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CONTRIBUTION OF NATURALLY DURABLE WOOD TO THE CIRCULAR ECONOMY

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ABSTRACT

Total wood demand is projected by the FAO to increase by 49% between 2020 and 2050, despite deteriorating supply conditions such as deforestation and degradation due to fire and biological damage to forests. Service life extension and reuse of wood can help to mitigate this projected gap between supply and demand. Common construction timber species with moderately durable heartwood include Scots pine, Douglas fir and Japanese cedar. However, this durability varies widely among clones, growing sites and within tree trunks. The selection and utilization of highly durable clones or individuals within these timber species could contribute to extending the service life of building and civil engineering structures that are at greater risk of biodegradation, such as building façades and landscape engineering applications. The authors would like to advance the discussion on measures to utilize this selected timber with higher durability, including maintenance strategies and the complementary use of treated timber within the circular economy.

Keywords: circular economy, heartwood, natural durability, service life, carbon storage, laboratory decay test, standard

IZVLEČEK

FAO predvideva, da bo skupno povpraševanje po lesu med letoma 2020 in 2050 naraslo za 49 odstotkov, ne glede na zmanjšanje razpoložljivosti zaradi krčenja gozdov in degradacije, ki jo povzročajo požari in biološki škodljivci. Podaljšanje življenjske dobe in ponovna uporaba lesa lahko pomagata omiliti predvideno vrzel med ponudbo in povpraševanjem. Pogoste vrste gradbenega lesa z zmerno odporno jedrovino vključujejo rdeči bor, ameriško duglazijo in japonsko cedro. Vendar se odpornost močno razlikuje med kloni, rastišči in notranjostjo drevesnih debel. Izbor in uporaba visoko odpornih klonov ali posameznih dreves znotraj teh vrst lesa bi lahko prispevala k podaljšanju življenjske dobe gradbenih in inženirskih objektov z večjim tveganjem za biološki razkroj, kot so fasade stavb in les na prostem. Avtorji v prispevku razpravljajo o ukrepih za uporabo tega izbranega lesa z višjo odpornostjo, vključno z vzdrževanjem in uporabo obdelanega lesa v smeri krožnega gospodarstva.

Ključne besede: krožno gospodarstvo, jedrovina, naravna odpornost, shranjevanje ogljika, laboratorijski test odpornosti, standard

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1 INTRODUCTION

1 UVOD

Many of the resources essential to humanity are finite and the way they are used will determine the future of the planet. An important renewable resource is wood provided by forestry, which has been used for construction, housing and firewood since ancient times. Global deforestation is still ongoing, mainly due to agricultural activities (West et al., 2025), and many forests are under extreme pressure from climate-related stressors such as wildfires and pests (MacCarthy et al., 2025; Guégan et al., 2023). At the same time, demand for forest products is rising. Global wood production is about 4 billion m^3 per year and in 2022 consisted of 2.04 billion m^3 of roundwood and 1.97 billion m^3 of fuelwood, at record levels. Global roundwood demand could increase by as much as 49% between 2020 and 2050 (FAO, 2024).

The FAO report suggests three measures to face these environmental stressors and rising demands on forests: new forest and land management, a bioeconomy of wood use and non-wood forest products for smallholders. From another perspective, Hellweg et al. (2024) indicate that biomass such as wood should be used in cascades and in long-term applications with biogenic carbon storage effects, replacing materials with large impacts, since the availability of sustainable biomass is limited.

Wood contributes to the circular economy as a natural and sustainable resource (European Wood Policy Platform, 2024). The total material stock of buildings in the world was 215 Gt in 2020 and is projected to increase to 400 Gt in 2060. The main material is concrete (more than 90%) followed by steel and construction wood (several percent) (Hatfield-Dodds et al., 2024). One of the measures to meet the growing demand for wood is to extend the service life of new buildings through naturally durable woody materials and to extend that of existing buildings through the replacement of degraded materials with durable wood. One benefit of using naturally durable wood will be that this material can be recovered and reused in the case of building demolition. One way to improve the sustainability of new building stock is to include recycled content and timber and to extend the lifetime of new buildings (Bruyninckx et al., 2024).

Extension of the service life of wood products with minimal chemical processing in various use conditions contributes to the sustainable use of natural resources and the mitigation of environmental impacts, which can be implemented within the framework of a circular economy. There are various methods for prolonging the service life of wood, including treatments using preservatives or natural substances, wood modification technologies, physical processing such as compression, painting and water-repellent treatments, the use of naturally durable tree species and design strategies to reduce water exposure in wooden structures (Sandberg et al., 2017; Yamamoto et al., 2019; Brischke, 2020). Each method has its advantages and disadvantages, and the choice of materials and designs depends on factors such as expected service life, the intended use of the wood, the environment in which it will be used, costs and user perspectives. This study examines the potential for uses of durable wood species in the field of architecture and civil engineering from a local perspective.

