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### ► To cite this version:

Dimitra Ioannidou, Régis Pommier, Guillaume Habert, Guido Sonnemann. Evaluating the risks in the construction wood product system through a criticality assessment framework. *Resources, Conservation and Recycling*, 2019, 146, pp.68 - 76. 10.1016/j.resconrec.2019.03.021 . hal-03484435

**HAL Id: hal-03484435**

**<https://hal.science/hal-03484435>**

Submitted on 20 Dec 2021

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# 1 Evaluating the risks in the construction wood 2 product system through a criticality assessment 3 framework

4  
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## 15 **Abstract**

16 The increasing use of wood in product eco-design focuses on the environmental merits of wood.  
17 Nevertheless, forest cover loss and other threats may hamper the supply of certain wood species, hence  
18 significantly impacting the economic sector. Supply risk has been intensively studied in the field of  
19 mineral resources; this has led to the emergence of the criticality concept, which evaluates the supply  
20 risks and main impacts of limited accessibility. In the case of biotic, renewable resources, lack of  
21 sustainable management can result in supply shortage. We developed here a criticality framework for  
22 wood to assess the risk of supply shortage of different wood species in different regions. Our  
23 motivation to look at wood is that it is the biotic resource most used in construction. The indicators  
24 used in the framework express all factors that can disturb the forest growth, such as fire and diseases,  
25 the sustainable supply of harvested wood, such as trade barriers and country governance, as well as the

26 impacts of the aforementioned factors on the construction wood product system. The value of the  
27 framework and of the observations that can be derived thereof is shown through application to four  
28 different wood species. Such a criticality assessment can help define points of intervention at different  
29 geographic scales.

30

## 31 **1. Introduction**

32

33 The last few years have seen a steady increase in the use of wood as a building material in Europe,  
34 China and North America (Food and Agriculture Organization and UNECE, 2018; Howard et al.,  
35 2017). The multifaceted properties of wood justify the recent enthusiasm of architects and engineers to  
36 use this material in their projects; in addition to its aesthetic quality, wood is considered an  
37 environmentally friendly material, extracted from a renewable resource with a replenishment rate of a  
38 few decades. Furthermore, construction wood fares well in environmental analyses due to its carbon  
39 sequestration properties and the climate benefits associated with the sustainable management and  
40 regrowth of forests (Bellassen and Luyssaert, 2014). Many research endeavors have dealt with the  
41 environmental impacts of wood products and the benefits of wood along the value chain (Bösch et al.,  
42 2015; González-García et al., 2011; Gustavsson and Sathre, 2006; Suter et al., 2017). Moreover, the  
43 value of the forest ecosystem services, their evolution over time and the disturbances they face is a  
44 thriving field of research (Costanza et al., 2014; Lawler et al., 2014; Ojea et al., 2016; Ouyang et al.,  
45 2016; Thom and Seidl, 2016). Ecosystem services range from regulating services such as the  
46 regulation of water quality and provision of hedge against natural hazards, such as flood and soil  
47 erosion (Hlásny et al., 2017) to cultural services such as recreation and spiritual fulfillment and to  
48 supporting services such as soil formation, nutrient cycling and a habitat for threatened or endangered  
49 species (Balmford, 2002). These forest services may be of utmost importance to the local population  
50 (Uhde et al., 2015).

51 However, despite the rich literature around wood and forests, the criticality of wood and the supply  
52 risk of some popular wood species for the construction industry has not been studied yet.

53 As a renewable resource, wood is rarely considered at risk by businesses, government or the public.  
54 However, actual data about wood may present a different story. A recent study based on satellite data  
55 documented the increasing deforestation in the tropical and boreal forests over the course of the last  
56 decade (Hansen et al., 2013). Forests are faced with different types of deforestation and forest  
57 degradation challenges, depending on the location of a forest and the economic and socio-political  
58 situation of the supplying country (Kissinger et al., 2012). Intense competition for available land leads  
59 to forest clearing in order to use the space for other economic activities, such as agriculture, biofuel  
60 plantations or urban expansion (Bradshaw, 2012; DeFries et al., 2010; Kissinger et al., 2012).  
61 Intensive harvesting and extraction of other forest products (fuelwood, charcoal) as well as other types  
62 of disturbances, including fires, adverse weather conditions and pathogen attack, degrade the forest  
63 quality (Hosonuma et al., 2012). The impact of the aforementioned drivers is amplified by weak  
64 governance conditions, which fail to ensure a sustainable forest management and to impede illegal  
65 trading of wood products (Lukumbuzya and Sianga, 2017).

66 Coupled with these general risks pertaining to deforestation are more specific supply constraints of the  
67 different wood species. Some types of wood are extracted only from a handful of countries and can  
68 serve competing uses (e.g. use as lumber versus use as pulpwood). In addition, the variety of  
69 ecosystem services provided by forests restricts the logging activities to a percentage of the existing  
70 forest. As a result, different wood species used in the construction and furniture manufacturing sector  
71 can present different supply constraints, which can impact the cost and even the timely production of  
72 the final product.

73 In the present article, we study wood from an economic sustainability point of view and we examine  
74 whether the current wood supply chains can satisfy human needs in construction and furniture  
75 manufacturing. This approach of the interactions between natural and social systems, which is at the  
76 core of the sustainability science (Kates, 2011), provides a new, complementary perspective to the  
77 study of the environmental impacts of wood. We develop a new framework, based on the criticality  
78 concept, to study the aforementioned interactions. Our point of departure is that not only abiotic (non-  
79 renewable) but also renewable resources need to be sustainably managed to avoid supply constraints.  
80 While for the former resources, sustainable management just delays their (unavoidable) exhaustion,

81 for the latter it makes it possible to avoid their exhaustion that would occur under unsustainable  
82 conditions. With the exception of the methodology developed by Bach et al. (2017), no other  
83 framework has been developed for the assessment of the availability of biotic resources. Therefore, the  
84 present framework is setting the foundation for the criticality assessment of wood, one of the main  
85 resources in construction and manufacturing. The value of the framework and of the observations that  
86 can be derived from such an assessment is shown through application to four different wood species.

