky Mountains) is anticipated.

In addition to its effects on the Douglas-fir's distribution and productivity, climate change could also affect wood quality. A study conducted by Stoehr et al. (2009) found that Douglas-fir's wood density in British Columbia (Canada) could decrease on average by 2.1% or 1.4% depending on the climate model. This decrease is mainly due to a change in latewood proportion driven by reduced rainfall during the month of July. According to the authors, these changes may imply reduced wood quality for structural construction.

In common garden experiments at nursery stage, St Clair and Howe (2007) estimated the risk of mal-adaptation to future climate of coastal Douglas-fir provenances from Oregon and Washington. Models connecting field traits to the climatic characteristics observed in the area of seed origin were used to predict the same traits for future climate conditions. The relative risk of calculated mal-adaptation corresponds to the proportion of non-overlap between the distributions of observed and predicted characters. The results obtained for the combination of characters including bud burst, germination, growth and stem/root allocation, show a high risk of mal-adaptation (0.50 to 0.90) depending on climate models used. Finally, the authors recommend an upward move of populations both in altitude (450–1,130 m) and in latitude (1.8° to 4.9°, i.e., 200 to 540 km to the north). However, this study suffers from several shortcomings: observations focused on seedlings and not on adult trees, phenotypic plasticity was not taken into account, and the consequences of this maladjustment on the physiology and development are poorly understood.

In conclusion, these studies show the high vulnerability to climate change of Douglas-fir stands located in the coastal part of Washington and Oregon states. For interior Douglas-fir, the results for the southernmost populations are more contradictory. Part of the explanation lies in the underlying assumptions of the models and especially, shortcomings in the simple empirical approaches of some of these models. Moreover, although deemed more important nowadays, genetic adaptation is rarely considered in such simpler models.

However, mapping programmes[1] already exist in north-west USA and British Columbia (Canada) to help forest managers match seed lots with planting sites, using current climate models or a climate change model. Still in development, these tools can be used to explore alternative future conditions, assess risk, and plan potential responses, but cannot tell the user exactly which seed lots will be optimally suited to a particular planting site in the future.

3.2.3 Consequences and forecasts for Douglas-fir in Europe

Whereas 2014, 2015 and 2018 were the warmest years on record in Europe to date, 2003 was certainly the year in which a summer drought had the greatest impact on the forests of Western Europe. Like most forest species, Douglas-fir suffered from these extreme drought and heat conditions. The most visible consequences were needle loss and the reddening of many trees. Added to these visual symptoms were effects on radial growth. A French study of 13 tree species (Girard, 2009) showed that Douglas-fir was the species whose production had been the most impacted in 2003 with a 24% reduction in radial growth in 2003 and an overall mortality of 7%.

Sergent (2011) showed that Douglas-fir decline in France since 1989 was clearly related to extreme and recurrent drought events, including that experienced in 2003. Soil water deficit (> 150 mm), as calculated by water balance, was highlighted to be the hazard responsible for decline, while topography, orientation (ie south or south west), mean climatic conditions and age were identified as vulnerability factors. Douglas-fir decays were very often observed on trees more than 30 years old, suggesting that reducing rotation length could be a good management practice to reduce Douglas-fir stand's vulnerability. Sergent's study also showed clearly that soil nutrient fertility is an important factor in Douglas-fir recovery after a drought event. Nitrogen fertilisation improves significantly carbohydrate stock as well as foliage and water-use efficiencies. Finally, Douglas-fir stand's resilience is noticeably improved when thinning is properly scheduled as it reduces tree competition for water.

In Europe, where Douglas-fir is primarily planted, the choice of forest reproductive material is crucial in terms of both adaptation to local environment and in the context

1 See for example: Seedlot Selection Tool (developed by the Oregon State University), or ClimateBC_Map (developed by the University of British Columbia).

of an evolving climate. With a view to identifying European areas suitable for growing Douglas-fir under future climates and to plan for assisted migration, Boiffin et al. (2017) combined transcontinental datasets of Douglas-fir occurrence and climatic predictors to compare the realised niches between native and introduced ranges. They calibrated a species distribution model (SDM)[2] in the native range and compared areas predicted to be climatically suitable with observed presences in Europe. The realised niches in the native and introduced ranges showed very limited overlap. The SDM calibrated in North America had very high predictive power in the native range, but failed to predict climatic suitability in Europe where Douglas-fir grows in climates that have no analogue in the native range. Climatic compensation factors, silvicultural practices, genetic plasticity and adaptation are put forward as explanatory mechanisms.

Monitoring individual trees after the severe 2003 drought, Martinez et al. (2008) observed that, among those Douglas-fir trees that had died as a result of the drought, very few (10%) had previously shown a decline in growth. For some of these drought-stricken trees, their relative growth during previous years had even been noticeably higher than those trees that had remained healthy during and after the drought. About a quarter of the trees that had decayed during the drought fully recovered their foliage within the following two years. Moreover, microdensity measurements on wood increment cores showed that this earlier higher growth of the dead trees corresponds to a lower mean wood density, mainly due to a lower density of the early (spring) wood. Based on these results, the authors suggest using wood density as a proxy of Douglas-fir drought tolerance. In the context of genetic improvement programmes, they recommend that such signs of vigour are controlled by maintaining a high level of wood density to avoid selecting trees with a lower water stress tolerance.

Since the middle of the 20th century, huge efforts have been deployed in Europe to improve Douglas-fir reproductive materials for reforestation. This has been done through identifying the best seed origins from the natural range and the establishment of seed orchards (see Chapter 3.3). In order to understand how these populations would respond to climate regime shifts, Isaac-Renton et al. (2011) and Boiffin et al. (2017) did a meta-analysis based on long-term growth of 2,800 Douglas-fir provenances established in 120 European test sites. The studies show a good plasticity in the populations already used within major European bioclimatic zones. Provenances from coastal and cascades ranges of Washington and northern Oregon show the highest growth rates in a large majority of European sites. They also revealed that, in Europe, Douglas-fir growth is optimal in areas where the average annual temperature is 2°C above the average annual temperature of their place of origin.

However, in the long-term (beyond 2050), bioclimatic models suggest replacing currently used seed sources with more southern forest reproductive materials. Indeed, analysing two provenance tests under the Mediterranean climate in France, Sergent (2011) outlined the good compromise "growth–survival" offered by northern coastal Californian seed sources, suggesting that this material could represent an alternative to current forest reproductive material for the second half of the 21st century.

2 Species distribution models (SDMs) statistically relate species occurrence to climatic variables. When SDMs are projected across times or spaces, it is assumed that species climatic requirements remain constant.

3.2.4 Conclusion

It is likely that climate change will impact Douglas-fir in both its natural and introduced ranges. Site factors such as soil depth, texture and slope aspect will be important in moderating or exacerbating the effect of global warming.

Under natural conditions, the local evolution or migration capabilities remain very limited because the number of generations necessary for a population to evolve to a new optimum may be too high. However, in Europe, where Douglas-fir is most often planted, these processes can be accelerated by human actions. Indeed, depending on silviculture practices, stands may be regenerated up to three times per century. During these renewals, with each rotation cycle, trees can be replaced by varieties more adapted to future conditions, thus accelerating the selection/adaptation process or simulating an accelerated migration. In addition to these mechanisms based on the selection of trees and plants, forest managers can also adapt forestry practices to mitigate the intensity of climatic hazards. These options require not only an awareness of the vulnerability factors involved in the decline (e.g. site, climate, silviculture etc) but also an understanding of the varieties that are most tolerant to drought.

Even if, as is very likely, productive Douglas-fir plantations will be possible at higher latitude and higher elevation than today, there are management practices that can help the present stands cope with the expected environmental changes, such as higher planting density, increased thinning and shorter rotations to allow for some natural and artificial selection within stands. Moreover, new Douglas-fir seed sources or varieties need to be experimented with today in order to be successfully planted on a larger scale tomorrow.

However, climate will also impact the functioning of the other organisms that make up the forest ecosystem. Thus, several authors have reported that, among the risks associated with climate change, there is an increased risk of diseases and pathogens due to changes in their distribution and impacts (Hemery et al., 2010; Chmura et al., 2011).

The next 20 years will clarify how Douglas-fir responds throughout the world to the risks of climate change. This period should also see significant improvements in our understanding of the vulnerability of Douglas-fir varieties and the use of high throughput methodologies (ie wood properties) to predict this vulnerability. Although many of the impacts of climate change may be decades away, developing strategies and strengthening monitoring programmes should start now.

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3.3

Genecology of Douglas-fir and tree improvement strategies

Monika Konnert and Jean-Charles Bastien

3.3.1 Genecology of Douglas-fir

Within the natural range of Douglas-fir, the environmental variations caused by specific climate and site conditions create various local adaptations, as demonstrated in studies on phenotypic traits (Savolainen et al., 2007), such as survival, height growth, frost or drought hardiness and bud phenology (Holderegger et al., 2006).

Understanding the variation patterns of these "adaptive traits" of Douglas-fir is important in choosing the right provenance to be planted, managing stands and establishing breeding strategies for future climates (Kappeller et al., 2013).

Douglas-fir trees or provenances with early bud flush are often damaged by late spring frosts, whereas trees that set bud later are likely to be damaged by early fall frosts and winter cold. Different adaptive traits are inter-related to a certain degree. For example, bud flush, bud set and second flushing are related to annual height growth. Early bud setting limits annual shoot elongation and therefore growth performance. Second flushing (when a tree sets a bud, then flushes a second time in the same growing season) promotes annual height growth but also increases the predisposition for fall frosts. Because second flushing of Douglas-fir occurs when temperature and moisture conditions are favourable, a higher probability of cold damage may be expected under climate change, especially for seedlings and young trees.

In its natural range, Douglas-fir shows high levels of genetic variation for different adaptive traits within and among varieties, provenances and populations. There is strong evidence that patterns of genetic variation of adaptive traits are associated with temperature and moisture regimes, which are the major selective forces for Douglas-fir. This explains why populations separated by only 100 m to 200 m in elevation can differ in adaptive traits. These findings are important when Douglas-fir provenances from the natural range are planted in Europe. They demonstrate that similarities in climatic conditions between regions of origin and planting regions in Europe have to be considered.

Adaptive traits of Douglas-fir have been examined in short-term provenance trials (common garden studies) in nurseries, greenhouses or growth chambers and in long-term provenance trials, where plant material of different origin was planted at several different sites in a field and measured for at least 10–30 years. Both approaches showed clinal variation patterns in tree growth, phenology and cold hardiness for Douglas-fir in the natural range. Clinal variation means that the relation is continuous between a trait and an environmental variable (for example, mean annual temperature, mean annual precipitation, total precipitation during the growing period). For Douglas-fir, clinal variation of adaptive traits is observed at the variety level and at the population level.

Variation in growth and adaptive traits at variety level

Within both Douglas-fir varieties (coastal and interior) west to east clines in adaptive traits are so distinct across the coast-mountain range that it can be considered ecotypic. North to south clines are less pronounced and seem to be stronger in the northern part of the interior Douglas-fir distribution range (Rocky Mountains).

In addition to the clinal variation, pronounced variety-related differences in growth performance and bud phenology were observed. Thus long-term provenance trials illustrated that coastal Douglas-fir populations have a lower growth rate than the interior ones. Populations from the transition zone in British Columbia and northern Rocky Mountains (the so-called "grey" Douglas-fir – var. *caesia*) are intermediate in growth. Compared to coastal populations, interior populations flush and set bud earlier and are more tolerant to fall frost, winter cold and winter droughts. When Douglas-fir is planted, winter drought damage can be of decisive importance for the survival of young trees. Such damage appears when soil is frozen with nearly no snow cover, the temperatures are low and the sun radiation is high. Under these conditions trees are unable to replace the water lost by transpiration. In European Douglas-fir plantations, in snow-poor winters, a mortality of over 50% could occur mainly for coastal Douglas-fir provenances.

At the other side, coastal provenances are more tolerant to both *Rhabdocline* needle cast and Swiss needle cast diseases.

Variation in adaptive traits at population level

Within varieties, temperature- and moisture-related patterns in adaptive traits can be observed in provenance trials. In this way, the timing of bud burst and bud set has been shown to be related to elevation, latitude, longitude and distance from the ocean. Populations from higher elevations, more northern latitude and greater distance from the ocean, meaning populations from colder locations, typically set bud earlier and are more tolerant to fall frosts and winter cold. On the other hand, these populations flush slightly earlier in spring and are, therefore, more susceptible to late frost events. This is due to a lower heat-sum (degree-day) requirement after reaching the chilling requirement. Interior populations are thought to have a lower heat-sum requirement because, when temperatures begin to warm interior regions, it usually means that winter is over and there is a lower risk of late spring frosts. In contrast, coastal populations are considered to be genetically programmed for a much higher heat-sum requirement because coastal winters are milder, but have a higher risk of late spring frosts. Populations from higher elevations are also better able to survive winter drought. The faster emergence of their seedlings seems to help their establishment as soon as conditions are favourable in the spring.

The described variation patterns were confirmed by nursery tests in Europe (e.g., southern Germany) with seeds from controlled harvests in the natural range and seeds originating from European stands of known origin. Progenies from European stands behave in the same manner as progenies from the stands of origin in the native range, showing that European stands have not already adapted to the new conditions in Europe.

Within the natural range of Douglas-fir, there is a pronounced decrease in precipitation and humidity from north to south and from west to east. Southern populations of both varieties are exposed to hot, dry climates with early summer droughts. Within both varieties, drought hardiness seems to increase from north to south and also from west to east.

Figure 8. Frost damage in spring (21.05. 2011) in an experimental plot in Freising (south Germany – provenance Salmon Arm (Canada, B.C,) – interior Douglas-fir (Photo: ASP Teisendorf).

Conclusions

Douglas-fir is an adaptive specialist. Clear differences in growth potential and adaptive traits between varieties and continuous clinal variation within varieties have to be considered when provenances are transferred to Europe or even when forest reproductive material from European stands is planted. In choosing the right provenance, comparison between the climate of origin and the climate of the planting site now and in the future is and remains important.

This is also true from the point of view that European stands have not yet adapted to the new conditions in Europe. Generally, progenies from European stands behave in the same manner as progenies from the stands of origin in the native range. Therefore it is important to know the origin of the seed stands at least at the variety level, to predict the growth and adaptive potential of the progenies.

Provenance recommendations for Douglas-fir in Europe, elaborated until now only at national levels, are generally based on the above described adaptive patterns, which were studied in provenance trials.

Given the good adaptability, adaptive traits pattern and growth of the coastal variety in Europe and, by contrast, the poor performance of the interior variety, the former is the first choice in all European countries. All the Douglas-fir seed sources recommended for reforestation in Europe are originating from the part of the range between 40° and 50° latitude, west of the cascade range and below 600 m elevation (Bastien et al., 2013; Fletcher and Samuel, 2010). In regions with fall and winter frosts, provenances from the middle elevation zone of the Cascades range in Washington and from northern Oregon seem to be best suited. In oceanic Europe, where frost is less likely, coastal provenances from Washington and Vancouver Island are primarily recommended. In Mediterranean Europe, provenances from coastal southern Oregon and northern California could be recommended for their better survival in comparatively harsher and drier sites.

As a next step, provenance recommendations at a European level should be developed, including both, provenances from the native range but also European seed source.

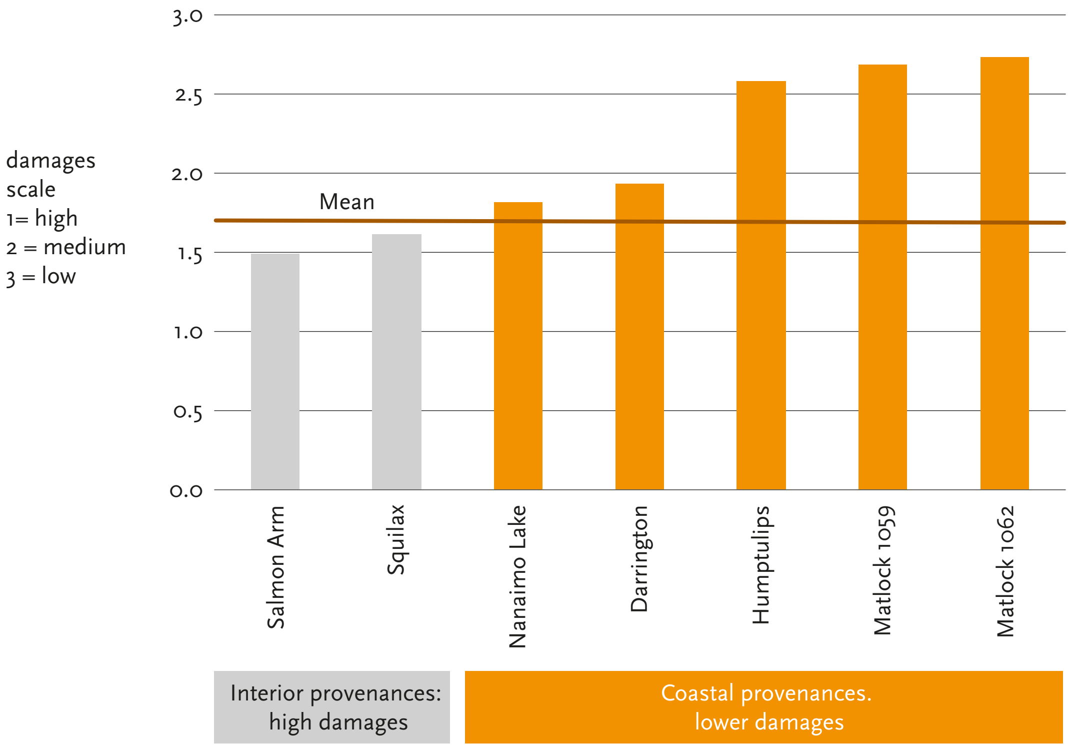

Figure 9. Late frost damage in a nursery study in southern Bavaria. Provenances from the Rocky Mountains (interior varieties), which flush earlier, are severely damaged by late frosts, whereas provenances west of the Cascades (coastal varieties) show lower damage. A clinal change from west (provenances Humptulips and Matlock) to east (provenance Darrington, Nanaimo Lake) is also observed.

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3.3.2 Breeding programmes

By the middle of the 20th century, Douglas-fir breeding began almost simultaneously in the natural range (Canada, USA Pacific North West) and in Europe. In the natural range, breeders delineated breeding zones within which breeding programmes were implemented separately. On the other hand, European breeders had, as a necessary prerequisite, to acquire knowledge on the intraspecific variability of this exotic species in order to identify the best genetic pools on which to build breeding programmes. This difference in context explains why a brief presentation of breeding programmes in the natural range precedes that of programmes conducted in Europe.

Breeding programmes in the natural range

In the Pacific Northwest, extensive breeding programmes for Douglas-fir are run with more than four million progenies from nearly 34,000 selected trees growing in more than 1,000 test sites (Howe and St Clair, 2007). Breeding began here in the 1950s when some government agencies, forest companies and forestry associations started to select elite trees from coastal Douglas-fir and established clonal seed orchards[3]. Today, most Douglas-fir improvement is carried out by four organisations: the Northwest Tree Improvement Cooperative (NWTIC), the Inland Empire Tree Improvement Cooperative (IETIC), the British Columbia Ministry of Forests (BCMoF), and Weyerhaeuser Company (Howe et al., 2006). The main goals of Douglas-fir breeding programmes are to improve the economic value of tree crops, maintain adaptability and increase disease resistance. Important traits are stem volume and quality, wood quality, spring and fall frost hardiness, drought hardiness, Swiss needle cast and *Rhabdocline* needle cast resistance, *Armillaria* and *Phellinus* root resistance.

The four breeding organisations have different approaches to selection, breeding zones, testing, seed orchards and deployment of improved material within seed planning zones.

The USA

The Northwest Tree Improvement Cooperative (NWTIC) is an umbrella organisation housed since 2004 at Oregon State University. It coordinates a decentralised system of independent cooperatives. The costs of breeding and testing are shared among the members of these cooperatives. Seed orchards are managed by individual organisations that are mostly independent of NWTIC. The NWTIC Douglas-fir breeding programme started with a low-intensity selection of first generation parents, the use of many small breeding zones and very large breeding populations which consisted of parents selected from natural stands within the breeding zone (Silen and Wheat, 1979). Since then, more than 26,000 parent trees have been evaluated (Lipow et al., 2003) and the large number of breeding zones reduced to just eight second-generation zones. About 2,000 parents have been selected for advanced-generation breeding (Howe et al., 2006).

The Inland Empire Tree Improvement Cooperative (IETIC) conducts Douglas-fir improvement for planting in eastern Washington, northern Idaho and western Montana. Compared to the Pacific North-West, Douglas-fir is less important in the Inland Empire than other conifers such as *Pinus ponderosa* or *Pinus contorta*. Since 1974, 200–300 trees

3 **Seed orchard**: an area where superior phenotypes or genotypes are established and managed intensively and entirely for seed production (definition FAO).

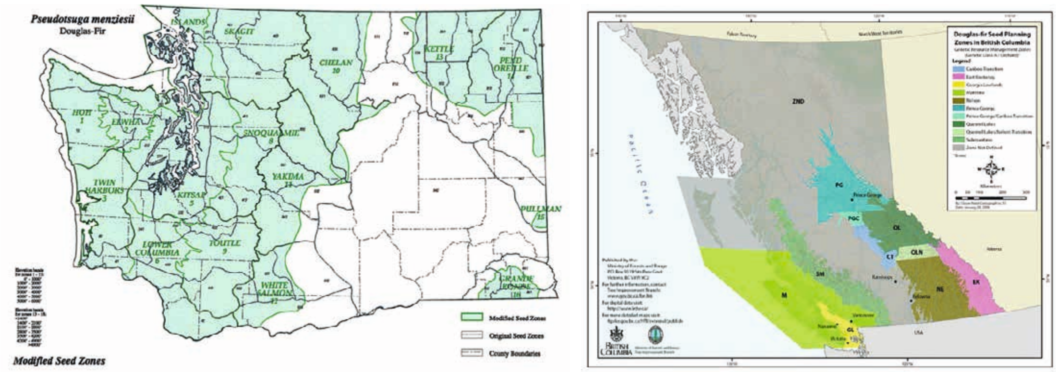

Figure 10. Douglas-fir seed planning zones in USA Washington State (left) and in Canada British Columbia (right).

have been selected in most of the 13 breeding zones. More than 2,500 first generation parents have been field tested to date. Four Douglas-fir seed orchards have been established.

Weyerhaeuser Company has run a large breeding programme since 1963. It started with an intensive elite-tree selection in natural stands aged 25 to 80 years. Altogether 3,500 trees were selected in six breeding zones in western Washington and western Oregon. The primary objectives of the first-generation programme were growth and stem quality (Howe et al., 2006; Stonecypher et al., 1996; Woods 1993). The second-generation populations are nearly completed, while the third generation of improvement is underway. As a result of intensive field tests, the number of breeding zones was reduced to one in Washington and two in Oregon. The long-term goal is to produce elite material via wind-pollinated seed orchards and somatic embryogenesis.

Canada

In **British Columbia,** first-generation selection and testing began around 1960 for coastal Douglas-fir and 1980 for interior Douglas-fir. Since 1998 the Forest Genetics Council (FGC), among other duties, coordinates the operational tree improvement programmes and the management of seed orchards. Within the FGC, the British Columbia Ministry of Forests is responsible for Douglas-fir breeding. In its early years the programme included intensive elite-tree selection, developing inbred lines for subsequent out-crossing, creating inter-varietal hybrids and testing provenances within coastal British Columbia (Orr-Ewing, 1972; Heamann, 1977). Subsequently, a pedigree breeding population was created using structured mating designs. In the coastal programme about 660 parents were tested in 130 field tests. Field tests showed, for example, that the average volume gain of the mid-gain families over the control was 12%, while the top-crosses outperformed the controls by an average of 17% (Stoehr et al., 2007). Currently, the breeding population for coastal Douglas-fir contains 360 genotypes and is sub-divided into 30 sublines, each with 10 to 15 parents, for future testing and breeding. The parents resulting from the tree selection and breeding programme are planted in seed orchards. Each orchard is comprised of clones (or occasionally seedlings) of up to 100 or more parents. The trees in one orchard are adapted for a particular set of biogeoclimatic conditions, forming a Seed Planning Zone (SPZ). SPZ are groupings by seed zone and elevation-bands and form the basis for tree breeding and seed production planning. For coastal Douglas-fir there are three SPZs, for interior Douglas-fir seven SPZs.

