Life-cycle assessment utilizing of freshly cut urban wood: A case study

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Acknowledgments

This project was made possible by financial and technical assistance provided by the U.S. Endowment for Forestry and Communities, Inc., and the USDA Forest Service, Forest Products Laboratory, joint venture agreement no. 18-JV-11111137-021 along with the USDA Forest Service Northern Research Station. This research was supported in part by an appointment to the USDA Forest Service Research. Participation Program administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Department of Agriculture Forest Service. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government. We thank Shaun Preston, yard master at Camp Small, and Baltimore city urban tree removal crews for providing data and information. We are grateful to the Wisconsin sawmill for providing data on their operation.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abstract

Large amounts of urban wood resources are generated through tree removals in urban areas. Therefore, there is a growing interest to improve the environmental performance of the urban wood supply chain by quantifying the environmental impacts of creating high-value products from urban tree removals to enhance its utilization. By surveying existing urban wood utilization operations for primary data in two major cities: Baltimore, Maryland, and Milwaukee, Wisconsin, a new life cycle inventory (LCI) dataset per m^3 of dry urban hardwood lumber and live edge slabs was created. Incorporating the new LCI data into life cycle assessment method, the total global warming (GW) impact of converting urban trees to kiln-dried lumber was estimated to be 122 kg CO_2 eq and 336 kg CO_2eq per m^3 of lumber produced for Baltimore and Milwaukee, respectively. In both cases, the total environmental impact of the product was dominated by the conversion of urban trees to kiln dried lumber at the sawmill processing stage. Using scenario analysis for the source of heat generation used in kiln (force) drying wood, substituting wood fuel from coproducts for natural gas in a boiler for Milwaukee resulted in a substantial reduction in fossil-derived GW impact. Urban and traditional hardwood lumber production follow similar GW impact trajectories over their life-cycle stages with the lumber processing stage having the highest environmental impacts for both. Increasing the overall lumber yield and decreasing kiln (force) drying would substantially improve the environmental performance of urban hardwood lumber and help make it comparable to traditional lumber.

Keywords: *Environmental impacts, greenhouse gases, lumber, supply chain, tree removal, urban forestry*

1 Introduction

Urban trees play an important role in urban living. Urban trees provide numerous ecosystem services to cities including a cooling effect, reducing air pollution, and mitigating climate change (Nowak, 2020; Pace et al., 2021; Trlica et al., 2020). They also contribute to the well-being of the people living in the cities, increasing property value, and lowering crime rates (Benfield, 2021; Conniff, 2021; Grilli and Sacchelli, 2020; Wolf et al., 2020).

Today, most wood products are sourced from non-urban forests. However, many cities generate large amounts of urban wood from tree removals for expanding infrastructure, routine maintenance, and development activities. This urban wood has typically been considered a waste that creates a financial burden to municipalities owing to the costs of handling and disposal. A portion of this resource could potentially be beneficially used by producing high-value wood products (Cassens, 2015). Generation of urban wood is expected to increase substantially as urban areas in the United States are projected to reach 163.1 million acres (8.6%) by 2060 from about 60.2 million acres (3.2%) currently (Nowak and Greenfield, 2018; U.S. Forest Service, 2020). In the United States, about 14.0–34.5 million green tonnes of woody biomass are generated through tree removals in urban areas, annually (Howe, 2013; McKeever and Skog, 2003; Nowak et al., 2019). Nowak et al. (2019) estimated the lumber production potential from urban trees by assuming that removals having a minimum diameter at breast height of 22.9 cm (softwoods) and 27.9 cm (hardwoods) could be sawn to produce lumber products. This led to an estimate of high-value wood products potential in the United States of 7 to 9 million m^3 (3 to 4 billion board feet (bf)) annually from urban wood (Nowak et al., 2019). To improve the environmental performance of the urban wood supply chain, quantifying the environmental profile of urban wood products is

vital, which can allow assessment of the best options for municipalities on handling the urban wood resource (Bergman et al., 2019).

To identify the life-cycle environmental impacts of the utilization of urban wood, life-cycle assessment (LCA) method can be used where the impacts at different steps in the process can be evaluated (Bergman et al., 2014; Bergman and Alanya-Rosenbaum, 2017; Hubbard et al., 2020). LCA is a comprehensive tool used to evaluate the environmental implications of products and services throughout their life cycles (ISO, 2006a, 2006b). Environmental implications of urban wood removals have not been investigated extensively. Araújo et al. (2018) analyzed the carbon footprint of end-of-life scenarios of urban pruning waste by looking into various disposal scenarios (landfill, incineration, and utilization as briquettes). They showed that the lowest-carbon disposal method was a landfill, whereas the best scenario was reuse of the pruning waste by converting them into briquettes to be used as fuel, which avoided new wood consumption. Another partial LCA study investigated the effect of vehicle and arboriculture equipment used, operational efficiency, and utilization method used on the resulting CO_2 emissions over 50 years (McPherson et al., 2015). The three scenarios evaluated by McPherson et al. (2015) to assess emissions from residue utilization were mulch, bioenergy, and lumber production. Total CO_2 emissions were lowest when the urban trees were converted into durable wood products.

However, urban wood sources are not beneficially used for a variety of reasons, most of which are economic, nor have they been investigated as intensively as traditional wood products on their environmental performance (Bergman and Bowe, 2012, 2008; Brashaw and Bergman, 2021; Hubbard et al., 2020). Typically, urban trees have not been utilized as lumber or value-added products because of supply chain issues such as a lack of familiarity with traditional wood product production, low priority, logistics, metal contamination, and the availability or scale of processing

69 infrastructure (Sherrill, 2017; Stai et al., 2017; Timilsina et al., 2014). In addition, urban trees have
70 a much greater proportion of larger branches in their crown compared with forest-grown trees,
71 which lowers overall lumber yields from the tree bole but sometimes allows for lumber recovery
72 from merchantable-sized branches. However, these large crowns can make removal more time-
73 consuming and demanding, thus costly. Overall, recent analyses have led to enhanced interest in
74 urban wood utilization by showing that the utilization of locally generated fresh-cut urban wood
75 has a high potential to generate economic benefits (Kampelmann, 2021; Nowak et al., 2019; Pitti
76 et al., 2020; Quantified Ventures, 2019).

77 This study focused on the environmental assessment of producing lumber and live-edge slabs
78 from urban forest resources to add value to urban wood waste. Lumber and live-edge slabs are
79 used interchangeably for the remainder of the paper. For urban trees along streets, in parks, and
80 small, forested areas in cities, freshly cut trees require a different set of processing and operational
81 production parameters compared to traditional tree harvesting. Thus, environmental evaluation of
82 lumber produced from urban trees requires generation of new data inventories. This study
83 generated a cradle-to-gate primary dataset on urban wood utilization into hardwood lumber in an
84 urban setting, which has not been done before. The term, cradle-to-gate, as part of an LCA assesses
85 a partial product life-cycle. For urban hardwood lumber production in this analysis, the cradle-to-
86 gate system boundary included silvicultural (production of raw material, planting seedlings), tree
87 removal (log felling) and processing, raw material transportation, sorting, and sawmill processing
88 stages.

89 The objective of the study was to quantify the environmental impacts and hotspots of producing
90 high-value wood products from urban wood removals in the United States, and to evaluate it
91 against traditional lumber production. The study outcomes can guide local decision makers on

environmental aspects as part of an overarching urban forest management strategy to address the issues related to increasingly large volumes of urban wood expected to be produced in the next several decades. In line with the goal of this study, a cradle-to-gate assessment was performed. This LCA provides insights into the environmental impacts of urban wood product production and opportunities to improve the environmental performance of urban wood management within the urban forest carbon cycle.

2 Methods

The LCA guidelines ISO 14040 and ISO 14044 provided the guidance and framework for estimating life-cycle environmental impacts (ISO, 2006a, 2006b). LCA consists of four main steps (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation (Fig.1). In the LCI step, energy and raw material inputs, outputs, and releases to air, water and land are quantified and presented. The data sources used are explained in detail in this section. In the LCIA step, the environmental impacts are quantified. Methods used are describe in the relevant section.

2.1 Life Cycle Analysis Goal and Scope

The goal of this study is to develop a full cradle-to-gate LCI data and LCA model to evaluate the environmental impacts associated with the use of freshly cut urban wood for the production of hardwood lumber and live-edge slabs. This study aims to provide an understanding of the environmental implications of producing high-value wood products from urban wood removals in the United States. The functional unit selected for this study was 1 m^3 of dry urban hardwood lumber and live-edge slabs produced. Live-edge slabs are produced where the log is cut across its full diameter into a trapezoid shape such that the natural curved edge of the log forms the edge of

114 the slab. System boundary of the project scope was delineated; in other words, where the processes
115 after the manufacturing step were not included in the system boundary.

