Huber et al. Annals of Forest Science (2023) 80:41
https://doi.org/10.1186/s13595-023-01206-7
INRAE
Annals of Forest Science

REVIEW PAPER **Open Access**

Potential alternatives for Norway spruce wood: a selection based on defect-free wood properties

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Abstract

Key message The application of material selection principles uncovered eight possible alternative tree species (two deciduous and six coniferous species) to substitute Norway spruce (*Picea abies* (L.) H. Karst.) and potentially prevent economic loss in European forest.

Context Climate change is a major challenge for the Central European forest and timber industry. Increasing biotic (e.g. beetle damage) and abiotic (e.g. drought) calamities have led to major losses in forest value, especially on Norway spruce (*Picea abies* (L.) H. Karst.) stands. Therefore, a transition to climate change adapted forest management is necessary. Concurrently, neophytes (e.g. tree of heaven (*Ailanthus altissima* (Mill.) Swingle), Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) and Paulownia (*Paulownia tomentosa* (Thunb.) Steud.)) are increasing their dominance in forest communities and causing additional adaption of the forest ecosystem. Both factors will lead to significant changes in wood species distributions in Central European forests, mainly at the expanse of Norway spruce, over the next decades.

Aims Choosing the "right" tree species for afforestation will become ever more complex and will require a holistic approach that combines forestry and technological aspects alike. Therefore, this review presents a selection approach based on available wood material data from literature and the material selection principles proposed by M. Ashby with the aim to identify suitable alternatives for Norway spruce (*Picea abies* (L.) H. Karst.) and further concisely assess their silvicultural relevance.

Methods For this wood species comparison and selection process, dry and raw density, bending strength and modulus of elasticity were chosen as key properties. Beam- and plate-like components subjected to a bending load were chosen as representative use cases.

Results European birch (*Betula* spp.), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) and silver fir (*Abies alba* Mill.) were identified as suitable alternatives for Norway spruce (*Picea abies* (L.) H. Karst.) from a technological as well as silvicultural point of view. In addition, Paulownia (*Paulownia tomentosa* (Thunb.) Steud.), Sitka spruce (*Picea sitchensis*

Handling editor: Jean-Michel Leban.

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(Bong.) Carrière), yellow pine (*Pinus strobus* L.), western red cedar (*Thuja plicata* Donn ex D. Don in Lambert) and loblolly pine (*Pinus taeda* L.) offer a technological advantage but currently lack relevance in the forest sector.

Conclusion The proposed selection process offers an evaluation of technical performance, and in combination with an assessment of the silvicultural relevance, it will be possible to optimize the wood-supply chain and prevent future economic loss of Central European forests.

Keywords Alternative wood species, Bending strength, Bending stiffness, Wood material properties, Material selection

1 Background

1.1 Climate change and tree species composition

Climate change (Masson-Delmotte et al. 2021; Stocker et al. 2014) causes significant changes to local temperature and precipitation. Consequently, significant impacts on local ecosystems and thus on stand stability and future forest management in Central Europe can be expected (Melillo et al. 2014). Forestry is reacting to these changes through adaption of tree species composition and changes in silvicultural management to maintain the ecological and economic performance of the forest wood supply chain in Central Europe.

Due to warmer summers (Huber and Knutti 2012; Karl 2009), with less precipitation, pronounce dry periods (Buras and Menzel 2018), increasing weather extremes, and bark beetle calamities (Guericke et al. 2016; Reif et al. 2009; Schramm 2013; Schüler et al. 2012, 2013; Stocker et al. 2014) are putting increasing pressure on Austria's bread tree. In fact, Norway spruce (*Picea abies* (L.) H. Karst.) does not always represent the potentially natural forest community on various sites but was established primarily for economic reasons (Brang et al. 2008). Especially on sites where conditions are close to the limit of the spruce's climate envelope, problems due to climate change are now occurring more frequently and are much more severe.

The increase in mean annual temperature will lead to a shift in the lower and upper alpine tree line (Nicolussi and Patzelt 2006), resulting in a different tree species composition from coline to low montane (Kilian et al. 1994; Leitgeb et al. 2006). At this low-montane zone, 16% of the Norway spruce stock in Austria is found, while 84% of the stock is found in the mid-montane to low-subalpine altitude zone (Schadauer and Freudenschuss 2019). This altitudinal range corresponds to the natural distribution range of Norway spruce in Austria (Kilian et al. 1994). In relation to the total stock, the ratio is similar and is 16% (coline to low-montane zone) and 84% (above mid-montane zone), respectively. The situation is different in Germany, where 68% of spruce stocks occur in the coline to low-montane altitude zone (BMEL 2018). In the coline to low-montane altitude zone, an increased occurrence of biotic and abiotic damage events is to be feared (Buras and Menzel 2018; Kölling et al. 2009). As a result, more storm events and bark beetle calamities are expected in the coming decades, which will lead to an increased supply of low-quality roundwood (Ebner 2018).

Climate change and land use are currently undergoing a more rapid change than expected (Pielke 2005). Changing climate conditions will inevitably lead to changes in management and silvicultural concepts (Bader 2014; Bürgi 1999; Liu et al. 2011) and tree species composition on different sites (Hanewinkel et al. 2013; Thuiller et al. 2008, 2011). Silvicultural concepts in the past have led to the so-called secondary sites of Norway spruce, especially at lower elevations in Austria and Germany. Many of these areas (about 9% of Austria's total forest area) would potentially be covered by European beech (*Fagus sylvatica* L.) and oak (*Quercus* spp.) forests (Gschwantner and Prskawetz 2005; Koukal 2005). It is expected that especially these areas will no longer be stocked with Norway spruce due to their ecological amplitude as a result of increasing annual mean temperatures (Ellenberg and Leuschner 2010).

Taking a look at past inventory data, shifts in tree species distribution are evidence for a beginning climate-adapted forest management (Heikkinen et al. 2006). For example, the share of deciduous tree species in Austrian forests has steadily increased. European beech (approx. 10% of the total Austria's stock, around 11.8 million solid cubic meters of stock) is the dominant deciduous species in Austria. In addition, oak, European ash (*Fraxinus excelsior* L.), sycamore (*Acer pseudoplatanus* L.), hornbeam (*Carpinus betulus* L.), black alder (*Alnus glutinosa* L.) Gaertn.), European birch (*Betula* L.) and poplar (*Populus tremula* L.) are also increasing (Schadauer and Freudenschuss 2019).

In addition to a climate-adapted forest management, wild-life management (including regulated hunting) also has an important influence on tree species composition (Daim et al. 2017; Reimoser et al. 2006, 2017). In particular, drought-resistant tree species such as white fir (*Abies alba* Mill.), oak and other broadleaf tree species are selectively browsed. Consequently, when wild-life population is high, these tree species are primarily browsed, resulting in a change in tree species composition (Heather et al. 2014; Walter et al. 2010). Thus, considering climate-adapted forest management on critical sites, where a shift from Norway spruce to more biodiverse stands is desired, hunting management and wild-life population need to be given special consideration (Leitner et al. 2022; Reimoser et al. 2006; Widl 2012).

1.2 Significance of Norway spruce in forestry

According to Fig. 1, Scots pine (*Pinus sylvestris* L.) as well as Norway spruce dominate the tree species composition of European forests (Buras and Menzel 2018). Based on findings by Brus et al. (2012), Norway spruce is predominantly found in central and pine in northern Europe (Brus et al. 2019). Especially, the alpine regions, such as Germany, Switzerland and Austria, are heavily dominated by Norway spruce.

In Germany, Norway spruce has 25% of the productive forest area, which represents 33% (1.2 billion m^3) of the total wood stock. The situation is even more pronounced in southern Germany (Bavaria), where the proportion of Norway spruce is 42% of the productive forest area, which corresponds to 50% (490 million m^3) of the total wood stock of Bavaria (Klemmt et al. 2017). In Switzerland, the situation is comparable. Norway spruce covers 38% of the productive forest area, which corresponds to about 43% (181 million m^3) of the total Swiss wood stock (Brändli et al. 2020). In Austria, the situation is similar where Norway spruce stands cover 49% of the productive forest area, which corresponds to about 59% (708 million m^3) of the total Austrian timber stock (1.2 billion m^3) (Russ 2019). In addition to the alpine region of Central Europe, spruce is also present in Scandinavia. In Finland for example, the dominant tree species are Norway spruce 34% (844 million m^3), 45% (1.1 billion m^3) pine and 21% (517 million m^3) in different hardwoods (Luke 2023; proHolz Austria 2013).

1.3 Significance of Norway spruce in technology

Norway spruce is currently processed into various wood products on a large scale (Wagenführ and Wagenführ 2022). With proper silvicultural treatment, it exhibits excellent natural pruning, straight stems and low stem taper. Compared to most deciduous tree species, spruce also yields a significantly higher stem volume, making it superior to other tree species not only in terms of annual growth but also in terms of trunk wood yield. Compared to other coniferous species, the branch angle of the spruce is relatively straight. The angle of the branch to the trunk axis is almost 90° in relation to the trunk axis. This leads to a small projected branch area in the wood, and thus, the yield is much higher than in pine (Charpentier et al. 2013; Müller et al. 2014).

However, remaining knots and resin pockets not only are a visual defect but also pose a technological challenge. Milling out small knots and resin pockets in cross-laminated timber or glued laminated timber represents a time-consuming and costly procedure, which to date is difficult to automate. In addition to these forestry aspects, the physical and mechanical properties also explain the current dominance of spruce in various fields of application. With relatively high mechanical performance at comparably low density, it is the ideal

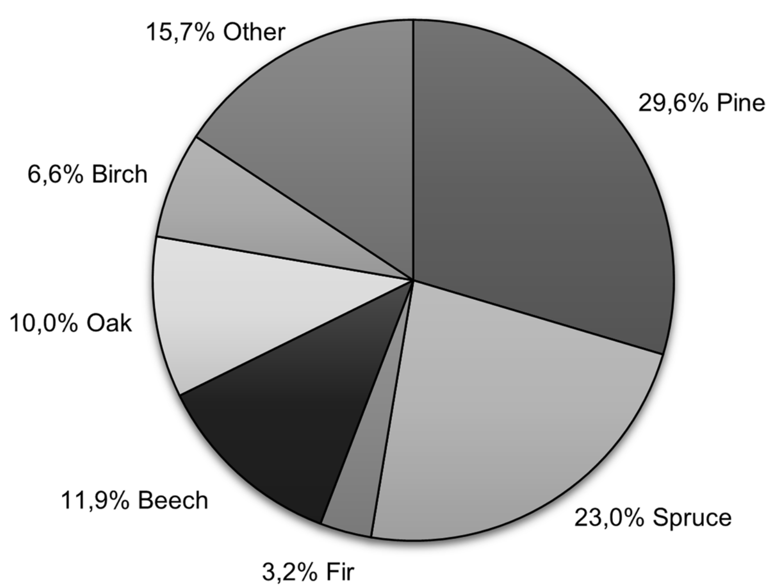

Fig. 1 Tree species composition in Europe in 2020 (Brändli 2020; Forest Europe 2020)

lightweight construction material (Kollmann and Côté 1968). This explains why load-bearing timber construction represents the main field of application of sawn timber of Norway spruce. Furthermore, the moderate density also supports processability and enables a high industry throughput. This high throughout is supported by the so-called chipper technology in wood primary processing. In combination with multiblade circular saws, the productivity of coniferous sawmills has increased dramatically in recent decades. Especially when processing logs with small diameters, as they occur in very large quantities during thinnings, this type of sawmill technology offers significant advantages compared to band and frame saws, which today are mainly used for deciduous and old growth large diameter trees. However, circular saw technology requires logs to be uniform in size, straight and with low stem taper. As the variability of the raw material increases, so does the challenge and effort of producing materials from it that meet the same or even higher requirements. With this change in round wood timber supply comes the necessity to further develop and adapt existing sawing technologies.

