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Increasing Carbon Sequestration, Land-Use Efficiency, and Building Decarbonization with Short Rotation *Eucalyptus*

Kate Chilton [1,*], Otavio Campoe [2], Nicholas Allan [1] and Hal Hinkle [1,3]

[1] Global Bamboo Technologies, Inc., Ocala, FL 34472, USA; nich@bamcore.com (N.A.); hal@bamcore.com (H.H.)
[2] Department of Forest Science, Federal University of Lavras, Lavras 37200-000, MG, Brazil; otavio.campoe@ufla.br
[3] World Bamboo Foundation, Plymouth, MA 02360, USA
* Correspondence: kate@bamcore.com

Abstract: Global construction activity remains the least responsive large economic sector to the exigencies of global climate change. The focus has centered on operating emissions of buildings, while upfront embodied emissions in building materials remain unabated. Softwood timber, a commonly used building material, can remove and store atmospheric carbon in buildings for decades. However, the upfront climate benefits of using softwoods in building frames are limited due to the multi-decadal growth and harvest cycles of forest plantations. The objective of this study was to demonstrate that fast-growing *Eucalyptus* is a superior carbon sequestration feedstock for building materials compared to slow-growing softwoods. We quantified the relative carbon benefits of *Eucalyptus* to a group of commonly used North American softwoods in an all-carbon-pools, risk-adjusted model that compares the net present value of carbon flows over a 100-year period. Using a novel carbon benefit multiple metric, the analysis shows that short-rotation, high-yield *Eucalyptus* plantations are 2.7× to 4.6× better at sequestering atmospheric carbon than softwoods, depending on the various risk perception scenarios. The results indicate that building decarbonization can be enhanced by using fast-growing and high-yielding *Eucalyptus* species plantations.

Keywords: bio-based; CO_2; fast-growing; materials; sustainable construction

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1. Introduction

Man-made climate change is impacting all areas of the globe and endangering humanity's current way of life. According to data from the National Oceanic and Atmospheric Administration (NOAA), as of July 2024, the record for consecutive months setting a monthly global average temperature record was set at 14 months (breaking the previous record set between May 2015 and May 2016) [1]. Simultaneously, public commentary about exceeding the 1.5 °C and 2 °C targets set by the Paris Agreement has shifted from "if" to "when". A recent meta-analysis of 37 different climate models projected the world will pass 1.5 °C by 2036 (95th percentile), meaning actions taken within the next decade or two are of the utmost importance [2]. Moreover, humanity is approaching multiple climate tipping points, which, once activated, accelerate the rate of climate change and are likely irreversible, likely for millennia. A recent climate tipping point example is the observed slowing of the vital Atlantic meridional overturning circulation (AMOC) caused by the continued increase in ocean surface temperatures and associated salinity levels [3]. A significant slowdown of the AMOC is projected to lead to severely negative climate impacts, especially for Western Europe.

Given these trends, there is an urgent need to both reduce greenhouse gas emissions and remove previously emitted carbon dioxide from the atmosphere. Natural land-based systems already remove approximately 2 Gt CO_2 annually, primarily from land use, land-use change, and forestry (LULUCF) activities like afforestation and reforestation. Meanwhile, a mere 0.0013 Gt of CO_2, less than 0.1% of total carbon dioxide removal (CDR), comes from novel, technology-based solutions such as direct air capture [4]. It is doubtful that technology-based carbon removal solutions can be deployed at the scale needed to avoid fast-approaching tipping points or achieve the USD100/ton cost of removed carbon seen as the maximum economic value required to accelerate widespread adoption [5]. Relative to building decarbonization, little attention has been given to reducing the built environment's embodied carbon footprint. Buildings and construction are responsible for well over one-third of total global emissions (37%), with over 7% coming from both concrete (the most used material in the building sector) and steel (the second most abundant material in buildings) [6].