116 The scope of this study covered the cradle-to-gate life-cycle stages of urban wood utilization,
117 which starts at tree seedling generation and planting and ends with the production of lumber and
118 slabs. The authors worked with other entities including Wisconsin Urban Wood (Bergman and
119 Peterson, 2019) while also investigating several other cities including Madison, Wisconsin to
120 identify the most proactive municipalities in finding optimal product solution for their urban wood
121 waste in their municipality. Two metropolitan areas in the United States selected for analysis were
122 Baltimore, Maryland, and Milwaukee, Wisconsin. Baltimore city has been progressive in shifting
123 to sustainable practices in their urban wood handling operations. They intend to convert their sort
124 yard to a zero-waste operation and produce lumber from high-quality urban wood removals. No
125 comparative assertion was conducted. The two case studies were included but only to see the
126 difference in urban tree utilization and assess the different wood utilization practices, but not
127 compared.

128 2.2 Descriptions of Urban Wood Utilization System Investigated

129 The cradle-to-gate life cycle analysis included five major life cycle stages and the unit processes
130 of each stage along with raw material transportation (Fig. 2). The typical urban wood utilization
131 supply chain includes silvicultural or production of raw material (urban trees), tree removal
132 (resource extraction), raw material transportation, sorting, and sawmill processing stages. The type
133 of equipment used in removal and processing operations mainly depends on the purpose of the
134 operation (Table 1). Details on each stage follows.

135 The first stage, production of raw material (silvicultural) covers seedling growth at nurseries,
136 transportation of seedlings, and planting. Raw material production is followed by the tree removal

137 stage, which includes part of or the whole tree. After planting, urban trees may be watered, sprayed
138 for insects, and pruned if necessary, based on different variables such as the location, health,
139 climate, or type of tree. In this study, maintenance of the trees planted were considered outside of
140 the system boundary. For both cases investigated, the urban trees were sourced from either public
141 streets or parks. Equipment used in removal includes chip truck, chipper, bucket truck, chain saws,
142 cranes, blower, and stump grinders in some cases. Some removal operations are performed using
143 a single truck, where bucket and chip truck are integrated. In this study, data were collected for
144 multiple truck tree removal operations. The equipment used in the study relied primarily on diesel
145 fuel and gasoline. Two types of chainsaws were used in almost all urban wood removal operations.
146 In this case, a small one (MS201TC-35cc) was used for small branches and pruning while a large
147 one (MS441C-70cc) for removal of larger branches and tree felling (Stihl Inc., Waiblingen,
148 Germany).

149 The merchantable volume of logs derived from an urban tree removal was assumed to be 40%
150 of the total volume of roundwood removed (MacFarlane, 2007). MacFarlane (2007) categorized
151 urban hardwood in six grading classes: (0) no saw volume, (1) grade 1 saw timber, (2) grade 2 saw
152 timber, (3) grade 3 saw timber, (4) construction grade, and (5) local use class. This study
153 considered the grades of 1, 2, 3, and crown biomass as merchantable. No grade was provided for
154 the merchantable crown logs because there are no standards for grading crown logs (MacFarlane,
155 2007). The average merchantable volume was calculated based on the grade data available for ash
156 (*Fraxinus spp.*), white oak (*Quercus alba*), and various soft maple (*Acer spp.*) species, which are
157 the common species received at the Baltimore city log yard. These wood species are also typical
158 commercial hardwood species utilized in the U.S. (Bergman and Bowe 2008; Bergman and Bowe
159 2012; Hubbard et al. 2020). About 2 to 3-m straight logs were considered merchantable, while the

160 rest of the material, branches, and smaller material were chipped and transported using the chip
161 truck. The recovered logs were typically left on the site for the log truck to collect later. At
162 completion of a street tree removal, a gasoline-powered backpack blower was used onsite to help
163 clean up the remaining woody biomass.

164 Urban trees removed are typically transported to private or city wood waste collection yards
165 (sort yard). The material received includes logs, limbs, and chips that can be high or low in quality.
166 At the log yard, the incoming wood is sorted into piles of logs, branches, compost, wood chips,
167 mulch, and sometimes short logs for wood turners. The sorted wood is then processed into many
168 different types of products (Table 1). In the urban wood supply chain, the final stage is the
169 processing of the high-quality logs to the final products investigated: lumber and live edge slabs.
170 After sawing, lumber is air dried for several months while live-edge slabs which are typically 76
171 mm or more thick are air dried for a year or two. After air drying, lumber dry kilns are used to
172 force dry the wood to achieve the final moisture content (Bergman, 2021).

173 2.2.1 Baltimore city case: woody biomass recycling center

174 Baltimore city's urban wood waste collection yard (Camp Small) is in downtown Baltimore,
175 MD and it is managed by the City's Division of Forestry. The sort yard receives urban wood
176 biomass from tree removals done by both city crews and contractors.

177 Baltimore city is progressively looking for improving the sustainability of its operations and
178 currently converting the Baltimore city sorting yard to a recycling center (Galvin et al., 2020).
179 New equipment was purchased to process the merchantable logs to lumber and live edge slabs.
180 Baltimore city generates about 70,760 tonnes of wood waste each year (Quantified Ventures,
181 2019). Baltimore city sort yard received about 7,260 green tonnes of wood input in 2018, with
182 about 5% ending in lumber and slabs (Quantified Ventures, 2019). This is equivalent to about 453

183 m^3 (192,000 bf) value-added wood product (i.e., lumber and slab) production per year. About 37%
184 of the wood input was considered as low quality (Quantified Ventures, 2019). Currently, a
185 substantial portion of Baltimore's urban wood is converted to wood chips, which are mainly used
186 in city landscaping projects. Other products include the large amounts of compost and small
187 number of high-quality logs sold to sawmills for processing lumber for sale to small-scale high-
188 end furniture manufacturers.

189 In Baltimore, the sawmill processing stage uses a hydraulic portable sawmill (Wood-Mizer
190 LT35) for sawing the hardwood logs (Wood-Mizer Indianapolis, IN). The yield for the sawing
191 process was assumed to be 60% (Hubbard et al., 2020). For kiln drying, a small-scale electric-
192 operated dehumidification kiln (Nyle 200) was used with about 9.44 m^3 (4,000 bf) capacity (Nyle
193 Systems, LLC, Brewer, Maine, USA). The electricity use of the dryer was calculated using the
194 equipment specifications and data provided by the manufacturer (Nyle, 2021). The lumber was
195 assumed to be air dried to a moisture content (MC) of 30%, then placed in the dry kiln to achieve
196 a target final moisture content of about 8%. The thickness of the lumber produced ranged from 51
197 to 76 mm unless the order received has different specifications.

198 2.2.2 Milwaukee city case: urban wood lumber manufacturing facility

199 A small-scale sawmill in eastern Wisconsin located about 64 km northwest of Milwaukee
200 metropolitan area was investigated. Primary data were collected using a mill survey along with a
201 subsequent site visit. The mill's annual lumber production is about 472-590 m^3 (200-250 thousand
202 bf). All incoming urban logs are sourced from the city of Milwaukee and six other outlying
203 municipalities in the area. The sawmill receives bole wood and larger limbs, where they saw logs
204 as small as 1.83 m in length and 15.24 cm in diameter. The sawmill supplements their lumber
205 production with purchased lumber from other mills in the form of rough green lumber which is

206 then re-manufactured into value-added products. The logs received from the urban tree removal
207 operations are sorted in the log yard. About 30% of incoming urban logs are converted to lumber
208 and slab, while the rest (about 70%) is processed into pulpwood, firewood, or chipped for use as
209 biofuel or mulch. In the sawing process, about 85% of the log is turned into rough green lumber,
210 and 15% of the log is turned into first cuts, edgings, sawdust, etc. After a variable period of air-
211 drying, sawn rough green lumber and slabs are batch kiln-dried in indirect steam-heated kilns run
212 on natural gas. The typical urban lumber generated at the facility was between 51 and 102 mm
213 thick.

214 2.3 Life Cycle Inventory Data

215 The life cycle inventory was generated using primary data (foreground) that represents the data
216 collected directly from urban harvesting operations and product manufacturing facilities, coupled
217 with secondary (background) data from existing databases and literature.

218 For the raw material production stage for seedling growth in a nursery (i.e., greenhouse), the
219 southeast U.S. softwood seedling model was used as a proxy for urban hardwood seedling
220 modeling (Table 2). A proxy was required for urban hardwood seedlings because U.S. hardwood
221 forest in a traditional setting tend to naturally regenerate, so no hardwood nursery LCI data are
222 available (Doroski et al., 2018; Ingram and Hall, 2016; Oneil et al., 2010). For the planting of
223 seedlings, it is assumed that the average travel distance per urban tree planted was 3.2 km and a
224 flatbed truck was used for planting (McPherson et al., 2015). Given the uncertainty of this
225 approach, this could lead to potential errors.