2 METHODOLOGY
2 METODOLOGIJA

In order to present a review of durable wood and the circular economy, a comprehensive literature review on wood and the environment was carried out (Fig. 1). There is now a substantial body of research on the natural durability of wood and its classification. First, we consulted standards and handbooks regarding the classification of wood durability. Standards for timber exist in most countries around the world, but here we focus on the standards of Europe, the United States and Japan. To examine the durability of wood, there are methods such as accelerated fungal decay tests, field stake tests and above-ground field tests. However, in this study, fungal decay tests were the primary focus due to the abundance of literature, the ease of comparing results and the natural durability standards that are universally based on decay fungi tests. Regarding wood species, common coniferous timber species for construction and civil engineering were the subject of the investigation. Tropical broadleaf species with high durability were not considered in this study. For

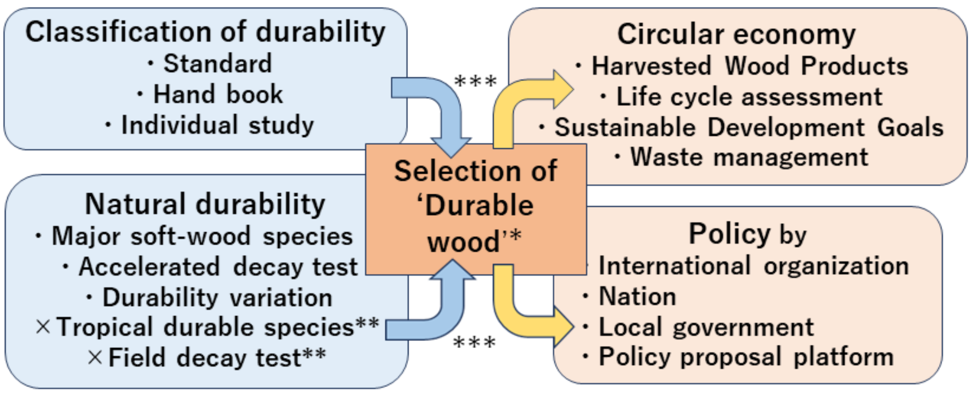

Fig. 1: Methodology of the literature review on wood durability and the circular economy
*Durable wood' is explained in Section 4.1. ** indicates exclusion from the search. *** The blue arrow indicates the selection criteria for 'durable wood' and the brown arrow indicates the utilization method for 'durable wood'.

Slika 1: Metodologija raziskovanja literature o odpornosti lesa in krožnem gospodarstvu
*Oznaka 'vzdržljiv les' je razložena v 4.1. ** označuje izključitev iz iskanja. *** Modra puščica označuje merila izbire za 'odporen les', rjava puščica pa način uporabe za 'odporen les'.

each tree species under study, we primarily selected peer-reviewed English articles, but we also referred to non-peer-reviewed reports (IRG documents) in order to examine a larger number of reports. Furthermore, we explored information such as Harvested Wood Products, Sustainable Development Goals, life cycle assessment and waste management, which form part of the circular economy, as well as policies to realize the circular economy using 'durable wood' from the global to the local level. Regarding Japanese-language policies, we have cited and appropriately summarized the in English.

3 RESULTS
3 REZULTATI

Natural durability is one of the most important wood properties and there are many reports on the natural durability of major tree species in many countries and regions (TRADA, 1979; Chudnoff, 1984). However, the methods for testing decay resistance and the classification of durability levels vary between reports or testing standards (ASTM D2017-05, EN 350:2016). Furthermore, it is known that even within the same tree species, the durability class can vary greatly (Nilsson, 1997; Edlund, 2004; Usta et al., 2006; Pollet et al., 2012; Irbe et al., 2012). Therefore, a proper understanding of wood durability requires appropriate information and knowledge. Here, we discuss natural durability, focusing on the classification of durability and its variability within species, based on literature and testing standards.

3.1 Classification system of natural durability
3.1 Razvrstitveni sistem naravne odpornosti

Natural durability of wood has been classified by laboratory decay tests using wood-rotting fungi in many standards (ASTM D2017-05, AWPA E30-16, EN 350, JIS Z 2101), and there is much research about the classification of natural durability of wood based on laboratory tests and field tests (Osborne, 1970; Hong and Yamamoto, 1989; Scheffer and Morrell, 1998). Classification rating systems and mass loss values of natural durability standards differ slightly from each other (Table 1). In addition to these differences, there are also differences in agar-block and soil-block methods, incubation periods and reference wood species. Outdoor testing is also important for assessing durability, and there are considerable differences in the criteria for visually evaluating degradation, the climate and soil diversity of the test sites, and the expected service life. As Stirling (2009) noted, the interpretation of natural durability ratings based on the various systems used around the world provides a useful tool for trading in wood products smoothly between different regions. These differences need to be understood to avoid confusion and misunderstandings when using these standard systems.

3.2 Variation of natural durability within species
3.2 Variabilnost naravne odpornosti znotraj vrst

There have been many studies on the variation of natural durability within individual timber species,