87

## 88 **2. Methodology**

### 89 **2.1. Framework and Concepts**

90 The use of the term “critical” indicates resources for which at least one indicator or attribute surpasses  
91 a threshold value (Bradshaw et al., 2013). Common criticality assessment methodologies developed  
92 evaluate the performance of a resource over two dimensions: how imminent is the risk of not having  
93 the resource in the future and what would be the repercussions of such a shortage on a social and  
94 economic level (Ioannidou et al., 2019; European Commission, 2010; National Research Council,  
95 2007). The concept of criticality was first developed for evaluating non-fuel minerals which are not  
96 domestically available and whose importation is subject to geopolitical risk. Although the initial field  
97 of application was the metals, the concept is slowly expanding to other resources, such as water  
98 (Sonderegger et al., 2015) and gravel (Ioannidou et al., 2017). At the policy level, the European  
99 Commission has lately included in the periodically updated criticality tables published, in addition to  
100 metals, biotic materials, such as natural rubber (evaluated as critical), natural cork, natural teak wood  
101 and sapele wood (European Commission, 2014). In addition, in 2017, the European Commission  
102 published a report providing some general guidelines about the assessment of biotic materials,  
103 however no concrete indicators were defined (Blengini et al., 2017). Previous research endeavors have  
104 addressed the issue of availability of biotic resources, however no study has been performed on the  
105 criticality of wood (Bach et al., 2017). Although the essence of the criticality concept remains the  
106 same, the nature and attributes of biotic resources radically change the challenges related to their  
107 supply. Nevertheless, the criticality concept can contribute to the understanding of the supply chain

108 risks related to the family of wood, which is a renewable and biotic resource and to the identification  
109 of potential measures to counteract supply shortages.

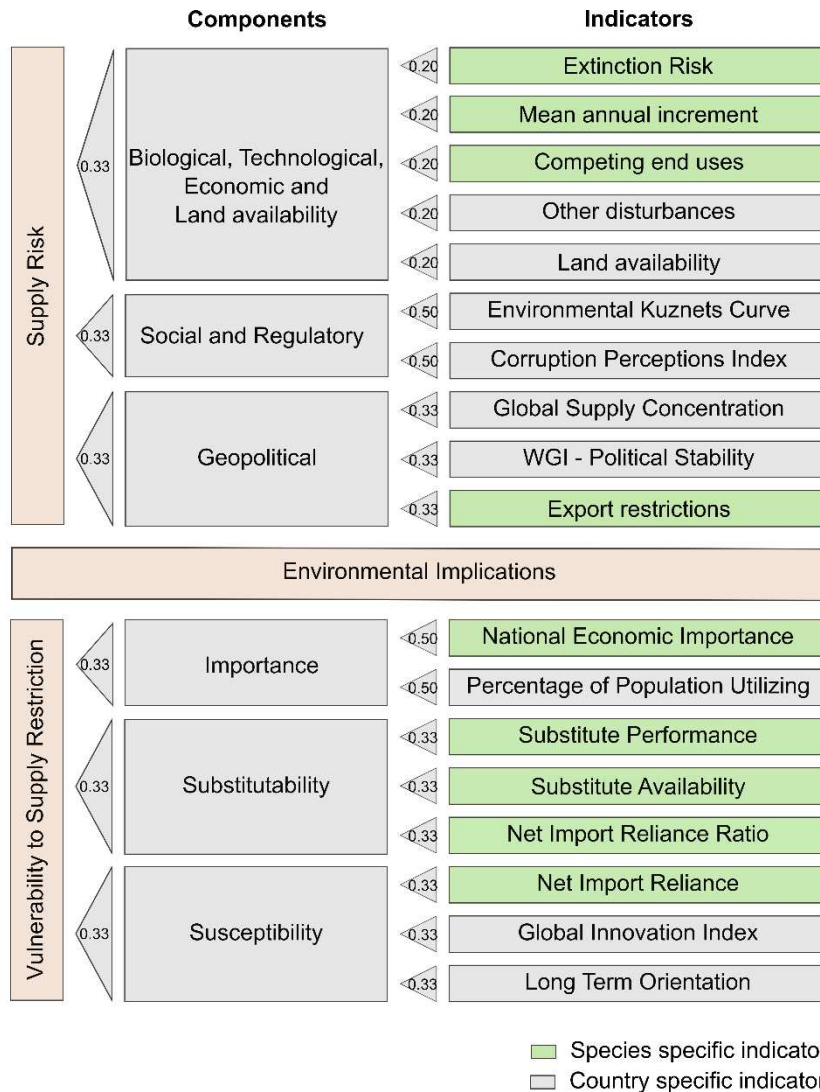
110 We herein developed a framework for criticality assessment of different wood species based on the  
111 methodology of metal criticality determination developed by Graedel et al. (2015, 2012). This  
112 methodology accounts for a multitude of socio-economic and environmental factors that can influence  
113 the supply of a resource and the reaction to a supply restriction (Graedel et al., 2012). The criticality  
114 framework has been applied to many minerals, such as iron (Nuss et al., 2014) and the geological  
115 copper family (Nassar et al., 2012). The indicators of the modified framework for wood are selected  
116 based on observed problems, are in sync with the guidelines of the European Commission and account  
117 for the characteristics of the biotic resources. We adhered to the rationale of the initial methodology to  
118 aggregate the indicators to components which express a particular area of focus and subsequently the  
119 components into the two criticality dimensions, Supply Risk and Vulnerability to Supply Restriction  
120 (Figure 1). The third dimension of Environmental Implications, foreseen in the initial methodology of  
121 Graedel et al. (2012), is included in the framework of Figure 1 but is out of the scope of the current  
122 study. Wood is a very peculiar material; it differs from the minerals in that the forests, which supply  
123 the wood, are multifunctional and provide several environmental (and not only) functions and services  
124 other than wood production. Furthermore, while for the metals we generally talk about environmental  
125 impacts, wood production and use do not only hold negative impacts but also benefits (e.g.  
126 contribution to climate change mitigation, water, soil and biodiversity conservation). The  
127 multiparametric dimension of Environmental Implications should be the topic of further study,  
128 building upon existing work in the current literature related to the environmental properties of wood.

129 Inside each component, all indicators are equally factored and similarly all components inside one  
130 dimension have the same weight. The indicators are either country-specific, depicting the  
131 environmental and socio-economic context of a country supplying the specific wood, or species-  
132 specific, accounting for the attributes of the particular tree which define its economic use and its  
133 adaptability to supply risks.