226 Primary data for the tree removal (extraction) stage were collected from Baltimore city's urban
227 wood operations. This same harvest model data was used for the Milwaukee, WI case. Data
228 collection for urban tree removal was challenging because the operations were not typically

229 tracked in terms of inputs and outputs. The input and output data for the urban tree removal life-
230 cycle stage are presented in Table 3. The primary data were collected on-site. Time and motion
231 studies were used to quantify the equipment use and on-site sorting/production of woody materials
232 that occur in urban tree removal operations and wood product production. Urban tree removal
233 operations of the city crews were monitored for three days, where pruning, delimbing and tree
234 removals occurred. The run time of the bucket truck aerial lift, two chain saws (1.8 kW and 4.2
235 kW), handheld blower and log loader were tracked. The run time per tree was calculated for a two-
236 day removal operation of a white oak (*Quercus alba*) with 76 cm diameter (diameter at
237 breast height).

238 The volume of an urban tree removed was calculated as approximately 6.27 m^3 with 25% being
239 merchantable log. Fuel consumption of the trucks used in removal, chip truck, and bucket truck,
240 was adopted from McPherson et al. (2015).

241 Primary data for the log (collection) transportation, sort yard, and sawmill processing life-cycle
242 stages were collected through surveys sent to a wood sorting/processing center in Baltimore,
243 Maryland, and an urban wood lumber production sawmill 64 km northwest of Milwaukee,
244 Wisconsin. Data collected represented operations for year 2018 (Table 4).

245 The inputs and outputs to urban wood lumber manufacturing are provided in Table 5
246 (Baltimore) and Table 6 (Milwaukee). For Baltimore, annual data for processing (sawmill and
247 drying) were not available, because the site only recently became operational. The log yard was
248 under transition from the city wood waste collection yard to a recycling center. The modeling was
249 done using the data obtained from the equipment manufacturers and literature. The Baltimore
250 facility also used a gas-powered sawmill which is rare except for small operations. Local electricity
251 grid models from DATASMART (US EI 2.2) database were used for Baltimore and Milwaukee.

For both cases, the drying process resulted in 7% shrinkage (Bergman, 2021). The packaging of the lumber produced was accounted for in the model adopted from Hubbard et al. (2020). Secondary data sources used for the background processes included the ecoinvent and DATASMART (US EI 2.2) databases, and literature (LTS, 2019; Wernet et al., 2016). The background processes are a part of the supply chain and background data include energy, fuels, and materials that are supplied to the foreground system.

2.4 Life Cycle Impact Assessment

The life-cycle environmental impacts were quantified using EPA's (Environmental Protection Agency) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 method (Bare, 2011) that includes the relevant impact categories used in the analysis. The life cycle impact categories used were global warming, acidification, eutrophication, ozone depletion, photochemical smog, and fossil fuel depletion. Mass allocation approach was followed for partitioning the input and output flows of unit processes when necessary. The two systems under investigation were modeled using SimaPro v9 software (PRé Consultants, 2019). Simapro is a commonly used LCA software package that includes a variety of LCI databases and LCIA methods. Biogenic carbon was tracked as part of the analysis to illustrate the impact on the two products.

Bio-based materials, including wood, contain biogenic carbon. In this study, the treatment of biogenic carbon conforms to the guidelines for the treatment of biogenic carbon set forth in ISO 21930 (ISO, 2017). Per ISO 21930, biogenic carbon enters the product system (removal) as primary material. In this context, carbon removal is taken as a negative emission. Biogenic carbon then exits the system (emission) as a product or co-products or directly to the atmosphere when

274 combusted and so is a positive emission. The carbon removals equal carbon emissions for this
275 analysis for reporting GW impact. Regardless, biogenic carbon emissions were reported.

276 2.5 Sensitivity Analysis

277 To analyze the sensitivity of the model and the data used, parameter sensitivity analyses were
278 performed. The effect of a 20% variation in the key parameters selected on GW impact was
279 investigated. Given the importance of the kiln drying process scenario, analysis was performed to
280 understand the impacts of variation. For business-as-usual (BAU), Milwaukee sawmill uses natural
281 gas for lumber drying. The effect of substituting natural gas with wood in boilers on the overall
282 GW impact was investigated. The boiler efficiency for natural gas and wood boilers were assumed
283 to be 80% and 61%, respectively (Forest Products Laboratory, 2004; Puettmann and Milota, 2017).
284 The higher heating value of wood was assumed to be 20.93 MJ/OD kg (Puettmann and Milota,
285 2017). Wood boiler data came from the wood boiler model generated by Puettmann and Milota
286 (2017), which was derived from 12 major wood product facilities in the United States. Electricity
287 consumed for grinding the unmerchantable urban logs used as fuel for the wood boiler was
288 accounted for and was assumed to be 13.3 kWh/OD t (Spinelli et al., 2012).

289 2.6 Scenario Analysis

290 Scenario analysis was performed to compare the environmental implications associated with
291 the handling of the urban wood logs removed exploring other utilization options (i.e., mulch and
292 wood fuel) and their disposal to a landfill (Table 7). Analysis was performed using Baltimore
293 supply chain data. Currently, some portion of the logs received at the log collection and sort yard
294 is sorted and converted to mulch to be sold. We used BAU practices for this scenario where
295 conversion to mulch scenario included urban tree removal, log transportation to sort yard, sorting,
296 processing the logs to mulch using a grinder, transportation to a user, and land application

297 emissions. Emissions constants for processing of logs converted to mulch and fuel at log collection
298 and sort yard were adopted from McPherson et al. (2015). These emissions came from the grinding
299 and handling equipment. The equipment included a light-duty truck, a medium-duty diesel truck,
300 and a diesel tub grinder. Mulch scenario analysis assumed 100% decomposition of the biogenic
301 carbon in mulch within the first year of the land application (McPherson et al., 2015). Given this
302 highly conservative rate could vary substantially depending on climate and geography, the authors
303 also looked at 50% decomposition scenario for the first year to evaluate the influence of
304 decomposition on the resulting impact. The release of biogenic CO_2 to the atmosphere through
305 decomposition was quantified based on the carbon content of the mulch. The same life cycle stages
306 and emission constants were used for the wood fuel scenario except that in this third scenario
307 emissions were derived from the combustion of wood in a wood boiler. The potential
308 environmental emission reduction of substituting natural gas use with wood fuel was quantified.

309 To quantify the substitution effect, natural gas boiler efficiency was assumed to be 80% (U.S.
310 Environmental Protection Agency, 2008). After processing, wood fuel and mulch were distributed
311 to a user within Baltimore city. The transportation distance was assumed to be 27 km, which is
312 about the furthest distance from Baltimore log collection and sort yard to any point along the city
313 border. From the landfill scenario, the logs were assumed to be transported to the landfill directly
314 after the tree removal. The landfill scenario analysis included the emissions from transportation of
315 urban logs to landfill, and methane and carbon dioxide emissions to the atmosphere resulting from
316 wood decomposition at the landfill. These emissions were estimated based on the data documented
317 by the U.S. EPA's Waste Reduction Model (WARM) model (EPA, 2019).

2.7 Additional Information on Assumptions and Limitations

To conform to ISO 14040 standard on LCAs, information on assumptions and limitations are to be provided for this study. Assumptions and limitations not already listed included the following:

1. Urban hardwood trees are planted although this is more likely for street trees than urban trees in general (Doroski et al., 2018; Massad et al., 2019). This choice is more conservative because additional inputs are needed for planted versus naturally regenerated trees (Oneil et al., 2010). The authors did not collect these data so used secondary data instead.
2. Carbon content for wood was assumed to be 50 percent by mass of oven dried (OD) wood.
3. Assuming a specific gravity for a mix of white ash, white oak, and red maple for freshly cut wood and 12%MC, the OD densities of hardwood lumber and live-edge slabs were 547 and 607 OD kg/m^3, respectively (Senalik, 2021).
4. During anaerobic decomposition of landfilled wood, biogenic methane produced and released from landfills was captured and burned at 75% efficiency.
5. Data collection at urban tree harvest sites is time-consuming and expensive. However, more data points on the urban tree removal stage data by monitoring multiple whole tree removal operations would lead a more robust inventory data. In addition, collecting field-based fuel consumption data would lead to higher accuracy.

338 **3 Results**

339 3.1 Life Cycle Impact Assessment

340 The results of the LCIA for Baltimore and Milwaukee are in Table 8 for 1 m^3 of urban hardwood
341 lumber manufactured. The contribution of each life-cycle stage to the relevant impact categories
342 is provided in Fig. 3. The term, hardwood lumber was used interchangeably for live-edge slabs. A
343 cradle-to-gate analysis was performed for ten impact categories. The impact resulting from the
344 five life cycle stages included in the foreground system boundary was quantified. Total GW impact
345 for Baltimore and Milwaukee were 122 and 336 kg CO_2 eq/m^3, respectively. The cradle-to-gate
346 GW impact in both cases was heavily dominated by the lumber processing stage, where sorted
347 logs were processed into rough, kiln-dried lumber (8% MC), and which included both the sawing
348 and drying unit operations. Relatively higher GW impact in Milwaukee compared with Baltimore
349 can be traced to differences in drying processes. Upstream stages had limited effect for all
350 environmental impacts compared to lumber processing.