Table 1: Comparison of natural durability classification

Preglednica 1: Primerjava klasifikacije naravne odpornosti

<table>
<tr><th>Class of durability</th><th>European Norm (EN 350)</th><th>American Society for Testing and Materials (ASTM D2017-05)</th><th>American Wood Protection Association Standard (AWPA E30-16)</th><th>Japan Industrial Standard (JIS Z 2101)</th><th>Osborne (1970)</th><th>Hong and Yamamoto (1989)</th></tr>
<tr><td>Very durable
(Highly resistant)</td><td>X*≦0.15
** -7.5%</td><td>0-10%</td><td>0-10%</td><td rowspan="2">Y***>151****
***** -13%</td><td rowspan="2">0-3%</td><td>0-3%</td></tr>
<tr><td>Durable
(Resistant)</td><td>X>0.15 but≦0.30
** 7.5-15%</td><td>11-24%</td><td>11-24%</td><td>3-10%</td></tr>
<tr><td>Moderately durable
(Moderately resistant)</td><td>X>0.30 but≦0.60
** 15-30%</td><td>25-44%</td><td>25-44%</td><td>Y=126~150****
***** 14-27%</td><td>4-10%</td><td>10-30%</td></tr>
<tr><td>Slightly durable
(Slightly resistant)</td><td>X>0.60 but≦0.90
** 30-45%</td><td rowspan="2">45%-</td><td rowspan="2">45%-</td><td rowspan="2">Y<125****
***** 28%-</td><td>11-20%</td><td rowspan="2">30%-</td></tr>
<tr><td>Not durable
(Non-resistant)</td><td>X>0.90
** 45%-</td><td>21%-</td></tr>
</table>

* Relative value (X) to reference wood (non-durable species). ** When the mass loss of reference wood is 50%.

*** Calculated relative value (Y) (Y= {100 – (mass loss of sample) / 100 – (mass loss of *F. crenata*)} ×100) to reference wood (*Fagus crenata*). **** Y has not been reflected in the classification of durability in the JIS; therefore, the criterion by Matsuoka and Shoji (1960) was referenced. ***** When the mass loss of reference wood is 42.7% by *Poria vaporaria* specified in the former JIS Z 2119 (1958).

particularly for the major construction timber species classified as near moderately durable, such as Scots pine (*Pinus sylvestris*), Douglas fir (*Pseudotsuga menziesii*), Japanese cedar (*Cryptomeria japonica*), larch (*Larix decidua, L. kaempferi* and others) and Norway spruce (*Picea abies*), due to the practical importance of their durability (Table 2). The durability class of each wood species in the EN 350 standard is clearly stated within a narrow range (for example 3–4 or 3), but the range of durability of particular species in individual studies is often wider (for example 1–5) than that in EN 350. These timber species have shown the potential to be highly durable (very durable or durable) within the range of durability variation, depending on the clones or individual trees. Highly durable tree species such as teak (*Tectona grandis*) and black locust (*Robinia pseudoacacia*), which already have established brand names, are not mentioned here.

In the case of Scots pine, Folin–Ciocalteu analysis of the heartwood of 520 trees showed that the total phenolic content varied widely from 1.9 to 21.7 mg per 1 g of sample in tannic acid equivalent, and that these values were highly negatively correlated with the rate of mass loss by *Coniophora puteana* (Harju and Venäläinen, 2006). The mean value of pinosylvin content, one of the heartwood components involved in decay resistance, varied from 1–5% among 17 clones in Norway, with one clone showing a higher intra-clone variation of 0.8–4.7% (Partanen et al., 2011). In the case of Douglas fir, the L-joint assessment of heartwood in Australia classified the material into durability class 4 (above-ground life expectancy of 0 to 7 years) in fast-grown material and durability class 3 (7 to 15 years) in slow-grown material based on the Australian Standard (AS 5604:2022, 4-class rating) (Francis, 2023). Mean mass losses of heartwood caused by *Rhodonia placenta* showed a variation between 5% and 30% among plantation sites in Belgium and between radial heartwood positions (Pollet et al., 2012) (Table 2). In the case of Japanese cedar, the average mass losses of 15 clones of heartwood in the Kanto region decayed by *Fomitopsis palustris* and *Pycnoporus coccineus* varied between 0% and 29% and 0% and 14%, respectively, and it should be noted that both sample trees of the Numata-2 clone had a mass loss of 0% (Yamamoto et al., 2004). Variation in mass losses of 13 clones (4 sites each) of Japanese cedar heartwood in the Kyushu region by *Fomitopsis palustris* was highly dispersed between clones, with 2 clones ranging from 0% to several percent and 4 clones ranging from 0% to 40–50% (Usta et al., 2006). In the case of larch, the average was moderately durable, but there is a high variability of durability class, ranging from 1 to 5, depending on sample level, individual tree level, larch species and provenance, according to a comprehensive review of *Larix* (Brischke et al., 2025). On the other hand, the variability of natural durability in Norway spruce appeared to be small within the species (Irbe et al., 2012).

As mentioned above, in the cases of Scots pine, Douglas fir, Japanese cedar and larch species, many studies found individuals or clones with higher durability classes compared to the durability classes indicated by the EN 350 standard. In Norway spruce, however, previous studies did not show a significant difference

Table 2: Reported variation of natural durability in some timber species classified as low to moderately durable

Preglednica 2: Variabilnost naravne odpornosti pri nekaterih vrstah lesa, ki so uvrščene kot malo do zmerno odporne

Species	Natural durability class to fungi specified in EN350 *	Examples of variation of natural durability in various reports
Scots pine	3–4	Durable, moderately durable in 6-month TMC test (Edlund, 2004)
		Very durable to not durable depending on the drying process and total phenolics (Sehlstedt-Persson and Karlsson, 2010)
Douglas fir	3–4 Cultivated in Europe 3 N. America	Slightly durable, not durable in British-grown material (Akhter, 2002)
		Very durable, durable, moderately durable, slightly durable in samples from disks (Pollet et al., 2012)
Japanese cedar	5	Very durable (3 clones), durable (6 clones), moderately durable (4 clones) in 13 clones (Usta et al., 2006)
		Very durable (4 clones), durable (5 clones), moderately durable (5 clones), slightly durable (1 clone) in 15 clones (Yamamoto et al., 2004)
Larch species	3–4	Moderately durable, slightly durable, not durable in several studies (Nilsson, 1997)
		Very durable to not durable in a review of many studies (Brischke et al., 2025)
Norway spruce	4	Not durable (10 clones) by *C. puteana* and *P. placenta*, and not durable (8 clones) and slightly durable (2 clones) by *G. trabeum* in 10 clones of 31-year-old trees grown in Latvia (Irbe et al., 2012)