134 The functional unit of the study is the harvested volume of a wood species that is used in construction  
135 and furniture manufacturing. Other uses of wood, such as pulpwood or charcoal, were only considered

136 in the indicator of Competing end uses, while non-monetary services provided by the forest were out  
 137 of the scope of the current study.

138



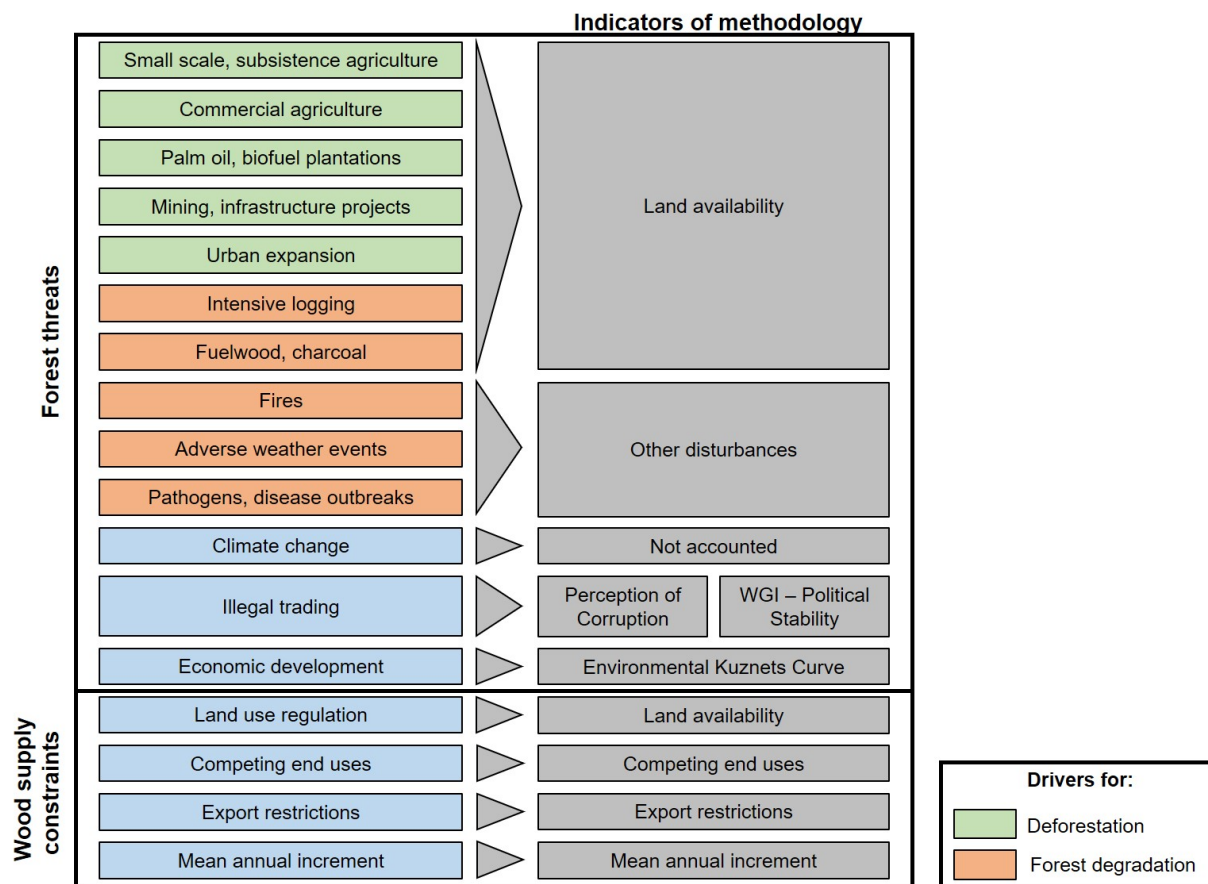
139

140 *Figure 1. Criticality framework for wood and indicators included in the two dimensions, Supply Risk*  
 141 *and Vulnerability to Supply Restriction. The indicators are either country-specific, depicting the*  
 142 *environmental and socio-economic context of a country supplying the specific wood, or species-*  
 143 *specific, accounting for the attributes of the particular tree species and the commensurate wood*  
 144 *extracted. Inside each component, all indicators are equally factored. The values in the triangles*  
 145 *indicate the weight of each indicator and component. The dimension of Environmental Implications is*  
 146 *out of the scope of the present study.*

147

148 **2.2. Supply Risk**

149 This dimension accounts for the challenges encountered in the supply chain of a wood species (Figure  
 150 2). These challenges are then translated into indicators in the modified framework, which are  
 151 categorized in three components: the Biological, Technological, Economic and Land availability  
 152 (BTEL) component, the Social and Regulatory component and the Geopolitical component (Figure 1).  
 153 We provide here an overview of the different wood-related challenges and the corresponding  
 154 indicators of the framework; a detailed explanation of the indicators is included in the Supplementary  
 155 Information.



156  
 157 *Figure 2. Forest threats and wood supply constraints and their components. Deforestation and forest*  
 158 *degradation are direct forest threats while the other threats are related to the overall socio-economic,*  
 159 *political and environmental context of the supplying countries. The right-hand column presents those*  
 160 *indicators in the criticality framework that are used to express the different challenges.*

161  
 162 The wood-related challenges are distinguished into two groups: the threats at the forest level and the  
 163 possible constraints in the supply chain of wood (Figure 2). Two main challenges at the forest level,  
 164 particularly for tropical forests, are deforestation and forest degradation (Blaser and Robledo, 2007).



165 Deforestation is connected to the permanent loss of forest area in favor of other economic activities,  
166 such that the forest is not expected to naturally regrow (Ramage et al., 2017). Deforestation is  
167 primarily due to an increased pressure for available land. The expansion of commercial and  
168 subsistence agriculture activities, including the rapid increase of biofuel and palm oil plantations, the  
169 creation of infrastructure projects, the urban expansion and the mining activities intensify the land  
170 competition, which negatively impacts the less economically profitable forestry. Furthermore,  
171 although wood is usually considered a regional resource, many species are globally traded, due to their  
172 unique mechanical and aesthetic properties. Global trade increases the pressure on these species and is  
173 highly associated with deforestation dynamics, especially in the case of tropical forests (Henders et al.,  
174 2015).