In addition, low water adsorption, moderate swelling and shrinkage (Richter and Ehmcke 2017) and excellent bonding behaviour compared to other wood species, particularly deciduous tree species such as beech, further provide significant technological advantages of Norway spruce. Compared to beech, with a very low dimensional stability, using Norway spruce means less delamination phenomena of glued members in load-bearing timber construction. The low water absorption due to the closed pits also provides a significant advantage in construction when structures are wetted by rain for short periods of time. On the other hand, the low moisture absorption means disadvantages in terms of impregnability.

Overall, these intrinsic advantages made Norway spruce particularly interesting for the wood industry and led to a focused research and development into this wood species. Over the last century, this caused Norway spruce to become one of the most investigated wood species in wood material science and therefore also explains its significance in wood technology.

1.4 Alternatives through property profiles

It becomes clear that the change in tree species composition will pose a significant challenge, and the identification of suitable substitutes for Norway spruce may be one of the biggest questions for the wood industry in the coming decades. One way to identify suitable substitutes from the perspective of wood utilization (Central European) will be through their property profiles.

For example, an intensive study (Brandner and Schickhofer 2013) of the technological properties of European ash, which is currently threatened by pest infestations, shows that it could be substituted by the tree of heaven. It should be emphasized that the silvicultural problems and the problem of toxicity and bad smell of the highly invasive tree species tree of heaven were not considered in these papers. However, it is important to clarify that, from a forestry perspective, this species should not be cultivated on a large scale, as there is a risk of invasive expansion. This is an essential characteristic of this tree species. In contrast to, e.g. grand fir, Douglas fir or Paulownia, this characteristic does not exist. Nevertheless, the example shows that a comparison of property profiles represents a possibility to identify potential substitute wood species that are currently not or only slightly used.

In the following, a systematic comparison of different wood species is presented based on the so-called Ashby maps (Ashby 2010). In those maps, properties of various material are plotted against each other, and materials of similar performance typically cluster into material groups or families. The respective properties can then be linked by the so-called design guidelines, which represent different load cases (e.g. a beam loaded in bending). The performance of the materials can then be compared with each other on the basis of the so-called material indices. For example, the weight of a beam with a fixed length under a certain load is a function of its cross-section and the choice of material. This function can then be represented as a line or curve in the Ashby maps. All materials along the function have the same performance, i.e. they are competitive with each other. Materials that lie above this line perform better; those that lie below perform worse.

In the case of wood, the behaviour under bending is one of the most important load cases. Relevant properties are the modulus of rupture (MOR) and modulus of elasticity (MOE). The fibre orientation, moisture content and the density have the strongest influence on the respective properties (Kollmann and Côté 1968). The fibre length and the composition of the wood tissue as well as the wood anatomy play a role but usually are overshadowed by the influence of density and fibre orientation. However, fibre orientation is not a suitable parameter for comparing wood species with each other as its influence is similar across all species, specifically in longitudinal direction. In contrast, basically all mechanical parameters of wood increase more or less linearly with density (Kollmann and Côté 1968). Consequently, it seems appropriate to relate mechanical properties to density in order to compare wood species with each other. From a design perspective, the idea would be to create lightweight design or lightweight structures. For these reasons, bending properties and density offer a good example to demonstrate the proposed selection process.

The following review therefore aims to survey the bending properties of all tree species that are available to forestry as approved forest plants and to compare them with Norway spruce. This should enable to anticipate suitable processing technologies and possible applications in the future. The work is thus intended to serve a climate-adapted forest management and as a preparation for the development of new value-added production chains.

2 The relevant literature

To compare the mechanical behaviour of middle European wood species, a literature search was carried out, considering material data from the last 100 years. For the comparison, the mean dry density (ρ_0 in kg/m^3), the mean MOR in MPa and the mean MOE in GPa were used. The selected literature and 38 wood species are summarized in Table 1.

A four-letter code based on ÖNORM B 3012 (2003) was assigned to each of the tree species. They were further divided into 15 coniferous and 23 deciduous tree species, commonly named softwood and hardwood. Additionally, the deciduous tree species were further divided according to the allocation of the vessel within the annual ring into ring-porous, semi-ring porous and dispersed-porous.

3 The relevant properties

In the following section, the dry density, modulus of rupture and modulus of elasticity for the selected wood species are presented. A full list of mean values, standard deviation and number of literature can be found in the appendix (Table 5 in Appendix).

3.1 Dry density (ρ_0)

For a detailed description of density and relevant definitions, please see Glass and Zelinka (2021). In the listed literature (Table 1), the values for dry density are not given for all wood species. Therefore, they were recalculated from the raw density using Eq. 1 according to Niemz and Sonderegger (2017), where ρ_0 corresponds to the dry density and $\rho\omega$ to the density at the respective wood moisture content (ω). The resulting mean ρ_0 are summarized in Fig. 2.

$$\rho_0 \approx \frac{(100 * \rho\omega)}{\left((100+\omega) - \left(0.85 * \rho\omega * \omega * 10^{-3}\right)\right)} \tag{1}$$

The unweighted mean ρ_0 of the 38 wood species is 557 kg/m^3 (mean), ranging from 256 to 795 kg/m^3 (Fig. 2). With a mean ρ_0 of 451 kg/m^3, Norway spruce (PCAB) ranks 8th of the 38 species (beginning from the lowest density). Coniferous species show rather low variability, ranging from 368 kg/m^3 for western red cedar (THPL) to 701 kg/m^3 for 4TXBC). This is due to the simpler wood structure and the uniform structure of early and late wood compared to deciduous species, which causes this more homogenous density range. In contrast, deciduous species show a high variation in density, ranging from 256 kg/m^3 for Paulownia (PLTT) to 795 kg/m^3 for hornbeam (CPBT). As mentioned earlier, these two also represent the lower and upper limits of all investigated wood species.

3.2 Accounting for differences in moisture content

For the literature values of Sell (1989), Knigge and Schulz (1966), Vorreiter (1949), Göhre (1961), Kollmann and Côté (1968), Senalik and Farber (2021), Wagenführ and Wagenführ (2022) and Vos (2006) and Riebel (1994), the densities were adjusted to a raw density of 12% in order to obtain values with a comparable moisture content. The calculation was based on Eq. 2 from Kollmann and Côté (1968). The factor was calculated based on Eq. 3 according to Kollmann and Côté (1968). Therefore, the volume swelling β_V in [%] is divided with the fibre saturation range ($u = 30\%$) and multiplied with the moisture content of 12%.

$$\rho_{12} \approx \rho_0 \frac{1+\omega_{12}}{1+factor} \tag{2}$$

$$factor \approx \left(\frac{\beta_{V\%}}{u_{30}}\right) * \left(\frac{\omega_{12}}{100}\right) \tag{3}$$

In addition to the density, also MOR and MOE were adjusted to a moisture content of 12%. Therefore, the values from Sell (1989), Knigge and Schulz (1966), Vorreiter (1949), Göhre (1961), Kollmann and Côté (1968), Senalik & Farber (2021), Wagenführ and Wagenführ (2022) and Vos (2006) and Riebel (1994) were corrected according to Eq. 4 from Kollmann and Côté (1968):

$$MOR_{12} \approx MOR_{15} + (MOR_{15} \times 4\%)\ per\%\ change\ in\ moisture\ content \tag{4}$$

MOE was adjusted analogues to Eq. 4. The values from Grabner (2017) and ÖNORM B 3012 (2003) were not changed, because values are already presented at 12% moisture content. In the remainder of the review, the used densities are based on these adjusted densities at 12% moisture content, MOR_{12} is referred to as MOR, and MOE_{12} is referred to as MOE.

Table 1 Overview of the relevant literature and used mechanical properties. The literature columns show which properties (*ρ* ρ_0, *σ* MOR, *E* MOE) were found in this publication and the sum columns how many values were found

Botanical name	Code	Common Trade name	Group	1	2	3	4	5	6	7	8	9	10	11	∑ ρ_0	∑ MOR	∑ MOE
Salix L.	SAXX	Willow	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Pyrus L.	PYCM	Pear	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Populus L.	PONG	Poplar	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	8	8	8
Sorbus tominalis (L.) Crantz	SOTR	Wild service	Diffuse-porous	ρ/σ/E	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	5	5	5
Acer pseudoplatanus L.	ACPS	Sycamore	Diffuse-porous	ρ/σ/E	ρ/-/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	6	7
Alnus glutinosa (L.) Gaertn.	ALGL	Common alder	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Carpinus betulus L.	CPBT	Hornbeam	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Corylus avellane L.	CYAL	Common hazel	Diffuse-porous	-/-/-	-/-/-	-/-/-	ρ/-/-	ρ/σ/E	-/-/-	-/-/-	-/-/-	ρ/-/-	-/-/-	-/-/-	3	1	1
Alnus incana (L.) Moench	ALIN	Grey alder	Diffuse-porous	-/-/-	-/-/-	ρ/-/-	ρ/σ/E	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	2	1	1
Tillia L.	TIXX	European lime	Demi-ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Betula spp.	BTXX	European birch	Diffuse-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Prunus avium L.	PRAV	European cherry	Semi-ring-porous	ρ/σ/E	ρ/σ/-	ρ/σ/-	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	6	6	4
Paulownia tomentosa (Thunb.) Steud.	PLTT	Paulownia	Semi-ring-porous	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	1	1	1
Fagus sylvatica L.	FASY	European beech	Semi-ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	9	9	9
Juglans regia L.	JGRG	European walnut	Semi-ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Eucalyptus globulus Labill.	EUGL	Southern blue gum	Ring-porous	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	1	1	1
Ulums L.	ULXX	Elm	Ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Castanea sativa Mill.	CTST	Sweet chestnut	Ring-porous	ρ/σ/E	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	6	6	6
Quercus rubra L.	QCXR	American red oak	Ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	7	7	7
Quercus spp.	QCXE	European oak	Ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	8	8	8
Ailanthus altissima (Mill.) Swingle	AIAL	Tree of heaven	Ring-porous	-/-/-	-/-/-	ρ/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	-/-/-	ρ/-/-	-/-/-	-/-/-	3	1	1
Fraxinus excelsior L.	FXEX	European ash	Ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	8	8	8
Robinia pseudoacacia L.	ROPS	Robinia	Ring-porous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	9	9	9
Juniperus virginiana L.	JUVR	Eastern red cedar	Coniferous	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	ρ/-/-	-/-/-	-/-/-	2	1	1
Taxus baccata L.	TXBC	Yew	Coniferous	ρ/σ/E	ρ/-/-	ρ/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	5	3	3
Thuja plicata Donn ex D. Don in Lambert	THPL	Western red cedar	Coniferous	ρ/σ/E	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	4	4	4
Pinus strobus L.	PNST	Yellow pine	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	7	7	7
Pinus nigra J. F. Arnold	PNNN	Austrian pine	Coniferous	ρ/-/-	-/-/-	ρ/σ/-	ρ/σ/E	-/-/-	ρ/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	4	2	1
Pseudotsuga menziesii (Mirbel) Franco	PSMN	Douglas fir	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	9	9	9
Picea sitchensis (Bong.) Carrière	PCST	Sitka spruce	Coniferous	ρ/σ/E	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	ρ/σ/E	-/-/-	-/-/-	-/-/-	3	3	3
Abies alba Mill.	ABAL	Silver fir	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	7	7
Pinus cembra L.	PNCM	Cembra pine	Coniferous	ρ/σ/E	ρ/-/-	ρ/-/-	ρ/σ/E	ρ/σ/E	-/-/-	ρ/-/-	-/-/-	ρ/σ/E	-/-/-	-/-/-	6	4	4
Cedrus Trew	CDXX	Cedar	Coniferous	ρ/σ/E	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/-	-/-/-	-/-/-	2	2	1