351 3.2 Contribution by Life-cycle Stages

352 The relative contributions of the main life-cycle stages to the six reported impact categories are
353 provided in Fig. 3. For both cases, contribution analysis showed that, during the urban hardwood
354 lumber production operations, most of the impacts resulted from the lumber processing stage in
355 all impact categories. The greatest contributor to total GW impact was the lumber processing stage
356 with about 92% and 88% contribution in Baltimore and Milwaukee, respectively. High
357 contribution of lumber processing to total GW in Baltimore arises from the electricity used at the
358 dehumidification dry kiln, while it is due to the natural gas combustion at the dry kiln in
359 Milwaukee. Drying contribution to total GW impact was about 80% and 68% in Baltimore and
360 Milwaukee, respectively. Raw material transportation has a relatively higher contribution to smog,

361 acidification, and eutrophication impact categories in Milwaukee from burning diesel. This was
362 because the sorting and lumber processing facility was located further from the city center, while
363 the Baltimore lumber processing facility was at the city center.

364 The GW impact of silvicultural stage was small compared with the overall impact in both
365 Baltimore and Milwaukee. Likewise, the contribution of silvicultural stage to the rest of the impact
366 categories was small, less than 1%, compared with other life cycle stages. As noted above, this
367 step would not be present in some urban tree removal operations, since the original trees in many
368 city parks, for example, were not 'planted' but rather established from natural seed dispersal and
369 germination. Further, only a proportion of these city forest tree removals are likely to be replaced
370 with new seedlings.

371 3.3 Sensitivity Analysis

372 Sensitivity analysis was conducted for four variables, testing their influence on the total GW
373 impact (Fig. 4). Three of the variables tested the sensitivity of the results to key parameters at the
374 manufacturing facility were the amount of fuel used for: 1) sorting, 2) sawing and 3) drying.
375 Another parameter tested was raw material transportation. In both cases, the change in lumber
376 dryer fuel consumption had a notable impact on the carbon footprint of the urban hardwood lumber
377 production supply chain. The variation in sorting fuel use had the smallest effect on the GW
378 impact.

379 3.4 Scenario Analysis

380 Scenario analysis was performed to investigate the effect of using a boiler fueled by wood
381 instead of natural gas for lumber drying in Milwaukee, WI case. The analysis revealed that the
382 choice of fuel used, and its associated emissions had a notable impact on the results. For base
383 scenario, the GW impact was about 336 CO_2eq per m^3 urban hardwood lumber and live edge slabs

manufactured. For (100%) wood boiler scenario, it was about 503 CO_2eq/m^3 accounting for biogenic carbon and 129 CO_2eq/m^3 not accounting for biogenic carbon. The ISO 21930 guidance document states that the wood sourced from sustainably-managed forests can be accounted as carbon neutral, where biogenic carbon entering the supply chain is considered as removal and is characterized as negative emissions and its release to the atmosphere is accounted as positive emission (ISO, 2017). This consideration is valid for North American wood products because national level inventory reporting shows overall neutral and/or increasing forest carbon stocks in recent years (FAO, 2020, 2015; Oswalt et al., 2019; Sahoo et al., 2019). A 62% decrease in GW impact can be achieved through a transition to wood boilers when carbon neutrality of biogenic CO_2 is considered.

To better understand the potential fate of urban wood, two alternative utilization scenarios and a disposal scenario were modeled to analyze the environmental impacts of other possible handling options of the urban logs (Table 9). Scenario analysis was performed for 1.78 m^3 of log input to each scenario, which is the volume of log used to produce 1 m^3 of urban hardwood lumber and live edge slabs. For these scenarios, carbon in the lumber was assumed to be stored for 60 years during its service life (ASTM, 2016; Gu and Bergman, 2018). The results showed landfilling had the lowest fossil-derived GW impact at 25 kg CO_2eq/m^3, followed by mulch at 44 CO_2eq/m^3. Wood landfilled only partially decays, about 12% while decaying far slower than wood used as ground cover (EPA, 2019). For fuel and landfilling scenarios, the negative value of -1,101 and -568 kg CO_2eq/m^3 represent the potential avoided carbon emissions resulting from substituting use of natural gas in industrial systems with urban wood fuel and landfill methane while -149 kg CO_2eq/m^3 represented avoiding traditional rough dry hardwood lumber production (Hubbard et al., 2020). For the two mulch scenarios, the lower decomposition of 50% improved the carbon

407 stored in the end product while generating half the biogenic CO_2eq emissions of 100%
408 decomposition. For the lumber case, the environmental benefits were substantial when considering
409 the temporary but immediate carbon storage.

410 **4 Discussion**

411 The results of the present study provide the environmental profile of urban hardwood lumber
412 production by highlighting the environmental hotspots of the supply chain investigated. The
413 lumber processing stage was the dominant contribution to the overall impact, with the drying
414 process having the highest impact. In turn, the lumber drying was affected by the type and the
415 quantity of the fuel used for drying, and the starting and ending moisture content. In line with these
416 findings, sensitivity analysis showed that lumber dryer fuel had a high influence on the resulting
417 impact. Contribution analysis can show which life-cycle stage has the greatest impact on product
418 production.

419 The relative contribution of life-cycle stages to the overall impact shows a similar trend for both
420 traditional and urban hardwood lumber supply chains. However, the lumber processing stage had
421 a greater effect on the overall environmental impact for urban hardwood lumber production
422 compared to the traditional hardwood lumber supply chain. For urban hardwood lumber, the
423 contribution of the lumber processing stage, where logs are converted to kiln-dried lumber, to GW
424 impact was above 88%. The manufacturing stage contribution at the traditional lumber mill was
425 slightly smaller, about 65% (Hubbard et al., 2020). One reason for the greater contribution of other
426 life-cycle stages in traditional lumber processing is the longer distances for log transport to the
427 sawmill in traditional lumber manufacturing. A potential reason for the higher processing impacts
428 at the urban hardwood mills can be the thickness of the lumber produced. The majority of
429 hardwood lumber produced in the U.S. has a thickness between 25.4 and 50.8 mm, while the urban

hardwood lumber sawn in our two case studies was thicker, between 50.8 and 101.6 mm (AHEC, 2021). Kiln drying times increase with thicker lumber as a way to minimize drying defects, which corresponds to additional energy required (Bergman, 2021; Comstock, 1976; Denig et al., 2000). Other sawmills processing urban wood into lumber tend to follow traditional thicknesses.

Urban wood processing facilities typically have large amounts of wood waste because not all the urban logs, nor the urban wood delivered in other forms are appropriate for lumber production. At traditional lumber manufacturing facilities, wood residues generated during production are typically used as an energy source to support processes such as lumber drying (Puettmann and Milota, 2017). In Milwaukee, about 70% of the incoming urban logs cannot be used for lumber production. This 70% can be utilized as wood fuel to supply energy for the drying process of the sawmill. Considering just the global warming impact as an example in Milwaukee, the substitution of natural gas-based drying to wood boilers using wood fuel, a 62% decrease in GHG emissions from 336 to 120 kg CO_2eq/m^3 urban hardwood lumber can be achieved. Other carbon benefits exist for urban wood products when producing and using such products (Brashaw and Bergman, 2021).

Temporary but immediate carbon storage is another potential environmental benefit of converting urban wood waste to lumber. According to the recent report published on hardwood lumber production LCA in the Northeast and North-central United States, 1 m^3 of planed dry hardwood lumber stores about 286 kg of carbon or 1,049 kg CO_2eq (Hubbard et al., 2020). Given that 19.3 million m^3 (8.18 billion bf) of hardwood lumber was produced in the United States in 2018, this corresponds to 20.3 million tonnes of CO_2eq stored during the life of the product (HMR, 2021). Based on urban wood values of 7-9 million m^3 potentially available if certain practices were implemented such as building deconstruction and assuming 50% of removed volume was

453 hardwood, this corresponds to 4.2 million tonnes of CO_2eq (Bergman et al., 2013; Nowak et al.,
454 2019). Even though there are approaches developed to calculate the effect of temporary carbon
455 storage on the GW impact calculated, there is still no consensus on this (Bergman, 2012; Brandão
456 et al., 2013; Head et al., 2021; Levasseur et al., 2010). For the cases where the downstream use
457 phase is included in the system boundary, the impact of temporary carbon storage can be subtracted
458 from the resulting GW impact. Accounting for the substantial carbon storage benefits for lumber
459 and expanding the system boundary, can lead to lower GW impact for the urban wood product life
460 cycle.