175 Degradation may be a temporary condition of the forest, as it allows the possibility for natural or  
176 artificial regeneration. In tropical forests providing furniture grade wood such as mahogany (*Swietenia*  
177 *macrophylla* King), degradation is primarily due to overharvesting (Shearman et al., 2012). Moreover,  
178 other disturbances, including fire, adverse weather, storms or floods deteriorate the forest quality, thus  
179 limiting the wood available for harvesting. Another challenge leading to degradation is related to  
180 pathogens and diseases, which can jeopardize the economic yields of the forest and thus significantly  
181 impact provisioning service providers, such as farmers or forest owners (Boyd et al., 2013). The  
182 impact of biological threats on forest provisioning and ecosystem services depends on the sensitivity  
183 of the wood species and the environmental conditions in the forest, which can favor or hamper the  
184 spread of a pest.

185 The risk of deforestation and forest degradation is expressed in the framework through the indicators  
186 of *Land Availability* and *Other disturbances*. The indicator *Other disturbances* includes biological and  
187 climatic threats that can affect the growth of a wood species. It is calculated from the percentage of  
188 forest area affected by these threats based on historical data from the national reports of the Food and  
189 Agriculture Organization (FAO) (Food and Agriculture Organization, 2015). The indicator *Land*  
190 *availability* expresses the land limitations due to most deforestation and forest degradation drivers  
191 (Figure 2) and the land competition with the protective function (conservation of forest area as a  
192 natural reserve) (eq. 1). The latter component is not a forest threat, but a risk for the wood supply

193 chain, as land use regulation can reduce the harvested wood by promoting conservation of some  
194 forests as natural reserve and a habitat for flora and fauna.

195

$$196 \quad \textit{Land availability} = (-\% \textit{Change in areas of forest and other wooded land} * 20 + \\ \% \textit{ of Forest protected}) * 50$$

197 (1)

198

199 where Change in areas of forest and other wooded land is calculated from the percentage of change in  
200 the forested and wooded area between 2010 and 2015 (Food and Agriculture Organization, 2015;  
201 Keenan et al., 2015) and the percentage of Forest protected is provided by FAO. As the change  
202 calculated in the first part of this indicator refers to a period of 5 years, a multiplication by 20 ensures  
203 a hierarchist perspective (Hofstetter et al., 2000). When the change in the forested and wood area is  
204 positive (forest growth), the first part of the equation 1 is assumed 0. If the indicator of Land  
205 availability is calculated as greater than 100, a value of 100 is assumed.

206 Another forest challenge is related to climate change, which can alter the climate conditions in a way  
207 that only specific wood species can survive and by providing a favorable environment for insect and  
208 pathogen outbreaks and for extreme weather events (Hanewinkel et al., 2013; Seidl et al., 2011). In  
209 literature, there exist forest models and studies which consider C change effects on forest (Kirilenko  
210 and Sedjo, 2007; Nabuurs et al., 2002). Despite the significance of this factor, it has not been included  
211 in the framework, because the study adopts a static rather than dynamic criticality approach. This  
212 means that a reevaluation of the criticality of the different wood species is required periodically. This  
213 static approach is commonly adopted by many criticality studies (Achzet and Helbig, 2013; Graedel  
214 and Reck, 2016) and by the European Commission (2018). A dynamic criticality framework however  
215 should account for the climate change impact on forestry.

216 In addition to the direct forest challenges, the socio-economic context in a country can significantly  
217 influence the forest management regime; illegal wood trading is an example of how weak governance  
218 can fail to manage forest harvesting. The case of *aucoumea klaineana* (okoumé), a tropical hardwood  
219 from Congo rainforest, shows that the increased demand for a popular wood from a country with a

220 loose legal framework and controlling systems can bypass the recent European Union Timber  
221 Regulations (Rowe, 2013). In the framework, the indicator *Corruption Perceptions Index*, which was  
222 developed by the Transparency International Organization, is used as a proxy for illegal trading.  
223 Furthermore, the level of economic development is associated to the forest exploitation; satellite data  
224 corroborate the existence of the first half of the *Environmental Kuznets Curve*, meaning that the higher  
225 the per capita income until the curve turning point the more pronounced the forest loss (Crespo  
226 Cuaresma et al., 2017). The calculation of the indicator *Environmental Kuznets Curve* is based on data  
227 from Cuaresma et al. (Crespo Cuaresma et al., 2017) and the PPP-adjusted per capita Gross Domestic  
228 product values from the Penn World Table from the University of Groningen. Countries with a GDP  
229 less than 5500 int. \$ follow the model of Cuaresma et al. (Crespo Cuaresma et al., 2017) while  
230 countries with a higher GDP are assumed to follow a linear regression model.

231 Regarding the constraints related to the supply chain of wood, a main factor is the competing end uses  
232 of a wood species; not all harvested wood can end up in construction as structural material or parquet  
233 flooring. For example, large volumes of *picea mariana* (black spruce) are used in paper production, as  
234 the species can give high quality pulpwood. The indicator of *Competing End Uses* expresses the  
235 economic incentives in using a wood species in different sectors. This indicator is associated to the  
236 value of the corresponding industrial sectors (Blengini et al., 2017) and is based on an economic  
237 allocation of the harvested amount of a wood species to the different end uses. When an economic  
238 allocation is not possible, an allocation based on the volumes of the wood for the different end uses is  
239 followed, similarly to the mass allocation in Life Cycle Assessment (International Organization for  
240 Standardization, 2006).

241 In addition, export restrictions and trade barriers imposed to particular wood species, which are  
242 considered endangered, increase the risk of use of these species. The indicator *Export Restrictions* is  
243 based on the Appendices of the Convention on International Trade in Endangered Species of Wild  
244 Fauna and Flora (CITES) (UNEP, 2017).