A less frequently discussed issue, but also of high importance, is the emerging "global land squeeze". As the total worldwide population continues to rise, so does the demand for land-based products and uses, namely food, wood products, and urban development. These three land uses will compete with the ability of the remaining native habitats to capture and store carbon and support biodiversity. The use of wood in construction is often asserted as a near-term climate mitigation strategy, and therefore, initiatives and policies to increase the use of wood in construction are accelerating. Despite other possible benefits, the increased substitution of wood for concrete, steel, and other extractive materials simultaneously increases land-use competition. It is estimated that there will be a 54% increase in total wood production between 2010 and 2050, requiring harvesting of about 600 M ha of secondary forests in addition to 200 M ha of existing plantations [7]. Furthermore, the true "carbon cost" of wood usage is often overlooked. There is a common misconception that wood is inherently "carbon neutral", yet in most scenarios, increasing absolute amounts of wood for construction increases atmospheric carbon for many decades until the harvested wood regrows and captures the emitted CO_2 [8–10]. However, there are instances when the harvest and subsequent use of bio-based materials can generate carbon removal benefits within a few decades or sometimes even immediately. In an all-carbon-pools analysis for a range of possible forests and harvest scenarios, the only scenarios that achieved high percentage emissions savings for construction material were those that met three conditions: high utilization rate, use of existing plantations or conversion to plantations, and high plantation growth rates, which only exist in selected species in warmer locations [7].

Given the need to durably sequester carbon for decades and transition to land-use efficient practices, *Eucalyptus* is underutilized as a climate-smart building material. Worldwide, *Eucalyptus* is the second most planted tree species for wood production, but it is primarily used for non-durable products such as pulp, paper, and energy products [11]. Because these *Eucalyptus* end-use products are typically short-lived, the carbon captured during the fast growth cycle of *Eucalyptus* is not durably stored. Because of this, harvesting *Eucalyptus* without durable storage results in a net warming atmospheric effect. However, *Eucalyptus* also possesses the necessary mechanical properties to be used as the structural frame of buildings where the sequestered carbon can be durably stored for many decades. In "Eucalyptus: An Overlooked Resource to Drive CO_2 Removal and Building Decarbonization", we outline how the superior strength, productivity, and growth rate of *Eucalyptus* make it an ideal candidate for expanded use in building decarbonization. With a high characteristic strength and modulus of elasticity, engineered wood products made from *Eucalyptus* are a logical choice to meet the increasing demand for wood-based structural building materials [11]. As one of the fastest growing tree species in the world, *Eucalyptus* can be harvested in as little as 10–12 years for use in engineered wood products, a staggering improvement over the commonly used softwoods of North America that typically take 40 to 75+ years to reach harvestable maturity. Because of these properties, we hypothesized that *Eucalyptus* more closely resembles timber bamboo in its carbon removal and storage capacity than three commonly used structural softwoods (Douglas fir, Loblolley pine, and Ponderosa Pine).

In 2019, we published "Carbon Farming with Timber Bamboo" to analyze how timber bamboo's fast growth and short annual harvest cycle can speed up carbon sequestration and turn timber bamboo plantations into perpetual carbon farms capable of producing high-grade structural fiber that stores the carbon. The analysis used a multi-species/multi-location growth model that was developed to estimate timber bamboo and wood-based annual carbon flows. Robust sensitivity analysis and time valuation of carbon flows, along with the development of a comprehensive metric called the carbon benefit multiple (CBM), were used to compare the carbon sequestration and storage potential of both fiber sources. Two unique features are captured in the CBM. First, all carbon flows are time-value discounted. Second, scenarios of time-value discounting are proposed that represent a range of perceived climate change risks. The results showed that with regular harvests turned into durable products, engineered timber bamboo sequesters between 4.9 and 6 times more time-weighted carbon than typical framing timber can [12].

Due to the similarly fast growth and short annual harvest cycle of *Eucalyptus* compared to other slow-growing wood, we hypothesize that *Eucalyptus* could have a CBM that is also superior to the North American softwoods commonly used for framing buildings. Our goal is to show the potential carbon removal and storage advantage of *Eucalyptus* to help advance a decarbonized built environment. The modeling framework was developed (1) to model the annual and cumulative carbon flows and (2) to time value those flows using discount rates that correspond to varying levels of climate change concern. Using the comprehensive CBM metric, we compare the carbon benefits of using *Eucalyptus* versus US-based softwoods for building products. Section 2 describes the data collection process and modeling framework, Section 3 presents the results of the analyses, and Section 4 discusses the implications of the study and areas of future research.

2. Materials and Methods

To compare carbon flows, we leveraged those previously developed [12], which were built from the US Forestry Services (USFS) model "Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States" [13]. This model allows us to directly compare numerous wood-based carbon flows across multiple species and growing locations. The calculation framework of the USFS model incorporates an all-carbon-pools approach by modeling the disposition of carbon flows across three broad categories: (1) the plantation, where all aspects of the ecosystem, including above- and below-ground biomass, ground litter, and soil organic carbon are tracked; (2) the harvest and harvested wood products (HWP), including manufacturing and service life; and (3) the final disposition of the HWPs at end-of-life [12].