Table 1 (continued)

Botanical name	**Code**	**Common Trade name**	**Group**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**∑ ρ_0**	**∑ MOR**	**∑ MOE**
Larix decidua Mill.	LADC	European larch	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	8	8	8
Picea abies (L.) H. Karst.	PCAB	Norway spruce	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	8	8	8
Pinus sylvestris L.	PNSY	Scots pine	Coniferous	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	-/σ/E	ρ/σ/E	-/-/-	ρ/σ/E	-/-/-	-/-/-	7	8	8
Pinus taeda L.	PNTD	Loblolly pine	Coniferous	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	ρ/-/-	-/-/-	-/-/-	2	1	1
Abies grandis (Douglas ex D. Don) Lindl.	ABGR	Grand fir	Coniferous	-/-/-	ρ/σ/-	-/-/-	-/-/-	-/-/-	-/-/-	-/-/-	ρ/σ/E	ρ/σ/E	ρ/σ/E	ρ/σ/E	5	5	4

[1, Sell (1989); 2, Knigge and Schulz (1966); 3, Vorreiter (1949); 4, ÖNORM B 3012 (2003); 5, Grabner (2017); 6, Göhre (1961); 7, Kollmann and Côté (1968); 8, Senalik & Farber (2021); 9, Wagenführ and Wagenführ (2022); 10, Vos (2006); 11, Riebel (1994)]

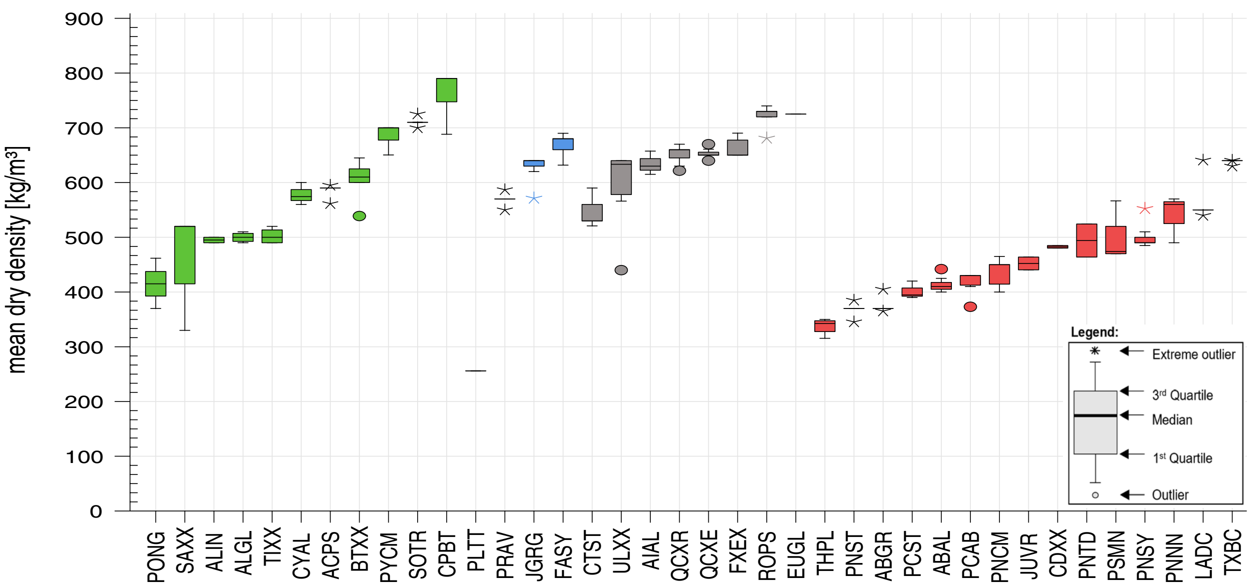

Fig. 2 Illustration of the mean dry density (ρ_0 = in [kg/m^3]) of the investigated wood species. Divided into the groups: diffuse-porous deciduous (green), semi-ring-porous deciduous (blue), ring-porous deciduous (grey) and coniferous (red) tree species

3.3 Modulus of rupture (MOR)

The unweighted mean MOR can be found in Fig. 3. For an ease of comparison, the order of wood species from Fig. 2 is maintained. In this way, the influence of density on the bending strength is already indicated.

Considering conifers (Fig. 3), western red cedar (THPL, 368 kg/m^3) and yellow pine (PNST, 398 kg/m^3) have the lowest mean bending strength of 58.1 MPa and 63.2 MPa, respectively. On the other side of the spectrum, European larch (LADC, 596 kg/m^3) has the highest MOR of 107 MPa. With a mean MOR of 80.4 MPa, Norway spruce (PCAB) ranks 28th of the 38 species (starting from the highest value = CPBT, 153 MPa). From this range of MOR, it becomes clear that relevant conifers only offer a very narrow array of bending strength to choose from.

In contrast, deciduous species again show a much broader range in bending strength, starting at 42.7 MPa for Paulownia (PLTT, 279 kg/m^3) and going up to 153 MPa for hornbeam (CPBT, 795 kg/m^3). This is in line with the equally high range in density. Within the diffuse-porous species, willow (SAXX, 498 kg/m^3) and poplar (PONG, 444 kg/m^3) show the lowest MOR of 47.6 MPa and 64.9 MPa, respectively. Common alder (ALGL, 531 kg/m^3) and grey alder (ALIN, 528 kg/m^3) are in the middle range between 98.0 and 102 MPa. With 153 MPa, hornbeam (CPBT) has the largest mean MOR of the diffuse-porous deciduous. Moving on to the semi-ring-porous species, Paulownia (PLTT) shows the lowest MOR (43 MPa) of all tree species examined. European cherry (PRAV, 604 kg/m^3) and European lime (TIXX, 530 kg/m^3) are in the middle range between 99.2 and 104 MPa. European beech (FASY, 705 kg/m^3) and European walnut (JGRG, 665 kg/m^3) close out the semi-ring-porous species with a bending strength of 127 MPa and 136 MPa. Considering the ring-porous deciduous, sweet chestnut (CTST, 585 kg/m^3) and Elm (ULXX, 629 kg/m^3) show the lowest MOR of 85.3 MPa and 88.3 MPa, respectively. American red oak (QCXR, 694 kg/m^3) and European red oak (QCXE, 692 kg/m^3) lie around 109 MPa and 105 MPa. Southern blue gum (EUGL, 719 kg/m^3) and Robinia (ROPS, 760 kg/m^3) complete the ring-porous deciduous with 100 MPa and 149 MPa.

3.4 Specific modulus of rupture (specific MOR)

Figure 4 depicts the mean specific bending strength based on mean MOR and mean raw density (ρ_{12}). The favourable ratio of the different tree species can be deduced from this.

In the diffuse-porous deciduous group (Fig. 4), birch (BTXX) has the highest mean specific MOR (0.226 MPa/(kg/m^3)) value. Furthermore, it is the highest mean MOR value of all investigated tree species. The tree species grey alder (ALIN, 0.195 MPa/(kg/m^3)) and Hornbeam (CPBT, 0.193 MPa/(kg/m^3)) have similar mean specific MOR value compared to Norway spruce (PCAB, 0.179 MPa/(kg/m^3)). The lowest value in this group and also in the other groups is Willow (SAXX) with 0.101 MPa/(kg/m^3). From all investigated tree species, willow has the lowest mean specific MOR value.

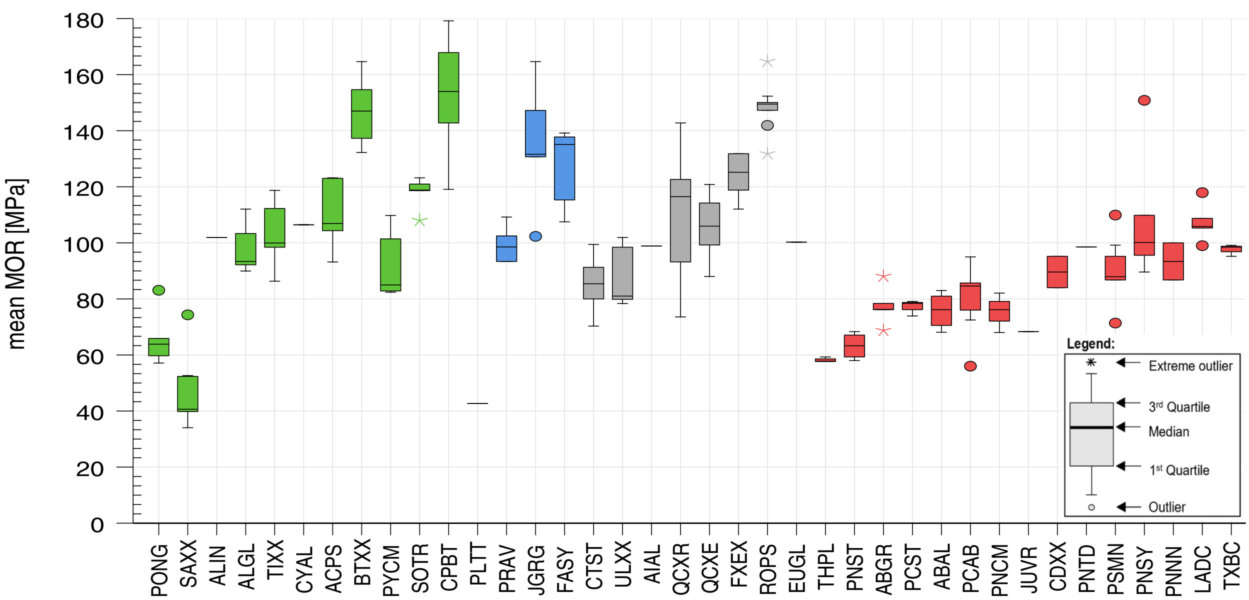

Fig. 3 Illustration of the mean MOR (*MOR* = in [MPa]) of the investigated wood species. Divided into the groups: diffuse-porous deciduous (green), semi-ring-porous deciduous (blue) ring-porous deciduous (grey) and coniferous (red) tree species