461 A comparison can be made with the GW impact for traditional hardwood lumber. Hubbard et
462 al. (2020) reported a GW impact of 166 CO_2 eq per m^3 of traditional planed dry hardwood lumber,
463 and about 149 CO_2 eq per m^3 of traditional rough dry hardwood lumber. Compared with the
464 production of traditional hardwood lumber, considering all the differences in the supply chain, tree
465 shape and type, and scale of the processing systems, the resulting GW impact of producing 1 m^3
466 of traditional rough dry hardwood lumber (122 OD kg CO_2 eq /m^3 rough dry lumber) was relatively
467 smaller, about 18% lower impact, for Baltimore. Yet, in Milwaukee, the GW impact for urban
468 hardwood was notably higher, about two times greater compared to traditional hardwood lumber.
469 As discussed earlier, greater GW impact in Milwaukee can be traced to the natural gas consumed
470 at the dryer. Unlike seen in our two small-scale operations, most traditional hardwood lumber
471 manufacturing facilities use sawmill (wood) residues for fueling their boilers which reduces their
472 fossil GHG impact (Bergman and Bowe, 2012, 2008; Hubbard et al., 2020).

473 Even though the equipment fuel consumption data generated was representative of urban wood
474 harvesting operations, the data on harvesting was limited in terms of the sample size. Using
475 average data based on long-term data collection and assessing statistical variability of the data

476 would help improve the quality and accuracy of the analysis. This is particularly important while
477 identifying the average transportation distance to harvest site and volume of logs generated from
478 the trees harvested in urban areas.

479 Another limitation to this study is that the uncertainty of the resulting environmental impact
480 was not evaluated using the parameter uncertainty of the primary data collected. This was due to
481 lack of uncertainty data. Future studies, providing statistical variability and performing parameter
482 uncertainty will allow improved environmental evaluation of urban wood harvesting operations.
483 Using an increased amount of data points for tree harvest stage and longer-term data collection
484 would improve the quality of the analysis. In addition, the transportation to the tree harvest site is
485 another important stage as shown in the results. Detailed data showing the yearly average
486 transportation distance to a tree harvest site would be very valuable for future analysis.

487 **5 Conclusions**

488 Utilization of wood from urban tree removals to produce value-added products can help reduce
489 the overall costs for municipalities and allow this resource to be utilized as a sustainable, renewable
490 resource. Municipalities are rethinking the way they handle urban tree removal and are seeking
491 cost-effective, sustainable options. An environmental LCA evaluation adds important information
492 to the evaluation of options. This cradle-to-gate environmental assessment suggests that utilization
493 of urban trees to produce hardwood lumber is a potential environmental feasible option instead of
494 the alternatives such as landfilling. Therefore, municipalities investing more resources to analyze
495 their supply chain to produce value-added urban wood products as shown in this study. In
496 particular, by providing high-quality logs to go into lumber and developing urban-scale sawmill
497 operations to produce high-quality lumber.

For the two cases investigated, most GW impact came from the kiln-drying process which is consistent with most other traditional wood products (Puettmann et al., 2010; Puettmann and Wilson, 2005). A sensitivity analysis shows that the results and conclusions are very sensitive to the impact from the drying process with the use of wood fuel instead of natural gas resulting in a substantially lower fossil GW impact. Increasing drying efficiency which could lower the overall energy use, decreasing the fuel use, or by using non-fossil fuel based drying systems (e.g., wood boilers) were identified as important ways to improve the environmental performance of the urban wood valorization supply chain. In addition, improving lumber yield through sawing optimization would lower the hardwood product's life-cycle environmental impact (Luppold and Bumgardner, 2019; Quesada et al., 2019; Thomas et al., 2021). Furthermore, designing and implementing new air-drying methods without loss of wood quality in conjunction with kiln drying using solar power for drying or for electricity generation would substantially reduce the environmental impacts of manufacturing hardwood lumber (Alanya-Rosenbaum et al., 2021; Bergman and Bilek, 2012; Bond and Espinoza, 2016; Denig et al., 2000; Lamrani et al., 2021). However, solar drying effectiveness tends to depend on location where solar radiation is high (Bergman and Bilek, 2012; Lamrani et al., 2019; Luna et al., 2009). Given the low cost of solar panels for generating electricity, this would be a great opportunity to link these systems together. Furthermore, kiln drying softwoods are now using a continuous drying system unlike hardwoods that are still using a batch methods (i.e., more control) to maintain the product appearance but continuously drying hardwoods could readily reduce energy consumption (Bergman, 2021; Bond and Espinoza, 2016). Compared to traditional hardwood lumber production, the environmental impacts of the urban hardwood lumber seem to be comparable if a non-fossil fuel-based or efficient drying process was used.

Acknowledgments

This project was made possible by financial and technical assistance provided by the U.S. Endowment for Forestry and Communities, Inc., and the USDA Forest Service, Forest Products Laboratory, joint venture agreement no. 18-JV-11111137-021 along with the USDA Forest Service Northern Research Station. This research was supported in part by an appointment to the USDA Forest Service Research. Participation Program administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Department of Agriculture Forest Service. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government. We thank Shaun Preston, yard master at Camp Small, and Baltimore city urban tree removal crews for providing data and information. We are grateful to the Wisconsin sawmill for providing data on their operation.

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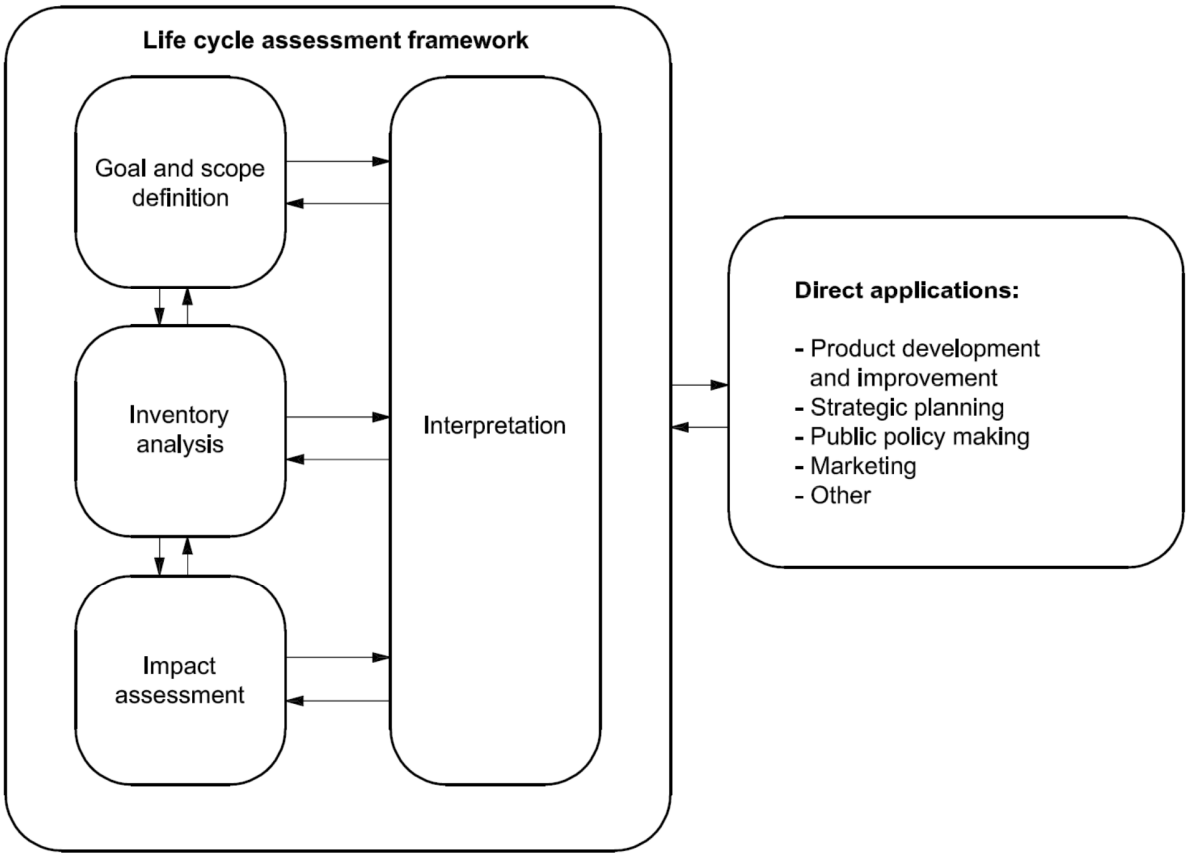
List of figures



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737 Fig. 1. Steps of a life cycle assessment (ISO 2006a).