245 Another factor affecting the supply is the mean annual increment (MAI), which expresses the long-  
246 term productivity of a plant or stand on a given site (Pretzsch, 2010). It is obtained by dividing the  
247 yield at a given time by the age of the stand. The indicator of *Mean annual increment* is given by

248 dividing the maximum mean annual volume increment in the FAO report (FAO, 2001), which is  
249 89.5m<sup>3</sup>/ha/yr for eucalyptus saligna, by the MAI for the specific wood species (eq. 2):

$$250 \text{ Mean annual increment} = \frac{89.5}{MAI_{\text{specific wood species}}} \quad (2)$$

251  
252 Apart from the aforementioned indicators, the framework includes some additional indicators. The  
253 *Extinction Risk* expresses the risk due to decrease in the population of a tree and is based on the Red  
254 List of Threatened Species of the International Union for Conservation of Nature and Natural  
255 Resources (IUCN) (International Union for Conservation of Nature and Natural Resources, 2000). The  
256 indicator of *Global Supply Concentration* (GSC) follows the Herfindahl-Hirschman Index (HHI) and  
257 is calculated from the squares of each country's annual production share. The *Worldwide Governance*  
258 *Indicator – Political Stability & Absence of Violence/Terrorism* (WGI—PV) is given by a database  
259 that assesses the governance conditions.

260 As a metric of the sensitivity of our results for Supply Risk and a possible alternative for  
261 Environmental Kuznets Curve, we also used forest certification as an indicator. The risk for the wood  
262 supply chain increases with the increase in the percentage of non-certified forests in every country.  
263 Certification is based mainly on the two international labels, the Program for the Endorsement of  
264 Forest Certification (PEFC) and the Forest Stewardship Council (FSC).

265

### 266 **2.3. Vulnerability to supply restriction**

267 In the criticality framework, the Vulnerability to Supply Restriction expresses the gravity of impacts  
268 of a potential cease of supply of a wood species. This dimension looks at the components of  
269 Importance, Substitutability and Susceptibility (Figure 1). The Importance component includes the  
270 indicators of *National Economic Importance* and *Percentage of Population Utilizing*. The former  
271 indicator accounts for the economic significance of a species for a country, based on importation data  
272 from the International Tropical Timber Organization, data from FAO about the importance of  
273 domestic forestry and the Gross Domestic Product of the country, according to the World Bank  
274 Database. These data refer to the end wood products and do not account for products that contain  
275 wood but are not classified under the categories of FAO (Food and Agriculture Organization, 2018).

276 In terms of Gross Domestic Product, forests generate 1% of the global economic activities (FAO,  
 277 2014). However, this percentage is significantly higher if the entire contribution of the forest and the  
 278 value of non-timber forest products and services is considered. Forests are an important employer,  
 279 with more than 13 million people involved in forest-related activities and around 1-1.5 billion people  
 280 deriving direct and indirect benefits from forests (Agrawal et al., 2013). The importance of forestry to  
 281 local economies is accentuated in forested areas where the population subsistence largely depends on  
 282 the exploitation of the forest products. For example, in Gambia, even though the forestry sector  
 283 officially contributes to 0.5 percent of the country's GDP, forests determine the fate of more than three  
 284 quarters of the population through the provision of food, construction materials and energy resources  
 285 (FAO, 2016).

286 The indicator **Percentage of Population Utilizing** (PPU) considers the per capita consumption of  
 287 wood in a country. Countries that have a high score of PPU are more likely to experience problems in  
 288 the case of shortage of wood because they are more dependent on the specific resource. For this  
 289 category, we consider specific types of wood that are used in the construction and furniture  
 290 manufacturing sector, namely plywood, sawlogs and veneer logs, sawnwood and veneer sheets to  
 291 estimate the per capita construction wood consumption in every country over the years (Food and  
 292 Agriculture Organization, 2018). The *Percentage of Population Utilizing* (PPU) follows the  
 293 transformation in eq. 3:

$$295 \quad PPU = \begin{cases} 12.5 + (x - \bar{x}) * \frac{12.5-0}{\bar{x}-x_{10}} \text{ for } x \leq \bar{x}, \text{ if } 12.5 + (x - \bar{x}) * \frac{12.5-0}{\bar{x}-x_{10}} < 0 \text{ then } PPU = 0 \\ 12.5 + (x - \bar{x}) * \frac{87.5-12.5}{x_{90}-\bar{x}} \text{ for } x > \bar{x}, \text{ if } 12.5 + (x - \bar{x}) * \frac{87.5-12.5}{x_{90}-\bar{x}} > 100 \text{ then } PPU = 100 \end{cases} \quad (3)$$

296  
 297 Where  $x$  is the per capita construction wood consumption in the country studied,  $\bar{x}$  is the median value  
 298 of the per capita construction wood consumption worldwide and  $x_{10}$  and  $x_{90}$  respectively the 10<sup>th</sup> and  
 299 the 90<sup>th</sup> percentile. The per capita consumption of construction wood in every country is given by the  
 300 Forestry Production and Trade dataset (FAO, 2018).

301 In the Substitutability component, the indicators assess the potential of using alternative wood species  
 302 to cover the same uses provided by the main species. The *Substitute Performance* follows a

303 quantitative evaluation of the attributes of the substitute as opposed to the attributes of the main  
304 species. A wood species has to serve a threefold function related to mechanical performance,  
305 durability and aesthetics. For the purposes of this study, the selection of the potential substitute was  
306 based on the available literature review. However, a more comprehensive procedure should include  
307 classification of all species to homogeneous clusters (“families”) with similar physical and mechanical  
308 properties. This classification can underpin the selection of adequate substitutes from within the same  
309 family. The creation of these quite homogeneous clusters of species can be achieved following either a  
310 deterministic or a fuzzy approach to define the technological proximity among the species (Lissouck et  
311 al., 2016). The indicator of *Substitute Availability* expresses the Supply Risk of the substitute species.  
312 The indicator of *Net Import Reliance Ratio* (NIRR) compares the Net Import Reliance of a wood  
313 species to its substitute. The Net Import Reliance of a wood species is defined in eq. 4:

314

$$315 \quad \textit{Net Import Reliance} = \frac{\textit{Imports} - \textit{Exports} + \textit{adjustments for government and industry stock changes}}{\textit{Apparent Consumption}} * 100$$

316 (4)