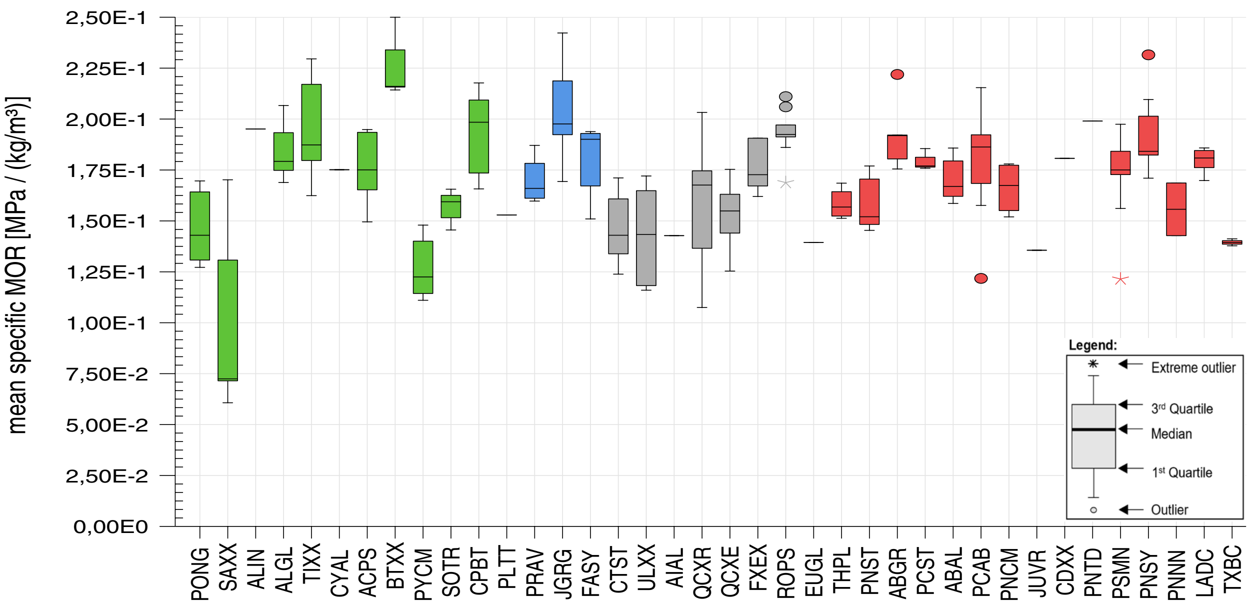

Fig. 4 Illustration of the mean specific MOR (*MOR* = in [MPa/(kg/m^3)]) of the investigated wood species. Divided into the four groups: diffuse-porous deciduous (green), semi-ring-porous deciduous (blue), ring-porous deciduous (grey) and coniferous (red) tree species

Walnut (JGRG) is in the semi-ring-porous group and has the highest value (0.204 MPa/(kg/m^3)). Paulownia (PLTT) has the lowest specific mean MOR value in this group (0.153 MPa/(kg/m^3)).

In the group of ring-porous deciduous trees, Robinia (ROPS) has the highest specific mean MOR value (0.101 MPa/(kg/m^3)) and sweet chestnut (CTST) the lowest specific mean MOR value (0.146 MPa/(kg/m^3)). It is remarkable that sweet chestnut (CTST, 0.146 MPa/(kg/m^3)), elm (ULXX, 0.143 MPa/(kg/m^3)) and tree of heaven (AIAL, 0.143 MPa/(kg/m^3)) have approximately the same mean specific MOR value.

In the coniferous group, loblolly pine (PNTD, 0.199 MPa/(kg/m^3)) has the highest and eastern red cedar (JUVR, 0.136 MPa/(kg/m^3)) the lowest mean specific MOR value. The tree species Larch (LADC, 0.180 MPa/(kg/m^3), Norway spruce (PCAB, 0.179 MPa/(kg/m^3)) and Sitka spruce (PCST, 0.179 MPa/(kg/m^3)) have the same mean specific MOR value.

Modulus of elasticity (MOE).

The unweighted mean MOE is summarized in Fig. 5. Overall, it can be seen that the influence of density on the respective MOE is less pronounced compared to MOR.

In regards to conifers, Fig. 5 shows that Eastern red cedar (JUVR, 491 kg/m^3) has the lowest MOE of 13.8 GPa, and European larch (LADX, 596 kg/m^3) together with Austrian pine (PNNN, 580 kg/m^3) have the highest MOE around 14.6 GPa and 13.4 GPa. With a mean MOE of 12.2, GPa Norway spruce (PCAB, 451 kg/m^3) ranks 22th out of the 38 wood species (starting from the lowest value = PLTT, 4.6 GPa).

Similar to ρ_0 and MOR, deciduous species show a broader range of MOE compared to coniferous, ranging from 4.6 GPa for Paulownia (PLTT) up to 17.4 GPa for European birch (BTXX, 649 kg/m^3). In regard to diffuse-porous species, willow (SAXX, 498 kg/m^3) and poplar (PONG, 418 kg/m^3) mark the lowest MOE of 8.0 GPa and 8.9 GPa. European birch (BTXX, 649 kg/m^3) has an MOE of 17.4 GPa and therefore ranks highest within the diffuse-porous species right before hornbeam (CPBT, 695 kg/m^3, 16.4 GPa). Moving on to the group of semi-ring-porous species, Paulownia (PLTT, 279 kg/m^3) has the lowest MOE (4.6 GPa) of all tree species investigated. In contrast, European beech (FASY, 705 kg/m^3) has the highest MOE (17.4 GPa) in this group, while European cherry (PRAV, 604 kg/m^3) and European walnut (JGRG, 665 kg/m^3) lie in the middle with a mean MOE of 10.7 GPa and 13.7 GPa. In regard to ring-porous deciduous, sweet chestnut (CTST, 585 kg/m^3) has the lowest MOE of 10.0 GPa. American red oak (QCXR, 694 kg/m^3, 13.5 GPa), European red oak (QCXE, 692 kg/m^3, 13.5 GPa), Robinia (ROPS, 770 kg/m^3, 13.9 GPa) and European ash (FXEX, 705 kg/m^3, 16.5 GPa) cover the middle, and Southern blue gum (EUGL, 719 kg/m^3) concludes this section with a mean MOE of 13.4 GPa.

3.5 Specific modulus of elasticity (specific MOE)

Figure 6 depicts the mean specific bending stiffness based on mean MOE a mean raw density (ρ_{12}). The favourable ratio of the different tree species can be deduced from this.

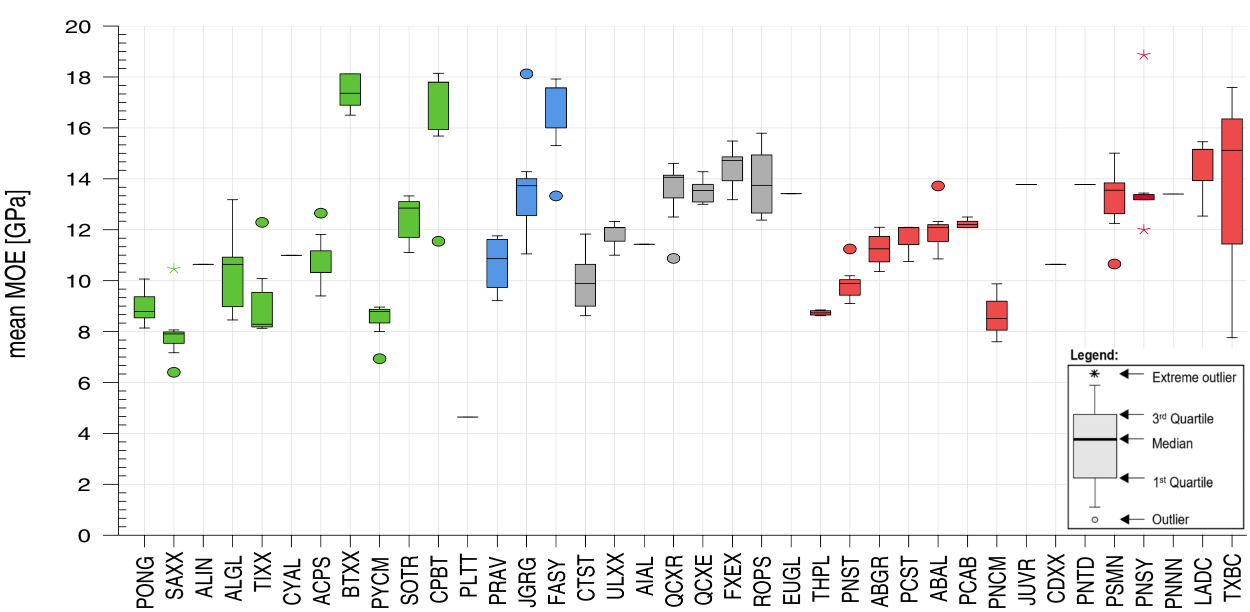

Fig. 5 Illustration of the mean MOE (*MOE* = in [GPa]) of the investigated wood species. Divided into the groups: diffuse-porous deciduous (green), semi-ring-porous deciduous (blue), ring-porous deciduous (grey) and coniferous (red) species

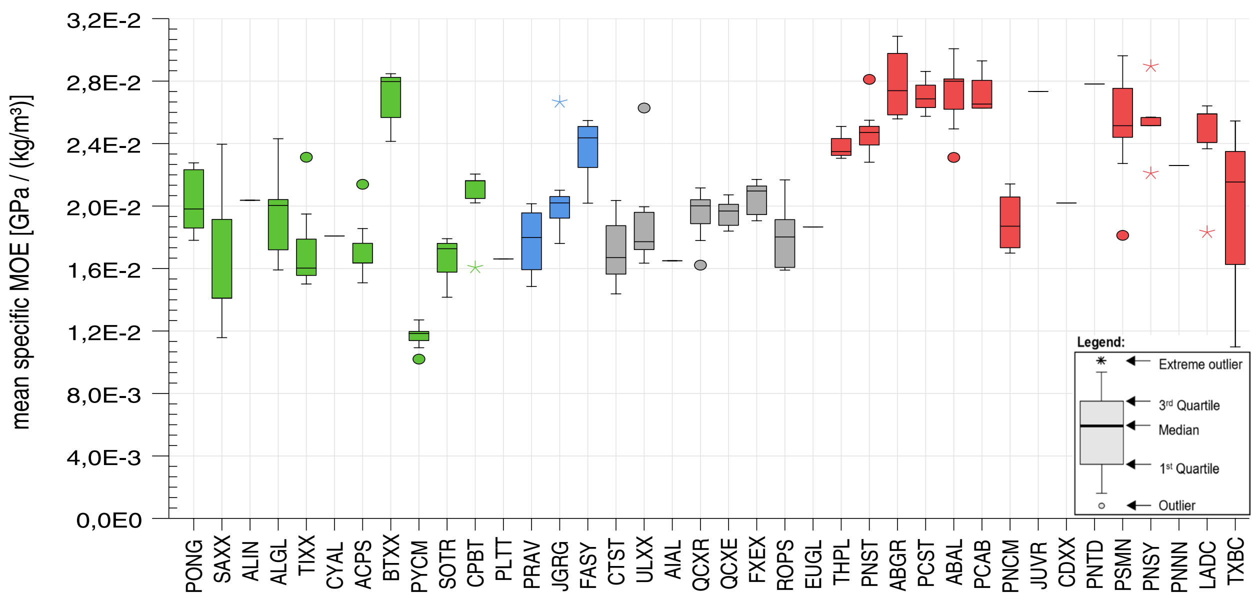

Fig. 6 Illustration of the mean specific MOE (*MOE* = in [GPa/(kg/m^3)]) of the investigated wood species. Divided into the groups: diffuse-porous deciduous (green), semi-ring-porous deciduous (blue), ring-porous deciduous (grey) and coniferous (red) tree species