Commercial softwood forestry is well-studied, and published pieces of literature containing models that project the longitudinal carbon flows from softwood plantations are available [14–18]. However, since *Eucalyptus* is predominately managed in short rotation cycles for pulp, paper, or energy, the availability of long-rotation data that more closely resemble the harvest management used for structural applications is limited. For long-rotation, longitudinal *Eucalyptus* plantation-level data, we combined four species for Brazilian-grown *Eucalyptus* (*E. grandis*, *E. saligna*, *E. urophylla*, and a hybrid of *E. grandis x E. camaldulensis*) with the single published dataset available for Australian-grown *Eucalyp-*

tus [19,20]. In total, five distinct *Eucalyptus* species-location combinations were analyzed. For the softwoods, three North American coniferous species were analyzed: Douglas fir (the largest growing commercial wood species in North America), Loblolley (the fastest growing and most widely planted commercial species in North America, also known as Southern Yellow Pine), and Ponderosa Pine (a commonly planted and widely used species). Using the USFS's report [13], carbon accumulation data for the three softwood species were selected from six North American locations for a total of seven distinct species-location combinations of wood.

Carbon stock over time for the Brazilian site was calculated by using species-specific aboveground biomass equations on sequential inventories of diameter at breast height (DBH, 1.3 m above ground) and total height. The dry mass was converted into carbon by multiplying each aboveground component by its specific carbon content, an average of 47%. More details related to the site, measurements, and fit of the biomass equations are described in Campoe et al., 2012, and le Maire et al., 2019 [19,21].

Brazil has a recognized history of advanced breeding and silvicultural practices relative to *Eucalyptus* [22,23]. Given the resulting speed and growth efficiency of Brazilian-grown *Eucalyptus*, rotation cycles of 10–12 years are common for sawlog feedstock [24]. To bias the analysis against our hypothesis, we applied a single 12-year harvest cycle assumption for all four Brazilian *Eucalyptus* datasets. We used biomass productivity (measured as the volume of wood produced per unit area per year) as a proxy for harvestable bole size of sawlogs. For the fifth *Eucalyptus* location, which was Australian, we used a projected 15-year harvest cycle. For the three species of softwoods, we obtained harvest rotations directly from the USFS model, ranging from 25 to 75 years. For comparability, we constrained the projected end-use allocations based on historical data for oriented strand board (OSB).

Two stages of biomass conversion efficiency were projected. First, at the time of harvest, the mass of felled trees is converted to roundwood for sawlogs that are taken to the mill while leaving the branches, stems, and leaves on the ground to decay, thus emitting considerable carbon in the first several years following harvest. Second, end-use conversion at the time of production of the end-use product (or harvested wood product, HWP) accounts for waste that is generated in the milling and manufacturing stage. To model the carbon flows coming from harvest and HWP production for softwoods, we used the USFS published data. Because published data for production efficiencies of long-rotation *Eucalyptus* into HWP are not available, we utilized the same conversion efficiencies published by the USFS, taking the averages of the harvest conversion efficiency and HWP production efficiency across the seven coniferous species locations and applying them to the five *Eucalyptus* flows.

Carbon flows through the product ecosystem as an in-use product before being recycled, discarded to a landfill, or burned (and immediately emitted as CO_2). For consistency, we modeled the same HWP disposition carbon flows for all fiber sources. We used the USFS half-life functions for the HWP service life and the end-of-life allocations between emissions and landfill deposition. For the portion in landfills, however, we updated the emission projections based on more recently published research for assumptions related to (1) the portion of HWP that was degradable in landfills, (2) when the degradation initiates, and (3) how long the degradation occurs before reaching the non-degradable residual state [25].

Once we obtained the annual carbon flows for all species-location datasets, we time-discounted them to value near-term atmospheric carbon removal and durable storage (i.e., building decarbonization) more than longer-term carbon removal and storage. Policy-based carbon accounting and decision-making often fail to consider the time value of atmospheric carbon, though advanced, dynamic climate modeling does realistically incorporate time value. This time-value modeling of carbon flows incorporates the reality that GHG emissions reduction and CDR that happen today are far more valuable than the emission cuts or carbon capture anticipated in the future. The presence of climate system tipping points justifies the incorporation of time-value discounting. In conventional finance, a discount rate is applied to each period of cash flow (or, more generally, any forward benefit or cost) [26,27]. The higher the discount rate, the more near-term benefits are valued. Similarly, the higher the discount rate, the less certainty or the greater risk is attached to the future carbon benefits. The net present value (NPV) of the future flows is the sum of the discounted carbon flows, calculated by using the net annual carbon flow (C) at time *t* and the chosen discount rate (r). The NPV enables a single point of comparison between the different species-location data pairs for a given set of discount rates.