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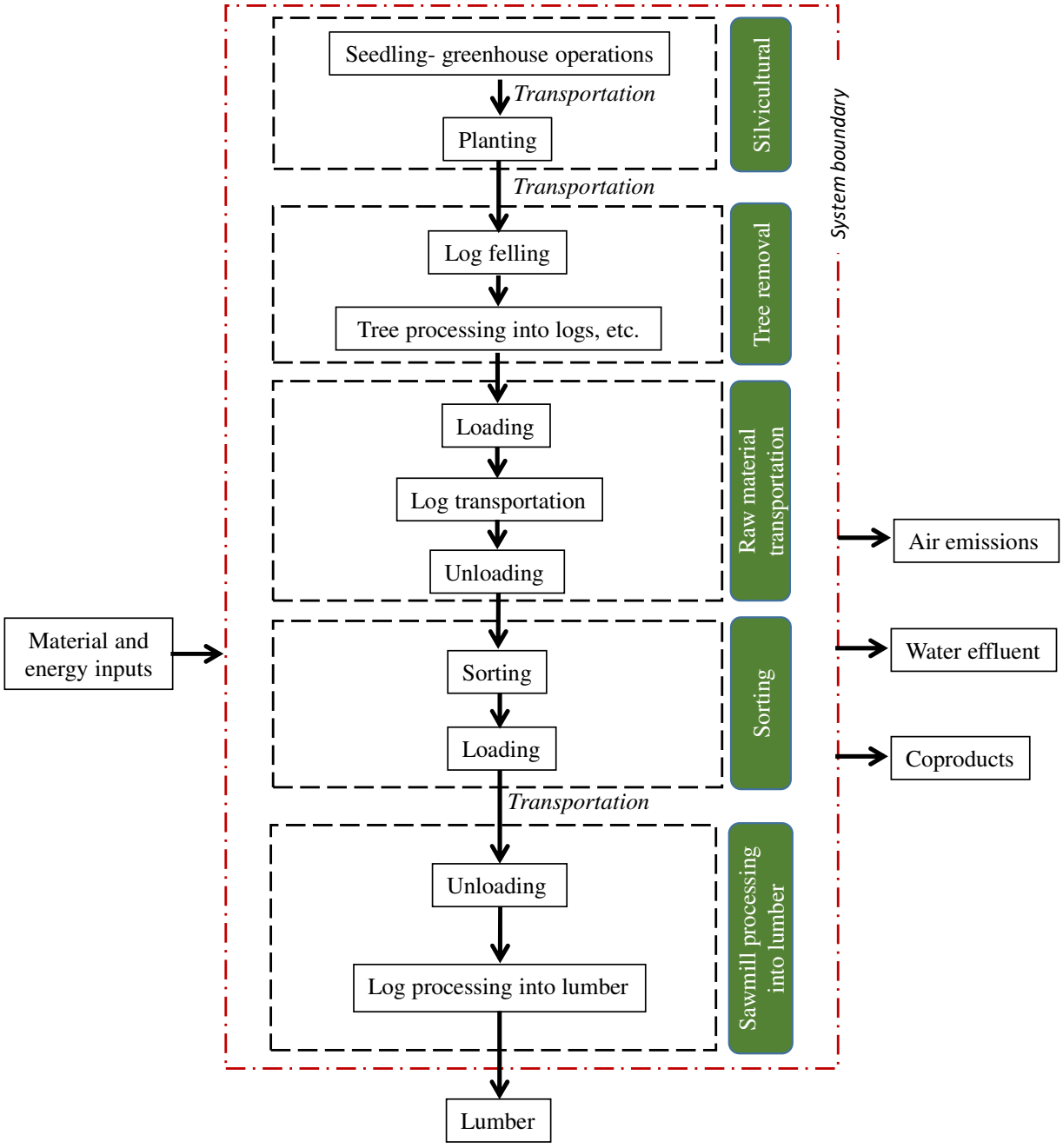

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745 Fig. 2. Cradle-to-gate system boundary for urban wood utilization includes five main stages 1.
746 Silvicultural (production of raw material), 2. Tree removal (extraction of raw material), 3. Raw
747 material transportation, 4. Sorting, and 5. Sawmill processing into lumber.

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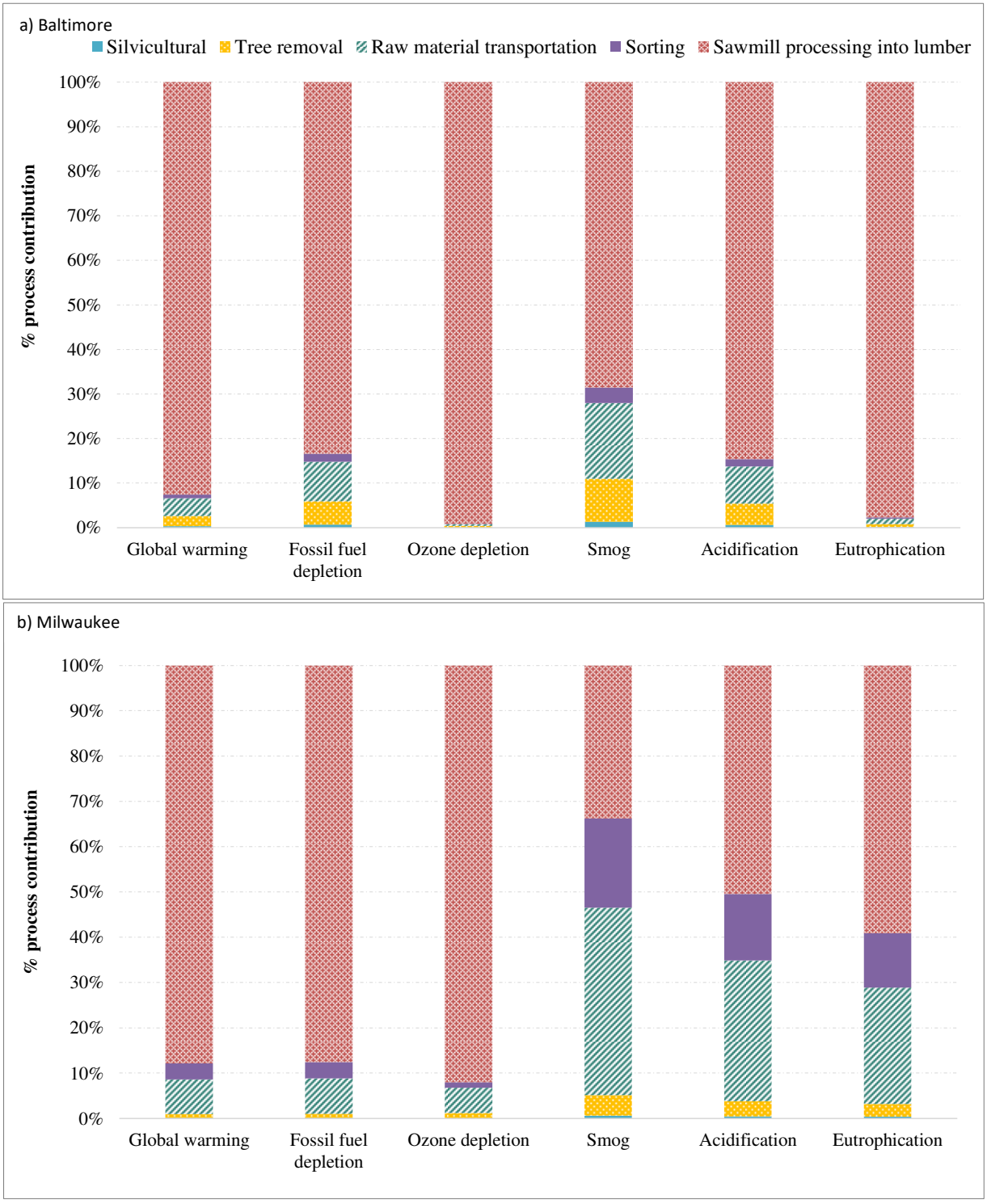
a) Baltimore
Silvicultural
Tree removal
Raw material transportation
Sorting
Sawmill processing into lumber
% process contribution
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Global warming
Fossil fuel depletion
Ozone depletion
Smog
Acidification
Eutrophication
b) Milwaukee
% process contribution
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Global warming
Fossil fuel depletion
Ozone depletion
Smog
Acidification
Eutrophication