In the group of conifers (Fig. 6), the tree species grand fir (ABGR, 0.0278 GPa/(kg/m^3)) and loblolly pine (PNTD, 0.0278 GPa/(kg/m^3)) have the same mean specific MOE value. These mark the highest mean specific MOE value in this group. The tree species Sitka spruce (PCST, 0.0271 GPa/(kg/m^3)) and silver fir (ABAL, 0.0271 GPa/(kg/m^3)) as also Norway spruce (PCAB, 0.0272 GPa/(kg/m^3)) and Eastern red cedar (JUVR, 0.0273 GPa/(kg/m^3)) have the same mean specific MOE value. It is important to note that in this group, the tree species Yew (TXBC, 0.0278 GPa/(kg/m^3)) shows the highest variation and have the lowest mean specific MOE (0.0145 GPa/(kg/m^3)) value.

In the group of ring-porous deciduous trees, European ash (FXEX) has the highest mean specific MOE (0.0205 GPa/(kg/m^3)) and tree of heaven (AIAL) the lowest mean specific MOE value (0.0165 GPa/(kg/m^3)). Furthermore, it is evident in this group that the tree species show a lower variation compared to the other groups.

Beech (FASY) is in the semi-ring-porous group and has the highest mean specific MOE value (0.0235 GPa/(kg/m^3)). Paulowian (PLTT) has the lowest mean specific MOE value in this group (0.0166 GPa/(kg/m^3)).

In the diffuse-porous deciduous group, European birch (BTXX) has the highest mean specific MOE (0.0269 GPa/(kg/m^3)) value. The tree species hornbeam (CPBT, 0.0206 GPa/(kg/m^3)) and grey alder (ALIN, 0.0204 GPa/(kg/m^3)) have similar the same mean specific MOE value compared to Norway spruce (PCAB, 0.0272 GPa/(kg/m^3)). The lowest mean specific MOE value in this group and also in the other groups is pear (PYCM) with 0.0116 GPa/(kg/m^3). From all investigated tree species has Pear the lowest mean specific MOE value.

From the previous section, it could be concluded that Norway spruce (PCAB) is just one of the "average" wood species in regard to mechanical performance. It ranks 28th in bending strength and 18th in stiffness out of the 38 investigated wood species. However, it also ranks 8th in density, making it one of the lighter wood species while also achieving respectable mechanical performance. Finding suitable substitutes will therefore require not only a comparable or higher absolute mechanical performance (e.g. MOE or MOR) but also a competitive density.

As already mentioned, potential wood species could be identified based on the material selection principles proposed by Ashby (Ashby 2010). To do so, two typical target objectives for a structural material were chosen: on the one hand, the ability to carry a maximum load without failure while minimizing the mass of the component and, on the other hand, minimizing the mass while maintaining a certain stiffness.

3.6 The material indices

The material selection according to Ashby is done based on the so-called material indices, which link the function (objective) of a component with the properties of a material. In regard to our first objective, two relevant indices for strength-based selection were chosen. Equation 5 represents columns and pillars, Eq. 6 represents beams and Eq. 7 represents plates, where σ is the MOR, ρ_{12} is the density at 12% moisture content and C stands for the respective material index.

$$\frac{\sigma}{\rho_{12}} = C = 0.1783 \text{ for Norway spruce(PCAB)} \quad (5)$$

$$\frac{\sigma^{\frac{2}{3}}}{\rho_{12}} = C = 0.04226 \text{ for Norway spruce(PCAB)} \quad (6)$$

$$\frac{\sigma^{\frac{1}{2}}}{\rho_{12}} = C = 0.02059 \text{ for Norway spruce(PCAB)} \quad (7)$$

With respect to our second objective, Eqs. 8, 9 and 10 represent the same design guidelines with respect to stiffness, where E is the MOE, ρ_{12} is the density at 12% moisture content and C stands for the respective material index.

$$\frac{E}{\rho_{12}} = C = 27.0008 \text{ for Norway spruce(PCAB)} \quad (8)$$

$$\frac{E^{\frac{1}{2}}}{\rho_{12}} = C = 0.00792 \text{ for Norway spruce(PCAB)} \quad (9)$$

$$\frac{E^{\frac{1}{3}}}{\rho_{12}} = C = 0.00531 \text{ for Norway spruce(PCAB)} \quad (10)$$

In all six cases, the material index for Norway spruce (PCAB) based on mean MOR/MOE and mean ρ_{12} was calculated. The case columns and pillars load (Eqs. 5 and 8) were not used for the further illustration and calculations. The reason for this is that the strengths and stiffness were calculated in bending loads. Therefore, these values were not used for further calculations. In order to identify suitable alternatives, these material indices are subsequently used to plot the selection guidelines, also known as design guidelines, on the property charts including the 38 wood species.

3.7 The property charts

The MOR and the MOE are plotted against ρ_{12} in Figs. 3 and 5, respectively. Contrary to usual property charts from Ashby, the axes are not logarithmically but linearly scaled. In addition to Chapter 3, the minimum and

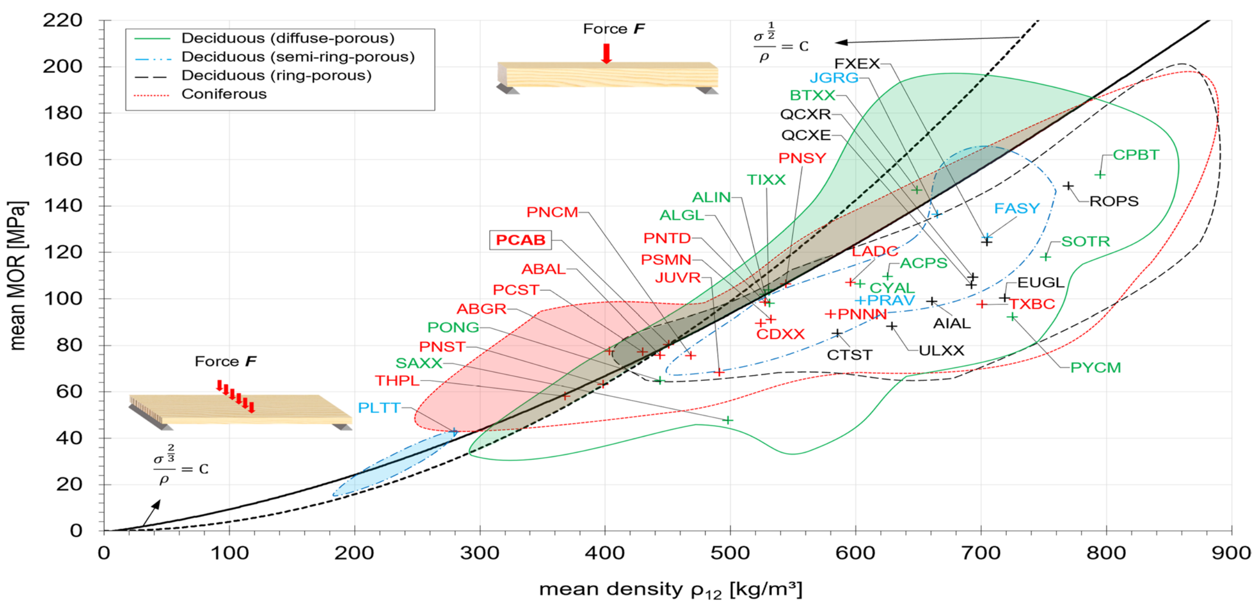

Fig. 7 Relationship between mean bending strength (MOR in [MPa]) and mean raw density [kg/m.³] at 12% moisture content. The softwood species (coniferous) are marked red. The deciduous species (hardwoods) are divided into diffuse-porous (green), semi-ring-porous (blue) and ring-porous (grey). The wood species above the design guidelines meet or overcome the material index for Norway spruce (PCAB)

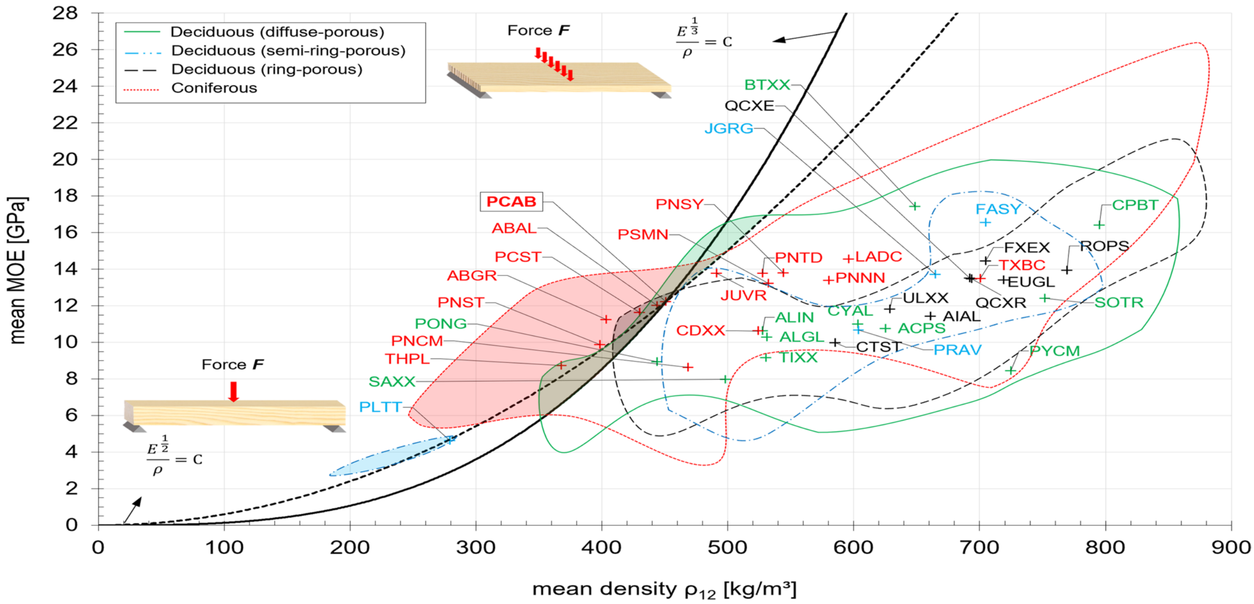

Fig. 8 Relationship between mean stiffness (MOE in [GPa]) and mean density [kg/m^3] at 12% moisture content. The coniferous are marked red. The deciduous trees are divided into dispersed-porous (green), semi-ring-porous (blue) and ring-porous (grey). The wood species above the design guidelines meet or overcome the material index for Norway spruce (PCAB)

maximum values of the different wood species were also included and represent the envelope for the different groups. The design guidelines derived from the Eqs. 6, 7, 9 and 10 can be seen as a performance threshold, which needs to be met or exceeded by potential alternative wood species.