* Natural durability classification by EN 350:2016. 1: Very durable, 2: Durable, 3: Moderately durable, 4: Slightly durable, 5: Not durable.

between the durability classes indicated by EN 350 and those shown in these studies. These four species show considerable variation in natural durability within the species, depending on clonal differences and probably on site and growth conditions (Freitag and Morrell, 2001). If durability higher than moderate can be ensured for such species, it may be possible in the future to use them without treatment to supplement preservative-treated timber to a certain extent.

4 DISCUSSION AND CONCLUSIONS

4 RAZPRAVA IN ZAKLJUČKI

4.1 Current state of wood utilization in Japan

4.1 Trenutno stanje izkoriščanja lesa na Japonskem

It would be useful to extend the service life of wooden structures by using naturally durable, untreated wood if tree clones or individual timber with higher durability could be selected within the major construction timber species, such as Scots pine, Douglas fir, Japanese cedar and larch (hereafter referred to as ‘durable wood’). In this section, we consider the measures that contribute to the circular economy by using naturally durable wood, using Japan as an example. Before that, we provide an overview of forests and wood utilization in the sectors of construction and civil engineering in Japan. The forest area in Japan is 250 thousand km^2, and the forest coverage rate is 67%, which has remained largely unchanged over the past few decades (Forestry Agency, 2022a). The demand for wood is estimated at 80 million m^3, including imported wood, and the self-sufficiency rate of domestic products has recently risen from 19% in 2002 to 43% in 2023 (MAFF, 2023a). The breakdown of wood into products is as follows: 22 million m^3 for sawn timber, 7 million m^3 for plywood, 28 million m^3 for pulp and chips, and 20 million m^3 for fuel materials (charcoal, firewood, fuel chips and pellets). The amounts of the main species for sawn timber are 8.1 million m^3 for Japanese cedar, 2.2 million m^3 for Japanese cypress (*Chamaecyparis obtusa*) and 0.7 million m^3 for Japanese larch *(Larix leptolepis*) in 2024 (MAFF, 2024). Here, we focus on the use of wood in construction and civil engineering. With the wood utilization promotion acts (Forestry Agency, 2010; Forestry Agency, 2021), the use of wood in public works for construction and civil engineering is progressing. The amount of wood used for construction is estimated to be about 80% of sawn timber (Forestry Agency, 2022b) and a certain amount of plywood (actual figures are not specified), leading to an estimated total of 20 million m^3. The total amount of wood used for civil engineering is approximately one million m^3 (Numata, 2017). Statistics on public works indicate around 200,000 m^3 under the jurisdiction of the Ministry of Agriculture, Forestry and Fisheries (MAFF, 2023b) and around 20,000 m^3 under that of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2022). Compared to the demand for wood in architecture and civil engineering, the usage of treated wood is rather small in Japan, and the annual total production of treated wood is only around 200,000 m^3 according to statistics from the Japan Wood Preservers Industry Association.

4.2 Selection and characteristics of 'durable wood'

4.2 Izbira in značilnosti 'odpornega lesa'

For the selection of ‘durable wood’, it would be realistic to develop durable clones through national breeding projects and to select high-durability heartwood through simple non-destructive testing of commercial logs similar to mechanical grading (Sandberg and Sterley, 2009). Large-diameter logs have the advantage of having a higher proportion of heartwood than small ones (Ihara, 1972). In addition, the unit price for each 1 m^3 of large-diameter logs in Japanese cedar is lower than for logs in the less-than-30-cm diameter class, partially because efficient utilization methods that match the needs have not been established (Ijichi and Endo, 2010). An important point with large-diameter logs is to make use of the characteristics of heartwood. There will be a need for wood processing to produce the sawn timber that includes only heartwood, without sapwood, as a substitute for treated wood (Brischke et al., 2018). To avoid a decrease in lumber recovery and economic efficiency from sawing ‘durable wood’ selectively from logs, it is important to maintain yield through integrated lumber cutting that takes the intended uses into consideration.

This selected timber, or ‘durable wood’, has a variety of characteristics and could be used for indoor or outdoor materials in buildings, as well as in civil engineering facilities. Where and how to use ‘durable wood’ is shown in Table 3. The advantageous features of ‘durable wood’ are that it is a natural product without any chemical processes, has high durability and can be reused or safely disposed of at the final stage of use. Since ‘durable wood’ is a natural timber composed only of heartwood, it should be fully understood that its durability performance varies depending on the variations within the position of the heartwood.