317

318 The Susceptibility component represents the ability to innovate in order to overcome a supply  
319 restriction. It consists of the indicators *Net Import Reliance* (explained above), *Global Innovation*  
320 *Index* and *Long Term versus Short Term Orientation*. The *Global Innovation Index* is a metric  
321 developed by INSEAD in collaboration with Cornell University and the World Intellectual Property  
322 Organization and is annually updated. It represents the out-of-the-box thinking and the investigation of  
323 non-conventional technologies and applications. Instead of a direct substitution of a wood species with  
324 another one (Pommier et al., 2016), a design-level intervention can optimize resource use in a project.  
325 Finally, the *Long Term versus Short Term Normative Orientation* indicator was developed by  
326 Hofstede to depict the dimensions of national culture (Hofstede, 2011). The culture and traditions in a  
327 country as well as the temporal view and attitude of its people can influence the acceptance of  
328 innovative technologies. Societies with a long term orientation tend to adopt a more pragmatic stance  
329 and adapt more easily to a shifting environment and the use of alternative materials (Hofstede, 2011).  
330 Innovation and willingness to accept and adopt change can be key factors in addressing the shortage of

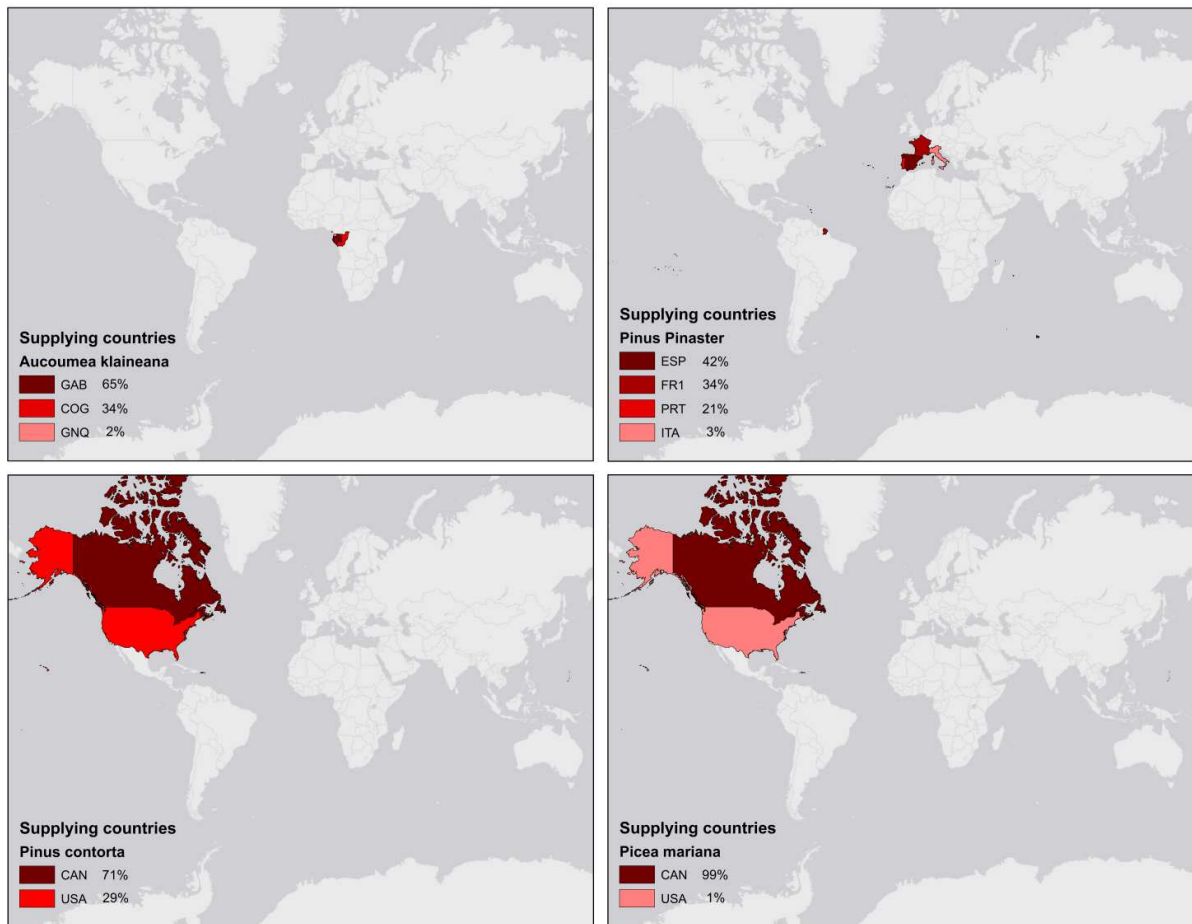
331 specific wood species, especially in the construction sector, which is by definition more conservative  
332 and slow moving. This indicator shows the capacity of a community to adapt and use other building  
333 materials than the ones traditionally used.

334

### 335 **3. Results**

336 To evaluate the general applicability of the criticality framework to different species and its capacity to  
337 address different challenges, we applied it to four wood species, two used in France (*aucoumea*  
338 *klaineana* and *pinus pinaster*) and two in the USA (*pinus contorta* and *picea mariana*). Our goal in  
339 selecting these species was to cover a wide range of factors that can play a role in the supply chain,  
340 namely to account for different climate regions by including both tropical and boreal species, which  
341 face different types of threats, to address the impacts in two different economies, to include both  
342 domestic and imported species and to study species with different supply constraints; *aucoumea*  
343 *klaineana* is classified as vulnerable and is subject to illegal trading, *pinus contorta* and *picea mariana*  
344 are threatened by wood-boring beetles and the spruce budworm respectively (Arbellay et al., 2017;  
345 Salomón et al., 2016) while *pinus pinaster* was severely hit by the Klaus Storm. We studied the supply  
346 distribution of each species (Figure 3) and weighed the indicators corresponding to each sourcing  
347 country by the percentage of harvested wood provided by that country. The goal of the case studies  
348 was not to perform an extensive assessment of wood species but to go more in depth in the selected  
349 species.