Figures 7 and 8 illustrate the excellent balance of mechanical performance and density of Norway spruce (PCAB). Only a handful of wood species overcome the material index given by Norway spruce (PCAB). This could possibly complicate the utilization of alternative species in the future, especially if the weight of the target application needs to be considered. Therefore, the potential alternatives will be discussed based on the full range of mechanical properties in the next section.

4 Potential alternatives for Norway spruce

Table 2 summarizes wood species with competitive or superior material indices compared to Norway spruce (PCAB). The comparison is done by relating the respective material indices, with positive values indication a percentage improvement and negative values indicating a percentage worsening compared to the material index of Norway spruce (PCAB).

Nineteen wood species (eight coniferous and eleven deciduous species) outperformed Norway spruce (PCAB) in terms of strength and 11 species (nine coniferous and two deciduous species) in regard to stiffness. However, this was only possible if the full range of mechanical properties and wood densities was taken into account. Considering only the mean values, a total of six species (four coniferous and two deciduous species) were superior in regard to strength and similarly six species (five coniferous and one deciduous species) in terms to stiffness.

Paulownia (PLTT), grand fir (ABGR) and western red cedar (THPL) outperformed spruce in regard to strength as well as stiffness, with Grand fir (ABGR) being competitive in all four use cases and Paulownia (PLTT) showing the best superiority compared to Norway spruce (PCAB). However, considering absolute performance, Paulownia (PLTT, MOR: 42.7 MPa and 4.6 GPa) will not be a suitable alternative where a certain minimum load-carrying capacity is exceeded. Contrary, grand fir (ABGR, MOR: 77.5 MPa and 11.2 GPa) exhibits comparable mechanical properties to Norway spruce (PCAB, 80.4 MPa and 12.2 GPa) and therefore could be seen as 1:1 substitute with regard to the investigated use cases. This underlines the potential

Table 2 Summary of wood species with competitive or superior material indices compared to Norway spruce (*PCAB* = 100%)

Botanical name	Code	Common trade name	Group	Material indices in relation to Norway spruce (PCAB) [%]			
				$\frac{\sigma^{\frac{1}{2}}}{\rho}=C$	$\frac{\sigma^{\frac{2}{3}}}{\rho}=C$	$\frac{E^{\frac{1}{2}}}{\rho}=C$	$\frac{E^{\frac{1}{3}}}{\rho}=C$
Alnus glutinosa (L.) Gaertn.	ALGL	Black alder	Diffuse-porous	−7.7[a]	−4.8	−23.5	−21.3
Populus L.	PONG	Poplar	Diffuse-porous	−9.5	−12.8[a]	−13.7	−9.1[a]
Salix L.	SAXX	Willow	Diffuse-porous	−27.9	−33.6[a]	−24.9	−19.5[a]
Acer pseudoplatanus L.	ACPS	Sycamore	Diffuse-porous	−16.6	−12.2[a]	−33.1	−31.7
Alnus incana (L.) Moench	ALIN	Grey alder	Diffuse-porous	−5.5	−2.3[a]	−21.7	−19.5
Tillia L.	TIXX	European lime	Semi-ring-porous	−5.5[a]	−1.6	−28.1	−24.6
Betula spp.	BTXX	European birch	Diffuse-porous	−6.7	3.1	−17.4	−22.2
Paulownia tomentosa (Thunb.) Steud.	PLTT	Paulownia	Semi-ring-porous	23.9	12.6	4.7	21.4
Juglans regia L.	JGRG	European Walnut	Semi-ring-porous	−13.5	−5.8[a]	−29.7[a]	−30.9
Quercus rubra L.	QCXR	Red oak	Ring-porous	−26.6	−22.9[a]	−33.3	−34.2
Quercus spp.	QCXE	European oak	Ring-porous	−26.7[a]	−23.3	−32.8	−33.9[a]
Abies grandis (Douglas ex D. Don) Lindl.	ABGR	Grand fir	Coniferous	7.5	6.1	4.6	6.6
Picea sitchensis (Bong.) Carrière	PCST	Sitka spruce	Coniferous	0.4	−0.9	−0.1	1.3
Pinus strobus L.	PNST	Yellow pine	Coniferous	−0.2	−4.5	1.1	5.0
Thuja plicata Donn ex D. Don in Lambert	THPL	Western red cedar	Coniferous	3.8	−2.3	3.1	9.6
Abies alba Mill.	ABAL	Silver fir	Coniferous	−2.0	−3.0	0.1	0.4
Larix decidua Mill.	LADC	European larch	Coniferous	−13.9[a]	−9.9	−18.6	−20.6
***Picea abies* (L.) H. Karst.**	**PCAB**	**Norway spruce**	**Coniferous**	**100**	**100**	**100**	**100**
Pinus sylvestris L.	PNSY	White pine	Coniferous	−4.6[a]	−0.2	−11.4	−13.2[a]
Pinus cembra L.	PNCM	Cembra pine	Coniferous	−2.8[a]	−3.5	−15.9	−11.2[a]
Pseudotsuga menziesii (Mirbel) Franco	PSMN	Douglas fir	Coniferous	−10.8[a]	−9.1	−12.8	−13.9[a]
Pinus taeda L.	PNTD	Loblolly pine	Coniferous	−1.8	0.9	−5.9	−7.3

Columns five and six show the results (MOR) according to Eqs. 6 and 7, and columns seven and eight depict the results (MOE) according to Es. 9 and 10

[a] These wood species only show improved performance when considering maximum MOR or MOE

importance of neophytes for the Central European forest sector.

Although European birch (BTXX, 147 MPa and 17.4 GPa) and European walnut (JGRG, 136 MPa and 13.7 GPa) have a lower material index than Norway spruce (PCAB), their high absolute properties offer potential for high performance applications where weight can be subordinated to higher load-carrying capacity.

American red oak (QCXR, 109 MPa and 13.5 GPa), European oak (QCXE, 106 MPa and 13.5 GPa), Willow (SAXX, 47.6 MPa and 8.0GPa) and sycamore (ACPS, 110 MPa and 10.8 GPa) show the highest decrease in performance based on mean values and only overcome the material index of Norway spruce (PCAB) when the top level of the respective properties is considered. Based on this, it becomes clear that the utilization of some alternative wood species will require an increased focus on characterization and on the use case-specific selection of raw material assortments.

Additionally, the tree species listed here are all related to the selected material indices. That is a significant aspect when it comes to the question of weight optimization of components. However, if the slenderness of components is relevant (lower heights and cross-sections), then the absolute values (Table 5 in Appendix) of MOR or MOE of the individual tree species would be important. This could be seen as an opportunity but also as an advantage in some construction. This includes a higher component weight, which would be more disadvantageous for the construction in terms of the required volume. This factor would be very relevant for structural elements such as columns and pillars in building construction.

4.1 Silvicultural relevance

The comparison of the mechanical properties and the potential that can be derived from them for various technical applications represents only one aspect for a possible substitution of Norway spruce (PCAB). The second important aspect is the forestry potential of the alternative wood species and the availability or cultivability. A good example for this is the tree of heaven (AIAL). It has excellent technological properties and could replace European ash (FXEX) without much effort and could also be used in wood-based materials (Brandner and Schickhofer 2013). However, due to its high invasiveness, this tree species is banned as a forest plant and therefore lacks relevance in the forest sector. In order to also critically reflect on this relevance in forestry, the selected wood species in the previous section where also assessed for their silvicultural relevance.

Grand fir (ABGR) has shown an excellent technological potential, but under the current climatic conditions in Central Europe, it can only be justified to a limited extent. There is a need for research into the performance of the genomes as well as their resistance against biotic and abiotic threats. These need to be identified in order to find suitable provinces for forestry applications. Paulownia (PLTT) is not approved as a forest plant and is currently managed only on plantations in Austria and Germany. Nevertheless, this tree species would show some potential over spruce in bar-type as well as plate-type bending (MOE) (Table 2). In comparison to the mechanical properties, the tree species has good thermal insulation properties (Huber et al. 2023).

Western red cedar (THPL), yellow pine (PNST) and loblolly pine (PNTD) also play a minor role due to availability (in stock cubic meters). Birch (BTXX) plays a secondary role in central European forests but has high relevance in northern Europe. Due to its excellent technical properties, it has high potential to substitute Norway spruce (PCAB) in high performance and building application. White fir (ABAL) would have potential because it occurs together with Norway spruce (PCAB). Currently, its share compared to Norway spruce (PCAB) is rather low, as it is strongly impaired in its growth behaviour due to the increased influence from wildlife. A significant advantage over spruce is the root system. White fir (ABAL) has a heart root system, and the spruce a shallow root system making it more resistant against wind damage and drought.

In addition to the mechanical properties, an important aspect is the availability and quality of the raw material. Table 3 shows the current volume distribution of the possible substitute tree species in Austria, Germany and Switzerland. The data were taken from the national inventory results and provides an overview of the current importance of the selected wood species for the central European forestry. This relevance is based on the currently available quantities (in stock cubic meters) and the general experience in the forest sector.

4.2 Other technologically relevant properties

The presented selection process is a first approach to identifying potential alternatives for Norway spruce (PCAB). However, a comprehensive material substitution for specific products requires additional technological properties as well as economical aspects. For example, in addition to density, wood characteristics like size of knots and knot angle also play a significant role in regard to strength (Arriaga et al. 2022; Torquato et al. 2014). Nevertheless, a complete consideration and evaluation would go beyond the scope of this review. To give a short overview of this complexity, some key technological aspects should be mentioned in the following section.

Whether the chipping technique widely used in sawing timber production of conifers can also be applied to potential deciduous wood species has not been investigated closely yet. However, the higher density and more inhomogeneous stem shape suggest that processing deciduous species would lead to a significantly lower material efficiency and decreased volume throughput.

An essential parameter for the use of wood is sawntimber drying. Norway spruce (PCAB) and other softwoods as well as some of the lower-density hardwoods can be dried relatively quickly. Hardwood timber such as oak (QCXR, QCXE), on the other hand, can take up to several months to dry. The drying time influences the production scheduling and thus the product costs via capital commitment and energy costs. The wood density and internal stresses of the timber in turn have an impact on the process technology.

Glueability has been examined to some extent in the literature. However, a comprehensive understanding of the adhesive technology for hardwood timber requires a more intensive and broader investigation. In addition to wood constituents and pH value, the swelling-shrinkage behaviour also influences glueability.