Table 3: Characteristics of 'durable wood' selected construction timber – example of Japanese cedar

Preglednica 3: Značilnosti izbranega 'odpornega' gradbenega lesa – primer japonske cedre

Characteristics and issues of 'durable wood'*	Ways to use 'durable wood'
Explanation of advantages • Selection of 'durable wood' from logs creates a new horizon for wood use • Logical explanation of why 'durable wood' is superior environmentally and from a circular-economy perspective • Mechanism for implementing 'durable wood' in local society by networking, public awareness and on-site technology	**Building (indoor)** • Housing foundations (Dodai), where specifications for ensuring durability are legally prescribed** • Components of under-floor or wall sheathing with potential for water condensation/leakage **Building (outdoor)** • Exterior walls of buildings • Landscape facilities such as decks and fences • Maintenance, such as repairing or replacing wood, is required • depending on the service life
Demands and performance • Adaptation of 'durable wood' to cases where the use of preservative-treated materials is not desired • Durability of 'durable wood' is not expected to be as high as that of highly durable tropical hardwood species • Variability in performance due to untreated and natural 'durable wood' • Prices of 'durable wood' are likely to be higher than for preservative-treated wood	**Civil engineering facilities** • Agricultural fences, erosion and flood control facilities • Allowing on-site disposal and replacement of wood in maintenance, as no preservatives are included

* Durability was examined only with respect to decay in a laboratory test, not with respect to soft-rot organisms, insects and termites.

** (MLIT, 2000).

4.3 Contribution of 'durable wood' to the circular economy

4.3 Prispevek 'odpornega lesa' h krožnemu gospodarstvu

Wood itself is a renewable and recyclable resource and environmentally compatible; furthermore, extending its service life would make it more sustainable, provided that the methods of service life extension do not create new impacts. Bruyninckx et al. (2024) outlined three key recommendations for building practice: materials that include recycled content and timber, lightweighting or lean design for new buildings and lifetime extension to improve the sustainability of new building stock. The use of selected 'durable wood' in buildings and civil engineering facilities would extend their service life and would not only enable longer carbon storage in the Harvested Wood Products mechanism but would also contribute to the circular economy in terms of ease of reuse, recycling or disposal at the final stage of use (Figure 2).

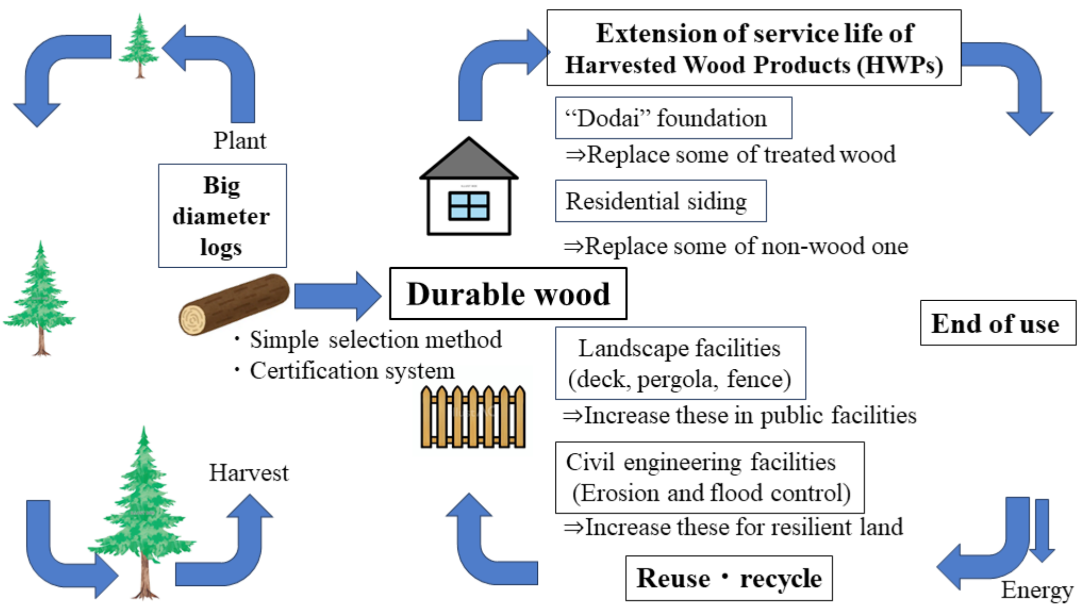

Fig. 2: Contribution of 'durable wood' to sustainable forestry and the circular economy

Slika 2: Prispevek 'odpornega lesa' k trajnostnemu gozdarstvu in krožnemu gospodarstvu

We think that a regional perspective is crucial if the 'durable wood' resource is to contribute to the circular economy. There are many policy-related activities to promote wood use in a region, such as training architects, organizing a network and constructing local public facilities (National Governors' Association Japan, 2024). Many case studies are underway on the impact of these activities in the context of circular cities or the circular economy (Herrador et al., 2023). Currently, wood use in exterior construction materials is promoted as a policy that contributes to carbon emissions reduction and also the beauty of streetscapes (JFWIA and HOWTEC, 2024). Although commercial use of Japanese cedar heartwood remains limited, recent efforts by municipalities and organizations (such as Nara Prefecture, 2025) are promoting its application in exterior walls, fences, decks and pergolas. Initial implementation is expected in housing foundations (Dodai), building exteriors and landscape structures (Figure 2). By replacing a few percent of existing products with 'durable wood', the quantity replaced is expected to be several thousand m^3 for Dodai and tens of thousands of m^3 for residential siding of ceramic, metal and resin-based materials. To leverage the characteristics of naturally 'durable wood' (preservative-free and long service life), policy support through certification and subsidy systems is crucial for broader adoption in public and private sectors. Relevant policies include the Regional Housing Greenification Project (MLIT, 2023), Agreement for the Promotion of Wood Use in Buildings (MLIT, 2025), Promotion Act for Wooden Structures in Cities (Forestry Agency, 2021) and Guidance on Assessment of Wood Use in Buildings (Forestry Agency, 2024).