350



351

352 *Figure 3. Supply distribution in percentages of the four species studied in this article: aucoumea*

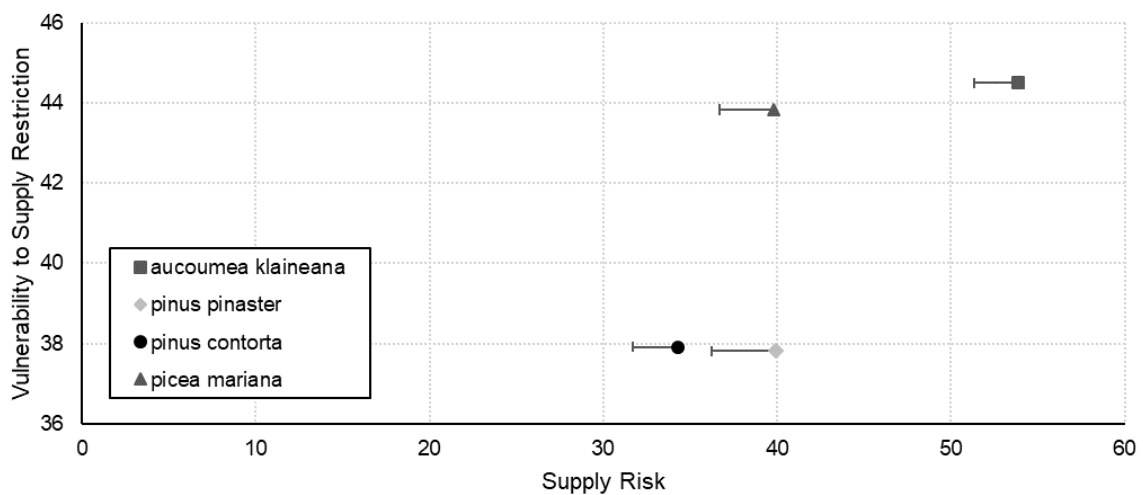
353 *klaineana, pinus pinaster, pinus contorta and picea mariana.*

354

355 In the case of aucoumea klaineana (okoumé), the criticality framework highlighted the significant  
 356 supply risk for this tropical wood (Figure 4 and Tables 1, 2). Okoumé is a hardwood used mainly for  
 357 plywood construction. It is extracted from the Congo Basin Forest and the main supplying country is  
 358 Gabon. However, the lack of systematic control in the exporting countries encourages illegal trade and  
 359 unsustainable harvesting practices. As a result, there is no clear legal and political framework ensuring  
 360 a sustainable forest management in the supplying countries. In the criticality indicators used here, the  
 361 weak governance conditions in the countries of the Congo rainforest were expressed by the Corruption  
 362 Perceptions Index and the World Governance Indicator. In addition, the Extinction Risk for this  
 363 species is high, as it is classified as vulnerable because of the reduction in the species population size  
 364 due to increased felling. For this reason, okoumé has the highest Supply Risk among the studied  
 365 species.



366 Regarding the ranking of the species in the vulnerability axis (Figure 4), it is evident that the use of  
 367 non-domestic species (*aucoumea klaineana*, *picea mariana*) increases the risk of dependence of an  
 368 economy to other countries for importing the wood, while at the same time reduces the contribution to  
 369 the Gross Domestic Product. The harvesting and treatment of local wood (*pinus pinaster* in France)  
 370 yields a series of indirect benefits to the local economy, associated with the employment of local  
 371 workforce for the harvesting and treatment of wood and the impact on the sectors affiliated to forestry.  
 372 On a cross-country comparison, the popularity in the use of wood in the USA amplifies the importance  
 373 of ensuring a sustainable supply of the most demanded wood species.  
 374



375  
 376 *Figure 4. Values of Supply Risk and Vulnerability to Supply Restriction for the four species studied.*  
 377 *Aucoumea klaineana has the highest score in both dimensions, because it is a vulnerable species with*  
 378 *weak governance conditions in its supplying countries and it is fully imported from the African*  
 379 *countries. The figure presents also the sensitivity of the results if instead of the Environmental Kuznets*  
 380 *Curve indicator (EKC), we consider the forest certification. A high score in both dimensions indicates*  
 381 *high risk. The highest score in each axis is 100.*

382  
 383 *Table 1. Indicators inside the Supply Risk dimension and values for the four species studied.*  
 384 *Aucoumea klaineana has the highest values for Corruption Perceptions Index and World Governance*  
 385 *Indicator, because of the inadequate legal and political framework in the supplying countries. BTEL*  
 386 *stands for Biological, Technological, Economic and Land availability component.*

Indicators	Wood species			
	<b>aucoumea klaineana</b>	<b>pinus pinaster</b>	<b>pinus contorta</b>	<b>picea mariana</b>
<b>Extinction Risk</b>	50.00	10.00	10.00	10.00
<b>Mean annual increment</b>	44.75	8.52	16.36	63.93
<b>Competing end uses</b>	20.00	32.47	15.40	57.68
<b>Other disturbances</b>	12.64	8.65	8.74	6.41
<b>Land availability</b>	11.68	7.84	4.42	4.05
<b>BTEL component</b>	27.81	13.50	10.99	28.41
<b>Environmental Kuznets Curve</b>	97.23	95.14	91.92	92.77
<b>Corruption Perceptions Index</b>	69.02	37.80	20.24	18.05
<b>Social / Regulatory component</b>	83.13	66.47	56.08	55.41
<b>Supply Concentration</b>	90.08	80.83	90.59	99.77
<b>World Governance Indicator</b>	61.91	38.78	16.67	6.90
<b>Export restrictions</b>	0.00	0.00	0.00	0.00
<b>Geopolitical component</b>	50.66	39.87	35.75	35.56
<b>Supply Risk dimension</b>	<b>53.87</b>	<b>39.95</b>	<b>34.27</b>	<b>39.79</b>

388

389 *Table 2. Indicators inside the Vulnerability to Supply Restriction dimension and values for the four*  
390 *species studied. Import Reliance Ratio is 100% for aucoumea klaineana, while pinus pinaster has the*  
391 *highest significance for the national economy.*

Indicators	Wood species			
	<b>aucoumea klaineana</b>	<b>pinus pinaster</b>	<b>pinus contorta</b>	<b>picea mariana</b>
<b>National Econ. Importance</b>	0.25	10.02	7.64	0.10
<b>Percentage of Population Utilizing</b>	49.20	49.20	94.94	94.94
<b>Importance component</b>	24.73	29.61	51.29	47.52
<b>Substitutability component</b>	47.10	56.16	23.79	39.94
<b>Import Reliance Ratio</b>	100.00	4.79	3.40	11.93
<b>Global Innovation Index</b>	45.82	45.82	38.60	38.60
<b>Long-Term Orientation</b>	37.00	37.00	74.00	74.00
<b>Susceptibility component</b>	60.94	29.20	38.67	41.51
<b>VSR dimension</b>	44.25	38.33	37.92	42.99

392

#### 393 4. Discussion

394 The importance of a criticality framework for wood is multifold. First of all, it can be a useful tool for  
395 companies and local authorities that want to ensure an economically sustainable supply of wood in