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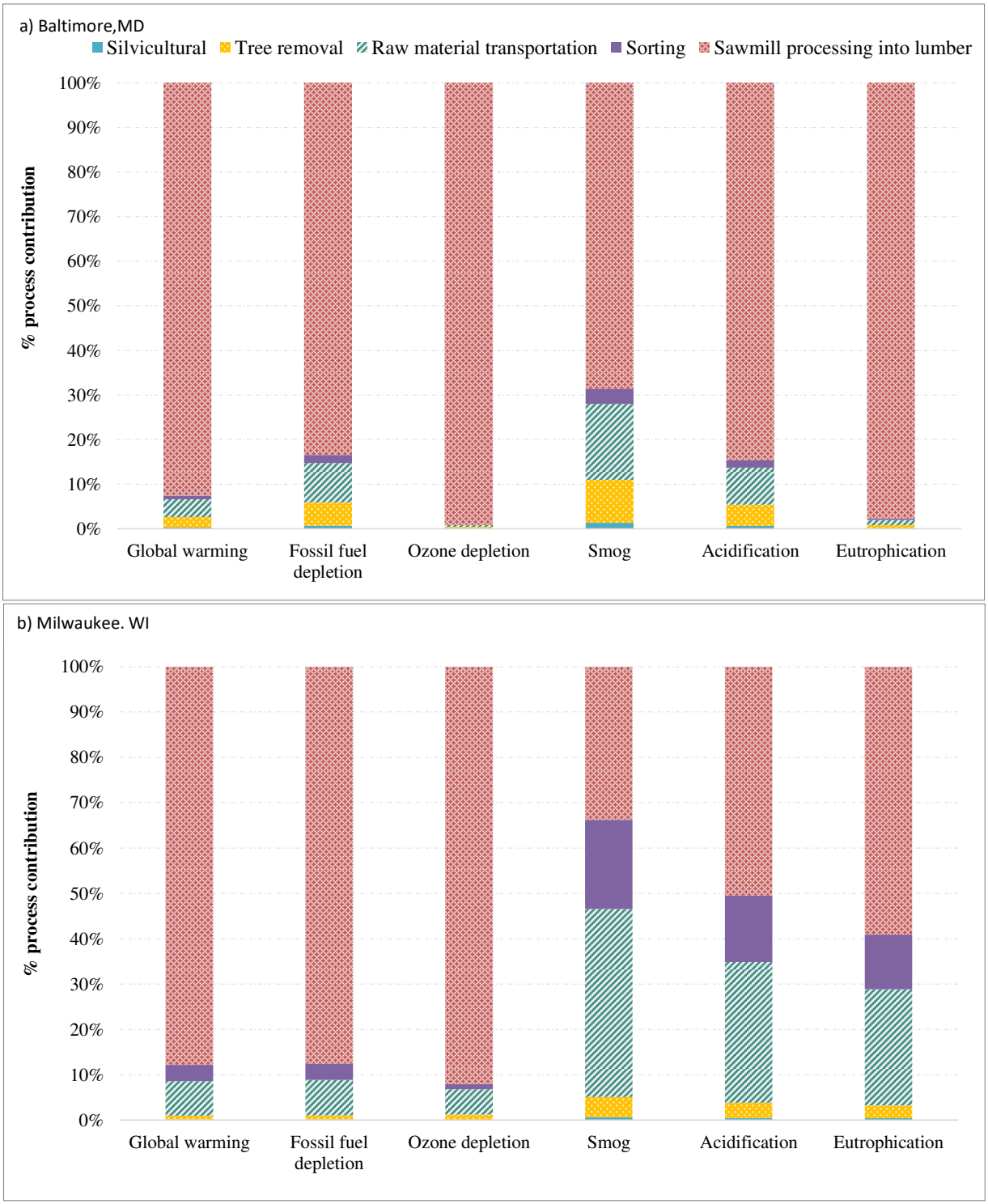

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753 Fig. 3. Relative cradle-to-gate life-cycle impact assessment contributions for urban hardwood
754 lumber and live edge slabs manufacturing by five life cycle stages for (a) Baltimore, MD and, (b)
755 Milwaukee, WI.

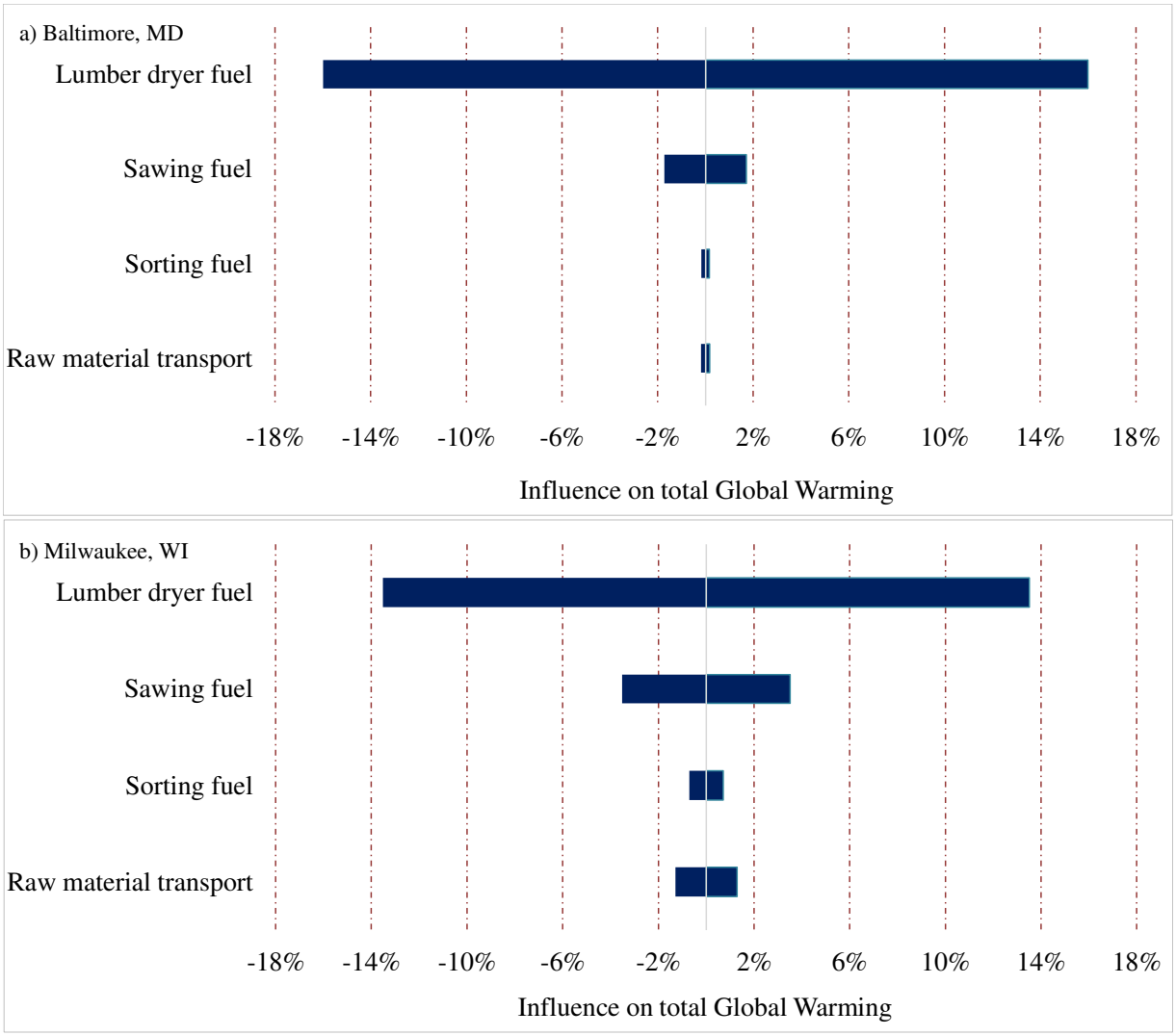

Fig. 4. Sensitivity analysis presenting the influence of four selected parameters (lumber dryer fuel, sawing fuel, sorting fuel, raw material transport) to GW impact. Analysis is performed for cradle-to-gate urban hardwood lumber and live edge slabs manufacturing. (a) Baltimore, MD and, (b) Milwaukee, WI

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764 Table 1 Equipment used in different stages of urban wood utilization activities

Life cycle stage	Equipment	Process	Output
Tree removal (extraction of raw material)	Chip truck Chipper Bucket truck Chain saw Blower	Log felling	Chips Merchantable logs Unmerchantable logs
Raw material transportation	Chip truck Log truck	Transporting	Chips Logs
Log collection and sort yard	Log loader Log truck Grinder Firewood splitter	Sorting	Chips Mulch Logs Firewood Compost
Sawmill processing into lumber	Portable sawmill Dryer	Sawing into lumber Drying	Live edge slabs Lumber

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Table 2 Data for the silvicultural (production of raw material) stage modeling. Softwood seedling production model was used as a proxy for hardwood seedlings

Raw material production	Unit	Value	Source
Seedling production	p seedling	1	(Milota, 2015)
Flatbed truck	L/100km	22	(McPherson et al., 2015)

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786 Table 3 Inputs and outputs of tree removal (extraction of raw material) stage per urban
787 hardwood tree removed