The importance of the durability of wood is expected to increase even more in the future due to greater demand, reduced supply and market concerns about sustainability. Wood is an inherently sustainable and advanced material, even without being addressed by the SDGs or the circular economy, and when forest management and wood production adhere to environmentally conscious processes, it becomes an exceptionally superior material. Wood protection technologies that enable established treated wood and naturally 'durable wood' to coexist and complement each other are needed. In order to achieve this strategy, it is both difficult and very important to achieve the ultimate goals of durability assessment that estimate the service life of wood in the actual environment where wood products are used (Brischke, 2020). Integrated technology based on the service life of treated wood and 'durable wood' in different usage environments is likely to make the most of the characteristics of each product.

In order to realize a circular economy, it is necessary to also consider the fate of products and the elimination of waste and pollution after their use. While the disposal of processed wood raises concerns such as dioxin generation from incineration and leaching of preservatives during landfill, untreated wood presents fewer of these issues (Abdolmaleki et al., 2025). The reuse or disposal of 'durable wood' is easier compared to treated wood at the end of service life due to various factors such as land use changes, different types of building needed, renovation, structural damage caused by seismic events or storms rather than biological deterioration.

5 SUMMARY

Wood is an important renewable resource that has been used for construction, housing and firewood since ancient times. MacCarthy et al. (2025) and Guégan et al. (2023) showed that global deforestation is still ongoing, mainly due to agricultural activities, and forests themselves are under extreme pressure from climate-related stressors such as wildfires and pests. At the same time, demand for forest products is rising. Global roundwood demand could increase by as much as 49% between 2020 and 2050. The FAO (2024) report suggests three measures to face these environmental stressors and rising demands on forests: new forest and land management, a bioeconomy in which wood is a major input and non-wood forest products for smallholders. Therefore, wood should be used in cascades and in long-term applications with biogenic carbon storage effects, replacing materials with large environmental impacts, since the availability of sustainable biomass is limited. Wood is considered to contribute to the circular economy as a natural and sustainable resource. One of the measures to meet the growing demand for wood is to extend the service life of new buildings through naturally durable woody materials and that of existing buildings through the replacement of degraded materials with durable wood.

In order to present a review of durable wood and the circular economy, a comprehensive literature review on wood and the environment was carried out (Fig. 1). Extension of the service life of wood products in various use conditions contributes to the effective use of natural resources and the mitigation of impacts on the environment, which can be implemented within the framework of a circular economy. There are various methods for prolonging the service life of wood, including treatments using preservatives or natural substances, wood modification technologies, physical processing such as compression, painting and water-repellent treatments, the use of naturally durable tree species and design strategies to reduce water exposure in wooden structures. Since the natural durability of wood is one of the important properties among various performance requirements, such as strength and workability, there are many reports on major tree species in various countries and regions. However, the methods for testing durability and the classification of durability levels vary according to each report or testing standard. Furthermore, it is known that even within the same tree species, the durability class can vary greatly. Therefore, a proper understanding of wood durability requires appropriate information and knowledge.

Natural durability of wood has been classified by laboratory decay tests using wood-rotting fungi in many standards, and classification systems and mass loss values of natural durability standards differ slightly from each other (Table 1). Understanding these differences is essential to avoid confusion and facilitate the wood product trade.

There have been many studies on the variation of natural durability within individual timber species, particularly for major construction timber species such as Scots pine (*Pinus sylvestris*), Douglas fir (*Pseudotsuga menziesii*), Japanese cedar (*Cryptomeria japonica*), larch (*Larix decidua, L. kaempferi* and so on) and Norway spruce (*Picea abies*), due to the practical importance of their durability (Table 2). The durability class of each wood species in the EN 350:2016 standard is clearly stated within a narrow range (for example, 3–4 or 3), but the range of durability of particular species in individual studies is often wider (for example, 1–5) than that in EN 350. These timber species have shown the potential to be highly durable within the range of durability variation, depending on the clones and individuals. In the example of Scots pine, Harju and Venäläinen (2006) indicated that Folin–Ciocalteu analysis of the heartwood of 520 trees showed that the total phenolic content varied widely from 1.9 to 21.7 mg per g of sample in tannic acid equivalents, and that these values were highly negatively correlated with the rate of mass loss caused by *Coniophora puteana*. In Douglas fir, Pollet et al. (2012) showed that mean mass losses of heartwood caused by *Poria placenta* varied between 5% and 30% among plantation sites in Belgium and between radial heartwood positions. In Japanese cedar, Yamamoto et al. (2004) demonstrated that the average mass losses of 15 clones of heartwood in the Kanto area decayed by *Fomitopsis palustris* and *Pycnoporus coccineus* varied between 0% and 29% and 0% and 14%, respectively, and one clone showing a mass loss of 0% should be noted. Usta et al. (2006) also showed that the variation of mass losses of 13 clones (4 sites each) of heartwood in the Kyushu area by *Fomitopsis palustris* was highly dispersed between clones, with 2 clones ranging from 0% to several percent and 4 clones ranging from 0% to 40–50 %. In the case of larch, the average was moderately durable, but there is a high variability of durability class ranging from 1 to 5 depending on sample level, individual tree level, larch species and provenance, as shown in a comprehensive review of *Larix* (Brischke et al., 2025). On the other hand, the variability of natural durability in Norway spruce appeared to be small within the species (Irbe et al., 2012). This is an important fact because the former four species have a large variation in natural durability within the species depending on clone and site and growth conditions, as mentioned by Freitag and Morrell (2001). If higher than moderate durability can be ensured for such species, it may be possible in the future to use them without treatments to supplement preservative-treated timber to a certain extent.