Breeding programmes in Europe

In Europe, Douglas-fir tree improvement is linked with the importance of the species in European forestry. At the beginning of the 20th century, when Douglas-fir started to become a significant tree species in European reforestations, problems appeared with seed imported from the interior part of the distribution area. This prompted the creation of provenance trials in Germany (1910) and in the Netherlands (1923). In 1954, the first European-wide provenance trials were launched with 39 commercial seed lots from British Columbia, Washington and Oregon (Schober et al., 1983). Ten years later, under the auspices of IUFRO[4], 182 Douglas-fir seed lots were collected over the whole natural range with true control of the origin. The aim was to identify and preserve the best genetic resources for immediate seed procurement and for future breeding. This collection was distributed to 59 institutions over 36 countries in the world (16 countries in Europe). Many European institutions took the opportunity to field test their own Douglas-fir artificial populations along the IUFRO native seed lots. Planted over 110 sites in Europe, this IUFRO collection was at the origin of a close international cooperation, which is still active even though many field test sites have been decommissioned.

The IUFRO provenance collection supported several studies on the Douglas-fir natural diversity (Burzyński, 1999; Ducci et al., 1989; Ontes et al., 2003; Kleinschmit et al., 1995; Merlo et al., 2008; Michaud et al., 1993; Thompson et al., 1995 among others). The IUFRO provenance collection was also used as a source of vegetal material for the development of DNA markers (isoenzymes, microsatellites) to distinguish the two varieties or even identify the main geographical origin in the natural range (Fussi et al., 2013).

Douglas-fir seed import (seed-zone, elevation) in Europe is still based on the results of the IUFRO provenance trials. The use in Europe of more appropriate imported seed sources increased the quality of the reforestations significantly and reduced late frost damages, *Rhabdocline* damage and improved growth overall. Provenance trials showed that a "good" provenance can provide a 20 to 25% supplement in volume growth over a random chosen seed lot (Fletcher et al., 2010).

Recently, data collected in the international provenance trials was used to quantify how Douglas-fir populations respond when subjected to climate regime shifts and whether bioclimatic envelope models, developed for North America to guide assisted migration under climate change, can retrospectively predict the success of these provenance transfers to Europe (Renton et al., 2014; Chakraborty et al., 2015). These models, which worked best for western Europe, showed that there is already a need to adapt Douglas-fir forests to climate change through provenance selection (see chapter 3.2).

After the installation of the IUFRO provenance trials in the 1970s, further seed collections were implemented by German, French and UK institutions to intensify provenance sampling in the best areas revealed by the IUFRO provenance trials. This seed has been used to establish ex-situ gene conservation plantations in Europe (Belgium, Germany and France), which today cover around 1,000 hectares. In 1985, six European countries (Belgium, Germany, the UK, France, Italy, and Spain) joined their efforts to collect and evaluate 1,000 open pollinated progenies from the seed sources that were known from previous tests to be the most appropriate in Europe. The progeny test network covers nearly 300 hectares over the six countries and will provide base material for long-term breeding in Western Europe.

4 **IUFRO** : International Union of Forest Research Organisations

Douglas-fir tree improvement began in Europe once information on the variability among natural seed sources was known. To reduce their dependency on imports and to secure their seed requirements, many European institutions started creating seed orchards, consisting of large widely spaced trees that are intensively managed to produce (for decades) large amounts of high quality seed. In the European Union, the great majority of the Douglas-fir seed orchards were planted with grafted copies of superior trees. Various methods were used to select these trees:

- Phenotypic selection in locally selected stands.
- Phenotypic selection in provenance trials.
- Selection of elite trees in open-pollinated progeny tests.
- Tree progenies tested in nursery or at young stage in forest progeny tests.
- Trees vegetatively propagated after selection in provenance/progeny tests at nursery stage, then field evaluated in clonal tests.

Selection criteria were generally similar across countries, with growth and general tree architecture being the most important traits. According to climatic specificities, some breeding strategies paid special attention to traits related to adaptation, such as bud flushing, growth cessation, drought or frost tolerance. Wood quality has never been used as a priority trait for improvement, but has sometimes been introduced in the selection index to ensure a minimum genetic gain (or at least no loss) for this trait, which is strongly negatively correlated with growth.

Today's Douglas-fir seed procurement in Europe relies both on seed imports from the natural range, and on seed harvest in European seed stands[5] and seed orchards. Imported seed is generally collected in natural stands within a limited number of seed zones. In Europe, around 600 Douglas-fir seed stands are registered in the *selected* category (e.g., they meet requirements of age, area, uniformity, adaptation, form and growth habit). They cover about 4,800 hectares. Germany certified in the *tested* category 19 seed stands (total area: 44.6 ha), based on their performance in provenance trials.

Douglas-fir seed orchards are registered in the *qualified* and *tested* categories, meaning that their components (generally clones) have been selected or tested on their outstanding performances. The recently published common list of forest base materials shows that 69 Douglas-fir seed orchards are registered in the European Union, covering a total area of 390 hectares. The detailed figures by country are shown in Table 4.

The average individual area of these seed orchards is 5.6 hectares (min 0.1 ha, max 34 ha). It should be noted that three quarters of the total Douglas-fir seed orchards area is planted in only four countries: France, Germany, Poland and Hungary.

Flowering stimulation is often implemented to promote, enhance and equalise seed crop (Philippe et al., 2006). Among many other techniques, stem girdling and injection of gibberellin (plant growth regulators) are most commonly used to stimulate Douglas-fir flowering. It has also been demonstrated that this practise improves pollen flow within the seed orchard, and hence has a beneficial effect on the genetic diversity of the harvested seeds.

In a joint collaboration, 10 EU seed orchards were tested in western Europe. Several of them outperformed the seed lots from the natural range in terms of growth and lateness

5 **Seed stand**: A group of trees that has been identified or set aside specifically as a seed source. The stand consists of selected trees with desirable characters (definition FAO)

Table 4. Number and area of Douglas-fir seed orchards in 15 European countries.

Countries	*Qualified* category		*Tested* category		Total	
	No.	Area (ha)	No.	Area (ha)	No.	Area (ha)
Austria	1	3			1	3
Belgium	3	10.1			3	10.1
Czech Republic	4	4			4	4
Denmark	5	9			5	9
Germany	16	70.1	2	5.6	18	75.7
France	8	43.5	2	48	8	91.5
Hungary	1	0.3			1	0.3
Ireland	1	5.4			1	5.4
Poland	12	74.8			12	74.8
Romania	5	28.1			5	28.1
Spain	2	2.6			2	2.6
The Netherlands	6	30			6	30
UK	1	1			1	1
TOTAL	**65**	**282.4**	**4**	**53.6**	**69**	**389.6**

of bud flushing. In 2009, France launched a wide-range test of its Douglas-fir seed orchards. Over the last seven years, eight varieties have been planted in 35 sites covering the present Douglas-fir plantation zones as well as the areas representative of tomorrow's climate. First results show that, surprisingly, seed orchard rankings for flushing and growth are very stable across sites, as a probable consequence of the broad genetic diversity (several hundreds of clones) included into these synthetic populations. In addition to importing seeds into Europe from the natural area that have proven their superiority, this result should also encourage foresters to make greater use of the seeds produced by European Douglas-fir orchards.

In several countries, research to propagate elite Douglas-fir trees vegetatively has begun. Despite promising genetic gains offered by the clonal varieties, their deployment has been limited by technical factors. Clonally dependent rooting percentage and aging effect of mother stock frequently resulted in lower rooting success and plagiotropic development of the cuttings.

In continental Europe, coastal Douglas-fir is often limited by its susceptibility to winter frosts. To counteract this disadvantage, hybrid families between interior and coastal varieties were created with controlled crossing. Even though some families were sensitive to Swiss needle cast, some hybrid families or clones, combining good growth with frost hardiness and resistance to Swiss needle cast were nevertheless identified (Braun, 1999). Unfortunately, for technical and economic reasons, the mass propagation by seed or by cuttings of these hybrid varieties has remained confidential. Currently, research is underway to develop Douglas-fir's somatic embryogenesis to enable the mass deployment of high-performance hybrid families at a cost compatible with the requirements of the forest plant market (Reeves et al., 2018).

As seen above, many European activities focused on assessing Douglas-fir genetic variability, preserving valuable genetic resources and developing a first generation of seed orchards. The cost associated with a long-term breeding strategy is a barrier for most EU countries where this species is still of minor economic importance. Only a few countries are maintaining a breeding activity beyond the first generation.

Belgium and France have started a selection of elite trees within the 1,000 progenies collected in the natural range in 1985 to create a new wave of seed orchards that will gradually replace older seed orchards. Although traits of interest will include flushing, growth and stem form, selection will focus on improving wood density and wood stiffness. For southern France, Californian genotypes will be included in the breeding population.

In Germany, the short-term breeding activity concentrates on the evaluation of both German artificial stands and European and US seed orchards, in order to offer tested seed sources to the seed and seedling chain as quickly as possible. For longer-term breeding, the programme is based on the evaluation, using progeny value, of several hundred elite trees selected in the best German artificial stands and their valuing as genitors in clonal seed orchards.

Conclusion

In the context of climate change, Douglas-fir will likely play an increasing role in European forestry. It is currently often planted in areas where Norway spruce suffers severe diebacks (cf Chapter 3.2). Moreover, new plantation fields have been established in northern Europe, where milder winter temperature enables Douglas-fir's survival.

Therefore, the demand for Douglas-fir seed will increase in Europe in the next decade and may exceed 2,000 kg per year (around 1,200 kg presently). For its supply, Europe keeps extensively importing seeds from seed zones of the natural area that provenance tests reveal as optimal. Climate change models show that these imports, currently focused on Washington State, will have to gradually move to Oregon for the needs of oceanic and central European countries, and even to northern California for southern European countries.

With nearly 400 hectares of seed orchards, Europe is nevertheless able to produce almost twice its expected needs in Douglas-fir seeds and even to ensure the supply of FRM for the reforestation of new regions that could open up for this species in northern Europe and at higher elevation sites.

This context would certainly justify a European-wide coordinated Douglas-fir breeding programme, based on 1) cross evaluation of existing varieties to stimulate their use in Europe and 2) the development of Douglas-fir harmonised breeding work in a limited number of biogeographical zones to prepare improved varieties better adapted to future challenges of the European forest.

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3.4

Impact of Douglas-fir on forests and open land habitats

Thomas Wohlgemuth, Julian Hafner, Anke Höltermann, Barbara Moser, Stefan Nehring and Andreas Rigling

3.4.1 Introduction

If Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) were a species like *Ginkgo biloba* L., used only in gardens and did not spread, there would be no need for this chapter. But Douglas-fir, which has been planted for a long time in forests on different continents, is now ranked number seven worldwide among invasive conifers outside the *Pinus* genus. In central Europe it is regarded as a valuable, drought resistant alternative to Norway spruce (*Picea abies* (L.) H. Karst.). The productivity of the latter species in lowland forests is presumed to be threatened by rising temperatures and decreasing precipitation. Due to the rapid growth and high wood quality of Douglas-fir, European foresters have promoted this species for many decades. As a result, 5% of the Belgian, 3% of the French and 2% of the German forest area is stocked with Douglas-fir. In some regions, Douglas-fir covers up to 20% of the forested area, such as in the city forests of Freiburg im Breisgau. Once established, Douglas-fir is considered more resistant to episodic drought than Norway spruce and has a lower potential of being attacked by insects. However, given the ongoing expansion of its cultivation in commercial forests, the impact of Douglas-fir on forest ecosystem functioning, biodiversity and ecosystem services must be addressed. Such an evaluation is particularly important for reaching agreements about general regulations for the management of non-native tree species now and in the future. This chapter provides information about Douglas-fir-related risks when planted in either vast numbers or in small quantities. In particular, short summaries are presented on the impact of Douglas-fir on soil conditions and biodiversity, and on life history traits of this species. A discussion among stakeholders in Germany is highlighted as an example of the use of an integrative process to evaluate the invasive status of a non-native tree species.

3.4.2 Impact on soil water and soil chemistry/nutrients

Douglas-fir needles decompose similarly or more rapidly than needles of Norway spruce, silver fir (*Abies alba* Mill.) and European larch (*Larix decidua* Mill.). However, in contrast to Norway spruce, Douglas-fir litter does not result in soil acidification. A study in Germany showed surprisingly low nutrient removal from the soil despite a large wood harvest. In particular, export of calcium, magnesium and potassium in Douglas-fir stands remained comparatively low in comparison to mixed forest stands of beech/Scots pine [*Fagus sylvatica* L./*Pinus sylvestris* L.], beech/sessile oak [*Quercus petraea* Liebl.] and beech monocultures, while export of phosphorus was greatest. Another study comparing beech, oak, Norway spruce and Douglas-fir stands on acidic soils in France reported a general enrichment of the rhizosphere with carbon, nitrogen, calcium, magnesium and potassium in stands with each species. A German study supports this, stating that forest floor stocks of organic carbon were always highest under Norway spruce and Douglas-fir and smallest under beech. In slight contrast, the transformation of 18 pure Norway spruce stands in southern Germany to pure Douglas-fir stands resulted in a loss of organic carbon from both topsoil and mineral soil layers and a reduced nitrogen stock on the forest floor layer yet a slight increase in the total soil nitrogen. Among the principal tree species of central Europe, the greatest biomass and nutrient exports were reported for Norway spruce and Douglas-fir. In summary, Douglas-fir cultivation results in rapid needle decomposition, which has positive effects on soil pH compared to stands of Norway spruce but tends to deplete carbon and nutrient pools in the topsoil (an effect that also holds for beech).

3.4.3 Impact on biodiversity

A (non-native) species that proliferates in a new habitat increasingly modifies its environment, with largely unpredictable consequences for the forest ecosystem, including species composition, richness and abundance. In agreement with the species-area relationship, which specifies an increase in species number with growing habitat area and, inversely, a decrease when area shrinks, changes in habitat sizes, such as more Douglas-fir area and less beech area, always influences species abundance. Relevant questions are which species or species groups benefit and which ones decrease in stands of Douglas-fir, and whether mixtures of Douglas-fir with other tree species could reduce negative effects of pure Douglas-fir stands on several species groups. Parts of these questions have been investigated by research, yet there is an urgent need for more exploration.

a) Soil organisms

A review of the ecological consequences of Douglas-fir cultivation leads to the conclusion that the indirect effects of Douglas-fir on soil chemistry seem to be similar to those of Norway spruce and Scots pine, which in turn allows the coexistence of these tree species with organisms living on and in the soil. This suggests that Douglas-fir influences the soil conditions of formerly broad-leaved forests in a similar way as other conifer species. If Norway spruce and Scots pine stands are replaced by Douglas-fir, this even improves e.g., the humus form. Whether Douglas-fir has allelopathic effects on soil organisms is unclear.

b) Fungi

Earlier studies assumed that non-native species have similar associated fungal species as native species, due to good dispersal abilities of the fungi. However, a recent study compared the fungal species richness associated with different non-native tree species with the area covered by these tree species and found a rather low fungal species number for Douglas-fir in comparison with, for example, black locust (*Robinia pseudoacacia* L.) and *Eucalyptus* spp. The authors of this study suggested that native fungi might be incompatible with Douglas-fir to a greater extent than with other species, which may lead to negative impacts on fungal diversity, especially in pure stands. This interpretation is in line with case studies in Germany and in France, where richness of fungal species in pure Douglas-fir stands was lower in comparison to fungal richness in stands of native tree species.

c) Understory vegetation

Based on several comparative studies in Germany and France on the understory vegetation in pure Douglas-fir stands, mixed Douglas-fir, and Norway spruce or European beech stands, a negative impact of Douglas-fir on vascular plant species diversity could not be found. However, in an extensive field survey in the Black Forest ranging from 300 to 900m above sea level on sites suitable for European beech (*Fagus sylvatica* L.), a higher vegetation cover (around 30%) in Douglas-fir stands resulted from higher light transmission (30%) compared with in beech stands (10%). In particular, grasses such as *Festuca altissima* All. and *Melica uniflora* Retz., ferns such as *Athyrium filix-femina* (L.) Roth and *Dryopteris* spp., and European blackberry (*Rubus fruticosus* aggr.) increased their cover. As a consequence of competitive exclusion by these rapidly expanding species, average species richness in Douglas-fir stands (52 vascular plant species) was lower than in beech stands (62 species). A recent study from the Czech Republic found a higher proportion of nitrophilous plant species in the understory vegetation of Douglas-fir stands in comparison to species assemblies under Norway spruce or European beech. However, other studies highlighted that the degree of light transmission and its influence on ground vegetation are mainly triggered by forest management. In a study comparing plant species richness in different forest stands in Lower Saxony, significantly higher numbers of vascular plant species in pure and mixed Douglas-fir stands were found in comparison to pure or mixed European beech stands. And a study in France concluded that the geographic and geological characteristics of sites influence the vegetation and the soil chemistry more than do the six tree species that were compared (Douglas-fir, oak, beech, Scots pine, silver fir and Norway spruce).

d) Interactions with arthropods

In Europe, only 87 arthropod species feed on introduced Douglas-fir, which is one-third of the species found on this tree in its native range (257). Most of these species are polyphagous. The low number of arthropod species on Douglas-fir in Europe is explained by the fact that Douglas-fir has no congeners there, i.e., no species of the same genus. In contrast, introduced pine species host most of the arthropods found on native congeners such as Scots pine. It is assumed that introduced insects that feed on Douglas-fir cause greater damage than that caused by native insects, due to a lack of natural enemies and indigenous competitors. Even though Douglas-fir tissues seem chemically comparable with Norway spruce tissues, bark beetles attacked Norway spruce 10 times more than they attacked Douglas-fir one and two years after the winter storm 'Lothar' (1999) in France. The consequences of accidentally introduced non-native herbivores or native insect species that may jump from one host to Douglas-fir and therefore exploit vacant niches, is even less certain. Such host jumps, together with fungal pathogens, are considered critical but have unknown ecological and economic consequences (see Chapter 3.5).

In summary, the cultivation of Douglas-fir influences the diversity, composition and abundance of species at different sites, and potential changes must be seen in the context of the area covered by Douglas-fir. While the richness of fungal species in Douglas-fir stands is generally reduced, the composition and richness of plant species in the ground vegetation changes as a result of the altered light transmission under Douglas-fir. Since such changes may also result from management, cautious interpretation is needed. Regarding soil organisms and arthropod species, Douglas-fir cultivation hardly seems to affect species richness/abundance of soil organisms, but it results in fewer arthropod species using Douglas-fir as a host.

3.4.4 Shade tolerance, competition with native species and site preferences

Seeds from Douglas-fir germinate under moist conditions, which are most likely to occur on mineral soils free of vegetation. Further, Douglas-fir is more susceptible to drought than species such as Scots pine during the first years after germination. Young seedlings need a minimum of 20% light transmission and 40% or more light is necessary for the establishment of saplings. In a German study, Douglas-fir seedling abundance was highest in stands with 30–50% light transmission, and sapling (>1.3 m tall) densities were highest in stands with more bright or sufficient lateral light (see Chapter 3.1). Douglas-fir grows slowly in the early stage and typically does not exceed a height of 1.5m after nine years. On nutrient rich and mesic sites, Douglas-fir may therefore often be competitively excluded by other tree species during its early life stage. To favour Douglas-fir, forest managers repeatedly cut dominant vegetation around Douglas-fir saplings. In contrast, on drier and acidic soils, such as in oak communities (e.g., *Sorbo torminalis-Quercetum*) or on nutrient-poor substrate indicated by the presence of *Avenella flexuosa* (L.) Drejer, *Vaccinium myrtillus* L. and *Calluna vulgaris* (L.) Hull, Douglas-fir can escape the ground vegetation or even outcompete it. Hence, despite the broad spectrum of environmental conditions where Douglas-fir can potentially establish if light conditions are sufficient, this non-native species only actually becomes established in a few forest community types, mostly where ground vegetation is less competitive due to nutrient limitations.

3.4.5 Invasion potential

Species are invasive to differing degrees and this is assessed on a range of criteria that covers biodiversity risks, survival and reproduction in the wild and dispersal and establishment at different sites.

For non-native tree species planted in or escaped to German forests, the German Federal Agency for Nature Conservation assessed the invasiveness of 13 tree species using an internationally developed tool for assessing the biodiversity risks of alien species. Nine tree species were found to be invasive in Germany according to the German Federal Nature Conservation Act, and Douglas-fir was one of them. In contrast, a study by representatives of leading forest research institutes in Germany proposed five criteria to evaluate a tree's status of invasiveness: a negative effect on site conditions, a high reproduction potential, a high dispersal potential, a tendency to outcompete other plant species on a site (excluding rare sites, e.g., boulder fields), and limited availability of measures to eradicate individuals on site. Douglas-fir did not meet any of the above criteria and was found to pose the lowest risk of invasiveness compared with 14 other non-native tree species on the list. This forestry-focused evaluation has been challenged by conservationists who consider the possibility of eradication a consequence of a species' invasiveness rather than a criterion of non-invasiveness.

In a worldwide review of all conifers outside the genus *Pinus*, Douglas-fir was ranked among the 10 most invasive species based on the three criteria of seed weight, mean period between large seed crops (intervals between mast years), and mean juvenile period (time from germination to first fructification). A closer look in Europe reveals a spread of Douglas-fir into particular communities. In lowland regions of Burgenland in Austria, Douglas-fir regenerates in acidophilous forest communities (*Sorbo torminalis-Quercetum*, partly also *Luzulo nemorosae-Fagetum silvatici*) as well as in forest clearings and along embankments of forest roads. In the Black Forest (southwest Germany) with locally high Douglas-fir proportions, 60–90% of the randomly selected sample plots in *Quercus petraea* forests, rock outcrops and forested boulder fields have been colonised by Douglas-fir. In Switzerland, Douglas-fir has been planted primarily in productive beech forest communities. A field assessment of regeneration in forests with Douglas-fir individuals older than 60 years revealed the presence of Douglas-fir seedlings in 80% of these forests, though no signs of excessive spread outside the plantations could be found. In comparison to Scots pine (*Pinus sylvestris* L.), germination and early growth of Douglas-fir is slow and thus the species' competitive ability is low during early establishment. Moreover, the shallow root system of Douglas-fir seedlings makes them prone to desiccation during drought spells, which suggests that the species' potential to disperse and compete with native vegetation will not amplify with the changes in temperature and precipitation projected for the coming century. Similarly, a model study for Germany and Austria led to the conclusion that suitable habitats of Douglas-fir may not increase under climate change. In contrast to eg invasive black locust, an unwanted spread of Douglas-fir can be easily controlled by management because Douglas-fir does not reproduce vegetatively.

3.4.6 An integrative process to evaluate the invasive status

In a recent paper, scientists from the Federal Agency for Nature Conservation (BfN) and the Union of German Forest Research organisations (DVFFA) jointly state that, from a national perspective and according to the current state of scientific knowledge, the cultivation of Douglas-fir does not pose a significant threat to biodiversity and ecosystem services at the vast majority of forest sites in Germany. To protect rare and specialised endemic species, the authors recommend that Douglas-fir generally not be cultivated at specific sites, such as open rocky patches or block-falls, shallow and nutrient-poor ridges, xeric grasslands and thermophilic forest communities (i.e., oak forest). Such sites, which are often protected by law and do not represent large areas, should be kept free of Douglas-fir in the long run by removing natural Douglas-fir regeneration, converting neighbouring Douglas-fir stands into mixed stands of other species and avoiding the establishment of new Douglas-fir stands in the neighbourhood. Existing legal regulations for protected areas with respect to alien tree species should remain untouched. If Douglas-fir is planted, it should be mixed with other tree species, ie European beech.

3.4.7 Questions awaiting answers

In order to provide evidence-based recommendations for the cultivation and limitation of Douglas-fir, the following pressing questions must be answered: (1) What is the site-specific invasion potential of Douglas-fir throughout Central Europe, i.e., which sites are most susceptible, and does abundant Douglas-fir outcompete other species? Answers to this question are lacking for several regions. (2) How far are Douglas-fir seeds dispersed? Although single seeds may be spread by wind over distances of 1–2 km, most seeds are distributed 100–150 m from a seed tree. Such numbers are reported from studies in North America and are not yet available for Central Europe. (3) To what degree can Douglas-fir be added to stands of other species, for example beech, without negatively affecting the various species groups?