Beside its influence on glueability, the dimensional stability of alternative wood species also plays a key role in regards to process technology and behaviour during the use phase. Especially, hardwood trees with high density

Table 3 Stock volume [m^3] from the national inventory results from Austria, Germany and Switzerland. The values only include commercial forests that are actively managed. Forests that are not in utilization are not considered

				Only harvested forests [1000 m^3]		
				Austria[1]	Germany[2]	Switzerland[3]
Botanical name	**Code**	**Common trade name**	**Group**	**[Million m^3]**	**[Million m^3]**	**[Million m^3]**
Alnus glutinosa (L.) Gaertn.	ALGL	Alder	Diffuse-porous	8.856 ± 1.050		
Populus L.	PONG	Poplar	Diffuse-porous	4.509 ± 595		
Salix L.	SAXX	Willow	Diffuse-porous	2.895 ± 533		
Acer pseudoplatanus L.	ACPS	Sycamore	Diffuse-porous	18.731 ± 1.030		14.767 ± 738
Tillia L.	TIXX	European lime	Semi-ring-porous	4.129 ± 549		
Betula spp.	BTXX	European birch	Diffuse-porous	6.482 ± 488		
Paulownia tomentosa (Thunb.) Steud.	PLTT	Paulownia	Semi-ring-porous			
Juglans regia L.	JGRG	Walnut	Semi-ring-porous			
Fraxinus excelsior L.	FXEX	Ash	Ring-porous	22.752 ± 1.412		14.686 ± 1.028
Quercus rubra L.	QCXR	Red oak	Ring-porous			
Quercus spp.	QCXE	European oak	Ring-porous	31.946 ± 2.225	363.999 ± 28.380.352	7.872 ± 787
Abies grandis (Douglas ex D. Don) Lindl.	ABGR	Grand fir	Coniferous			
Picea sitchensis (Bong.) Carrière	PCST	Sitka spruce	Coniferous			
Pinus strobus L.	PNST	Yellow pine	Coniferous	186 ± 0		
Thuja plicata Donn ex D. Don in Lambert	THPL	Western red cedar	Coniferous			
Abies alba Mill.	ABAL	Silver fir	Coniferous	50.931 ± 3.130	97.234 ± 19.464.810	64.723 ± 2.589
***Picea abies* (L.) H. Karst.**	**PCAB**	**Norway spruce**	**Coniferous**	**714.945 ± 14.669**	**1.187.414 ± 76.319.926**	**175.091 ± 3.502**
Pinus sylvestris L.	PNSY	White pine	Coniferous	70.754 ± 3.671		
Pinus cembra L.	PNCM	Cembra pine	Coniferous	5.411 ± 1.043		2.875 ± 374
Pseudotsuga menziesii (Mirbel) Franco	PSMN	Douglas fir	Coniferous	1.494 ± 384	94.673 ± 18.250.282	
Juniperus virginiana L.	JUVR	Pencil cedar	Coniferous			
Pinus taeda L.	PNTD	Loblolly pine	Coniferous			

Relevant literature [1, BFW (2023); 2, Thünen-Institut (2023); 3, WSL (2023)]

show lower dimensional stability, durability and significantly higher swelling and shrinkage coefficients compared to Norway spruce (PCAB).

Hardness limits the bearing surfaces of large beams and influences the machinability of components. Shear, transverse tensile strengths and thermal resistance are important factors for construction applications. A whole range of properties specific to current applications of Norway spruce (PCAB) could be listed and need to be considered when choosing a suitable alternative.

In addition to the chipping technique, drying, glueability and hardness, the durability according to EN 350–2 (1994) has a significant influence on the specific application. As an example, the alternative tree species such as yellow pine, grand fir, Douglas fir and red oak are in the same class (four) as Norway spruce. Birch is even worse than Norway spruce and is in class five. Thus, durability is a significant factor for outdoor applications and is not recommended without constructive wood protection (Table 4).

5 Conclusion and outlook

In this review, a total of 38 wood species were compared based on defect-free bending properties, and a selection process based on M. Ashby to identify potential alternatives for Norway spruce (PCAB = *Picea abies* (L.) H. Karst.) was proposed. Based on the results discussed, the following conclusions can be drawn.

Coniferous woods, especially Norway spruce, show a smaller range in density and mechanical performance than deciduous wood species and exhibit a better balance between density and bending performance,

Table 4 Durability [-] as well as volume shrinkage [%] of the analysed species. The numbers in column five show the durability class according to EN 350–2 (1994) (one represents the highest and five the lowest durability). The durability class represents the resistance against fungi. In column six, the volume shrinkage rate was calculated as an average value, because in the literature only min and max values were given in several cases

Botanical name	Code	Common trade name	Group	Durability classes according to EN 350–2	Volume shrinkage rate mean β_V [%] literature
Salix L.	SAXX	Willow	Diffuse-porous	5	9.6[1]
Pyrus L.	PYCM	Pear	Diffuse-porous		14.2[1]
Populus L.	PONG	Poplar	Diffuse-porous	5	11.9[1]
Sorbus tominalis (L.) Crantz	SOTR	Wild service	Diffuse-porous		17.2[1]
Acer pseudoplatanus L.	ACPS	Sycamore	Diffuse-porous	5	11.7[1]
Alnus glutinosa (L.) Gaertn.	ALGL	Common alder	Diffuse-porous	5	13.4[1]
Carpinus betulus L.	CPBT	Hornbeam	Diffuse-porous	5	18.8[1]
Corylus avellane L.	CYAL	Common hazel	Diffuse-porous		16.1[2]
Alnus incana (L.) Moench	ALIN	Grey alder	Diffuse-porous	5	12.7[3]
Tillia L.	TIXX	European lime	Semi-ring-porous	5	15.3[1]
Betula spp.	BTXX	European birch	Diffuse-porous	5	14.0[1]
Prunus avium L.	PRAV	European cherry	Semi-ring-porous	3–5	13.9[1]
Paulownia tomentosa (Thunb.) Steud.	PLTT	Paulownia	Semi-ring-porous	5	6.7[2]
Fagus sylvatica L.	FASY	European beech	Semi-ring-porous	5	17.9[1]
Juglans regia L.	JGRG	European walnut	Semi-ring-porous	3	13.7[1]
Eucalyptus globulus Labill.	EUGL	Southern blue gum	Ring-porous	5	32.4[1]
Ulums L.	ULXX	Elm	ring-porous	4	12.8[1]
Castanea sativa Mill.	CTST	Sweet chestnut	ring-porous	2	11.5[1]
Quercus rubra L.	QCXR	American red oak	ring-porous	3–4	13.1[1]
Quercus spp.	QCXE	European oak	ring-porous	2–4	14.1[1]
Ailanthus altissima (Mill.) Swingle	AIAL	Tree of heaven	ring-porous		20.2[2]
Fraxinus excelsior L.	FXEX	European ash	ring-porous	5	13.2[1]
Robinia pseudoacacia L.	ROPS	Robinia	ring-porous	1–2	11.8[1]
Juniperus virginiana L.	JUVR	Eastern red cedar	Coniferous	2	7.8[1]
Taxus baccata L.	TXBC	Yew	Coniferous	2	5.3[1]
Thuja plicata Donn ex D. Don in Lambert	THPL	Western red cedar	Coniferous	2	7.1[1]
Pinus strobus L.	PNST	Yellow pine	Coniferous	4	9.0[1]
Pinus nigra J. F. Arnold	PNNN	Austrian pine	Coniferous	3	12.6[3]
Pseudotsuga menziesii (Mirbel) Franco	PSMN	Douglas fir	Coniferous	3–4	12.0[1]
Picea sitchensis (Bong.) Carrière	PCST	Sitka spruce	Coniferous	4–5	11.5[4]
Abies alba Mill.	ABAL	Silver fir	Coniferous	4	10.9[1]
Pinus cembra L.	PNCM	Cembra pine	Coniferous	3–4	9.8[2]
Cedrus Trew	CDXX	Cedar	Coniferous	1–2	7.8[1]
Larix decidua Mill	LADC	European larch	Coniferous	3–4	13.2[1]
Picea abies (L.) H. Karst.	PCAB	Norway spruce	Coniferous	4–5	11.8[1]
Pinus sylvestris L.	PNSY	Scots pine	Coniferous	3–4	11.8[1]
Pinus taeda L.	PNTD	Loblolly pine	Coniferous	3	12.3[1]
Abies grandis (Douglas ex D. Don) Lindl.	ABGR	Grand fir	Coniferous	4	11.0[4]

Relevant literature: 1, Wagenführ and Wagenführ (2022); 2, Grabner (2017); 3, ÖNORM B 3012 (2003); 4, (Senalik & Farber 2021) complicating the substitution of Norway spruce in applications where weight plays an important role. The selection process based on M. Ashby offers an objective evaluation of the technical performance of the 38 investigated wood species and identified eight (European birch (BTXX = *Betula* spp.), Paulownia (PLTT = *Paulownia tomentosa* (Thunb.) Steud.), Sitka spruce (PCST = *Picea sitchensis* (Bong.) Carrière), yellow pine (PNST = *Pinus strobus* L.), Western red cedar (THPL = *Thuja plicata* Donn ex D. Don in Lambert), silver fir (ABAL = *Abies alba* Mill.) and loblolly pine (PNTD = *Pinus taeda* L.) and Grand fir (ABGR = *Abies grandis* (Douglas ex D. Don) Lindl.)) potential alternatives for Norway spruce. Grand fir and Paulownia showed the greatest potential in regards to bending performance and underline the necessity to also consider neophytes in the Central European forest sector.

From the aspect of structural timber engineering, it should be mentioned that apart from bending performance, the listed alternative tree species offer additional technological advantages and disadvantages for certain applications (e.g. dimensional stability and durability). Therefore, the successful substitution of Norway spruce in structural applications will require a holistic approach to identify the right alternative for a specific application.

For a final silvicultural assessment and evaluation, the findings from the current trial plots on plantations have to be combined with the technological assessment. An important aspect is the availability of the raw material, which is an essential criterion for the intersection between silviculture and technology. The available plot on plantations material should therefore make it possible to assess potential risks in the further cultivation of these wood species. In case of a positive evaluation, which is the case for Paulownia for example, the technologically relevant tree species could be an interesting consideration for the Central European forestry in the future.

Overall, the proposed selection process in combination with a subsequent assessment of the silvicultural relevance could serve as an additional decision tool in order to optimize the wood-value chain and prevent future economic loss of central European forests.

Another aspect is the number of available values for some of the investigated tree species (see also Table 1). The tree species common hazel (CYAL = *Corylus avellane* L.), grey alder (ALIN = *Alnus incana* (L.) Moench), Paulownia (PLTT = *Paulownia tomentosa* (Thunb.) Steud.), southern blue gum (EUGL = *Eucalyptus globulus* Labill.), tree of heaven (AIAL = *Ailanthus altissima* (Mill.) Swingle), eastern red cedar (JUVR = *Juniperus virginiana* L.), western red cedar (THPL = *Thuja plicata* Donn ex D. Don in Lambert), Austrian pine (PNNN = *Pinus nigra* J. F. Arnold), Sitka spruce (PCST = *Picea sitchensis* (Bong.) Carrière), cedar (CDXX = *Cedrus* Trew), grand fir (ABGR = *Abies grandis* (Douglas ex D. Don) Lindl.), European cherry (PRAV = *Prunus avium* L.), loblolly pine (PNTD = *Pinus taeda* L.), yew (TXBC = *Taxus baccata* L.) and cembra pine (PNCM = *Pinus cembra* L.) need to be investigated in more detail, because less than five data points were listed. Therefore, the variability from these tree species could not be depicted in the Figs. 2, 3 and 5. For future studies, these tree species would have to be examined more closely in order to obtain the variability and possible site differences.