Tree removal	Value	Unit	Mass Allocation
Products/Co-products			
Merchantable logs	1.61	m^3	25%
Logs (firewood)	2.42	m^3	39%
Residues (brushes)	2.24	m^3	36%
Fossil fuel			
Seedling, planted	1.00	p	
Chip truck	0.79	L	
Bucket truck	0.79	L	
Aerial lift	3.24	L	
Chain saw #1	0.25	L	
Chain saw #2	0.05	L	
Blower	0.19	L	
Ancillary materials			
Chainsaw mixing oil	0.01	kg	
Chainsaw lubricant	0.11	kg	
Lubricant	0.07	kg	

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790 Table 4 Data used for the raw material transportation. Data given as transportation of the
791 merchantable urban logs to the log collection and sort yard per m^3 log

Transportation	Unit	Baltimore	Milwaukee
Log transportation			
Log loader travel	L	0.312	6.271
Log collection and sort yard			
Log loader loading	L	0.549	0.549
Log loader unloading	L	0.549	0.549
Lubricant	kg	0.022	0.097

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803 Table 5 Baltimore, MD case inputs and outputs of the sorting (at log collection and sort yard)
804 and processing (sawmill and drying processes) stages for producing urban lumber and live edge
805 slabs

	Value	Unit	Allocation
Log collection and sort yard process for 1 m^3 of log sorted			
Outputs			
Products/Co-products			
Merchantable urban logs, sorted	1	m^3	100%
Inputs			
Wood input			
Merchantable urban log	1	m^3	
Fossil fuel			
Diesel-log loader	0.027	L	
Diesel-skidsteer	0.29	L	
Ancillary materials			
Lubricant	0.005	kg	
Sawmill processing for sawing 1 m^3 of green lumber			
Outputs			
Products/Co-products			
Sawn green lumber	1.00	m^3	60%
Wood residue	0.68	m^3	40%

Inputs			
Wood input			
Merchantable urban logs, sorted	1.68	m^3	
Fossil fuel			
Gasoline-powered portable saw	6.18	L	
Ancillary materials			
Lubricant	0.10	kg	
Drying processing for kiln-drying 1 m^3 of dry lumber			
Outputs			
Products/Co-products			
Sawn dry lumber	1.00	m^3	100%
Inputs			
Wood input			
Sawn green lumber	1.07	m^3	
Electricity (dehumidification dry kiln)	168	kWh	

811 Table 6 Milwaukee, WI case inputs and outputs of sorting (at log collection and sort yard) and,
812 sawmill processing (sawmill and drying processes) stages for producing urban hardwood lumber
813 and live edge slab

	Value	Unit	Allocation
Log collection and sort yard process for 1 m^3 of log sorted			
Outputs			
Products/Co-products			
Merchantable urban logs, sorted	1	m^3	100%
Inputs			
Wood input			
Merchantable urban log	1	m^3	
Fossil fuel			
off-road diesel, sorting	3.47	L	
Gasoline- sorting	0.039	L	
Ancillary materials			
Lubricant	0.008	kg	
Sawmill processing for sawing 1 m^3 of green lumber			
Outputs			
Products/Co-products			
Sawn green lumber	1.00	m^3	85%
Wood residue	0.18	m^3	15%
Inputs			
Wood input			

Merchantable urban logs, sorted	1.18	m^3	
Fossil fuel			
Off-road diesel	1.51	L	
Electricity (traditional saw)	60.0	kWh	
Ancillary materials			
Motor oil	0.16	kg	
Lubricant	0.03	kg	
Drying process for kiln-drying 1 m^3 of dry lumber			
Outputs			
Products/Co-products			
Sawn dry lumber	1.00	m^3	100%
Inputs			
Wood input			
Sawn green lumber	1.07	m^3	
Fossil fuel			
Natural gas (boiler)	72.6	m^3	
Electricity (fans)	20.0	kWh	

819 Table 7 Summary of the urban wood utilization scenarios investigated

Scenario	Primary data sources	Secondary data sources
Fuel	Primary data from Baltimore was used for urban tree removal, log transportation to sort yard, sorting.	The wood harvested was assumed to be used in the wood boiler. The wood boiler model developed by Puettmann and Milota, 2017 was used.
Mulch	Primary data from Baltimore was used for urban tree removal, log transportation to sort yard, sorting.	Processing the logs to mulch using a grinder, transportation to a user, and land application emissions adopted from McPherson et al. (2015)
Landfill	Not any	The wood is directly landfilled after the harvest. Landfill emissions were estimated based on the data documented by the U.S. EPA's Waste Reduction Model (WARM) model (EPA, 2016)
Lumber	Primary data from Baltimore and Milwaukee	Not any

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821 Table 8 Cradle-to-gate life cycle impact assessment results for Baltimore and Milwaukee for 1 m^3 dry urban hardwood lumber and

822 live edge slabs produced

Baltimore							
Impact category	Unit	Total	Silvicultural (production of raw material)	Tree removal (extraction of raw material)	Raw material transportation	Sorting	Sawmill processing
Global warming	kg CO_2 eq	1.22E+02	3.77E-01	2.83E+00	4.89E+00	9.89E-01	1.13E+02
Fossil fuel depletion	MJ surplus	1.14E+02	7.64E-01	6.04E+00	1.01E+01	2.05E+00	9.55E+01
Ozone depletion	kg CFC-11 eq	7.39E-06	6.79E-10	3.05E-08	2.79E-08	6.26E-09	7.33E-06
Smog	kg O_3 eq	1.22E+01	1.61E-01	1.18E+00	2.08E+00	4.19E-01	8.37E+00
Acidification	kg SO_2 eq	7.71E-01	4.97E-03	3.66E-02	6.43E-02	1.30E-02	6.52E-01
Eutrophication	kg N eq	3.40E-01	3.16E-04	2.39E-03	4.14E-03	1.02E-03	3.32E-01
Respiratory effects	kg $PM_{2.5}$ eq	4.57E-02	9.80E-05	7.23E-04	1.28E-03	2.61E-04	4.33E-02
Carcinogenics	CTUh	7.81E-06	5.47E-09	4.09E-08	7.06E-08	1.73E-08	7.68E-06
Non carcinogenics	CTUh	2.51E-05	5.23E-08	3.92E-07	6.76E-07	1.63E-07	2.38E-05
Ecotoxicity	CTUe	5.86E+02	9.98E-01	7.47E+00	1.29E+01	4.16E+00	5.60E+02
Milwaukee							
Impact category	Unit	Total	Silvicultural (production of raw material)	Tree removal (extraction of raw material)	Raw material transportation	Sorting	Sawmill processing
Global warming	kg CO_2 eq	3.36E+02	3.77E-01	2.83E+00	2.56E+01	1.21E+01	2.95E+02
Fossil fuel depletion	MJ surplus	6.75E+02	7.64E-01	6.04E+00	5.28E+01	2.46E+01	5.91E+02
Ozone depletion	kg CFC-11 eq	2.58E-06	6.79E-10	3.05E-08	1.45E-07	2.91E-08	2.37E-06
Smog	kg O3 eq	2.62E+01	1.61E-01	1.18E+00	1.09E+01	5.15E+00	8.86E+00

Acidification	kg SO_2 eq	1.08E+00	4.97E-03	3.66E-02	3.36E-01	1.59E-01	5.47E-01
Eutrophication	kg N eq	8.43E-02	3.16E-04	2.39E-03	2.16E-02	1.02E-02	4.99E-02
Respiratory effects	kg $PM_{2.5}$ eq	4.36E-02	9.80E-05	7.23E-04	6.68E-03	3.14E-03	3.30E-02
Carcinogenics	CTUh	2.19E-06	5.47E-09	4.09E-08	3.69E-07	1.75E-07	1.60E-06
Non carcinogenics	CTUh	1.15E-05	5.23E-08	3.92E-07	3.53E-06	1.68E-06	5.87E-06
Ecotoxicity	CTUe	1.46E+02	9.98E-01	7.47E+00	6.73E+01	3.20E+01	3.79E+01

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825 Table 9 Fossil and biogenic carbon dioxide emissions, potential avoided CO_2eq emissions and
826 carbon stored in the wood product for different end products from 1.78 m^3 of urban logs
827 removed. Assumed lumber service life is 60 years. Values are reported in kg CO_2eq.

End product scenario	Fossil CO_2eq emissions	Biogenic CO_2eq emissions	Total CO_2eq emissions	Potential avoided CO_2eq emissions	Carbon stored in product after use-phase
Fuel	136	1,677	1,813	-1,012	0
Mulch[1]	44	1,784	1,828	0	0
Mulch[2]	44	892	936	0	892
Landfill	25	1,076	1,101	-568[5]	856
Lumber[3]	122	5	127	-149	1,112
Lumber[4]	336	3	339	-149	1,112

828 [1] 100% decomposition
829 [2] 50% decomposition
830 [3] Baltimore, MD
831 [4] Milwaukee, WI
832 [5] Landfill methane emitted was captured and burned at a 75% efficiency