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3.5

Pests and diseases in the native and European range of Douglas-fir

Alain Roques, Marie-Anne Auger-Rozenberg, Paolo Capretti, Daniel Sauvard, Nicola La Porta and Alberto Santini

3.5.1 Introduction

Douglas-fir pests and diseases have been well studied in the native North American range. While records show that more than 250 species of phytophagous arthropods and several hundred species of fungi develop on this tree species, only a few of them have so far been introduced to Europe. It is therefore important to identify the species that may be introduced. Identifying the precise steps in the colonisation process of pests native to Europe is also necessary in order to understand which tree structures have to be surveyed more carefully in the future.

3.5.2 Pests and diseases in the native North American range

Arthropod pests in the native North American range

The fauna associated with Douglas-fir in Western North America is highly diverse, with nine orders and 45 families involved. However, coleopteran beetles and lepidopteran moths are largely dominant, each group including about 100 species, whereas fewer than 20 species of hymenopteran sawflies or hemipterans (aphids and woolly aphids) are recorded (Figure 11). However, only a limited number of species cause economic damage. Recurrent outbreaks of defoliating moths have been observed over large areas. Larvae of the tortricid moth, the western spruce budworm (*Choristoneura occidentalis*), and a lymantriid moth, the Douglas-fir tussock moth (*Orgyia pseudotsugata*), may rapidly defoliate a tree. Whole trees can die if they suffer repeat attacks over several seasons. Nonfatal defoliation by moth larvae may also weaken the trees to the point of inviting fatal attacks by xylophagous insects. Among them, the Douglas-fir bark beetle, *Dendroctonus pseudotsugae*, is a major pest all over the Douglas-fir range, from British Columbia to Mexico. It usually prefers weakened trees in which populations expand rapidly and, in subsequent generations, the beetles attack and kill nearby healthy trees. Although devastating (e.g. 8.3 million m^3 of standing trees killed between 1949 and 1953), these outbreaks are usually short-lived because, as more of the susceptible hosts are killed, attacking beetles are forced into increasingly healthier trees and populations decline. Other noticeable wood-boring insects include the Douglas-fir engraver *Scolytus unispinosus*, the Douglas-fir pole beetle, *Pseudohylesinus nebulosus*, the ambrosia beetles *Gnathotrichus sulcatus* and *Trypodendron lineatum*, and several *Monochamus* long-horned beetles. However, all these species usually infest weakened or dead trees and do not represent a significant threat to standing trees. An exception is the flatheaded fir borer, *Melanophila drummondi*, which can kill apparently healthy trees in the case of a large infestation, especially on dry sites. Root borers may cause chronic mortality through predisposition to fungal infection, and especially affect young trees by girdling them to death. An emerging concern is the Warren root collar weevil *Hylobius warren*i whose larvae bore into and feed on the bark and cambium. Sap feeders are essentially represented by the Cooley spruce gall adelgid, *Adelges cooleyi*, which has Douglas-fir as secondary host, the primary one being spruce, *Picea* spp. The adelgid requires both tree species to complete its lifecycle over two years but, in the absence of spruces, asexual parthenogenetic generations persist on Douglas-fir. On *Pseudotsuga*, the presence of the adelgid, indicated by white cottony tufts on the new needles, shoots and cones, may cause heavy discoloration and shedding of foliage, especially in poor sites and in nurseries. Another sap- feeding arthropod observed to break out in nurseries and immature stands is the spruce spider mite, *Oligonychus inunguis*. The mites spin a webbing of fine silk around twigs among the needles which show a mottled, bleached discoloration. Seedlings and small trees are often killed in the case of large infestations, which are favoured by hot, dry weather. Three species of needle midge, *Contarinia pseudotsugae*, *C. constricta*, and *C. cuniculator* have been recorded to gall the needles, which subsequently darken or redden and fall precociously. Cones and seeds host a rich fauna of 26 species, most of them being specific to these reproductive structures. They induce large damage in seed orchards all over the western coast. The major species include the Douglas-fir moth, *Barbara colfaxiana*, the Douglas-fir cone gall midge, *Contarinia oregonensis*, several species of *Dioryctria* cone moths, the Douglas-fir seed chalcid, *Megastigmus spermotrophus*, and the Western conifer seed bug, *Leptoglossus occidentalis*. Additionally, the Douglas-fir twig beetle, *Pityophthorus orarius*, mines and kills tips of apparently healthy twigs, killing primordia and developing conelets, and may constitute a problem in seed orchards.

Diseases in the native North American range

P. menziesii hosts hundreds of fungi in its native range, but relatively few of them cause serious problems. Various species that cause damping-off (in order of importance, *Fusarium, Phytophthora, Pythium, Rhizoctonia* and *Botrytis)* may cause significant loss of seedlings in nurseries. In plantations, *Rhizina undulata*, *Armillaria* spp. (shoestring root rot), and *Phellinus weirii* (laminated root rot) can cause significant damage and loss. *P. weirii* becomes a serious threat to second-growth Douglas-fir after 50 years. Fast-growing trees are rapidly killed and are easily wind-thrown, which can also damage nearby healthy trees. Of the many heart rot fungi (and there are over 300), the most damaging and widespread is red ring rot due to *Phellinus pini*, which is the widest diffused agent of white rot. Knots and scars resulting from fire, lightning and falling trees are the main causes of infection. Losses from heart rot far exceed those from any other decay. Douglas-fir is the primary host for *Grosmannia wageneri,* previously known as *Leptographium wageneri* var. *pseudotsugae*. This fungus colonises the sapwood of the roots and lower stem. Affected trees grow poorly for several years and then usually die. The disease typically occurs in enlarging foci, spreading at rates of about 1m per year. It is considered a major threat to managed crops of Douglas-fir. The fungus is indigenous and, so far, strictly confined to western North America. Other heart rot fungi include *Echinodontium tinctorium*, *Fomitopsis cajanderi* and *F. pinicola*, three species causing major damage, and *Fomitopsis officinalis, Phaeolus*

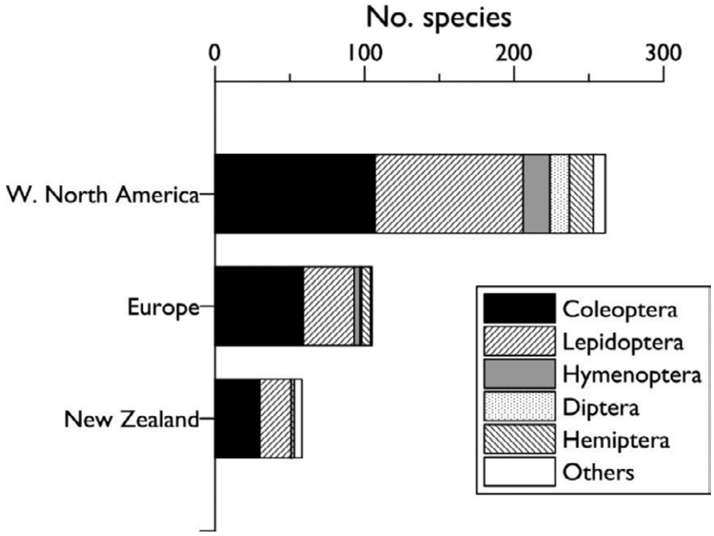

Figure 11. Comparison of the composition of the arthropod phytophagous fauna associated with Douglas-fir in the native western North America and the invaded Europe and New Zealand.

schweinitzii and Sparassis crispa (Hepting, 1971; Siepmann, 1976). *Heterobasidion* spp., presenting with different species in North America and Europe, is a serious cause of root and butt rot in Douglas-fir. In North America the most virulent of this host is *H. occidentalis*, more common in the western part of the continent, but *H. irregulare* can also infect Douglas-fir, with more minor virulence (Garbelotto and Gonthier, 2013). The Ascomycetes *Leucostoma kunzei*, formerly known as "*Valsa kunzei*", is the causal agent for the branch and stem cankers on Douglas-fir that were first described by Waterman in 1955 in Washington. Later, *L. kunzei* was reported in several other states, including eastern USA. *Pesotum picea* complex is the causal agent of bluestain in several conifer species, but the holotype of this species was obtained from stained wood of Douglas-fir, (isolate C1194, CBS 102358, T. Harrington).

Among several needle diseases, the most harmful are the needle casts caused by two ascomycetes: *Rhabdocline pseudotsugae* and *Phaeocryptopus gaeumannii*. First described from provenances from Montana and Idaho, *R. pseudotsugae* has since been found wherever Douglas-fir is grown and is a major problem in young plantations, reaching damaging proportions only after prolonged periods of rain while the new needles are appearing. Some varieties of Douglas-fir, as var. *cesia* and *glauca*, are more susceptible to the disease. While var. *menziesii* shows a general higher level of resistance, this varies significantly among provenances; low elevation provenances are more resistant than high elevation provenances. Christmas tree plantations are particularly vulnerable because they are planted in closely spaced, highly susceptible monocultures and because there is no rotation of species. Another native of western North America, *Phaeocryptopus gaeumannii*, was also detected in Switzerland in the mid-1920s and, for this reason, the disease it causes is called Swiss needle cast. It also occurs on *P. menziesii* throughout its natural range, usually causing modest damage. However, since the late 1980s and early 1990s, Swiss needle cast has been causing an epidemic affecting hundreds of thousands of hectares along the Oregon coast range. Growth losses in the area of the epidemic

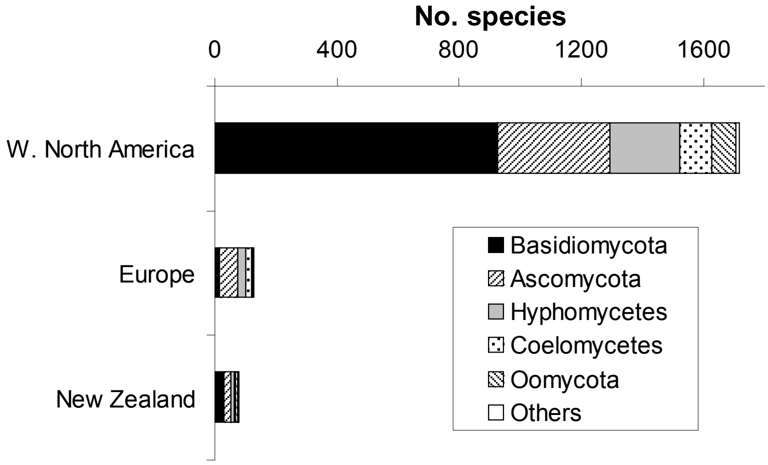

Figure 12. Comparison of the composition of the pathogenic fungi associated to Douglas-fir in the native western North America and the invaded Europe and New Zealand. (USDA and NZFFA database)

generally range from 20 to 50%, and annual growth impacts are estimated to exceed \$200m per year. Another important disease is the needle rust caused by *Melampsora medusae*. The infected leaves turn yellowish-orange. The disease affects mostly conifers, including Douglas-fir, western larch, tamarack, ponderosa, and lodgepole pines. The primary telial hosts of *M. medusae* are *Populus* spp and their hybrids, while the secondary aecial hosts are conifers. In Canada and the USA, Douglas-fir and young plants of *Pinus* spp. and *Larix* spp., are the principal hosts for the aecial state of the fungus (Ziller, 1965; Newcombe et al, 1994). *M. medusae* is indigenous to North America and has already spread from there to other continents. However, its status in Europe is not yet clear. *Arceuthobium douglasii* is a significant parasitic plant throughout most of the natural range of Douglas-fir.

3.5.3 Current pests and diseases in Europe

Limited colonisation by native European insects

After more than a century of extensive plantation in Europe, Douglas-fir has attracted slightly more than 100 native phytophagous arthropod species (Figure 11), a situation similar to other regions where Douglas-fir has been planted (such as New Zealand). This limited recruitment has been hypothesised to result from the phylogenetic distance of *Pseudotsuga* with the indigenous conifers. However, at local scale (such as in Bavaria) the arthropod community associated with Douglas-fir could be rather rich compared those observed on other conifers. The native phytophagous species which has switched to Douglas-fir is composed of xylophagous species, mostly bark beetles and long-horned beetles (about half the total), followed by external lepidopteran defoliators (33%) but very few endophagous species (Figure 12). Thus, so far the fauna essentially consists of species in the orders Coleoptera (56 spp) and Lepidoptera (34 spp). The major part of the colonisers are polyphagous (39%), originally feeding on different conifer families and/or on angiosperms, whereas oligophagous species (feeding on several native genera of Pinaceae) and monophagous species (feeding on only one genera of Pinaceae) account

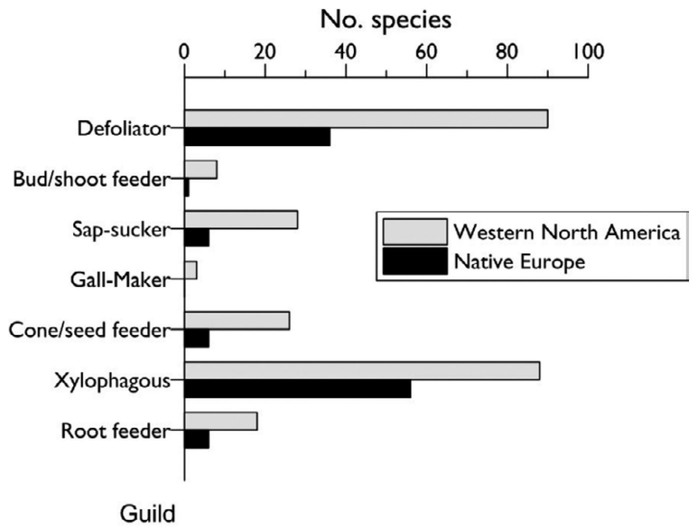

Figure 13. Comparison of the guild composition of the arthropod phytophagous fauna associated with Douglas-fir in its native Western North America and the invaded Europe

for 31.0% and 30.0% of the switches, respectively. Most of the monophagous insects originated from Scots and Black pine, Norway spruce and European fir.

These native species rarely cause large damage to Douglas-fir plantations in Europe. The only exceptions concern lepidopteran defoliators. A lymantriid moth, the vapourer moth (*Orgyia antiqua*), severely defoliated Douglas-fir stands in Poland in the mid-1970s. Another lymantriid species, the nun moth (*Lymantria monacha*), showed local outbreaks in the 1980s to 1990s, especially in central France, while the number of records of larval colonies of the pine processionary, a notodontid moth, largely increased on Douglas-fir since the mid-1990s (see below). Larvae of *Dioryctria mutatella*, a pyralid moth originally associated with cones and shoots of Scots pine, caused increasing damage to the large branches and stem of Douglas-fir, evidenced by the presence of pitch masses mixed with frass. By feeding at tree collar, the large pine weevil, *Hylobius abietis*, also induced severe damage in young plantations in France and Sweden. However, it is noticeable that the 24 native European bark beetles reported so far on Douglas-fir did not cause any severe damage even following the storms and droughts which have hit Europe since 1999. Nevertheless, Douglas-fir was shown to constitute an adequate substrate for the development of the six-toothed spruce bark beetle, *Pityogenes chalcographus*. Females of the pine sawyer *Monochamus galloprovincialis*, the vector of pine wood nematode in Europe, can lay eggs on *Pseudotsuga* but the larvae cannot achieve a full development. Very few sap feeders have colonised Douglas-fir yet. Unlike the native range, cones and seeds also attracted a very limited native fauna, with only the pyralid moth *Dioryctria abietella* causing minor damage, especially in seed orchards.

A (quite) empty niche for North American arthropod invaders

Six alien arthropod species have been introduced to Europe together with their Douglas-fir host. However, in the absence of both indigenous competitors and natural enemies some of them tend to occupy the entire corresponding niche, often causing more damage

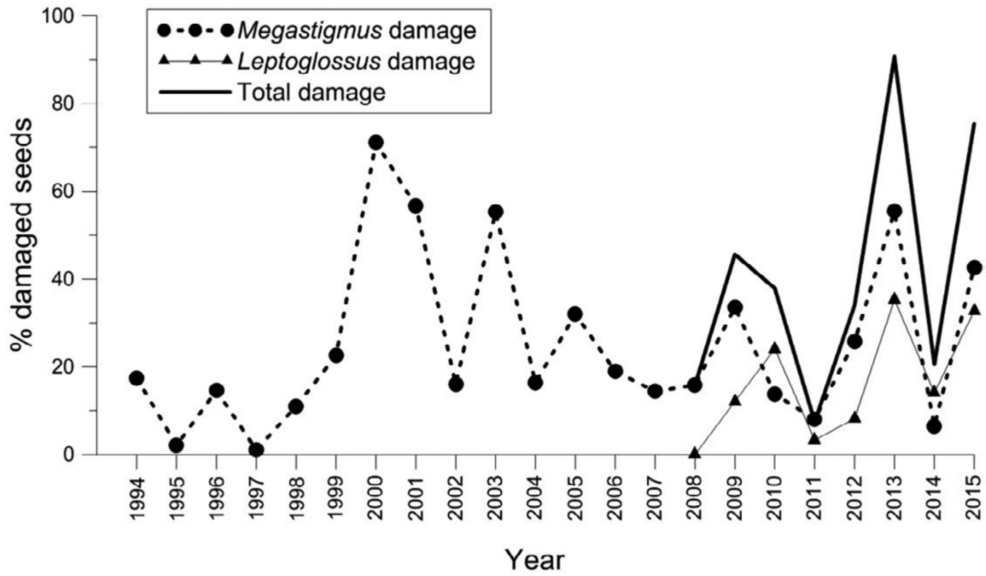

Figure 14. Annual fluctuations in seed damage by the Douglas-fir seed chalcid, *Megastigmus spermotrophus*, and the Western conifer seed bug, *Leptoglossus occidentalis*, in a seed orchard of southwestern France during 1994–2015. *L. occidentalis* was first detected there in autumn 2008.

than in the original range. This is especially true for two species of sap-feeders and two seed insects although the two other exotic species, the bark beetle *Xylosandrus germanus* and the mite *Oligonychus ununguis,* were apparently less successful. Thus, two exotic woolly adelgids, *Adelges cooleyi* and *A. coweni*, probably introduced by the early 1990s, are the dominant sap feeders on Douglas-fir needles. Outbreaks are observed on young open stands and nurseries, especially following mild winters. Damage can be spectacular with trees covered with white tufts in spring but the impact is usually limited. Recently (2015), an exotic needle gall midge, suspected to be the North American *Contarinia pseudotsugae,* has also been detected in Belgium and the Netherlands. The empty seed niche has also been colonised by two exotic seed insects. The Douglas-fir seed chalcid, *Megastigmus spermotrophus*, was probably introduced in Europe together with its host seeds during the last part of 19th century. At present it is the major seed pest in Douglas-fir seed orchards and plantations. Although it is largely dominated by other cone pests in the native American range, this invasive chalcid has virtually no competitors nor natural enemies in Europe and thus tends to occupy the entire seed niche, being responsible for damage rates of up to 100% of the seeds. This extended impact often results in a significant seed deficit, especially in the case of low seed crop, although chalcid damage largely varies in relation to the annual fluctuations in seed crop (Figure 13).The recent introduction of another exotic seed feeder, the Western conifer seed bug, *Leptoglossus occidentalis* (Hemiptera: Coreidae), first recorded in Italy at the end of the 1990s and rapidly spreading all over Europe, may aggravate the situation because the chalcid and bug damage may be cumulative. Any feeding uptake by *Leptoglossus*, even if limited, strongly affects seed germinability.

Current diseases in Europe

Significant reductions in Douglas-fir growth have been associated with needle casts caused by *Rhadocline pseudotsugae* and *Phaecryptopus gaumanni* (*R. pseudotsugae* was

Figure 15. Fruiting bodies of *Phaeocryptopus gaumannii* breaking out from stomata of a *P. menziesii* needle.

first reported in Scotland in 1921, from where it spread extensively throughout Great Britain, finally reaching continental Europe. To date, the fungus has been considered an obligate biotrophic needle parasite. *R. pseudotsugae* can develop an endophytic stage, during which the plant is asymptomatic, and therefore the fungus is easily transported with plants for planting. The presence of the fungus in seeds is also considered to act as a pathway for the introduction of the disease in new environments. Swiss needle cast caused by *P. gaumannii* is an old disease that until recently was considered a classic example of a normally benign plant parasite becoming pathogenic when its host is grown beyond its native range. The disease was first described as devastating Douglas-fir plantations in Switzerland in the early 20th century. Swiss needle cast has tempered the initial promise of extensive Douglas-fir wood production in central Europe, as plantations soon showed symptoms of chlorosis and premature needle loss, generally following the prevailing winds, resulting in poor height and diameter growth. The success of infection is linked to several contributing factors among which moisture on needles plays fundamental role. For this reason the amount of rainfall, as well as a temperature around 20°C, are key factors in the development of the disease. The genetic origin of the host is linked to the resistance to Swiss needle cast. In general, provenances from the interior range of the Rocky Mountains are more susceptible than those from the coast. Trees originating from dry areas are particularly susceptible when planted in sites with significant levels of rainfall. When spring rainfall is substantially above average, even resistant provenances can be affected.

Allantophomopsiella pseudotsugae is the causal agent of canker and shoot disease in Douglas-fir. *A. pseudotsuagae* has a wide range of host species and its infections can result in dieback of young shoots, causing the most serious damage in nurseries and on young trees. The disease is widespread all over north and western European plantations of Douglas-fir (Phillips and Burdekin, 1992).

Diplodia sapinea is a well-known latent pathogen of *Pinus* spp., with a worldwide distribution but mainly present in warm-temperate environments. Infections have so far been limited by the absence of a vector able to disperse *D. sapinea* from pines to Douglas-fir. This picture may change with the introduction of the seed bug *Leptoglossus occidentalis*, which has been shown to be a reliable vector for *D. sapinea*. Root rot caused by *Heterobasidion* spp is also noticeable. Tree susceptibility varies according to the type of forest. Damage is mostly associated with *H. annosum* s.s., from central Europe and UK, where Douglas-fir is planted near or mixed with pine species. The same problem, but to a lesser extent, occurs in presence of Norway spruce affected by *H. parviporum*. However, Douglas-fir generally escapes the infection when growing in proximity or in substitution with silver fir plantations heavily damaged by *H. abietinum*. This situation is common in the Mediterranean region, particularly along the Apennines in Italy where Douglas-fir has been largely planted to replace silver fir stands.

3.5.4 Potential future pests and diseases to be surveyed

Pine processionary moth, an increasing threat with global warming

In the future, global warming may interfere with the slow process of adaptation of native insects to Douglas-fir. The pine processionary moth (*Thaumetopoea pityocampa*) is a pine pest mainly living around the Mediterranean basin, its gregarious larvae forming conspicuous white silky nests during autumn and winter. For a long time its distribution range has limited its contact with Douglas-fir, which was rarely planted in these areas. However, since 1990 the moth range has extended in both latitude and altitude with warmer weather favouring its survival during winter. As the moth reached the bioclimatic range where Douglas-fir has been extensively planted, increasing records of moth colonies on *Pseudotsuga* trees have been reported, especially in southwestern France since 2000 (Figure 16). Surveys carried out there during 2001–2006 in areas where pines and Douglas-fir coexist showed that colony density varied similarly for both species, suggesting that their infestations resulted from the same moth populations. Early instar larvae can achieve a full development when fed with Douglas-fir needles. Moreover, larvae presented a faster growth until the fourth larval instar than those fed with laricio pine, the overall mortality being similar for both tree species. It has been hypothesised that Douglas-fir could provide better food for these moths but is less favourable in other aspects; e.g., the Douglas-fir foliage structure may be less suited for colony nest building. Another constraint is that female moths still need to adapt to lay their eggs on Douglas-fir needles which are unsuitable for oviposition. If such an adaptation occurs, this species may switch from being a potential pest to presenting a serious problem for Douglas-fir stands.

Other potentially risky insect pests

Another candidate to be surveyed in relation to future climate warming is the Siberian moth, *Dendrolimus superans sibiricus*, which is moving west from Siberia. In laboratory conditions the larvae selected Douglas-fir to the same degree as their usual larch host, and *Pseudotsuga* is also highly suitable for larval development. The present trends in the introduction of alien arthropods in Europe (19.6 new species per year on average) are likely to result in the arrival of new species associated with Douglas-fir in its native American range. Considering the present limited colonisation by native wood-boring species, quarantine measures have to be reinforced to prevent the introduction of Douglas-fir bark beetles and, especially, the highly damaging

Figure 16. White silky tent indicating the presence of a larval colony of pine processionary moth on Douglas-fir in southwestern France.