Within the literature, there was partly no information on how many individuals or how many samples were tested. Thus, the variability within the tree species (see Figs. 2, 3 and 5) is not evident. The data sets could be considerably expanded in future, and national and international databases could be integrated in order to take the variability but also any differences in site conditions into account.

Furthermore, in addition to the density variation between the coniferous and hardwood groups, there are also intraspecies variations. These can be influenced by different factors such as genetics, site conditions (slope, exposure, altitude, water supply, etc.) and different conditions of the site soils (Verkasalo and Leban 1994). Soils differ in many chemical, physical, biological and morphological properties and characteristics from the rock from which they were formed. The chemical and physical properties are determined to a particular extent by the soil type, which in turn depends on the parent rock and the degree of weathering (Amelung et al. 2018). In addition to the site conditions, different silvicultural practices (e.g. thinning) as well as silvicultural management (commercial forest, protection forest, short rotation, etc.) can also have a significant influence (Sauter and Scheiding 2023; Šilinskas et al. 2020). Thus, certain target densities could be achieved with, e.g. different combinations of tree ring width, tree age and latewood proportion (Verkasalo and Leban 1994, 2002) in future.

Appendix

Table 5 Mean values for the 38 investigated wood species

			ρ_0 [kg/m^3]			ρ_{12} [kg/m^3]			MOR [MPa]			MOE [Gpa]		
Botanical name	**Code**	**Common name**	**N**	**CI**	**±SD**	**N**	**CI**	**±SD**	**N**	**CI**	**±SD**	**N**	**CI**	**±SD**
Salix L.	SAXX	Willow	7	392–534	76.9	7	422 – 574	82.1	7	35.0 – 60.2	13.6	7	6.8 – 9.1	1.2
Pyrus L.	PYCM	Pear	7	668–705	20.4	7	703 – 747	23.8	7	81.0 – 103	12.1	7	7.8 – 9.1	0.7
Populus L.	PONG	Poplar	8	388–442	32.0	8	416 – 472	33.4	8	58.1 – 71.7	8.1	8	8.4 – 9.5	0.6
Sorbus torminalis (L.) Crantz	SOTR	Wild service	5	700–722	9.0	5	729 – 774	18.1	5	111 – 125	5.8	5	11.2 – 13.6	1.0
Acer pseudoplatanus L.	ACPS	Sycamore	7	576–597	11.3	7	611 – 640	15.5	6	97.4 – 122	11.6	7	9.8 – 11.8	1.1
Alnus glutinosa (L.) Gaertn.	ALGL	Common alder	7	492–508	8.6	7	523 – 539	8.6	7	89.9 – 106	8.8	7	8.8 – 11.8	1.7
Carpinus betulus L.	CPBT	Hornbeam	7	727–799	38.7	7	758 – 832	39.9	7	134 – 173	20.9	7	14.3 – 18.6	2.3
Corylus avellane L.	CYAL	Common hazel	3	628–528	20.3	3	551 – 656	21.1	1	106		1	11.0	
Alnus incana (L.) Moench	ALIN	Grey alder	2	431 – 559	7.1	2	460 – 595	7.5	1	102		1	10.6	
Tillia L.	TIXX	European lime	7	490–515	13.6	7	516 – 544	15.2	7	93.2 – 114	11.4	7	7.7 – 10.6	1.6
Betula spp.	BTXX	European birch	7	574–639	34.9	7	628 – 670	22.9	7	135 – 158	12.4	7	16.8 – 18.1	0.7
Prunus avium L.	PRAV	European cherry	6	557 – 582	11.7	6	591 – 616	11.7	6	92.9 – 106	6.0	4	8.8 – 12.5	1.2
Paulownia tomentosa (Thunb.) Steud.	PLTT	Paulownia	1	256		1	279		1	42.7		1	4.6	
Fagus sylvatica L.	FASY	European beech	9	652–683	20.3	9	690 – 720	20.0	9	117 – 136	12.7	9	15.4 – 17.7	1.5
Juglans regia L.	JGRG	European walnut	7	604–651	25.8	7	639 – 691	27.9	7	117 – 156	21.2	7	11.6 – 15.8	2.3
Eucalyptus globulus Labill.	EUGL	Southern blue gum	1	725		1	719		1	100		1	13.4	
Ulmus L.	ULXX	Elm	7	525–661	73.5	7	557 – 701	78.1	7	78.4 – 98.2	10.7	7	11.4 – 12.3	0.5
Castanea sativa Mill.	CTST	Sweet chestnut	6	516–571	26.4	6	557 – 613	26.5	6	74.9 – 95.7	9.9	6	8.8 – 11.2	1.2
Quercus rubra L.	QCXR	American red oak	7	635 – 668	18.2	7	711 – 676	19.4	7	85.5 – 133	25.7	7	12.3 – 14.7	1.3
Quercus spp.	QCXE	European oak	8	645–660	9.0	8	684 – 700	9.8	8	96.8 – 115	11.0	8	13.1 – 13.9	0.5
Ailanthus altissima (Mill.) Swingle	AIAL	Tree of heaven	3	581 – 688	21.5	3	590 – 732	28.6	1	99		1	11.4	
Fraxinus excelsior L.	FXEX	European ash	8	647–676	17.4	8	686 – 724	22.4	8	118 – 131	7.5	8	13.8 – 15.1	0.8
Robinia pseudoacacia L.	ROPS	Robinia	9	710–736	17.0	9	755 – 784	18.3	9	142 – 155	8.7	9	13.0 – 14.9	1.3
Juniperus virginiana L.	JUVR	Eastern red cedar	2	304–601	16.5	2	330 – 652	17.9	1	68.3		1	13.8	
Taxus baccata L.	TXBC	Yew	5	632–644	4.6	5	693 – 708	5.8	3	92.4 – 103	2.1	3	0.79 – 26.2	5.1
Thuja plicata Donn ex D. Don in Lambert	THPL	Western red cedar	4	313–362	15.3	4	341 – 394	16.7	4	56.9 – 59.4	0.8	4	8.6 – 8.9	0.1
Pinus strobus L.	PNST	Yellow pine	7	358–379	11.7	7	387 – 410	12.6	7	59.1 – 67.3	4.4	7	9.2 – 10.5	0.7
Pinus nigra J.F.Arnold	PNNN	Austrian pine	4	486–604	37.0	4	518 – 642	38.9	2	9.3 – 177	9.4	1	13.4	
Pseudotsuga menziesii (Mirbel) Franco	PSMN	Douglas fir	9	470 – 528	38.1	9	502 – 562	38.8	9	82.9 – 99.3	10.6	9	12.2 – 14.3	1.3
Picea sitchensis (Bong.) Carrière	PCST	Sitka spruce	3	362–442	16.1	3	387 – 473	17.3	3	70.2 – 84.1	2.8	3	9.7 – 13.6	0.8
Abies alba Mill.	ABAL	Silver fir	7	400–428	14.9	7	430 – 457	14.6	7	70.0 – 81.5	6.2	7	11.1 – 12.9	0.9
Pinus cembra L.	PNCM	Cembra pine	7	411–459	26.0	7	442 – 494	28.3	4	66.4 – 84.8	5.8	4	7.1 – 10.1	0.9
Cedrus Trew	CDXX	Cedar	2	452–513	3.4	2	491 – 557	3.7	2	18.4 – 161	7.9	1	10.6	
Larix decidua Mill.	LADC	European larch	8	533–588	32.8	8	566 – 626	35.8	8	103 – 112	5.3	8	13.7 – 15.4	1.0
Picea abies (L.) H.Karst.	PCAB	Norway spruce	8	402–435	20.0	8	439 – 463	14.3	8	70.6 – 90.3	11.7	8	12.1 – 12.4	0.2
Pinus sylvestris L.	PNSY	Scots pine	7	479–523	24.1	7	500 – 589	47.9	8	90.3 – 123	19.3	8	12.0 – 15.5	2.1
Pinus taeda L.	PNTD	Loblolly pine	2	111–878	42.7	2	118 – 937	45.6	1	98.6		1	13.8	
Abies grandis (Douglas ex D. Don) Lindl.	ABGR	Grand fir	5	356–396	16.3	5	382 – 425	17.5	5	68.9 – 86.1	6.9	4	10.1 – 12.4	0.7

The four-letter code was chosen according to ÖNORM B 3012 (2003), ρ_0 dry density, ρ_{12} calculate raw density at 12% moisture content, *MOR*, modulus or rupture at 12% moisture content, *MOE*, modulus of elasticity at 12% moisture content, *N*, number of literature references, *SD*, standard deviation, *CI*, confidence interval at 95%. The mean specific MOR and mean specific MOE can be calculated by dividing the respective mechanical property (MOR or MOE) with the respective density (ρ_{12})

Code availability
Not relevant.

Authors' contributions
Conceptualization, CH, MP, JK and UM; methodology, CH and MP; formal analysis and investigation, CH; writing—original draft preparation, CH, MP, ML and UM; writing—review and editing, CH, ML, AS, EH, MG, AT, JK, MG, UM and MP; funding acquisition, UM, JK and MP; resources, MG, UM and MG; and supervision, UM. All authors have read and agreed to the published version of the manuscript.

Funding
Open access funding provided by University of Natural Resources and Life Sciences Vienna (BOKU). The authors are grateful for research funding from the Federal Ministries BMK and BMDW as well as the Province of Styria within the COMET—Competence Centers for Excellent Technologies programme, as well as funding from the companies ACstyria Mobilitätscluster GmbH, Collano AG, IB STEINER, DYNAmore Gesellschaft für FEM Ingenieurdienstleistungen mbH, EJOT Austria GmbH & Co KG, Forst-Holz-Papier, Fill Gesellschaft m.b.H, Glanzstoff Management Consulting GmbH, Holzcluster Steiermark GmbH, Klumpp Coatings GmbH, LEAN Management Consulting GmbH, Volkswagen AG and Weitzer Wood Solutions GmbH. The COMET programme is administered by the Austrian Research Promotion Agency (FFG 882.509) and the Styrian Business Promotion Agency (SFG 1.000.065.896). Additionally, the results presented in this study are part of the research project "Strong Hardwood—a new resource-efficient material concept based on hardwood branches" (FTI20-003). The financial support by Amt der Niederösterreichischen Landesregierung is gratefully acknowledged.

Availability of data and materials
Data will be made available on request.

Declarations

Ethics approval and consent to participate
The authors declare that the study was not conducted on endangered vulnerable or threatened species.

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests.

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Received: 11 April 2023 Accepted: 4 October 2023
Published online: 23 October 2023

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