There are significant variations of natural durability within individual timber species, particularly for the major construction timber species classified as moderately durable such as Scots pine, Douglas fir, Japanese cedar and larch. It would be useful to extend the service life of wooden structures using naturally durable common species if tree clones or individual trees with higher durability could be selected. When making the selection of ‘durable wood’, it would be realistic to develop durable clones through a national breeding project or to select heartwood with high durability through simple non-destructive testing of commercial logs like mechanical grading.

The use of selected ‘durable wood’ in buildings and civil engineering facilities would extend their service life and would not only enable longer carbon storage in the Harvested Wood Products mechanism but would also contribute the circular economy in terms of ease of reuse, recycling or disposal at the final stage of use (Table 3, Figure 2). A regional perspective to accommodate detailed requests would be crucial in order to contribute the circular economy (Table 3). Integrated technology based on the service life of treated wood and ‘durable wood’ in different usage environments is likely to make the most of the characteristics of each product. The importance of the durability of wood is expected to increase even more in the future due to greater demand, reduced supply and market concerns about sustainability.

5 POVZETEK

Les je pomemben obnovljiv vir, pridobljen z gozdarstvom, ki se že od davnine uporablja za gradnjo bivališč in kurjavo. MacCarthy et al. (2025) in Guégan et al. (2023) so pokazali, da se globalno krčenje gozdov še vedno nadaljuje predvsem zaradi kmetijskih dejavnosti, prav tako pa so gozdovi sami pod velikim pritiskom zaradi podnebno povezanih dejavnikov, kot so požari in škodljivci. Hkrati povpraševanje po gozdnih proizvodih narašča. Svetovno povpraševanje po okroglih hlodih bi se lahko med letoma 2020 in 2050 povečalo za kar 49 odstotkov. Poročilo FAO (2024) predlaga tri ukrepe za spoprijemanje s temi okoljskimi obremenitvami in naraščajočimi zahtevami po gozdnih sortimentih: novo upravljanje gozdov in zemljišč, bioekonomijo z lesom kot glavno surovino ter ne-lesne proizvode. Zato je treba les uporabljati v kaskadah in za dolgotrajno uporabo z učinki shranjevanja biogenega ogljika, pri čemer naj bi nadomeščal materiale z velikim vplivom, saj je razpoložljivost trajnostne biomase omejena. Les prispeva h krožnemu gospodarstvu kot naraven in trajnosten vir. Eden izmed ukrepov za zadostitev naraščajočega povpraševanja po lesu je podaljšanje življenjske dobe novih stavb z naravno odpornimi lesnimi materiali, prav tako pa tudi obstoječih stavb z zamenjavo razkrojenih materialov z odpornim lesom.

Za predstavitev pregleda odpornega lesa in krožnega gospodarstva je bil sprejet celosten pristop k raziskovanju literature o lesu in okolju (slika 1). Podaljšanje življenjske dobe lesenih izdelkov v različnih razmerah uporabe prispeva k učinkoviti rabi naravnih virov in zmanjševanju vplivov na okolje, kar je mogoče izvajati v okviru krožnega gospodarstva. Obstajajo različne metode za podaljšanje življenjske dobe lesa, vključno z obdelavo z biocidi ali naravnimi snovmi, modifikacijo lesa, fizikalno obdelavo, kot je stiskanje, barvanjem/obdelavo za povečanje vodoodbojnosti, uporabo naravno odpornih vrst lesa in konstrukcijsko zaščito za zmanjšanje izpostavljenosti vodi v lesenih konstrukcijah. Ker je naravna odpornost lesa ena izmed pomembnih lastnosti med različnimi lastnostmi, kot sta trdnost in obdelovalnost, obstaja veliko poročil o glavnih lesnih vrstah v različnih državah in regijah. Vendar se metode za preverjanje odpornosti in klasifikacija odpornosti razlikujejo glede na posamezno poročilo ali standard testiranja. Poleg tega je znano, da se lahko že pri isti vrsti lesa razredi odpornosti zelo razlikujejo. Zato ustrezno razumevanje odpornosti lesa zahteva primerne informacije in znanje.

Naravna odpornost lesa je bila v številnih standardih določena z laboratorijskimi testi razkroja z uporabo gliv, ki razkrajajo les, pri čemer se klasifikacijski sistemi in vrednosti izgube mase po standardih naravne odpornosti med seboj nekoliko razlikujejo (tabela 1). Razumevanje teh razlik je bistveno za preprečevanje zmede in olajšanje trgovine z lesnimi izdelki.