Dendroctonus pseudotsugae. Recent models predict that most of western and central Europe are suitable for the establishment of beetles belonging to the lineage *D. pseudotsugae pseudotsugae* of this species (USA and Canada) but not for those of the Mexican lineage *D. pseudotsugae baragani*. However, it is worth noting that no *D. pseudotsugae* has ever been intercepted by phytosanitary inspections at European borders. A moth at risk of invasion is the major defoliator in the native range, the Douglas-fir tussock moth, *Orgyia pseudotsugata,* because lymantriid moths are frequently introduced as egg masses with imported used vehicles and containers, and then disseminate by 'flying' larvae. Attention could also be directed to an endemic looper (Lepidoptera: Geometridae) from New Zealand, *Pseudocoremia suavis,* which exhibited large outbreaks in plantations of Douglas-fir there.

Potential future pathogens to be surveyed

Climate change has a widespread impact on ecosystems, which are subject to severe disturbances and become more vulnerable to many biotic and abiotic stress factors. Warmer temperatures have been associated with an increased risk of disease development in plants. Changes in rainfall regimes, such as longer dry periods followed by abundant rainfall, increasingly stress trees which are more prone to infections, even of secondary pathogens. Moreover a sudden increase in temperature allows the pathogens to establish in regions where it was previously impossible (La Porta et al., 2008). The appearance of Swiss needle cast (*Phaecryptopus gaeumannii*) along the coast of Oregon has been hypothesised to be the result of increased winter temperatures and spring precipitations. Under the currently predicted climate warming, Swiss needle cast epidemics and new outbreaks are expected to become more severe and widespread in the near future even in the Douglas-fir natural range. The spread of *Diplodia sapinea* in France in the last 15 years is probably due to more favourable climatic conditions, ie milder winters and wetter summers. In Italy, the episodic emergence of *D. sapinea* has been related to extreme weather conditions and repeated periods of exceptional drought. The introduction of the American *Heterobasidion irregulare* in the Italian peninsula has been hypothesised to result in the colonisation of Douglas-fir plantations by the fungus. Although this exotic organism is at present mainly affecting pine woods along the coast, it could move to *Juniperus* and *Pseudotsuga,* as in its original range.

3.5.5 Conclusion

Compared to other exotic conifers introduced to Europe, Douglas-fir is still relatively free of biotic damage because its phylogenetic distance to native tree species is preventing rapid switches of most native pests. However, climate warming and the worldwide movement of plants for planting is likely to accelerate the arrival of pests from the native range. For example, the arrival of needle gall midges has been reported recently, while the host switch by native species, especially pine processionary moth and various pathogens, is also possible.

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4.

Management of Douglas-fir and technological properties of its wood

Chapter editor: Ulrich Kohnle

4.1 Management of Douglas-fir

Ulrich Kohnle, Joachim Klädtke and Bruno Chopard

4.1.1. General aspects: growth potential and production goals

Growth potential

One of the outstanding characteristics of Douglas-fir is the species' tremendous growth potential. In central Europe, Douglas-fir clearly is among the most productive conifers. For example, in France Douglas-fir currently covers slightly under 400,000 hectares (National forest inventory, 2016) producing an annual increment of 14.8 $m^3 \cdot ha^{-1}$. In Germany, according to the latest national forest inventory (2013), the species grows across more than 200,000 hectares and exhibits an average annual increment of 18.9 $m^3 \cdot ha^{-1}$. In both countries, Douglas-fir increment exceeds the average annual increment of conifers by 76% (France; 8.4 $m^3 \cdot ha^{-1}$) or 47% (Germany 12.8 $m^3 \cdot ha^{-1}$), respectively. Among the major conifers Douglas-fir is the fastest grower, outdistancing even Norway spruce (France 13.2 $m^3 \cdot ha^{-1}$; Germany 15.3 $m^3 \cdot ha^{-1}$).

Even though the species is already widely distributed across Europe, it is possible that a range of ecological conditions even wider than those in which it is currently planted might be suitable. In comparison to Norway spruce or silver fir, it can be assumed that the ecological amplitude of Douglas-fir extends further into drier and/or warmer conditions and, therefore, the species is expected to provide an alternative under the expected climate warming conditions of the next decades. However, there is some concern about reliably gauging the full range of the species' potential for long-term bio-climatic adaptation.

A considerable range of sites is well placed to choose either Douglas-fir or Norway spruce as site-adapted species for growing productive and stable stands. Although the growth potential of Douglas-fir on such sites generally tends to exceed that of Norway

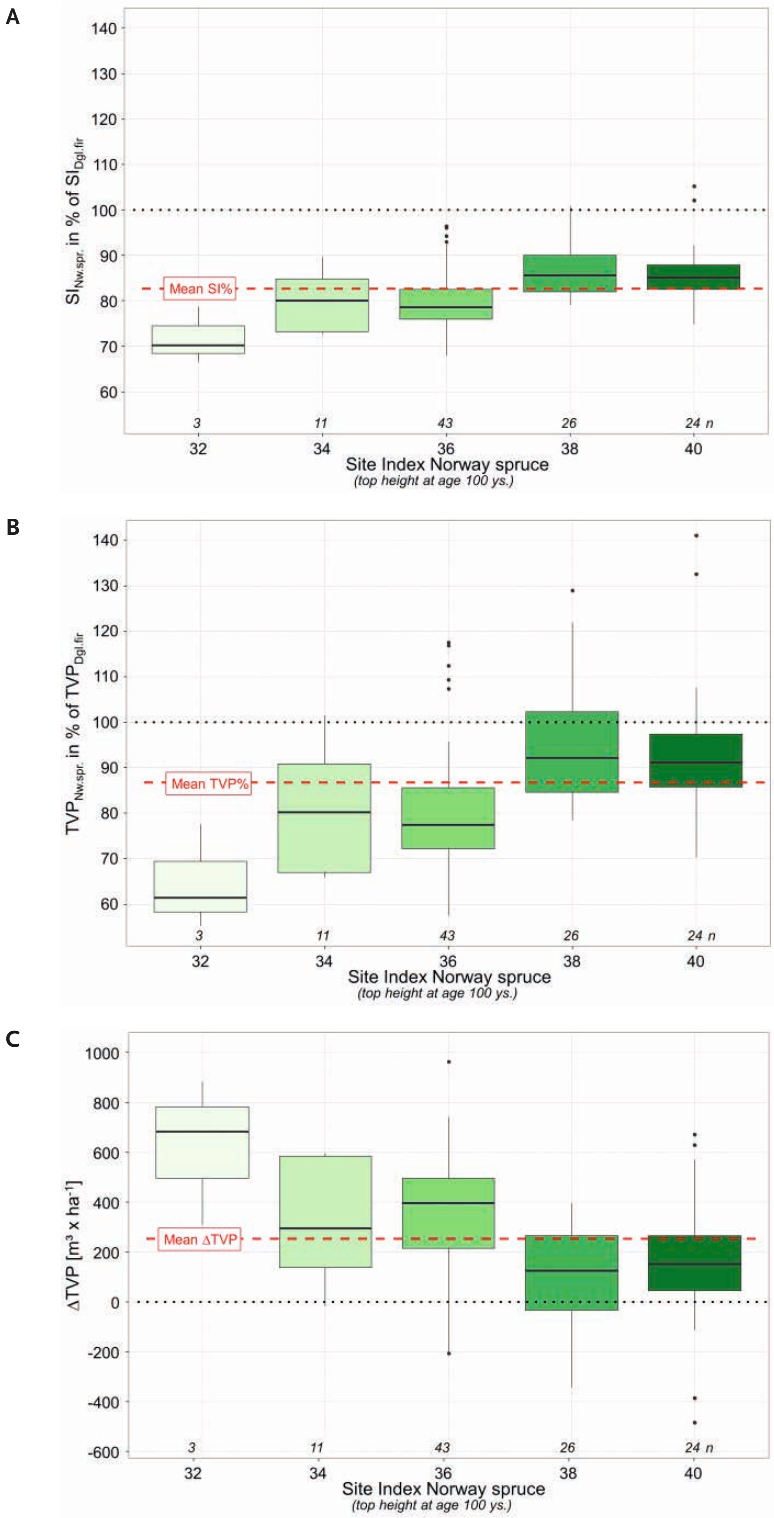

Figure 17. Growth potential of Douglas-fir stands growing at 101 different experiment locations in southwestern Germany in relation to stands of Norway spruce growing in experiments in the vicinity. The comparison between the two species is either based on the respective species' site index (A) or total volume production (B). The method of comparison is described in Klädtke (2016), and the graphs have been derived by recalculating the data analyzed in the paper targeting specifically Douglas-fir and Norway spruce. (C) presents the difference in growth performance (total volume production of Douglas-fir minus Norway spruce) on different sites in absolute terms. The x-axis shows the site index classes for Norway spruce. The fat dotted lines in black highlight the level where the two species' growth potentials would be equivalent; the narrow dotted lines in red display the mean relative growth potential of Norway spruce calculated from all included experiments.

spruce, the relation between the two species' growth potential appears subject to variation. Interestingly, observations in France and southwestern Germany (Figure 17) indicate that the growth superiority of Douglas-fir appears to diminish, but does not disappear, along a gradient of increasing site productivity. The magnitude of the differences between the two species appears slightly more pronounced when the comparison is based on site index (Figure 17A) rather than total volume production (Figure 17B).

In order to exploit successfully the considerable growth potential of Douglas-fir, management has to address the following aspects in particular:

- Definition of the production goals to be achieved (e.g. timber dimension and quality).
- Establishment of site-adapted, healthy and vigorously growing stands.
- Treatment regimes (e.g., spacing, thinning, pruning, even/uneven structured) that achieve an optimum between the aspects of (diameter) growth speed, quality development and associated potential risks (e.g. storm damage).
- Control/maintenance of desired admixed species.

Production goals

Interests and goals vary considerably among different forest owners, interest groups and/or regions. Consequently, there is no such thing as a universally applicable production goal upon which forest managers may agree unanimously. A "one size fits all" solution does not exist: situation-specific production goals have to be derived in accordance with the particular interests of the respective owner, the requirements of the potential customers (wood industry), and in compliance with the locally applicable legal and societal context. In the following, it is therefore only possible to outline a framework of known general relations how management interventions (*causes*) may affect the development of Douglas-fir stands (*impact*). Operational management is then challenged to exploit these general cause-impact relations to develop a substantial, clearly defined management/production plan that optimally achieves the desired situation-specific goals.

However, despite the challenge of developing optimized situation-specific management strategies, it is blatantly obvious that the tremendous growth potential of Douglas-fir, in conjunction with the fine technical properties of its wood and timber (Chapter 4.3), provide an excellent basis for economically satisfying results (Chapter 5.1). Or, to quote Martin Gross, the long-time head of the Kandern forest district (Black Forest), where Douglas-fir has been grown for more than a century, "*To me, Douglas-fir appears a rather treatment resistant species – it is darned difficult not to make money with it!*" – with the added proviso that the critical establishment phase has been successfully completed (see the following chapter), the ecological conditions suit the species' demands and wildlife populations are at adapted densities.

4.1.2. Stand establishment / regeneration

In Europe Douglas-fir is usually artificially regenerated as is common for newly introduced species. However, the importance of natural regeneration is increasing.

Natural regeneration

Drawing from extensive experience in France, in most ecological conditions (particularly acid sandy filtering soils), natural regeneration appears easily to achieve in regularly treated stands through progressive regeneration thinnings. If the residual stand is rapidly removed and the newly established regeneration is soon growing without canopy competition, growth dynamics can be expected to be similar to the regeneration processes in the native range of Douglas-fir in North America. In very dense natural regenerations it appears advisable to reduce stand density to around 2,000 stems·ha^{-1} (or less) through pre-commercial thinning, to avoid overly detrimental effects of competition on growth and stability.

Interestingly, it is not uncommon in Europe that, in response to thinnings, Douglas-fir regeneration establishes naturally and grows for prolonged periods under canopy shelter, which rarely occurs in the natural North American domain. The reasons for this different ecological expression have not been thoroughly investigated so far. However, one might speculate that this phenomenon might perhaps rest to some extent with differences in the availability of estival soil water in the two domains, which might affect shade tolerance of the regeneration.

At first glance this appears to offer good opportunities for managing Douglas-fir under continuous cover forestry regimes with prolonged regeneration periods typical for shade-tolerant species in close-to-nature silviculture systems. However, from recent investigations it becomes apparent that there are restrictions: although the shoot development of Douglas-fir growing under canopy shelter appears quite satisfactory when light levels are sufficient, namely less than 30 $m^2 \cdot ha^{-1}$ of the canopy stand, (prolonged) canopy competition is clearly detrimental for root development.

For practical management purposes this suggests that there is no good reason not to make use of Douglas-fir regeneration establishing naturally under canopy shelter. However, it appears advisable to keep the phase during which the regenerated trees have to grow under the influence of canopy competition as short as feasible and/or competition within the regeneration cohort is reduced effectively.

Planting: provenances and planting quality

For successful Douglas-fir planting consideration of the following aspects appears of particular importance:

- Suitable planting area
- Choice of provenance
- Quality of planting material, and planting technique

Suitable planting area

In its natural North American range Douglas-fir usually regenerates on large open areas after stand removal through natural “disasters” (e.g., fire) or clear cutting. However, in the European arena, planting Douglas-fir on excessively large clear cuts has repeatedly proven sub-optimal. There, the freshly planted trees are either vulnerable to summer drought or suffer from desiccation in winter. Critical conditions develop when the soil is still frozen but relatively warm air temperatures cause the plants to open the stomata and start to transpire. Therefore, in Europe, areas at the edges of existing stands have been found to present optimal situations where the newly planted trees do not suffer from overstory competition but still benefit from the protection of the adjacent stand.

Choice of provenance

Within the vast natural range of Douglas-fir, the gene pool is well known to be divided into a multitude of site-adapted provenances. It is therefore generally accepted that it is important to choose a provenance adequately adapted to environmental conditions at the planting site. Clearly, in this context, the most important aspect is whether to choose a provenance from the coastal, interior or intermediate form of Douglas-fir. Generally, in western and central Europe, the best choices are provenances from coastal Douglas-fir, whereas interior provenances should be completely rejected for pathological reasons (see Chapter 3.3).

From a multitude of provenance experiments there is ample indication that Douglas-fir provenances actually differ in genotype as well as in phenotype expression (e.g. growth speed, stem form, branchiness etc.). As a result, there are often helpful national and/or regional recommendations about which provenances to favor under which site conditions.

However, where such specific evidence-based provenance recommendations are lacking, there is no need to despair. Simply choose a provenance originating from the proper form of Douglas-fir (usually coastal) and there is only a very limited potential to err completely. For example, throughout the whole range of the "Douglas-fir proper" (except the "fog belt") prolonged summer drought periods are the rule, and therefore for all coastal provenances a capacity for tolerating summer drought can be confidently expected.

Analysis of long-term growth and yield experiments covering a considerable geographic range of provenances from truly coastal to intermediate coastal/interior origin (Seho and Kohnle, 2014) indicate that initially significant differences in (height) growth between the provenances obviously had diminished in the course of the five decades of the experiments, and the magnitude of the absolute differences in height growth had become rather marginal. Furthermore, the provenances' ranking of growth speed had proved quite inconsistent along an (elevational) site gradient. And although there were statistically significant differences with respect to economically important phenotype expressions (e.g., stem taper, bark thickness, branch insertion angle, heartwood proportion), the magnitude of these provenance-specific differences after five decades was of minimal economical relevance, if at all.

Quality of planting material and adequate planting technique

The use of high-quality nursery stock and the application of an adequately site- and plant-adapted planting technique are critical requisites for the successful establishment of Douglas-fir. It is crucial that Douglas-fir nursery stock extracted from the soil is planted as soon as possible. Douglas-fir plants appear to be much more impaired by prolonged storage periods than other species. Although the practice of growing plants in containers somewhat eases the particular storage challenges of bare-rooted plants, the challenge of using only fresh plant material that is not affected by prolonged storage remains.

Another important aspect of plant quality is a well-balanced ratio between the plants' shoot and root compartments. Overly rapid growth of nursery stock triggered by excessive fertilization, as well as stock being subjected to serious competition caused by excessive plant densities, impair the plants' potential to establish successfully after planting at the new site. In this context, the ratio between a plant's height and its diameter at the root collar has proven to be a versatile quantitative tool in judging the balance between the plant's root and shoot compartments.

With respect to the planting technique, it should be self-evident to use a technique adapted to the plant material and the given site specifics rather than to "adapt" the plant material to a favored, pre-selected planting technique (e.g. excessive reduction of roots). Nevertheless, one must acknowledge that successful Douglas-fir planting is relatively challenging with higher failure rates than for example, Norway spruce, even when planting prime nursery stock with adequate techniques under regular ambient conditions.

4.1.3. Spacing/thinning: impact on dimension growth and timber quality

The spacing of planted trees, the use of pre-commercial thinning and subsequent commercial thinning are well-established management tools. In a silvicultural context, they manage growing space dynamics (i.e. the growing space available to the trees) in a sequence of treatments along the development of the stands and are thus used to regulate how fast the trees grow in terms of diameter. Therefore, the following attempts to describe all three tools in an integrated way within the same chapter.

Spacing is directly associated with the cost of planting and the impact on competition between the trees, thus significantly influencing the development of the regenerated stands particularly during the early stages of the stand. Later on, pre-commercial and commercial thinning provide the tools for shaping the further development of the stands through moderation of inter-tree competition.

The impact of competition can be attributed to effects on two different levels: the more general effect expressed at the stand level through stand density (e.g. the number of trees planted/kept per area unit) which may subsequently be modified at the individual tree level by the spatial distribution of the tree's immediate neighbors.

Whereas stand density has (almost) no effect on height growth, it is well known that with Douglas-fir, as with other species, stand density directly influences the growth of stem diameter and branches, in particular. The general rule is that both increase in growth with decreasing stand density.

There is ample evidence that Douglas-fir branch characteristics are, at least in part, under genetic provenance-specific control. However, with respect to the development of branch diameter and its economic consequences, the impact of spacing clearly overrides provenance effects. As Douglas-fir exhibits a more or less constant ratio between branch length and branch diameter (ca. 100:1), potential maximum branch diameters may be easily calculated for different spacing designs and dynamics by using crown size development (maximum branch length), driven by the growing area available to the respective tree.

With respect to spacing the following general recommendations apply. These recommendations are derived from the results of a comprehensive series of spacing experiments in Douglas-fir involving more than 100 plots planted with densities of 500 / 1,000 / 2,000 / 4,000 trees per hectare (Klädtke et al., 2012). On one hand, in the young stands, stem diameter growth clearly benefits from decreasing planting densities. Likewise, the height: diameter ratio of the trees decreases indicating improving stability of the stems. On the other hand, maximum branch diameter also increases with decreasing planting density, which is detrimental to the quality of the stem timber produced (Figure 18). With respect to optimizing gross volume production, planting densities in the range of around 1,000–2,000 Douglas-fir per hectare are advisable.

Furthermore, branch diameter development during the subsequent thinning phase is also clearly related to inter-tree competition and may be predicted using quantified models for a given thinning regime.

Under current conditions, a range of planting densities between ca. 1,000–2,000 Douglas-fir per hectare appears to offer an optimal balance between quality, stability, total volume growth and diameter growth speed. If significantly fewer than 1,000 trees per

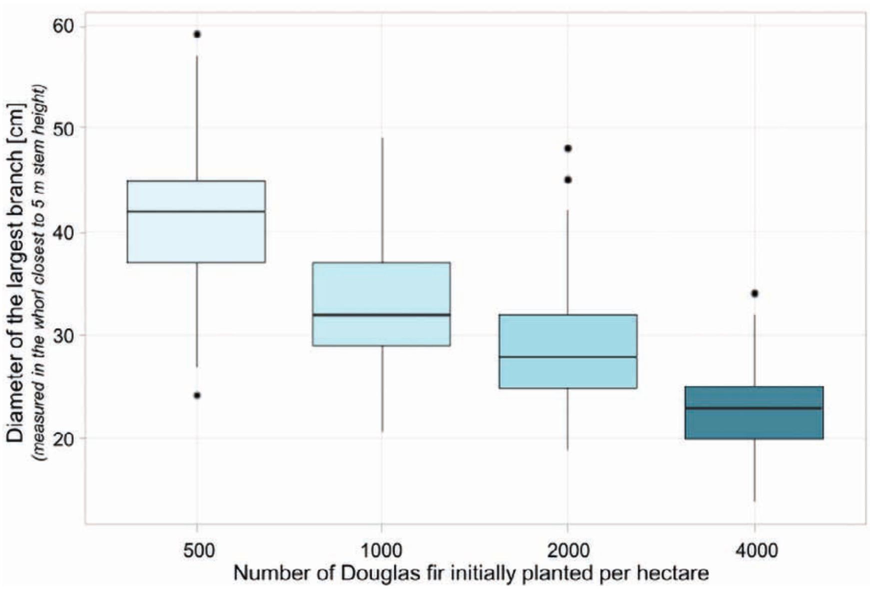

Figure 18. Diameter of the largest branch measured in the whorl closest to 5m of stem height in target crop trees selected in stands planted at initial densities of 500–4,000 Douglas-fir per hectare. Experiment described in Klädtke et al. (2012).

hectare are planted, total volume production is clearly reduced (Figure 19) and timber quality develops marginally (Figure 17), whereas planting significantly more than 2,000 trees per hectare is detrimental to diameter growth and stability and results in unacceptably high planting cost without an increase in total volume production.

With respect to thinning regimes, it is essential to remove the major competitors of those trees selected to grow to maturity. This is particularly important in the early thinning phases of the young stands. Generally this is achieved through intensive high thinnings. In this context, the "crop-tree-concept" appears particularly promising. Here, specific future crop trees are selected and selectively promoted by repeatedly releasing them from competitors.

Based upon the relationship between stem and crown diameter, the maximum possible number of (mature) trees can be estimated for any desired target diameter (Figure 20; Klädtke and Abetz, 2010). The intensity with which trees are released from competitors, particularly in the young development stage, will determine the time (tree height) at which the target diameter will be reached. The rule of thumb is:

- The lower the target diameter, the higher the maximum possible number of crop trees per area unit.
- By enlarging the growing space, diameter growth speed increases with the intensity of the release from competitors.
- However, as wider spacings / more intensive release regimes result in larger crowns, they are invariably associated with the development of longer and therefore thicker branches.

Depending on a particular owner's goals, the optimal spacing / thinning regime needs to be developed by aligning and balancing these aspects. In this context it is important

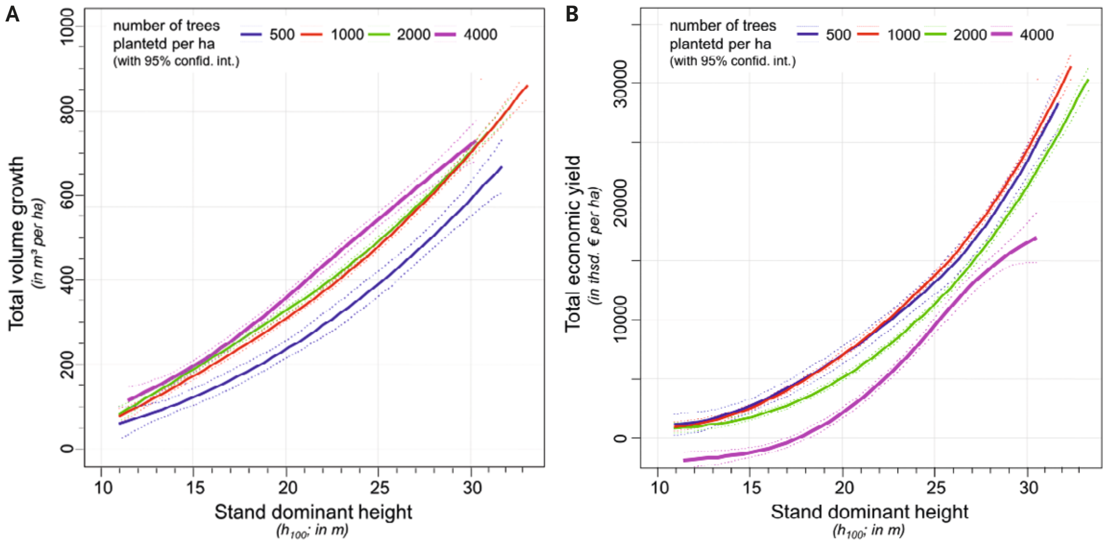

Figure 19. Total volume production (A; left) and net value of timber production (B; right) yielded by stands of Douglas-fir planted at initial densities varying from 500–4,000 trees per hectare. Net value of timber production is calculated without the costs for planting and without interest rate (Klädtke et al, 2012).

to emphasize that these recommendations are subject to regional/national variation with respect to basal area of the mature (final) stands. For example, in France the recommendations suggest that stands managed for target diameter at breast height (*dbh*) of approximately 55–65 cm should not exceed 40–45 $m^2 \cdot ha^{-1}$ (Sardin, 2013). In contrast, recommendations for Germany are in the range of around 50–60 $m^2 \cdot ha^{-1}$ (Kenk and Hradetzky, 1984; Figure 20).