396 construction. An additional benefit of the application of this framework is not only the absolute value  
397 of the two dimensions, but also the value of the different indicators, in order to define the specific  
398 issues related to a wood species and be able to effectively address them. Such a framework offers two  
399 points of intervention; at a country and species-level. In the first case, we can identify which issues  
400 (e.g. insect attacks, absence of solid governance and legal framework)t may threaten the forest and the  
401 wood extraction activity in a specific country. I In the second case, we can substitute a species by  
402 another one that is less critical or research the possibility of a design-level substitution. For example,  
403 one of the main risks in the supply chain of aucoumea klaineana is the increased value of Corruption  
404 Perceptions Index. The unstable regulatory framework in the producing countries does not ensure the  
405 sustainable supply of this wood species and more effective rules should be applied to avoid  
406 overharvesting and seeking short-term profit. In the case of picea mariana, we observe that more than  
407 half of the harvested amount goes to other uses and not for construction. That means that if demand  
408 for the other uses increases, the price for this wood may go up or the quantity available for  
409 construction may decrease, which will affect the construction planning. From an impact point of view,  
410 the use of non-domestic wood species that are mainly or entirely imported (such as aucoumea  
411 klaineana) raises the risk for manufacturing and construction, considering that the trade map and the  
412 trade restrictions can easily change.

413 The use of this framework in the design with wood should be coupled with the environmental  
414 assessment of the impacts of the harvesting and treatment of the specific wood species. A point that  
415 should be considered is that wood production, provided done sustainably, does not hold only negative  
416 impacts, but also a lot of benefits, arising from the harvesting patterns, especially in plantation forests  
417 (Brockhoff et al., 2008; Vangansbeke et al., 2017). The “paradox” in wood is that, even though a  
418 natural material, it is submitted to considerable treatment before it is used in construction. Such a  
419 chemical (polymer) treatment converts a versatile material to a certified material possessing specific  
420 properties and complying with codes and regulations.

421 Moreover, the use of the criticality framework allows a localization of problems and can indicate  
422 preferable sources of supply. From the study of picea mariana, we observe that the value of the Supply  
423 Risk indicators is lower for wood coming from the Canadian forests, because the disturbances that the

424 Canadian forests faced in the last decade are significantly lower than the corresponding value for USA  
425 (table in SI). Depending on the species, this observation can also lead to the decision for plantations of  
426 a wood species in a country.

#### 427 **4.1.Limitations**

428 The current study focused on setting the foundations for considering the constraints in the supply of  
429 different wood species and promoting an economically sustainable procurement, which should be  
430 considered at a design level. Nonetheless, due to the pioneering character of the topic, the research has  
431 some limitations and further work could be directed to enhance the framework with additional  
432 features.

433 The current framework does not account for the value of the ecosystem services other than wood  
434 production, since the perspective adopted here is from the wood supply chain point of view. Defining  
435 the balance between ecosystem services of a forest and wood extraction needs to be aligned with the  
436 principles of sustainable development; human needs to create value from nature not by acting against  
437 it but by accounting for its complexity and its role and significance.

438 Moreover, no metric for climate change has been included in the framework. Climate change leads to  
439 variations in temperature and rainfall and can even affect the pathogens in a way that the environment  
440 is more positive to their diffusion (Sturrock et al., 2011). However, as mentioned earlier, the current  
441 study adopted a static criticality approach and therefore the inclusion of such a dynamic factor was out  
442 of the scope of this framework. With respect to forest certification, an alternative framework included  
443 in the Supplementary Information uses the percentage of certified forest as an indicator. Nevertheless,  
444 there is some caution and mistrust toward existing certification systems and their effectiveness on  
445 battling deforestation (Blackman et al., 2015). For this reason, certification was not integrated in the  
446 final framework, considering the criticism against the labels because the evaluation is based on auditor  
447 expertise and there is a lack of a robust auditing system (Lopatin et al., 2016). Moreover, forest  
448 certification is criticized for commodification of natural resources (Kopnina, 2017), which  
449 disadvantages the local populations, and for failure to address the primary environmental issues related  
450 to forests (Blackman et al., 2017). A more transparent certification system is required that can provide  
451 an accurate overview of the forest stands and address the challenge of field assessment. To this end,

452 satellite monitoring can provide a powerful tool; the use of remote sensing technology is evidenced to  
453 have contributed to reducing deforestation (McDermott et al., 2015). The use of satellite imaging and  
454 the interpretation of the data in combination with the implementation of the developed framework can  
455 be used to define harvesting strategies and ensure sustainable forestry.

456 Finally, the framework used the indicator “Environmental Kuznets Curve” to address the importance  
457 of the local environment in defining optimal forest management strategies; local conditions can affect  
458 the dynamic behavior of a system and the magnitude of the impact of socio-economic pressure on  
459 deforestation (Brander and Taylor, 1998). However, the “Environmental Kuznets Curve” is a global  
460 approach in linking cause and effect in forest cover loss and further research in the field of  
461 environmental economics may need to consider additional local parameters in defining the social  
462 pressure - deforestation relationship.

463

## 464 **5. Conclusion**

465 In this article, we developed a criticality framework for evaluating the supply risks and the impacts of  
466 a potential supply disruption in the wood supply chain. Our point of departure was that not only  
467 abiotic resources but also resources that regenerate need to be sustainably managed to avoid supply  
468 constraints. We considered in the criticality framework direct threats related to forest cover loss and  
469 degradation and indirect threats related to the socio-economic environment of the supplying countries.  
470 The application of the framework to four case studies indicated risks and points of intervention for  
471 these wood species. The impact of robust regulations and a solid legal context which can protect the  
472 forests from illegal harvesting and trading is important in order to decrease the Supply Risk of a wood  
473 species. In addition, for the species studied, the use of local species decreased the risk related to import  
474 restrictions and at the same time had a more significant contribution to the local economy. The  
475 framework facilitates the comparison across different raw materials and can complement existing  
476 environmental tools used in the design phase of construction and manufacturing.

477

## 478 **Acknowledgement**

479 D.I. thanks the Swiss National Science Foundation (project P2EZIP2\_175297). We thank S. Cahoon,  
480 G. Christensen, C. Barnett and C. Toney from U.S. Forest Service for provision of data on spruce.

481

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