Obstaja veliko raziskav o variabilnosti naravne odpornosti znotraj posameznih vrst lesa, zlasti za glavne vrste gradbenega lesa, kot so rdeči bor (*Pinus sylvestris*), ameriška duglazija (*Pseudotsuga menziesii*), japonska cedra (*Cryptomeria japonica*), macesen (*Larix decidua, L. kaempferi* in podobno) ter smreka (*Picea abies*) zaradi praktičnega pomena njihove odpornosti (tabela 2). Razred odpornosti posamezne vrste lesa v standardu EN 350:2016 je jasno določen znotraj ozkega razpona (na primer 3–4 ali 3), medtem ko je razpon odpornosti posameznih vrst v posameznih raziskavah pogosto širši (na primer 1–5) kot v EN 350:2016. Te vrste lesa so pokazale potencial, da bodo zelo odporne znotraj razpona variacij odpornosti, odvisno od klonov in lesa posameznih dreves. Na primeru rdečega bora sta Harju in Venäläinen (2006) navedla, da je analiza Folin-Ciocalteu lesa jedrovine 520 dreves pokazala, da se je skupna vsebnost fenolov močno spreminjala od 1,9 do 21,7 mg na 1 g vzorca v ekvivalentu taninske kisline in da so bile te vrednosti močno negativno povezane s hitrostjo izgube mase zaradi razkroja z glivo *Coniophora puteana*. Pri ameriški duglaziji so Pollet et al. (2012) pokazali, da povprečne izgube mase lesa jedrovine, ki jih povzroča gliva *Poria placenta*, kažejo variacijo med 5 in 30 % med lokacijami rastišč v Belgiji in radialni lokaciji v jedrovini. Pri japonski cedri sta Yamamoto et al. (2004) pokazala, da so bile povprečne izgube mase 15 klonov jedrovine na območju Kanto, ki so jih izpostavili glivam *Fomitopsis palustris* in *Pycnoporus coccineus*, različne med 0 % in 29 % ter 0 % in 14 %, pri čemer je treba posebej omeniti en klon z izgubo mase 0 %. Usta et al. (2006) so prav tako pokazali, da se je razpon izgub mase 13 klonov (4 lokacije vsak) lesa jedrovine na območju Kyushu zaradi glive *Fomitopsis palustris* močno razlikoval med kloni, pri čemer sta se 2 klona gibala med 0 % in nekaj odstotkov, 4 kloni pa med 0 % in 40–50 %. V primeru macesna je bila povprečna odpornost zmerna, vendar je velika variacija v odpornostnem razredu, ki se je gibala od 1 do 5, odvisna od mesta odvzema vzorca, posameznega drevesa, vrste macesna in izvora, kot je prikazano v celostni preglednici vrste *Larix* (Brischke et al. 2025). Po drugi strani pa se je variabilnost naravne odpornosti pri smrekovini pokazala kot majhna (Irbe et al. 2012). To je pomembno dejstvo, saj imajo prve štiri vrste veliko variabilnost naravne odpornosti znotraj vrste, odvisno od klonskih značilnosti in verjetno tudi od rastišča in rastnih razmer, kot sta omenila Freitag in Morrell (2001). Če bi za take vrste lahko zagotovili večjo odpornost kot zmerno odpornost, bi jih v prihodnosti lahko uporabili brez obdelave z zaščitnimi sredstvi, da bi do določene mere nadomestili les, obdelan z zaščitnimi sredstvi.

Obstajajo pomembne razlike v naravni odpornosti znotraj posameznih vrst lesa, še posebej pri najpogosteje uporabljenih lesnih vrstah gradbenega lesa, ki so uvrščene kot srednje odporne, kot so rdeči bor, ameriška duglazija, japonska cedra in macesen. Koristno bi bilo podaljšati življenjsko dobo lesenih konstrukcij z uporabo naravno odpornih pogostih vrst, če bi lahko izbrali klone dreves ali posamezen les z višjo naravno odpornostjo. Pri izbiri »odpornega lesa« bi bilo realno razviti klone z odpornim lesom v okviru nacionalnega gojitvenega projekta ali izbrati jedrovino lesa z visoko odpornostjo z uporabo preprostega nedestruktivnega testiranja komercialnih hlodov, kot na primer mehansko razvrščanje.

Uporaba izbranega »odpornega lesa« v stavbah in objektih bi podaljšala njihovo življenjsko dobo, hkrati pa ne bi le omogočila daljšega skladiščenja ogljika v gradbenem lesu, temveč bi tudi prispevala h krožnemu gospodarstvu z vidika enostavnosti ponovne uporabe, recikliranja ali odstranjevanja ob koncu življenjske dobe (tabela 3, slika 1). Regionalna perspektiva za upoštevanje podrobnih zahtev bi bila ključnega pomena za prispevek h krožnemu gospodarstvu (tabela 3). Integrirana tehnologija, ki temelji na življenjski dobi obdelanega lesa in »odpornega lesa« v različnih razmerah uporabe, verjetno omogoča maksimalno izkoriščenost značilnosti vsakega proizvoda. Pomen odpornosti lesa naj bi se v prihodnosti še povečal zaradi večjega povpraševanja, zmanjšane ponudbe in tržnih zahtev glede odpornosti.

DATA AVAILABILITY
DOSTOPNOST RAZISKOVALNIH PODATKOV

Research data are the property of the Forestry and Forest Products Research Institute. Contact the authors for more information. No research data created in any Slovenian public research organization were used.

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