4.1.4. Timber quality / pruning

Douglas-fir management in Europe is usually targeted at producing saw-timber (see Chapter 4.3). In contrast, producing fibre wood – although exploited as a by-product – is not regarded as a high priority production goal. Interestingly, with respect to saw-timber, there appears a wide range of economically appealing target diameters. For example, the production of medium-sized timber of moderate quality may be as economically feasible as the production of larger-sized timber of high quality, depending on regionally varying market conditions.

With respect to the quality classification of timber, the top priority is the logs' branch characteristics. On the one hand, classification of medium diameter saw logs as moderate (industrial) quality allows for maximum branch diameters up to 4 cm, and can be provided straightforwardly through regular thinning procedures (see above). On the other hand, large-sized logs only classify as high value logs if they contain large enough proportions of "clear" (heart-)wood, free of knots or branches. In North America, such timber might develop naturally over several centuries in virgin, old-growth stands. However, the production periods of managed Douglas-fir are much shorter and far from coming close to simulating such conditions. As a consequence, producing branch-free timber in managed stands depends (almost) exclusively on artificial pruning.

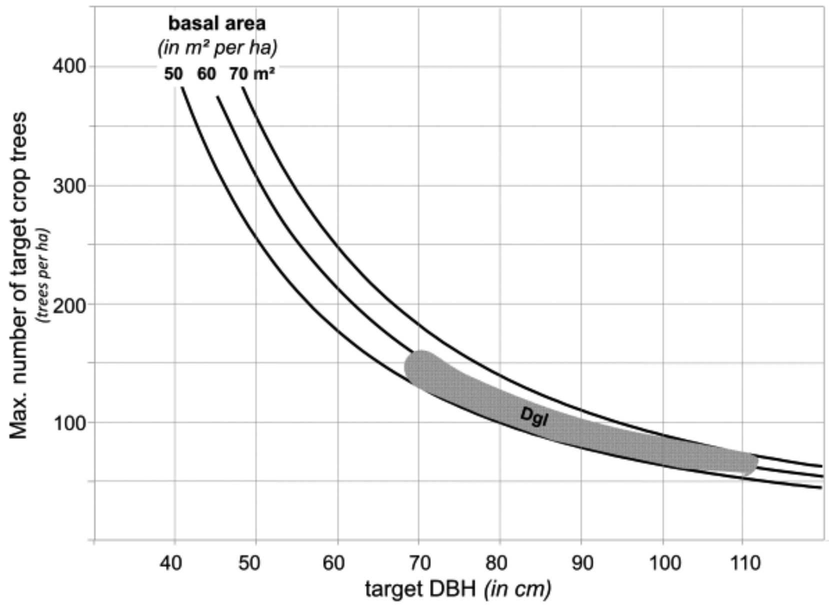

Figure 20. Suggested (maximum) number of Douglas-fir target crop trees per hectare depending on the trees' target diameter (*dbh*) and the basal area of the final stand (Klädtke and Abetz, 2010).

Although provenance has some influence on branch characteristics and spacing/thinning has a significant impact on branch development, only pruning is known to enable branch-free timber within reasonable production times. Even at a rather costly high planting density of 4,000 Douglas-fir per hectare, competition-induced self-pruning almost never results in branch-free timber.

The following requirements are of major importance in pruning strategies:

- Proportion of clear wood:
  from a wood use perspective, a log should contain at least two thirds of its diameter of branch-free wood surrounding a "branchy" core of a maximum of one third of the diameter.
- Retention of green crown:
  to avoid significant losses in increment, it is necessary to retain a proportion of the length of the green crown of at least 50% of the stem length.

These aspects clearly indicate that, although pruning should be executed as soon as possible, this must not happen too early or too severely. If one wishes to prune the first log section (e.g. 5–6 m) at the stem's base, trees need to be 10–12 m tall to retain a minimum length of the green crown of 50%. As a rule of thumb, vigorously growing trees have then achieved a *dbh* of approximately 15–20 cm, requiring management for a minimum target *dbh* of around 60–70 cm (De Champs, 1997).

If pruning subsequent log sections along the stem is intended, it has to be executed correspondingly later and management adapted to adequately increased target *dbh*. For example, if the intention is to prune a second log section of similar length, a target *dbh* of around 80–90 cm is required to allow for the formation of an adequate proportion of clear wood along this portion of the stem. As a consequence of the increased target *dbh*, the maximum number of target crop trees to select and prune needs to be reduced (Figure 20).

The economic feasibility of pruning depends on several factors. Of particular importance are the interest rates employed in the respective calculations. In general, feasibility of pruning decreases with increasing interest rates. Furthermore, pruning only yields productive results if the pruned trees grow until the necessary target diameter is achieved. Therefore, a major consequence of this requirement is not to prune more trees than a stand can carry at the intended target diameter.

Furthermore, it should be taken into account that – although economically feasible – pruning stem sections at increasing heights is associated with increasing production time (tree height). This is not unproblematic. As the risks from natural events such as storms generally increase with height of the trees, it is essential from an economic perspective to account for the fact that, when pruning sections higher along the stem, costs increase and the investment is increasingly threatened by risk factors.

4.1.5. Mixture

Although Douglas-fir may in principle be grown in mono-species stands, the vast majority of current silvicultural guidelines recommend the admixture of (native) tree species. These recommendations are mostly based on the general principle that increasing biodiversity of mono-species stands can be expected to serve the following purposes in particular:

- Increase resistance and resilience to biotic agents detrimental to the stand's health.
- Link stands of the "exotic" Douglas-fir to the natural forest community – an aspect of particular importance within the concept of "close-to-nature" forest management.

However, if Douglas-fir is intended to be grown in mixed stands, one needs to consider the particular growth characteristics of Douglas-fir. With very few exceptions, in comparison to potential (native) admixtures such as, for instance, European beech (*Fagus sylvatica*), Douglas-fir almost invariably grows considerably faster and/or may achieve substantially taller terminal heights.

Therefore, it is advisable to introduce the admixtures in large enough patches where it will be feasible, in the long run, to preserve them in the presence of dominant Douglas-fir in the neighborhood. Furthermore, top priority in managing the admixtures should be keeping them alive within the Douglas-fir stand without necessarily managing them for timber production. Clearly, with the admixtures quality aspects take second rank to safeguarding their survival and/or promoting their growth vigor.

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4.2

Douglas-fir biomass production and carbon sequestration

Jean-Charles Bastien

4.2.1. Forests as carbon sink

Forests and the forest industry are considered a strategic area for climate change mitigation. Their beneficial role combines dynamic carbon **sequestration** in the ecosystem (biomass and soil) and reversible **storage** in the economic sphere (wood products), as well as a cumulative and acquired **substitution**, resulting from the wood being used to replace non-renewable energy and materials with a less favourable energy balance.

Photosynthesis is the biological process that enables a tree to store the energy necessary to its metabolism as carbohydrates[6]. To ensure its metabolism and development, the tree uses these carbohydrates and releases carbon dioxide (the respiration process). When carbon inflow from photosynthesis exceeds the respiration outflow, the tree stores carbon. Growing forests (new forests, young plantations) act as a carbon sinks. From a certain age, a stand reaches an equilibrium and its carbon footprint is null. When a forest is disturbed (such as through fire or biotic attacks), the carbon stock can be quickly released. Therefore, to prevent a stand from becoming a carbon source, it is necessary to anticipate these risks. At the forest ecosystem level, soil and microorganisms are also important carbon sinks or sources. Western European forests absorb around 12% of the total CO_2 emissions in Europe (IPCC, 2014). At global biosphere level, it is estimated that world forests absorb 9.2 $GtCO_2$, i.e., 2.5 GtC[7] (IPCC, 2014)

4.2.2. Douglas-fir and carbon sequestration

The amount of carbon fixed by wood volume unit is dependent on dry wood density, whereas the relative carbon rate in dry woody biomass is (almost) not species dependent and averages 0.475 (Loustau, 2004). Douglas-fir dry wood density is on average 0.45 $t \cdot m^{-3}$ (see also Chapter 4.3). Therefore, $1m^3$ of Douglas-fir solid wood fixes 0.214 tC, ie 0.78 tCO_2; which is, with larch, the highest fixation content among the temperate conifers. By comparison, $1m^3$ of oak wood fixes 1.0 tCO_2 and $1m^3$ of poplar wood 0.57 tCO_2 only.

6 During this reaction, the tree will capture carbon in mineral form (atmospheric CO_2), synthesise carbon in organic form (carbohydrates) and release the oxygen thanks to the light energy. The chemical equation of photosynthesis is: $6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ CO_2$

7 Molar weights of C and CO_2 are respectively 12 and 44 (12 + 2 x16). To convert a ton of C (tC) in tons of CO_2 (tCO_2) just multiply by the ratio, 12/44 i.e. 3.67. Therefore 1tC equals 3.67 tCO_2

The assessment of carbon (or CO_2) sequestration in a forest stand is a dynamic process stepwise using allometric relations between stem biomass and both aerial and root total biomass. In order to predict carbon sequestration in a Douglas-fir stand, Ponette et al. (2001) and Ranger and Gelhaye (2001) analysed numerous Douglas-fir biomass studies published throughout the world. They reported that some 88 stands of Douglas-fir have been sampled for above-ground biomass, and 38 for below-ground biomass. Using all these studies, two linear regressions were fitted to predict, from *dbh*, above ground biomass (r^2 =0.9963) and root biomass (r^2=0.994). Resulting expansion factors were 1.335 for crown and 1.3 for roots, respectively.

With a view to applying these models to Douglas-fir stands in New Zealand, Knowles et al. (2010) realised that both the above fitted linear regressions include an intercept, resulting in a negative stem and root biomass values of respectively 9.6 $t \cdot ha^{-1}$ and 1.4 $t \cdot ha^{-1}$ when above-ground biomass is zero. They showed that young stands have a much higher proportion of crown biomass relative to stem biomass compared to older stands. Therefore these authors fitted a non-linear regression predicting crown biomass from stem biomass, but without an intercept (r^2=0.9978). Similar models, built in France on young unthinned stands, showed that an average total biomass yield of 10 dry $tons \cdot ha^{-1} \cdot year^{-1}$ can be expected by age 25. This initial yield is, of course, highly depending on the initial planting density and can be significantly increased by using improved varieties (Bastien et al., 2015). However, long-term experiments indicate that such initially observed differences driven by planting density (Klädtke et al., 2012) or provenance (Jansen et al., 2013; Seho et al., 2014; Neophytou et al., 2016) may change, diminish and/or disappear within five decades (see Chapter 4.1).

An application of these models is given in the following example of the evaluation of carbon sequestration in a 55-year-old Douglas-fir stand (Martel et al., 2015). Hypothesis is as follows: total wood volume production over 55 years: 1,107 m^3, Douglas-fir wood density: 0.45; branch expansion factor: 1.335; root system expansion factor: 1.3; wood's carbon content: 0.475. The product of all these parameters gives the amount of carbon sequestered in a 55-year-old Douglas-fir stand, i.e., 411 $tC \cdot ha^{-1}$ (i.e., 1506 tCO_2/ha). This quantification does ignore the carbon included in the soil and litter biomass, which is difficult to estimate given significant uncertainties in the scientific literature on the soil organic carbon.

At the scale of France, in the frame of the EMERGE project, Deleuze et al. (2013) estimated the amount of carbon fixed per hectare and per year by different forest species, taking into account the "productivity/wood density" balance as well as the expansion coefficients. These authors showed that Douglas-fir, with an average of 3.67 $tC \cdot ha^{-1} \cdot year^{-1}$ is the most efficient forest species in metropolitan France (by comparison: hornbeam 3.16, Norway spruce 2.43, silver fir 2.19, ash 2.08, chestnut 2,03, beech 1.94, Maritime pine 1.73, sessile oak 1.20, Scots pine 1.03)[8]

4.2.3. Douglas-fir, carbon storage in wood products and substitution

The wood that is harvested in the forest is processed into wood products, extending the carbon storage period before the carbon returns to the atmosphere. When burned, fuel wood will quickly release this stored carbon, while lumber wood will extend carbon

8 These carbon fixation rates are averages obtained from French forest inventory data, taking into account the age class distribution.

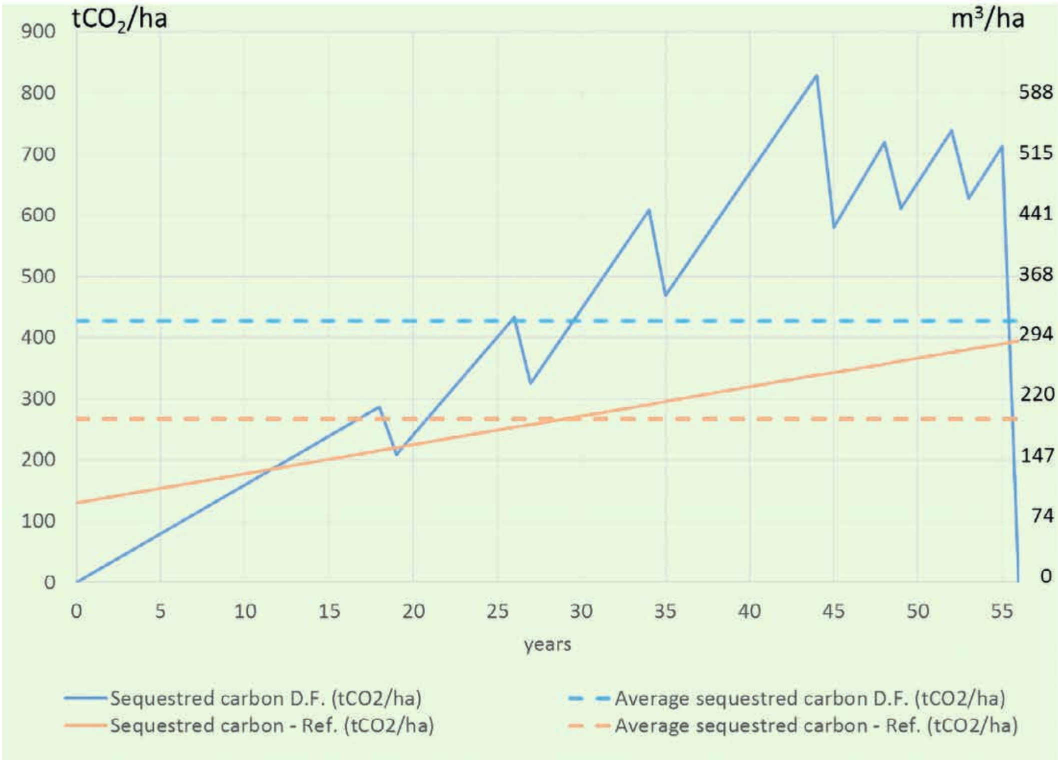

Figure 21. Carbon sequestration in a Douglas-fir stand compared to an unmanaged forest "reference scenario". Orange lines: Douglas-fir plantation, blue lines: reference scenario; solid lines: evolution with time of sequestered CO_2 (t/ha), dashed lines: average sequestered CO_2 (t/ha). (After Martel et al, 2015)

storage during the life of the final product. The wood is also involved in two substitution levels: energy and material.

Using wood as an energy source avoids carbon emissions associated with the extraction of fossil fuels. This energy substitution effect depends on the energy source replaced by wood. According to ADEME (2005), 1 m^3 of round wood used directly for heat production in industry and collective housing as a substitute for fossil fuels, avoids about 0.5 tCO_2 (this value varies according to the assumptions used).

Furthermore, material substitution takes place when the use of wood for construction replaces cement, aluminium, steel or polyvinyl chloride. Indeed the provision of these non-renewable materials is very energy consuming since often one must extract minerals, then carry out a succession of transformations in the industries to produce them.

4.2.4. Carbon balance computation for a Douglas-fir growth cycle (example)

We will take the example of a Douglas-fir plantation managed in a 55-year rotation to illustrate the species' impressive carbon balance. A typical Douglas-fir management scenario includes a planted stand under a regular thinning regime, with, at the end, the possibility to naturally regenerate the population (see Chapter 4.1). This is compared with an abandoned farmland reference scenario, spontaneously colonised by a natural forest with a mean annual increment of 2.4 $m^3 \cdot ha^{-1} year^{-1}$ (Martel et al., 2015).

Figure 21 shows that over the 55-year period, the “reference scenario” (orange dashed line) allows sequestering on average 267 $tCO_2 \cdot ha^{-1}$, whereas over the same period, the “Douglas-fir scenario” (blue dashed line) allows sequestering on average 427 $tCO_2 \cdot ha^{-1}$, i.e. 160 $tCO_2 \cdot ha^{-1}$ more than the “reference scenario”.

Moreover, Douglas-fir silviculture will also put on the market products with a high carbon storage potential as 70% of the harvested wood is sawn wood and only 30% pulpwood. Processed timber harvested over the 55 years revolution represents an average long-term carbon storage of 66 $tCO_2 \cdot ha^{-1}$ (i.e., 13% of the total sequestration + storage). This wood, particularly for construction purposes, represents a carbon stock that will take many years to decompose because the lifespan of construction wood is high.

4.2.5. Conclusion

The Kyoto protocol (1997) requires states to account for carbon emissions and sequestration. In the frame of a carbon market, mechanisms presently exist to exchange carbon credits. In July 2016, the European Commission published a legislative proposal for incorporating greenhouse gas emissions and removals due to land use, land use change and forestry into its 2030 Climate and Energy Framework, aiming at a total emission reduction of 40% by 2030 for all sectors together.

Considering that the forests’ share can achieve much more than what is in the present regulation, Nabuurs et al. (2017) proposed a range of measures, based on the concept of “climate smart forestry”, that can be applied to provide positive incentives for more firmly integrating these climate objectives into the forest and forest sector framework and, eventually, nearly doubling the mitigation effect of EU forests by 2050. While maintaining the forests’ ecosystem services, the goals of these measures are to optimise the carbon balance of forests and to guide management and adapt silvicultural practices towards capturing more carbon compared to the baseline scenario: i.e., replace less productive forests, replace low quality coppices and increase wood use for construction.

Due to its potential to yield high volumes (see Chapter 4.1) and its exceptional wood properties (see Chapter 4.3), Douglas-fir has particularly high potential for mitigating climate change.

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4.3

Technological properties of Douglas-fir wood

Jean-Marc Henin, Caroline Pollet, Uwe Schmitt, Jan-Henning Blohm, Gerald Koch, Eckhard Melcher, Johannes Welling, Franka Brüchert, Ulrich Kohnle and Udo Hans Sauter

4.3.1 Introduction

To a greater or lesser extent, growth conditions and forest management practices influence the anatomical, chemical, physical and mechanical characteristics of wood, causing tangible variations of its properties. As a result, although wood from centuries-old North American Douglas-fir, known as Oregon Pine, has remarkable technological properties, the resource produced nowadays in second-growth American forests, as well as in areas where Douglas-fir has been introduced, may be very different.

In Europe, where Douglas-fir plantations burgeoned after the second world war, growth rate is considerably higher than that observed in old-growth forests and, for technical and financial reasons, rotations rarely exceed 100 years while cutting-diameter is generally below 70 cm. In this context, the figures and trends discussed in this chapter rely on studies dedicated to Douglas-fir grown in Europe only (although similar trends or figures can be observed in other exotic areas or in its native range).

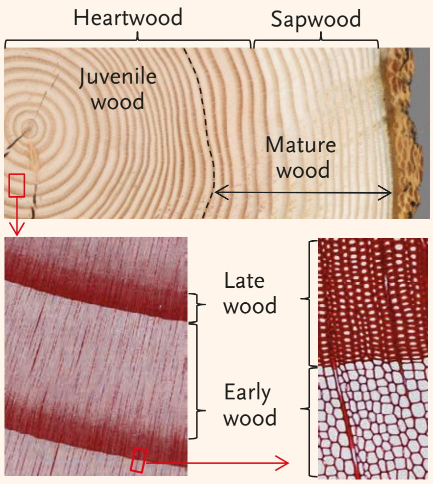
Finally, before getting into more details, it should be noted that, besides the influence of growth conditions and silviculture, wood properties also vary based on the genetic origin of the trees (which will not be discussed in this chapter) as well as the location of the wood within the tree. In this respect, besides variations related to height, considerable variations in wood properties are observed from pith to bark. The three sources of these variations, which rely on anatomical, functional and chemical differences at the cell level, are presented in Box 1.

4.3.2 Visual characteristics of the wood

Douglas-fir heartwood presents a light brown to salmon colour, with red and yellow hues; sapwood is whitish to yellowish. When exposed to full weathering conditions (e.g. UV rays and rain), wood initially darkens and then turns to grey.

Although the species is known for its remarkable productivity, ring width displayed by Douglas-fir varies considerably depending on the growth conditions, the silvicultural practices applied to the stands, the genetic endowment of the trees, their age and social position within the stand and on the crown development, as well as on the nature of the wood (juvenile or mature). Depending on all these factors, the average ring width observed at breast height on a whole radius is generally comprised between 2 mm and

Box 1. On a radial transect, three dichotomous variations are observed:



1. Just under the bark, the functional tissues produced inwards by the cambium constitute the ***sapwood***. The latter usually consists of 10 to 20 rings[9] ensuring sap conduction. Beyond this belt and towards the pith, ***heartwood*** is made of tissues enriched with compounds enhancing resistance against biological agents.
2. Starting from the pith and at any height level, the first 10 to 20 rings[10] constitute the ***juvenile wood***, produced by young cambial tissues. Beyond these rings, anatomical changes at the cell level induce the production of ***mature wood***.
3. Finally, within each annual ring, the seasonal alternations result in the production of ***early wood*** (or ***spring wood***), characterised by large lumen and radial diameter in order to facilitate sap transportation, and ***late wood*** (or ***summer wood***), made of smaller cells provided with thick walls.

7 mm in European Douglas-fir trees. However, in plantations with extremely low tree density, the annual radial increment of young trees may exceed 10 mm during several years. Likewise, the average ring width measured on lumber may be less than 2 mm or, in contrast, exceed 10 mm when it is sawn in the juvenile wood. Forest managers should thus keep in mind that growth rate is a classification criterion according to the standards regulating the visual grading of round softwood and the visual strength grading of structural softwood timber (Table 5). Obviously, the thresholds presented in Table 5 are not taken into consideration when lumber classification is performed with grading machines. Also, from a practical point of view, it should be mentioned that, in a context of rapid growth, ring width regularity is of equal or higher importance than average ring width. In particular, timber with irregular growth ring structure has been shown to be more prone to distortion than timber with regular rings.

It should also be kept in mind that steady growth can only be achieved when there is a productive and well-developed crown, which obviously implies disadvantageous branching. Yet, branching and consequent knot abundance and size are among, if not the most, important feature(s) conditioning the grading of round wood, veneer and timber. Likewise, increasing tree growth rate can negatively impact the breakdown of structural timber and cladding among quality grades. In this context, dynamic silvicultural practices (plantation density lower than 1,000 or 1,500 plants/ha; early and/or heavy thinning) should ideally – if not necessarily – be combined with artificial pruning in order to enable the most rewarding uses of the wood (see Chapter 4.1.4).

Another visual property is texture, defined as the ratio between latewood thickness and total ring width. While generally below 30% in other conifer species, texture is relatively

9 Values higher than 30 rings can be reached.
10 Although some authors report maximum values exceeding 35 rings of juvenile wood.

Table 5. Maximum growth rate allowed to access the highest strength class according to different national standards of structural timber visual grading.

Country	Highest mechanical strength class[11]	Maximum growth rate applying visual grading standards
Austria	C35	6 mm
Belgium	C30	6 mm
France	C30	6 mm (cross section≤18.000 mm²) 8 mm (cross section>18.000 mm²)
Germany	C35	6 mm
Great Britain	C18 or C24*	6 mm
Poland	C30	4 mm
The Netherlands	C30	4 mm

*depending on the standard and lumber section

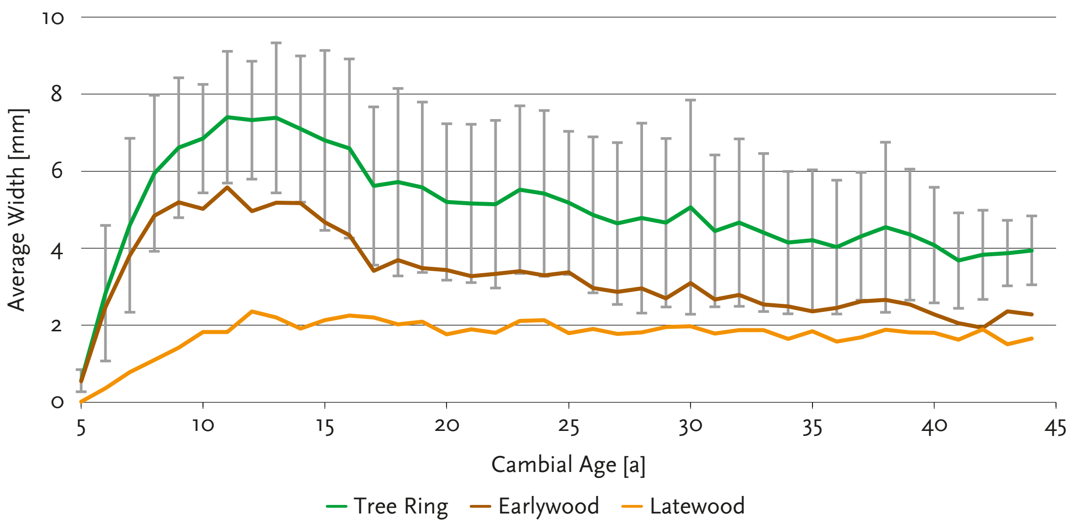


Figure 22. Average earlywood, latewood and ring width according to cambial age (Blohm, 2015).

high in Douglas-fir: normally ranging from 30 to 45% though values exceeding 55% can be observed. As illustrated in Figure 22, texture is lower in the juvenile wood and increases in the mature wood.

Texture was shown to decrease as the rate of growth increases. However, this trend is less pronounced than that observed in other common species of *Picea* sp., *Pinus* sp. or *Larix* sp.

4.3.3 Physico-mechanical properties

Standardised classification of structural timber relies on wood density, stiffness (modulus of elasticity – MoE) and bending strength (modulus of rupture – MoR). The latter

11 Strength classes of softwood structural timber are labelled C (Coniferous) followed by the percentile 5% of the static bending strength values in the corresponding lumber population. In other words, there is a 95% probability that the bending strength of a lumber graded C30 exceeds 30 MPa.

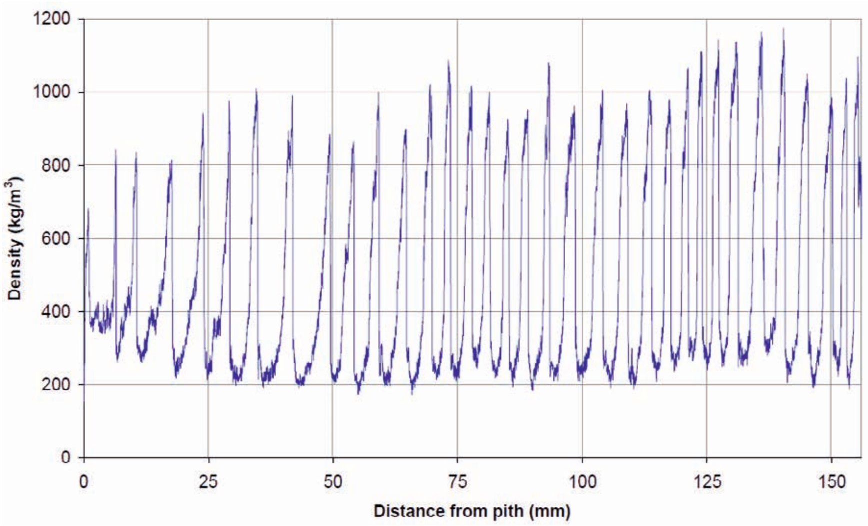


Figure 23. Density profile as a function of distance from the pith, recorded on a British Douglas-fir (Bawcombe, 2012[12]).

are thus of the highest importance for Douglas-fir, which in Europe is mainly employed in structural uses.

According to large national samples gathered throughout Europe (Belgium, France, Germany, Great Britain, Italy and Poland), the average density of Douglas-fir wood is approximately 500 kg·m^{-3} at 12% moisture content[13]. This property does not substantially differ between sapwood and heartwood. Conversely, for a given ring width, mature wood is approximately 10% heavier than juvenile wood. In fact, along a radius density typically decreases from the pith to a minimum value around the fifth or tenth ring; then it increases outwards to exceed the initial value and level off in the mature wood. Nonetheless, the highest density heterogeneity is observed within annual rings, where density rockets from less than 300 kg·m^{-3} in earlywood to more than 900 or even 1,000 kg·m^{-3} in latewood (Fig, 23).

This considerable gradient is mainly explained by the anatomical characteristics of early- and latewood, namely the tracheids lumens' area and wall thickness (see Box 1). Within-ring density heterogeneity is one of the main issues concerning Douglas-fir woodworking (cf Chapter 4.3.5). Besides, as density appears under strong genetic control, selecting for higher density homogeneity within annual rings, which has been shown to be highly beneficial to veneer quality and timber workability, has been suggested.

Trials on clear wood specimens showed that Douglas-fir static bending strength and stiffness are superior to those of most other common conifer species[14]. The low sensitivity of these mechanical properties to the increase of growth rate was also highlighted. Moreover, while structural-sized timber displays features (knots, distortions, shakes, resin pockets, etc.) affecting the values measured on clear wood, French researchers confirmed on lumber the trends observed on defect-free specimens (Figure 24).

12 Bawcombe J.M. (2012). A study of Douglas-fir anatomical and mechanical properties and their interactions. PhD Thesis, University of Bath, UK. 360 p. http://opus.bath.ac.uk/32245/

13 Wood moisture content (*mc*) is expressed with reference to the oven dry mass, as follows: *mc* (%) = *100*(humid mass – oven dry mass) / oven dry mass.*

14 European larch (*Larix decidua* Mill.) is an exception and has higher stiffness and bending strength.

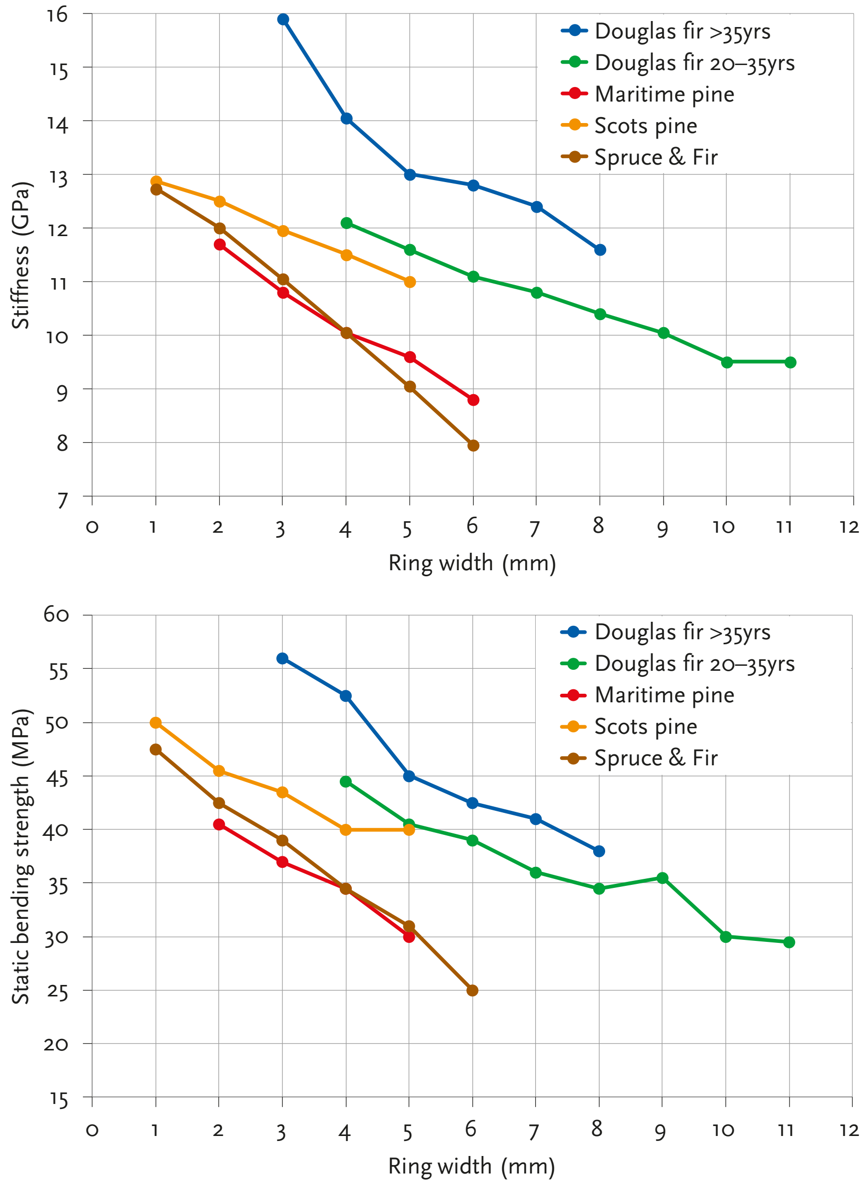


Figure 24. Lumber stiffness – MoE (top) and static bending strength – MoR (bottom) according to ring width, for the most common conifer species in France (Nepveu & Blachon, 1989[15] in France-Douglas 2012).

In practical terms it can be considered that, although highly variable, the stiffness and static bending strength of Douglas-fir lumber roughly average 12,000–13,500 MPa and 30–40 MPa, respectively. For a given rate of growth, the lower performances displayed by younger trees (Fig 24) result from their higher content of juvenile wood, characterised by around 20% lower stiffness and strength when measured on defect-free specimens. As a corollary, the highly beneficial impact of augmenting rotation age on the breakdown of structural lumber into the different mechanical grades is illustrated in Figure 25.

15 Nepveu G., Blachon J.-L. (1989). Largeur de cerne et aptitude à l'usage en structure de quelques conifères: Douglas, Pin sylvestre, Pin maritime, Epicéa de Sitka, Epicéa commun, Sapin pectiné. Rev. For. Fr. 41(6): 497-506. http://documents.irevues.inist.fr/bitstream/handle/2042/26001/RFF_1989_6_497.pdf?sequence=1

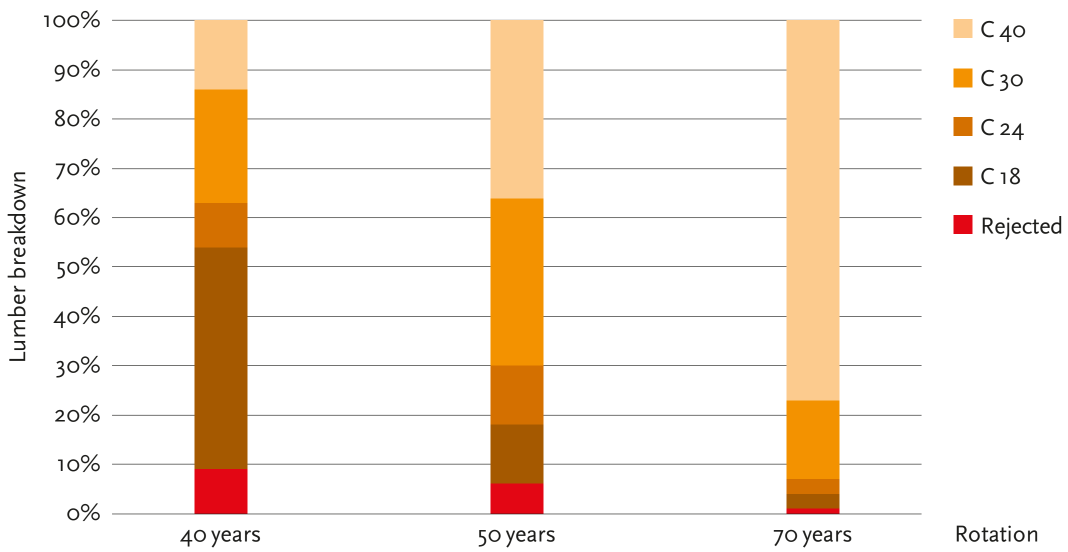


Figure 25. Breakdown of structural lumber into the different mechanical strength grades, depending on the age of final cutting (CTBA, 2003, in France-Douglas 2012).

Resilience (or *impact bending strength*) is a measure of the energy needed to cause breaking of standardised specimens in dynamic bending (shock). This is an important property for mobile uses (packaging material, sport articles, handle tools, etc.). Douglas-fir resilience averages 5–6 $J \cdot cm^{-2}$, which is similar to that of European larch and somewhat higher than that of Norway spruce. Resilience strongly increases with density and is ≈30% lower in juvenile wood.

Measurement of compression strength involves progressive crushing of wood in the axial direction, until breaking or cracking of the specimen. Similar to that of larch and spruce, Douglas-fir's compression strength is around 50 MPa in mature wood and ≈15% lower in juvenile wood.

For the stability of wood structures as well as for the persistence of coatings over years, swelling and shrinkage may be of great importance. Total radial and tangential shrinkages[16] average 4.4% and 7.8%, respectively. Additionally, warping increases with the ratio between tangential and radial shrinkage. This ratio is around 1.7 in Douglas-fir instead of 2 in most other softwood species grown in Europe. Lumber sawn in mature wood also displays lower warping than those sawn in the juvenile wood, although radial and tangential shrinkages increase from pith to bark. More marginal – except in compression wood – longitudinal shrinkage (0.1%–0.2%) shows an opposite pattern.

Hardness, which is the resistance of the wood to the penetration of a hard body, is an important criterion for flooring and decking applications. Several standard methods exist to measure this property, leading to different values. Whatever the method applied to measure it, hardness of Douglas-fir appears comparable to that of larch and much higher than that of spruce. On average, hardness is 30% higher in mature wood than in juvenile wood; accordingly, it also strongly increases with wood density.

16 Total linear (ie radial, tangential or longitudinal) shrinkages represent the reduction of dimension in the corresponding direction when wood mc decreases from the fibre saturation point – ≈30% – to 0%.

4.3.4 Natural durability

Douglas-fir has a reputation of high resistance against biological attacks. However, according to EN 350 (2016) and several studies on Douglas-fir grown in Europe, its heartwood is only moderately to slightly durable (natural durability class[17] 3–4). As for all species, Douglas-fir sapwood is not durable against fungi (class 5), which renders it unsuitable for outdoor use without additional protection measures. Unlike heartwood, sapwood is also susceptible to old house borer (*Hylotrupes bajulus*) and *Anobium* sp. attacks. Both sapwood and heartwood are also susceptible to termite attacks.

Nevertheless, despite the official classification of Douglas-fir heartwood as moderately to slightly durable, it is important to note that the responsiveness of the wood, i.e., the time it needs to regain equilibrium moisture content when hygrometry varies, must also be taken into account when considering the risks of biological attacks. In comparison with other common conifer species, Douglas-fir is characterised by its low responsiveness: once the wood is in use, this property will slow down moisture content intake and will make it lower than in more responsive species (potentially impeding the development of wood decaying fungi). That is why some Douglas-fir constructions last for decades, even when employed in *use class*[18] 3.1 (while other Douglas-fir constructions in use class 3.2 do not last more than 15 years). Since the classification in EN 350 (2016) represents a relative value, this data should thus be considered cautiously and should not contribute to tarnishing unnecessarily the reputation of a species that has demonstrated its durability through decades of use in Europe (and even centuries in its native range). Nor should it raise questions as to the suitability of Douglas-fir for its conventional uses, provided that the wood is properly installed and that the sapwood is purged (or adequately treated). Finally, since the silviculture applied by forest managers can influence the properties of the final product, it is worth mentioning that natural durability does not seem to be influenced by growth rate nor by the juvenile or adult nature of the wood.

4.3.5 Workability and main uses of Douglas-fir wood

Because of the hardness and acidity of its wood, Douglas-fir should ideally be sawn in the green state with stainless metal. Reduced sawing speed is required on dry wood, using tungsten carbide teeth. Inappropriate set-ups (for sawing but also planing, profiling, etc.) may lead to the stripping off of layers of early wood and poor surface finishes, particularly if texture is low or if within-ring density heterogeneity is high. Workability – notably nailing – of timber from fast-grown trees (growth rate > 6 mm) is also more problematic because of increased density heterogeneity and knottiness; coatings also

17 According to CEN/TS 15083-1 (2005), *natural durability classes* are based on the mass loss measured on standard clear specimens after 16 weeks' exposure to specific decaying fungi. The maximum mass loss allowed to access durability class 1, 2, 3 and 4 are respectively 5, 10, 15, and 30% (corresponding to highly durable, durable, moderately durable, and slightly durable wood); beyond this threshold, the species or tissue is classified as not durable.

18 EN 335 (2013) defines five *use classes*, depending on the conditions in which the wood is used: from permanently dry (class 1: wood mc always < 20%) to permanently wet (class 4 and 5, the latter concerning wood in contact with salt water: wood mc always > 20%). Use class 3 corresponds to wood not in contact with ground but exposed to the weather, undergoing short (3.1) or long (3.2) re-wetting above 20% mc. Based on the use and natural durability classes, EN 460 (1994) quantifies the risks of biological attacks and the subsequent need of preservative treatments.

degrade faster. Some authors therefore advocate maintaining growth rate under 5–6 mm, although lumber with wider rings is mechanically compatible with structural uses.

Provided it is properly applied (i.e., more slowly than for other softwood species), drying is quite easy and Douglas-fir wood is less prone than other common softwood species to display fissures and distortion.

Sapwood treatability is medium to low, while heartwood is not impregnable. This impermeability, which explains Douglas-fir's low responsiveness, constitutes an advantage when Douglas-fir is used in humid environments. In contrast, the low water-permeability of heartwood, combined with its low moisture content (30 to 40%), is a major hindrance to Douglas-fir veneer production in Europe. Also, despite the high density and porosity contrast between early- and latewood (see Box 1), gluing and coating of Douglas-fir is easy.

Because of its remarkable mechanical properties, combined with a relatively low density (compared to hardwood species) and advantageous dimensional stability, Douglas-fir is particularly well suited to structural applications such as timber frames, floor and roof trusses, glue-laminated beams or flooring, for instance. Its resistance against wood-damaging biological agents makes it suitable for any indoor applications or outdoor constructions without ground contact, such as cladding, subroofing, decking and various other gardening and landscaping constructions. More rewarding applications include interior joinery and furniture, door and window frames. Low-quality lumber and small diameter logs are valued as pallets, crates or stakes, for example.

4.3.6 Conclusions

Douglas-fir grown in Europe produces high-grade timber, which generally equals or exceeds the value of timber from indigenous softwoods species and from other widespread exotic species (Sitka spruce, Japanese larch, *Pinus* sp., ...). Douglas-fir wood properties are also less affected than those of other softwood species by increasing growth rates, as long as growth remains below some thresholds. This constitutes an advantage for forest managers who have the opportunity to enhance production by speeding up growth rates without excessively compromising technological wood properties.

However, dynamic growth should only be encouraged if the ensuing levels of wood knottiness and the proportions of juvenile wood and of sapwood are counterbalanced by adequate silvicultural practices and management options.

So, while there may be financial, technical or phytosanitary advantages to shorten rotations to 45–50 years, it can also be regarded, from a purely technological point of view, as cutting the corn before it is ripe. In such situations, the 10–20 rings of juvenile wood inwards and of sapwood outwards only leave a very small proportion of mature heartwood, which is associated with advantageous mechanical properties and higher natural durability than sapwood. In addition, short rotation policies increase the heterogeneity of the final products, offering lumber with higher durability and lower mechanical properties inwards (included higher tendency to warping), versus low durability and high mechanical performances outwards. Longer rotations, combining limited growth during the juvenile phase and regular ring width in the mature wood, provide a more homogeneous material.

In this context, a particular challenge for forest managers arises from the fact that different outcomes – better wood properties or risk reduction – require different silvicultural strategies, at least in part. On the one hand, slower radial growth usually benefits technological wood properties (reduced proportion of juvenile wood, branch diameters, etc.). On the other hand, faster radial growth reduces the bioclimatic risks (e.g. storm damage) as trees can achieve desired target diameters and roundwood volume more rapidly, at lower heights – (see also Chapter 4.1). Like so often, the challenge is to find a finely balanced compromise.

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5.

Economic and social aspects of growing Douglas-fir

Chapter editor: Norbert Weber

5.1 Economics of growing Douglas-fir

Jorie Knook and Marc Hanewinkel

This chapter will discuss the economic performance of Douglas-fir compared to other productive species in Europe such as Scots pine, silver fir and Norway spruce. From an ecological perspective, Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco var. *menziesii*) is regarded as better adapted to drought and less vulnerable to biotic disturbances than other productive species such as Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.) and silver fir (*Abies alba* Mill.). However, the economic consequences of the introduction of this species are little known. We have, therefore, conducted a simulation study for 30-year-old even-aged pure stands of these four species and compared the economic output. We discuss management strategies to convert pure Douglas-fir stands into mixed, and even-aged into uneven-aged stands, and elaborate on the potential of Douglas-fir to serve as an alternative to Norway spruce under climate change considerations.

5.1.1 Introduction

Douglas-fir is one of the most valuable and productive species in the Pacific Northwest. It was introduced to Europe for the first time in 1827 and is currently the most abundant non-native tree species cultivated in central European forests. Countries with large Douglas-fir plantations are France, Germany, the United Kingdom and the Netherlands (see Chapter 2). In Europe it is one of the fastest growing trees. The net revenue of the Douglas-fir may be more than 100% greater than that of Norway spruce, the second most productive species in Germany. Compared to mixed stands with fir, spruce and beech, the net revenue from pure Douglas-fir stands may even be up to three times higher according to a study in southwest Germany. However, the overall economic performance also depends on the planting costs. Establishing Douglas-fir stands is usually linked to high planting costs, and comparing planted Douglas-fir stands to naturally regenerated stands of other species largely reduces the advantage of the former, especially if higher interest rates are taken into account. Comparing planted stands of Douglas-fir with naturally regenerated stands of other species, e.g. silver fir, significantly reduces the differences between the species, if a whole management cycle is taken into account.

5.1.2 Economic evaluation of Douglas-fir compared to other conifers

To identify the economic performance of stands, it is necessary to assess the productivity of the stand and know the stumpage prices. When looking at the timber production of a forest stand, the optimal harvest moment is usually calculated by maximising the net present value (NPV), which is defined as the difference between the present value of cash inflows (i.e. the gross revenue for harvested timber) and the present value of cash outflows (i.e. the timber harvesting costs).

Maximising the NPV does not always give the optimal solution. For instance, it suggests unbalanced outputs when risks such as price volatility and the hazard probabilities of trees are included in the analysis.

For this calculation we used annuities in order to work out what the NPV would be for a time series of several consecutive years rather than single values for time periods of varying lengths. An annuity is the yearly constant amount that can be removed within the lifetime of an investment project under capital maintenance, so when a project has at least maintained the amount of its net assets during an accounting period. The annuity is positive as long as the internal rate of return of the investment is higher than the rate of return used for the calculation. This means that profit is essentially the increase in net assets during a period.

We conducted a simulation to compare the differences in annuities between Scots pine, Norway spruce, silver fir and Douglas-fir. The simulation illustrates the differences in timber production. The annuities were calculated using a standard approach that is often used for even-aged forests. Here, the starting points for the calculation were 30-year old even-aged pure stands with an area of one hectare for each species. The investigated silvicultural scenarios refer to the management currently applied in southwest Germany (Baden Wuerttemberg). The simulations were conducted using the growth simulator BWINPro-S. It was assumed that no regeneration takes place during the simulation. The rotation ages of the species differ from each other according to the current management prescriptions for these species. The annuities for Douglas-fir were calculated over 100 years, for Norway spruce over a rotation period of 120 years, while for silver fir and Scots pine the rotation period was 140 years. As the growth model is not able to simulate very young stands, we used the plantation costs for each species as the initial economic values to calculate the annuities. In the figure we display annuities from age 35 to 140, i.e. over a simulation period of 105 years (see Figure 26 in Box 3).

The results of the simulation show that the economic performance of Douglas-fir is considerably higher than that of all other productive conifer species. The difference

Box 3. Results of a simulation with the single-tree growth simulator BWinPro-S.

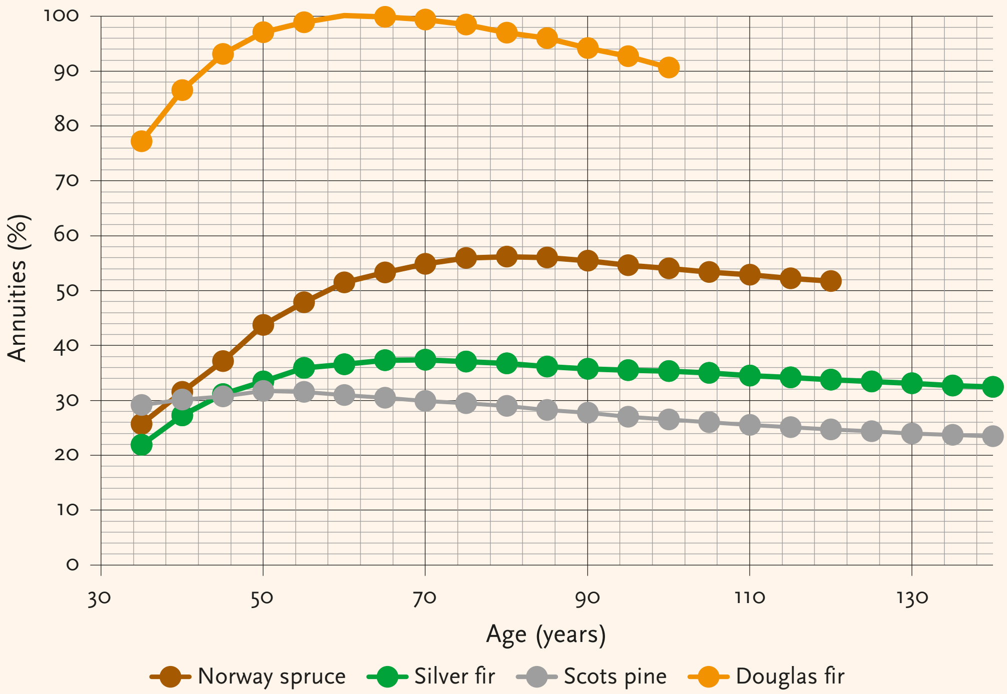

Figure 26. The annuities for the four main coniferous species in Europe as a result of simulations with the single-tree growth simulator BWinPro-S.

The figure shows the results of a simulation with the single-tree growth simulator BWinPro-S. The simulation was started with 30-year-old pure model stands for the four species: Douglas-fir, Norway spruce, silver fir and Scots pine under identical site conditions. The simulation was run for a "business-as-usual" scenario, i.e. a standard crop tree-oriented management scheme (N crop trees varied between 100 and 200), with thinning intervals following development stages depending on the dominant height (hdom) of the trees (three stages, according to the different growth dynamics – stage 1: hdom = 12–15 m, stage 2: hdom = 22–25 m, stage 3: hdom = 28–35 m). The thinning intensity was limited by a maximum thinning intensity per intervention (60–80m^3/ha in stage 1 to 3). Thinning interventions were followed by target diameter harvest with target diameters between 45 and 100 cm depending on the species. The economic parameter observed was the annuity, a net present value broken down to a yearly basis using a capital recovery factor (see text). To calculate the annuities, we started with actual plantation costs for each of the species and made a linear interpolation with the value of the stands of year 30, the start of the simulation. Price – cost relations are those of the year 2016, interest rate used was 2%.

Note: the purpose of the simulation experiment was to show the relative difference between Douglas fir and the other coniferous species. That is why the results in Figure 26 are expressed in %.

reaches a peak at age 60, where the annuities of Douglas-fir are almost two times higher than the next productive species (Norway spruce). This difference is clearly due to the much higher growth potential of Douglas fir compared to the other species. This result is in line with investigations for the species in Europe, showing distinct differences between Douglas-fir and other coniferous species. However, we have to allow for the fact that no risks are taken into account in these simulations. This may considerably alter the results, yet, looking at the vast differences, we do not expect that from an economic point of view these results would be completely reversed under different risk scenarios.

5.1.3 Impact of management strategies – transformation and conversion with Douglas-fir

The economic results of managing a species like Douglas-fir, which is usually planted, are very much affected by the costs of plantation. Reducing the planting density (maximum planting density in southwestern Germany is 1,600 trees per hectare) will decrease the planting costs, but will affect timber quality as the diameter of the branches will increase. Pruning is a common management activity in Douglas-fir stands where it is used to improve wood quality, especially with low planting densities. Pruning up to bole lengths of 12 m in Douglas-fir stands is a significant investment that has to take into account expectations towards timber volumes and qualities within a proper investment calculus. Unlike other coniferous species, such as Norway spruce, for which the timber price does not increase beyond a certain diameter, Douglas-fir is a species that achieves very high timber prices in specific markets for large diameters, if the quality is good. In some parts of central Europe this leads to very high target diameters of 80–100 cm that are linked to long production times, despite the rapid growth of the species. However, the tree heights that are achieved with these diameters (often beyond 50 m), increase the risk of storm damage, which has to be taken into account when managing the Douglas-fir stands.

The management strategy has a strong influence on the productivity and stability of a forest. In Europe a conversion to stable, more resilient forests is said to only be possible through active forest management interventions. An example of this type of management is conversion management, in which a species is replaced by another more resilient species or a pure stand is converted to a mixed species stand. The discussion about these conversion management strategies is mainly based on ecological arguments. Mixed stands have been found to be more resistant to various forms of damage, due to a higher biodiversity and because they offer more ecosystem services, e.g. recreation and protection, than pure, single-species stands. Mixed stands of Douglas-fir and Norway spruce were found to have a higher resistance to storm damage when compared to pure stands in a study in Switzerland. Furthermore, climate change can severely impact timber production and forest diversity when pure Norway spruce stands are maintained according to a business-as-usual scenario. Developing adaptation scenarios, such as mixing silver fir or Douglas-fir into the Norway spruce stand, may therefore decrease the impact of climate change on forest goods and services.

Transforming even-aged to uneven-aged stands may also be an economically interesting option to successfully manage Douglas-fir stands, but has to be carefully planned in terms of timing (cutting cycles) and transformation strategy, because Douglas-fir is less shade tolerant than, for example, Norway spruce. This may influence the survival probability of the young Douglas-fir trees in the understory.

The forest owner's attitude towards risk plays a central role in the choice of tree species. The optimal share of the highly productive species Douglas-fir within a portfolio of tree species is a matter of the decision-maker's level of risk aversion and the level of the expected risk and should not exceed a certain percentage. If multiple risks (such as disturbances, but also volatility of timber prices) are taken into account, it is never favourable to establish pure stands of productive coniferous species such as Douglas-fir or to exceed a certain threshold in the overall species portfolio.

5.1.4 Douglas-fir – an alternative under climate change?

The consequences of climate change, such as an increase in temperature and longer periods of drought, are expected to have an impact on the productivity and mortality of productive coniferous tree species in Europe, such as Norway spruce. If the potential reduction of the share of these species in European forests is not compensated by appropriate management actions, timber production could fall and there could be a loss in the overall value of European forestland, a decrease in biodiversity and reduced carbon sequestration.

Pure even-aged stands of Norway spruce, Scots pine and Silver fir in Europe spruce are considered to be vulnerable to climate change to varying extents. Depending on the climate scenario, Norway spruce, the most vulnerable of the productive conifers in Europe, might lose large parts of its present area. Climate change has effects on ecosystem goods and services, which are the benefits people obtain from ecosystems, such as the timber production and carbon sequestration provided by forests. The effects of climate change on these goods and services were studied in different regions in Europe. An increased temperature and an increased quantity of CO_2 in the atmosphere is expected to result in a positive effect on tree growth and wood production, especially in the northern and western part of Europe. However, an increased risk caused by droughts and natural disturbances, is likely to outweigh these positive effects.

A study of the economic consequences of the replacement of Norway spruce by Douglas-fir in France highlights the two main problems in forest management: 1) high uncertainty due to limited knowledge of the effects of climate change on forest species and 2) knowledge of climate change impacts – and the advantages and limitations of adaptation options – is likely to increase over time. Climate change is a continuous process. Therefore, if it is unknown whether or not Douglas-fir will prove to be a good alternative in the longer term, such as in the second or third rotation, it might be beneficial to apply a delaying strategy, whereby the decision-maker gets more time to gather more information about which strategy suits best.

The ecological consequences of the introduction of Douglas-fir in plantations seem to be small, although Douglas-fir is still sometimes seen as a species with some invasive potential (see Chapter 3.4). It is therefore still subject to restrictions in, for example, the FSC certification scheme of Germany. Appropriately managed Douglas-fir plantations can be a prime source of forest products. Since Douglas-fir is discussed as an alternative to other economically interesting conifers, it is essential to assess its resistance to climate change. Seedling survival, yield, wood quality and drought for 18 provenances of Douglas-fir, which were representative for European conditions, were tested. Northern provenances were generally more productive, while the drought tolerance increased towards the south. An optimal provenance is therefore very location-dependent (see

Chapter 3.3). Besides an increased temperature and longer periods of droughts, storms are expected to increase in severity and the vulnerability of tree species to storm damage is another important feature in future forest management. Pure stands of Douglas-fir show a comparable storm resistance to pure Norway spruce stands.

5.1.5 Conclusion

From an economic perspective Douglas-fir might offer an interesting alternative to other coniferous species due to its high productivity. Under today's environmental and market conditions this leads to significant differences in economic performance that are displayed here as the annuities of four main coniferous species in Central Europe (see Box 3). Including risks in this type of economic analysis will alter the results. In addition, comparing planted Douglas-fir stands with naturally regenerated stands composed of other species will lead to smaller differences in the economic output. Under climate change, Douglas-fir may replace productive species that are considered to be particularly sensitive, such as Norway spruce, to mitigate the economic effects of the loss of these coniferous species, such as for the timber industry. However, if climate change is a continuous process, although Douglas-fir seems adapted to current climate change circumstances it might no longer be suited to the long-term climate in the second or third rotation, unless suitable provenances adapted to future climatic conditions can be used. Therefore, from an economic perspective, irreversible decisions made under conditions of uncertainty, such as establishing pure stands of Douglas-fir over large areas, should be avoided. Yet, Douglas-fir is certainly an economically interesting species that can enlarge the portfolio of tree species in European forestry by admixing it to broadleaves of low productivity or by replacing – to a certain degree – more vulnerable coniferous species. To improve the economic analysis, long-term species trials including different provenances and mixtures of the species with other species, taking into account a variety of ecosystem services, should be investigated to reduce the uncertainty related to growth and vulnerability.

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5.2

An (un)welcome guest – perception of Douglas-fir in seven European countries from the perspectives of forestry and nature conservation

Jakob Derks

5.2.1 Introduction

An important factor that influences the use of Douglas-fir is the perception surrounding the species, which is, as for many other non-native species, quite divided. In order to achieve a meaningful identification of perception we need to focus on a defined subset of society. This section focusses on two types of communities: national and organizational. On the organizational level we compare the forestry sector with the nature conservation sector. The focus is on Germany, France and the UK, the three European countries with the largest Douglas-fir area. Other examined countries are Belgium, the Czech Republic, the Netherlands and Switzerland.

Science is often intertwined with values and beliefs, and opinions are usually shaped on the borderline between the two. The objective of this section is to get an idea of the controversy surrounding Douglas-fir in Europe and to what extent opinions diverge between different countries and different interest groups.

In this section, three different levels of knowledge are distinguished. First there are facts, known knowns. These include information that is not contested, such as the high growth rate of Douglas-fir and the value of its wood. Secondly, there are uncertainties, or known unknowns. These are aspects we know exist, without being fully aware (yet) of their precise extent, importance and details. Examples include the interaction of Douglas-fir with different arthropod species, or its place within a certain ecosystem. This framework is used to analyse the responses to the questions that were asked to the respondents during a semi-structured interview. Lastly, there are the unknown unknowns, also called black swans: events impossible to foresee and thus not relevant for this analysis.

Not much research has been conducted on the societal and political perception of non-native tree species in Europe, let alone on the specific topic of Douglas-fir. To overcome this shortage of first-hand information, one has to resort to proxies. One indicator for the heed paid to the potential problems with Douglas-fir is the number of publications on the topic. A search on "Douglas-fir OR *Pseudotsuga menziesii* AND perception" yields no results on Web of Science, but in combination with words like soil, water, fauna, flora, fungi, vegetation, ecosystem, biodiversity, competition, regeneration or risk gives 84 results in France and 80 in Germany. All the countries in this comparison produce quite

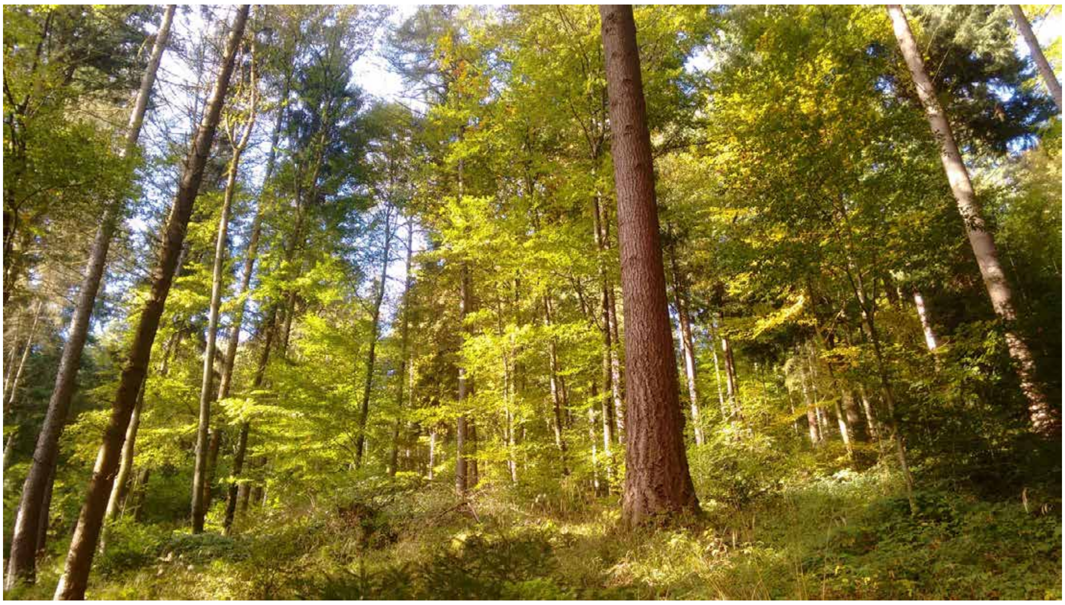

Figure 27. Douglas fir in the city forest of Freiburg.

Table 6. Overview of the respondents.

	Nature conservation	Forestry
Belgium	x	x
Czech Republic		x
France	x	x
Germany	x	x
Netherlands		x
Switzerland	x	x
United Kingdom	x	xx

a lot of research on Douglas-fir. A study of grey literature could also be insightful as the less scientific nature leaves room for more opinionated articles.

The main approach of this treatise however was to gather information through a qualitative inquiry based on twelve semi-structured expert interviews. The respondents were chosen based on their 'intermediate' position in the field. The people that were interviewed are mid- to high-level managers of local forest districts, forest owner cooperatives and nature conservation organisations. They form the transitional group from practice to theory and have sufficient knowledge of both to support their opinions. No scientists or researchers were included as the interviews aimed at gauging perception rather than known facts. On the other hand, forest workers and volunteers for NGOs were ruled out based on their lack of influence in the actual decision making on the terrain. The experts come from seven different European countries: Belgium, the Czech Republic, France, Germany, the Netherlands, Switzerland and the UK. They represent the forestry sector and the nature conservation sector.

Interview questions and responses

The experts were asked to answer the following questions:

- What are in your opinion the two biggest opportunities for Douglas fir in your country?
- What are in your opinion the two biggest risks connected to expanding Douglas fir in your country?
- Do you know of any legal restrictions/encouragements concerning Douglas fir in your country?
- Would you say that there is a conflict or debate between stakeholder groups (notably nature conservation, forest and wood industries, public perception)?

One hypothesis was that there would be a connection between high distribution of Douglas-fir in a country and a high acceptance of the species. The perception in France for instance was expected to be more favourable than in Germany. The second assumption was that the forestry sector is especially interested in potential economic gains, while the conservation side prioritises the potential environmental risks, leading to a more risk-averse view on the matter compared to the forester's more risk-prone attitude.

Concerning the two biggest opportunities, there was relative unanimity. Virtually every respondent praised the tree's fast growth and outstanding wood quality. A point that was mainly stressed by conservationists is the potential of increased carbon storage and Douglas-fir's propensity to adapt to climate change better than spruce. There were also references to the faster litter decomposition compared to spruce. Basically the answers did not differ too much between countries or organisation types. The responses to this question are based on facts ('known knowns') and were not contested by any of the interviewees.

When asked about potential risks connected to Douglas-fir the answers were slightly more diverse. The most common replies included the potential invasiveness and the risk of new pests and diseases, either wiping out Douglas-fir or being transmitted from Douglas-fir to other tree species. Some foresters also noted that the place of Douglas-fir in many European ecosystems is still unknown, as the European experience with the species is relatively recent to forestry standards. The most marked difference with the first question is not so much the marginally higher diversity of answers, as the certainty with which they were expressed. The concerns were extenuated by doubt and preceded by adjectives such as *possible*, *potential* or *probable*. The experts are aware of the fact that the tree has an impact on the local flora and fauna but are unsure about the extent of any negative consequences. A factor that was stressed by both foresters and conservationists from the UK, Belgium and France is the negative impact on the landscape. In these countries Douglas-fir tends to be used in even-aged monocultures, making this more an issue of management than an intrinsic characteristic of the tree species.

The third question had a double purpose: on one hand to get a brief overview of the most relevant regulations, which can in some way be seen as proxies for a wider societal perception, on the other hand to gauge the respondents' knowledge of and opinion on these rules. Every country has its own laws, its own certification standards for FSC and PEFC and can choose how to translate European nature directives into practice. Few interviewees knew the precise details of the regulations concerning the use of non-native tree species in their forests, especially when it comes to the allowable share of exotic species in certified forests and in Natura 2000 areas. While the foresters generally

Table 7. Overview of the responses to questions 1 and 2 by sector and country (code).

		Nature	Forestry
positive	Wood quality, high increment	B, D, GB	CZ, D, F,GB, NL
	Climate change adaptation, carbon sequestration	D, GB	B, CZ, D, F, GB
	Other	B	B, F, NL
negative	Invasiveness	B, D	CZ, GB
	Unknown risk of pests and diseases, unclear place in ecosystem		CZ, D, F
	Other	B, D, GB	F, GB, NL

knew about the regulations, the conservationists showed a more detailed knowledge of the matter. There are considerable differences between the countries when it comes to forest-related regulations. In France big clearfellings and non-native plantations are still allowed, even in certified forests and Natura 2000 areas. Nonetheless, the French forestry interviewee considered the regulations to be too strict. The German forester on his turn mentioned that the limit of 20% non-natives in FSC-certified forests can be impractical. Perception is to a great extent a matter of perspective.

There also turns out to be a difference in how countries differentiate between forests and plantations. While largely a semantic discussion, this influences forest management practices and regulations in the different countries. In Germany for instance all forests is considered to be semi-natural and are subject to the same standards, while in the Netherlands there is a clear distinction between natural forests and production forests entailing different rights and obligations.

The last question focused on the relations between the nature conservation sector and the forestry sector, as well as on the public opinion. Every interviewee stated that the public opinion does not have any direct consequences and that most people don't even have an opinion. The average recreationist does not know the difference between Douglas-fir and Norway spruce or Silver fir. One forest manager responded that what people perceive as a natural forest depends more on the management than on the species composition. A mixed continuous cover stand with Douglas-fir, Sitka spruce and Giant fir will generally be regarded as more natural than an even-aged monoculture of Norway spruce.

According to the experts there are conflicts and debates between conservationists and foresters but with different degrees of constructivism. Germany has a long history of forestry and at the same time an important presence of nature conservation organisations. Forestry in Germany is organised on the federal state level and there is hardly any national forest. The forestry sector and the conservationists share a long history of dialectic discourse which continues to this day. On the topic of Douglas-fir the Bundesamt für Naturschutz (BfN) and the Deutscher Verband Forstlicher Forschungsanstalten (DVFFA) recently published a common paper, a compromise on the management of Douglas-fir.

In France, the camps are more divided. The Office National des Forêts (ONF) manages all the national forests, and private owners are quite well organised in a number of big cooperatives. The nature conservation sector however is more divided with thousands of small regional or local organisations, creating a clastic union. This makes it more difficult for the French conservationists to defend a single viewpoint and more often than not, the forestry view prevails.

This difference between Germany and France seems to percolate the local resistance against Douglas-fir. In Germany, Greenpeace has staged a protest in which a newly planted stand of Douglas-fir was ripped out, but apart from that incident the general debate is rather constructive according to the respondents. In France the resistance against Douglas-fir is less organised but fiercer. A French respondent stated that plantations get damaged or destroyed on a regular basis by anonymous collectives. The anonymity of the protesters makes a debate like the one in Germany, on the level of political advocacy groups, less likely to happen in the foreseeable future.

In the UK there is a plethora of nature protection organisations, such as the Royal Society for the Protection of Birds (RSPB), the National Trust and the Woodland Trust. The Forestry Commission is the country's biggest land manager. Both sectors are well organised, yet the UK hardly seems to experience the conflicts that mark its continental counterparts. Although there are considerable differences between British regions and countries, the interviewees were rather optimistic about the dialogue, mentioning that the forestry sector and the nature organisations largely operate on separate spatial and thematic levels. The mostly non-native softwood plantations are the realm of foresters, while in the ancient native broadleaved woodlands nature conservation is usually the priority.

Conclusions

Some clear conclusion can be drawn from the expert interviews that were conducted. The shared answers which were often given reflect a shared knowledge between all the respondents. The 'known known's go unchallenged, and the differences overwhelmingly stem from the 'known unknowns' or uncertainties. The main point of disagreement is the invasiveness of Douglas-fir. Scientific research on the topic is still unsure about the long-term impact, but this debate is equally a matter of definition. When research shows that there is a risk of invasion in rare biotopes such as rocky slopes and oak forests on poor soils, the foresters tend to focus on the large areas where the is no risk, while the nature conservationists stress the exceptional ecological importance of exactly those sites. The potential outbreak of new diseases caused by the spread of Douglas-fir or affecting the tree itself is a risk, which was only mentioned by foresters.

There is a clear difference in focus and priorities of the respondents. The foresters tend to stress the economic benefits of the tree, and on the ecological level often compare it to Norway spruce, which, also largely planted outside of its native range, does not always fare better. The conservationists on the other hand focus more on the vulnerable biotopes and species, which might be at risk and would like to proceed more cautiously. They mostly consider the existing legal framework and certification standard to be insufficient, while some foresters find them cumbersome and overly strict.

When comparing the different countries, results are less clear. One could tentatively divide the countries into three major groups that share a number of common characteristics.

The first group consists of Germany, Switzerland and the Czech Republic. These countries have a high degree of multifunctional, mixed forests where wood production and nature conservation are integrated, as well as an extensive forest research tradition. In Germany, the debate seems to be the most explicit, but at the same time it is organised in a constructive fashion.

The second group encompasses France and Belgium (notably the Walloon region). While these countries also have some experience with mixed uneven aged stands, much of the wood is procured from monocultures based on a clearcutting and replanting system. The conflict between forestry and conservation on the topic of Douglas-fir is less prominent in academic circles and in the public debate, less organized but more polarized.

The United Kingdom and the Netherlands form the last group. Practically all their wood production stems from – largely non-native – planted monocultures, while the remaining native woodlands are often strictly protected. This clear segregation between protection and production forest limits the conflict between nature conservationists and foresters.

In conclusion, national differences exist to a certain extent, but the dichotomy on the organizational level, between nature conservation and forestry, is bigger, with the first tending to be rather risk- averse and conservative and the latter more risk-prone. There is of course a high level of interaction between the two examined levels: the nature and forest sector influence the national stance and vice versa. The public opinion is described by the interviewed experts as being of little importance and ill-informed on the topic. While the scope and the extent of the interviews was rather limited, the resuls seem telling and consistent.

Parallel to the ongoing fundamental research on Douglas-fir, a constructive dialogue is paramount if the species is to be judged in a rational way, based on its merits and defaults and not on its origin. Any decision that is not supported by one or more significant sectors will spur opposition and impede a long-term strategic vision.

Most of the research surrounding Douglas-fir is conducted within the realm of quantifiable hard science. Policy however is not merely based on observable facts and science is often contested. Decisions should be optimized based on the available information, recognising potential knowledge gaps and cognitive biases. When we are discussing the future of Douglas-fir in Europe, the social aspect cannot be neglected.

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5.3

Douglas-fir discourse in Germany

Klaus Pukall

5.3.1 Germany as example of an intense discursive struggle about Douglas-fir

In April 2012, the conflict in Germany between nature protection organisations and foresters about the use of Douglas-fir escalated. In the north Bavarian Spessart forest, which is dominated by beech and oak, Greenpeace Germany pulled out 1,967 Douglas-fir seedlings as part of its beech forest campaign and, shortly after, displayed them in front of the Bavarian Ministry of Agriculture and Forestry in Munich. Greenpeace's slogan was "Beech forests are not industrial forests". In Greenpeace's view, Douglas-fir plantations created by the state company Bayerische Staatsforsten (Bavarian State Forests) within a Natura 2000 site contravene the EU Habitats Directive. Forestry actors reacted harshly to the Greenpeace campaign, describing its activities as "professionally not competent, illegal and ideological motivated" executed by "eco-terrorists" who were fighting a "green war" (Pukall, 2014).

The previous section gave an overview of possible discourses about Douglas-fir in Europe on the basis of expert interviews and has shown that there is a discursive struggle between corporate and societal actors in Germany. In this section, the case of Germany will be explained in more detail on the basis of document analysis.

Discourse is here defined as "a specific ensemble of ideas, concepts and categorizations that are produced, reproduced, and transformed in a particular set of practices and through which meaning is given to physical and social realities" (Hajer, 1995: 44). The set of practices are e.g. scientific publications, statements and press releases of different social actors, media coverage as well as policy documents and regulations. Discourse about Douglas-fir mainly occurs on the expert level. Forestry sector and environmental sector actors try to influence policymaking with their perception of Douglas-fir as an economically profitable tree species, as a necessary tool for climate change adaptation, or as a foreign, alien or invasive species. Within the discourse different value orientation and knowledge bases are relevant.

5.3.2 Story-lines for and against Douglas-fir

From an analytical standpoint, Douglas-fir discourse can be divided in four main story-lines in Germany. In the following paragraphs, the central arguments are presented.

Douglas-fir as an economically profitable tree species

A forester of the Bavarian State forest captured the story-line in a nutshell: "We would have to invent Douglas-fir, if it did not exist, with its entirely positive qualities. The tree fits excellently into close-to-nature forestry and tending is easy. It is resistant to biological pests and produces valuable timber within a short time period" (LWF 2008: 44, translation by author). Within this story-line it is argued that, due to the ice age, there is only a limited choice of both suitable and economically valuable tree species for forestry in Europe. Douglas-fir fills a gap between Norway spruce and Scots pine stands due to its tolerance to relatively dry conditions. The tree species is fast growing yet its wood quality is also very good. The stand dynamics of Douglas-fir fits well with European tree species, thus it can be easily planted in mixed stands. Disease risk is rather low. The roots of this story-line date back until the beginning of modern forestry. The search for valuable tree species had already begun in the 19th century – the first introduction of Douglas-fir to Europe dates back to 1824. In Germany this story-line contributed to the so-called "Douglas-fir wave" in the 1960s and 1970s. About 90,000 hectares of Douglas-fir were planted during this period. Important knowledge for this story-line originates from forest sciences, especially silviculture, yield, soil and wood sciences.

Douglas-fir is important for climate change adaptation

This story-line emerged over the last 10–15 years when the issue of climate change adaptation became more prominent on the political agenda. It is argued that Douglas-fir is well adapted to climate change in certain areas of Europe due to the warm climate in the natural range of the species. By actively introducing Douglas-fir into pure and mixed stands the stability of these stands should be increased and the risk of the destruction of stands due to climate change diminished. This story-line partners with the first story-line mentioned above. Douglas-fir, as an economically interesting species, is much better adapted to the expected climate change in Germany than Norway spruce. As well as the forest sciences mentioned in the previous paragraph, knowledge from meteorological and climate science is an important resource. This story-line has already influenced practices within forest enterprises. For example, Hessen Forst (state forest enterprise of Hesse) has nearly doubled the long-term target for the area covered by Douglas-fir within the last 10 years.[19] According to the National Forest Inventory, more than 35,000 hectares of Douglas-fir have been planted in the last 10 years (which is less than during the "Douglas-fir wave").

This story-line is directly contested by nature conservation actors. They argue that the genetic variability of Douglas-fir in Europe is limited and thus the adaptation potential of the species is small in comparison to native trees. Natural stands with long coevolution should be less vulnerable to climate change.

Douglas-fir as an alien species

Non-native, foreign, alien species or neophytes are criticised in this story-line on the basis of two different arguments. On the one hand, cultural arguments are used. Douglas-fir does not fit into the typical landscapes of Europe, it undermines the diversity, beauty and uniqueness of cultural landscapes. The story-line is using one of the roots of nature protection, the Heimatschutz (natural heritage) movement (end of 19th, beginning 20th

19 In the 2008 silvicultural handbook of Hessen Forst the long-term objective for Douglas-fir was to increase its area from actual 3% to 6%. In a footnote it is stated that the long-term objective for spruce and Douglas-fir should be redefined "due to the background of climate change" (Hessen-Forst, 2008: 6). In 2014 the long-term objective for the area covered by Douglas-fir is 10% (Hessen-Forst 2013).

century), which tried to preserve traditional landscapes against the threat of industrialisation and overuse. This line of argument is criticised, for example by the German biologist Josef Reichholf, due to its racist and xenophobic undertones. On the other hand, ecological arguments are also used. Due to a lack of co-evolution, Douglas-fir is a bad habitat for native fauna and flora. Negative impact is mostly reported for birds and arthropods (see Chapter 3.4 for more details). Therefore, Douglas-fir is blamed as an "ecological desert" by nature conservation actors. Within this story-line biological and ecological knowledge is of high importance.

Actors from forestry or forestry sciences are arguing against this story-line with two different strategies. On the one hand, they use results from scientific studies which show only a minor impact of Douglas-fir on the environment. Management practice, such as planting Douglas-fir only in mixed stands reduces the negative effect of Douglas-fir. Additionally, forestry actors argue that biodiversity is increased by additional tree species, especially in pure spruce or beech stands. On the other hand, positive terms such as Gastbaumart (guest tree) and Spätheimkehrer (late returnee) are also used for Douglas-fir. It is argued that Douglas-fir has been part of the European flora since before the ice age. Thus, forestry is only reintroducing a former native species.

Douglas-fir as invasive species

The story-line described above is further enlivened by arguing that Douglas-fir is not only an alien species but can also be invasive. It has the potential to invade natural habitats and destroy them due to its early maturing, its light seeds which can be distributed by wind up to two km, and its highly vigorous growth. It could therefore be an immediate threat for the native biodiversity. In Germany, a central and oft-mentioned study was conducted by Knoerzer (1999) in the Black Forest. It describes how, on acid and termid soils, the natural regeneration of Douglas-fir can dominate. In particular, screes and rock habitats can be invaded. In Spain, scientific evidence for the invasive potential of Douglas fir is also reported (Broncano et al., 2005). Behind these arguments are international guidelines or regulations like the IUCN guidelines for the prevention of biodiversity loss caused by alien invasive species (IUCN 2000) or the Convention on Biodiversity. The knowledge base for this argument is invasion biology.

This story-line is contested, especially by forestry scientists. For example, Eggert's (2014) study does not find evidence of invasive behavior by Douglas-fir in Bavaria. Forestry scientists complain that knowledge which has been accumulated in forestry about the competitiveness and ecology of Douglas-fir in Germany is not perceived within this story-line. For example, data from the National Forest Inventory is not used within the invasiveness assessment of the Bundesamt für Naturschutz (German Federal Office for Nature Conservation) which has included Douglas-fir in the list of invasive species (Nehring et al., 2013). Forestry scientists conducted their own invasiveness assessment for Douglas-fir (Vor et al., 2015). In addition, legal arguments were used. According to article 41 of the German Nature Protection Law of 2010, alien species had to be a "substantial" threat to native biodiversity. The question was whether the invasiveness assessment really considered this issue.

In 2016, the members of the Bundesamt für Naturschutz and the forestry scientists published a joint management concept while the controversies about the methodologies defining invasiveness remained (Vor et al., 2016: 155):

"1. On the vast majority of forest sites in Germany the management of Douglas fir does not pose a significant threat to biodiversity and ecosystem services on the national level according to the current state of scientific knowledge.

2. At special habitats, such as open rocky screes, shallow and nutrient-poor ridges, xeric grasslands and thermophilic forest (i.e. thermophilic oak forest) communities, Douglas fir should not be grown in order to protect rare and endemic species. Such sites, which are mostly protected by law and do not represent large areas, should be kept free of Douglas fir by: removing natural Douglas fir regeneration; converting neighbouring Douglas fir stands into stands of native species; and avoiding the establishment of new Douglas fir stands. In addition to these general recommendations, in protected areas specific legal regulations in respect of alien tree species apply.

3. Generally, Douglas fir should be mixed with other native tree species, like European beech (Fagus sylvatica L.).

This management concept is not legally binding for forest owners. Nevertheless, this compromise might help to de-escalate the conflicting discourse about Douglas-fir in Germany.

5.3.3 Influence of regulations on the discourse

As already mentioned, international agreements influence the discourse about Douglas-fir. Central is the Convention on Biological Diversity (CBD), especially Article 8: "Each Contracting Party shall, as far as possible and as appropriate [...] (h) Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species". Right now, two conflicts have emerged on this basis.

1. The EU Habitats directive, which is the central European programme to implement the CBD, is used by Greenpeace to question Douglas-fir cultivation in forest habitat types. Greenpeace has launched a complaint to the EU in April 2012 because of the above-mentioned Douglas-fir plantations within the Natura 2000 site "Hochspessart". Greenpeace argues that these plantations are projects in the sense of article 6 (3) of the Habitats directive. As of July 2018, there has been no decision by the European Commission. The project definition has been clarified by the European Court of Justice several times. Nevertheless, there is an ongoing debate about the question of whether "normal" forestry actions are projects or not. In the official justification for the amendment of the German Nature Protection Law in 2009 it is stated that forest operations which are in line with the Nature Protection Law are generally not regarded as projects (Deutscher Bundestag, 2009: p. 65).

2. Until 2014 Article 8 of the CBD was implemented in Germany in article 40 of the Nature Protection Law and on the European Level in Article 22 of the Habitats Directive. The legal definition in the CBD, in the German Nature Protection Law and the Habitats Directive, is not referring to the scientific definition of invasiveness potential. Only the possible threat to native biodiversity is important. Invasive dispersal strategies which are studied within biological science are of minor relevance within the legal definitions. For example, the Bundesamt für Naturschutz (German Federal Office for Nature Conservation) which is responsible for creating a national list of invasive species takes only the threat on native biodiversity into account for the decision that Douglas-fir is an invasive species (Nehring et al., 2013). The negative impact of Douglas-fir on ecosystems and ecosystem services was the central justification. The reproduction potential and the dispersal potential are only additional criteria which are mentioned but are not seen as really relevant for the overall decision.

Contrary to this approach, the regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of invasive alien species considers the invasive potential of alien species. The necessary risk assessment takes into account:

- The "reproduction and spread patterns and dynamics including an assessment of whether the environmental conditions necessary for its reproduction and spread exist" (Article 5(1b)).
- The "risk of introduction, establishment and spread in relevant biogeographical regions in current conditions and in foreseeable climate change conditions" (Article 5(1d)).

Until the transposition of the EU regulation into the German Nature Protection Law in 2017, the legal consequences of the German law and the EU regulation were completely different. While in Germany the decision that Douglas-fir is part of the list of invasive species had no legal consequences for forestry (Article 40(4) German Nature Protection Law), the cultivation of Douglas-fir would be impossible if Douglas-fir were to be listed on the European level (Article 7 EU Regulation on invasive species). German forestry actors feared that the German decision would also influence the decision on the European level. This fear was unjustified. The impact assessment of the European Commission (2013) for the planned regulation mentions mostly threats for forests and forestry by invasive pests. Only black locust was seen as a tree species that is both invasive and economically interesting.

5.3.4 Conclusions

The described discursive struggle between nature conservation actors and forestry actors has a long tradition in Germany, deeply rooted in different world views on forests and goals of forestry or ecosystem management (Winkel et al., 2011). It is a power struggle over the right to define how forests should be managed. Therefore, different discourses are instrumentalised to convince the public and, especially, political actors. Late returnee, guest tree species vs alien, invasive species – all these metaphors are transmitting value judgments intended to influence the audience (Larson, 2008).

Additionally, it is a conflict about the right type of knowledge. In the course of the invasiveness assessment of the German Federal Office for Nature Conservation, the conflict between forestry scientists and biologists or ecologists became manifest.

Yet, solutions are possible – see the above mentioned compromise management concept (Vor et al., 2016). Similar compromises were published already in the 2000s (e.g. LWF, 2008). These compromises might help to influence management practices of the forestry sector but will not solve the ongoing power struggle.

Additionally, the existing legal regulations on the basis of the CBD are mostly not in favour of these solutions. Due to the inherent value orientation of the invasive species concept (Larson, 2008), alien species are only perceived as a threat which has to be controlled by management options. The notion that the forestry sector wants to use an economically interesting alien tree species with an unclear invasive potential without posing a major threat to the environment is hardly manageable within the nature protection regulations. Therefore, any possible legal solution to the Douglas-fir conflict should be implemented within forest regulations and/or the national forest laws.

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5.4

Certification initiatives for Douglas-fir products

Mauro Masiero and Davide Pettenella

Among the soft policy tools and non-state market-driven instruments for the responsible management of forest resources and the marketing of forest products, a central role is normally assigned to certification. With regard to Douglas-fir, multiple certification options can be considered. These include, in particular: (i) forest certification according to the standards developed by the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification schemes (PEFC); (ii) green building certification; (iii) certification or conformity declaration based on technical norms and programmes for construction materials. In the following pages we will consider the three groups of standards; a section will follow with a discussion on the links between forest certification and some existing policy or voluntary tools.

5.4.1 Main standards used in Douglas-fir certification

5.4.1.1 Forest certification

As of 1 June 2018 a total of 232 Forest Management[20] certificates that include Douglas-fir among wood species have been issued according to the FSC standards. This corresponds to a total area of about 26.6 million hectares[21], i.e., about 13.2% of the total FSC-certified area worldwide. Certificates are mostly concentrated in Germany (20%), the UK (13%), the USA (10.4%) and Bulgaria (9.5%). Additionally 3,041 FSC Chain of Custody (CoC) certificates including Douglas-fir within their scope have been issued, corresponding to roughly 9% of total FSC CoC certificates at global scale. About two-thirds of these certificate holders process and trade roundwood, sawnwood and wood for construction (i.e., doors, windows and window frames, flooring and housing/building elements), while fewer than 100 organisations operate in the pulp and paper sector. The USA (16.4%) and the UK (10.2%) are the leading countries in terms of number of CoC certificates including Douglas-fir among species.

20 These include 231 joint Forest Management and Chain of Custody certificates and one joint Forest Management and Controlled Wood.

21 This figure doesn't specifically refer to forest areas hosting only Douglas-fir, rather to all forest management certificates including Douglas-fir within their scope.

As regards PEFC certificates, the available data is a bit vague, since the international PEFC database, when searching via "Douglas-fir" or "Douglas" as keywords[22], provided just four results corresponding to CoC certificates in the UK (2), Belgium and Canada. However, these figures are believed to be incomplete and unrealistic because simple research via both general and sectorial search engines shows multiple results. Spot reference to the presence of PEFC-certified Douglas-fir stands and products can be also found on national websites and databases managed by PEFC national offices (e.g.Italy). When searching the Sustainable Forestry Initiative (SFI) database, 30 results are found for the USA and Canada, and 12 of them explicitly include a PEFC CoC certificate.

When considering forest management certification, the presence of Douglas-fir might be a relevant issue outside North America (USA and Canada) with regard to requirements for native species and, in some cases (e.g.New Zealand), the management of forest plantations. Both certification schemes adopt a precautionary approach by stating that native species and local provenances shall be preferred, and the use of non-native species shall be carefully monitored to avoid adverse ecological impacts[23]. Terminology and wording are ambiguous among different schemes: FSC standards speak about *exotic* species (FSC Principles and Criteria for Forest Stewardship version 4-0) or *alien* species (FSC Principles and Criteria for Forest Stewardship version 5-0), while PEFC standards make reference to *introduced* species. In any case, the use of non-native tree species can be limited by national standards. For example, FSC forest management standards for Germany require that tree species that are not part of natural forest associations (including exotic species) are positioned as single trees or small groups to an extent which does not jeopardise the long-term development of the stands into natural forest associations. Furthermore, these species cannot exceed 20% of the planned stocking goal at forest management unit scale, unless it is professionally justified that the development does not put the natural forest plant association at risk. In other cases limitations can be even stronger. FSC standards for Sweden, for example, state that, from 2009, the use of exotic species like Douglas-fir shall be limited so that the total area of newly established stands of such species does not exceed 5% of the productive forest area.

In addition to forest management and COC certification standards, both FSC and PEFC have developed specific rules for project certification. Among certified projects a special mention is deserved by the 2012 Olympic Park in London, that represents the first dual (i.e. both FSC and PEFC) project certification in the world. In this perspective, certified Douglas-fir wood could find an interesting market niche, encouraged by uptake by the green-building sector and the increasing appeal and visibility of related communication within both public and private procurement policies.

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22 Keywords have been typed in the "Name of product" field, because the new version of the online PEFC database, recently implemented, doesn't allow searching of certified organisations by selecting them according to the wood species.

23 See Criteria 6.9 and 10.4 for FSC (FSC-STD-01-001 V4-0, FSC Principles and Criteria for Forest Stewardship) and Indicator 5.4.5 for PEFC (PEFC ST 1003:2010, Sustainable Forest Management - Requirements). As for FSC new Principles and Criteria for Forest Stewardship, approved in 2013, reference shall be made to Criterion 10.3 (FSC-STD-01-001 V5-0).

5.4.1.2 Green building certification and programmes

The construction sector represents a leading end user of Douglas-fir wood products. A dynamic segment of the construction sector is represented by the "green building" movement. The prominence of wood in green building largely depends on green-building standards, technical norms and building codes and the related public incentives available for the use of different raw materials.

The Leadership in Energy and Environmental Design (LEED) scheme, developed by the US Green Building Council (USGBC), is normally seen as the frontrunner among certification schemes in this field. The standard encourages the use of certified timber by issuing a so-called Materials and Resources Credit. In such a way LEED has created a link with the use of forest certification standards (Bowyer et al, 2014).

FSC and PEFC certificates are also recognised by other certification schemes operating in the building sector, such as for example the Building Research Establishment Environmental Assessment Methodology (BREEAM).

There is empirical evidence of the use of Douglas-fir wood in the green building sector in USA, Canada, Japan and other countries, also chosen for its superior technical performances, but unfortunately no data is available.

5.4.1.3 Technical norms and programmes for construction materials

With reference to the construction sector and apart from voluntary certification systems, many technical norms define the characteristics and performance for materials and products to be used in the building sector. The European Construction Products Regulation (CPR) (Regulation (EU) 305/2011) came into force across the EU in July 2013, modifying Council Directive 89/106/EEC. The Regulation introduced conditions for placing or making available on the market construction products by establishing harmonised rules on how to express the performance of construction products in relation to their essential characteristics and on the use of CE marking on those products. In other words, the Regulation defined requirements for construction works and required harmonised technical specifications (i.e., EN technical norms) to set up the essential characteristics of construction products. For specific families of construction products covered by a harmonised standard, the European Commission shall define essential characteristics for which the manufacturer shall declare the performances of the product placed on the market. This might include, for example, window frames, beams, etc made with Douglas-fir wood.

In addition to the above indicated issues, EU norms on construction products emphasise the concept and role of the Environmental Product Declaration (EPD). A technical norm (EN 15804) has been specifically developed in 2012 for the purposes of setting core and shared rules (i.e., indicators) for the performing of Life Cycle Analysis (LCA) and the creation of EPDs for construction and building sector products, including those for which Douglas-fir wood is used.

5.4.2 Links between forest certification and existing policy and other voluntary tools

Forest certification can also be instrumental in the implementation of requirements laid down by existing policies and other voluntary tools. As for policies, reference can be made, for example, to those policies/regulations aiming to address illegality in the forest sector, such as the European Union Timber Regulation (EUTR), the Lacey Act (USA) and the Australian Illegal Logging Prohibition Bill. Within these regulatory systems forest certification is not seen as an automatic proof of legality for wood and wood-based products being traded, nevertheless it can be a common tool adopted for assessing and mitigating illegality risks. For example, a EU-based importer (so-called “operator” in the EUTR) can simplify its Due Diligence System established according to the EUTR requirements when importing FSC or PEFC certified Douglas-fir wood from the USA or Canada. The same is true for an EU-based forest manager managing and harvesting certified forest stands in Europe: the placing of certified products on the market can support the implementation of EUTR requirements.

Forest certification is also mentioned as a tool within Green Public Procurement (GPP) policies adopted by many governments at both national and local level. Environmental criteria for GPP regarding forest-based products (paper, office and outdoor furniture, construction elements, flooring, etc) have been defined at both regional (e.g.EU) and national scale. When referring to virgin wood or fibres, FSC and PEFC certifications are a common reference.

Finally, forest certification can also be linked to different technical norms and certification tools that might be relevant for Douglas-fir products. For example, the certification of wood pellets for residential use according to the ENplus standards (i.e., the technical norm ISO 17225-2 and additional requirements) developed by the European Biomass Association (AEBIOM) and managed by the European Pellet Council (EPC) emphasises the use of input materials originating from FSC or PEFC certified sources. At the moment around 431 pellet producers are ENplus certified and, according to AEBIOM estimates, more than 50% of EU domestic pellets are already certified. This can help when placing a value on processing residues from sawmilling operations on certified logs, including Douglas-fir ones, especially when considering that wood pellet exports from North America to Europe have doubled in recent years to reach 4.7 million tons in 2013.

5.4.3 Some final considerations

Douglas-fir wood production is concentrated in those countries in North America and Europe that are more advanced in developing and implementing standards, codes and regulations for supporting the use of products of responsible and legal origin. This should create some competitive advantages to Douglas-fir products with respect to other wood species coming from regions where the use of such tools is lagging behind.

Douglas-fir covers a wide range of end uses; sawmilling is, in almost all the supply chains, a common fundamental step in Douglas-fir wood product marketing. A recent trend toward concentration has emerged among European sawmills: at regional scale 12 sawmills process more than 600,000 cubic meters per year, and are located in just four countries (Austria, Finland, Germany and Sweden). The capacity to process huge volumes of raw materials implies scale economies and high product standardisation, often based on a limited number of species (mainly spruce and pines), thus reducing competing capacities for smaller enterprises that might remain competitive only on specialised products (such as Laminated and Structural Veneer Lumber, for which Douglas-fir wood is increasingly being used). This trend might be emphasised by the implementation of technical norms on construction products, with smaller enterprises not being able to fill the gap, and suffering the competition of well-structured and organised large sawmills. The emergence of green building, promoted through multiple policy tools, and the increasing use of wood in the construction sector can create room for even medium-to-small players that are more flexible in tailoring their production to specific market needs. Just as an example, about one-third of the buildings shortlisted for the 2017 Wood Awards, the UK's premier competition for excellence in wood architecture and product design, made use of Douglas-fir wood. In a scenario where "wood mobilisation" represents one of the key concepts for the green economy applied in the forestry sector, the capacity to promote primary and secondary wood processing, focusing on added value products, local and short supply chains, certified materials etc, seems to represent a potential strategy for remaining competitive in the market.

Recommended reading

Bowyer, J., Howe, J., Pepke, E., Bratkovich, S., Frank, M. and Fernholz, K. 2014. LEED V4: Understanding the changes and implications for use of wood as a building material. Dovetail Partners Inc., Minneapolis.

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