$$\mathrm{NPV} = \sum \frac{\mathrm{C}(t)}{(1+\mathrm{r})^{t}} \tag{1}$$

The choice of discount rate applied to the future carbon flows is a subjective and exogenous input in the analysis. To avoid a model influenced by a single discount rate assumption, we tested a range of discount rates that reflect a range of risk perceptions. Instead of using a single discount rate for the entire period of carbon flow, we applied a step function of increasing discounts over time to reflect both the delayed early action and increasing information and awareness over time. The three resulting discount rate scenarios applied to the carbon flows for the twelve species-location datasets are illustrated in Figure 1. The modest risk scenario starts at a 1% discount rate, the serious risk scenario starts at 5%, and the extreme risk scenario starts at 10%. The higher rates imply greater uncertainty about the future, but they also suggest that impacts from distant years are virtually neglected [28]. The use of higher rates may, therefore, be reasonable for someone with extreme concern about climate change if they view the situation existentially (i.e., it assigns little weight to the future).

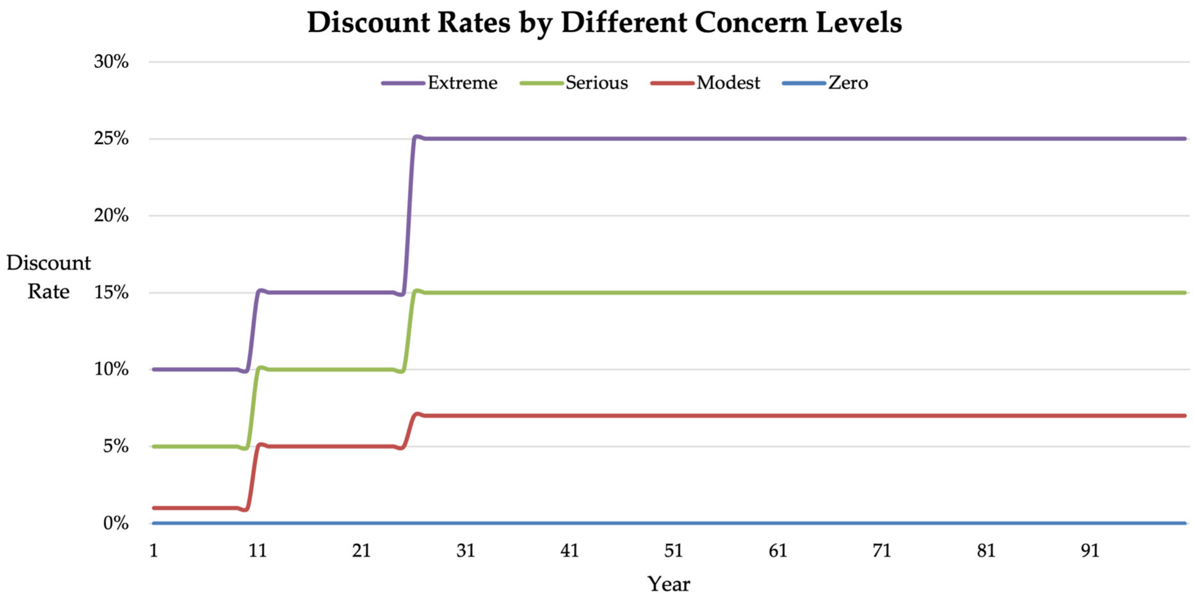


Figure 1. Step function discount rates for four scenarios that represent varying levels of concern of the decision maker about climate change.

To test the hypothesis that *Eucalyptus* building materials are preferred carbon storage materials to softwood building materials, we calculate the carbon benefit multiple (CBM), which reflects the ratio of the average PV of the five *Eucalyptus* datasets to the average PV for the seven softwoods datasets for various scenarios of time discounting.

$$\text{Carbon Benefit Multiple: } NPV_{Euc}/NPV_{softwoods} \tag{2}$$

If the CBM is greater than 1, *Eucalyptus* contributes more to building decarbonization than softwoods. If the CBM equals 1, *Eucalyptus* and softwoods are equivalent. If the CBM is less than 1, softwoods contribute more to building decarbonization than *Eucalyptus*. The greater the difference from a CMB of 1, the greater the relative impact.

The various stages of work, starting with model development and working through data collection and analysis, are outlined in Figure 2.

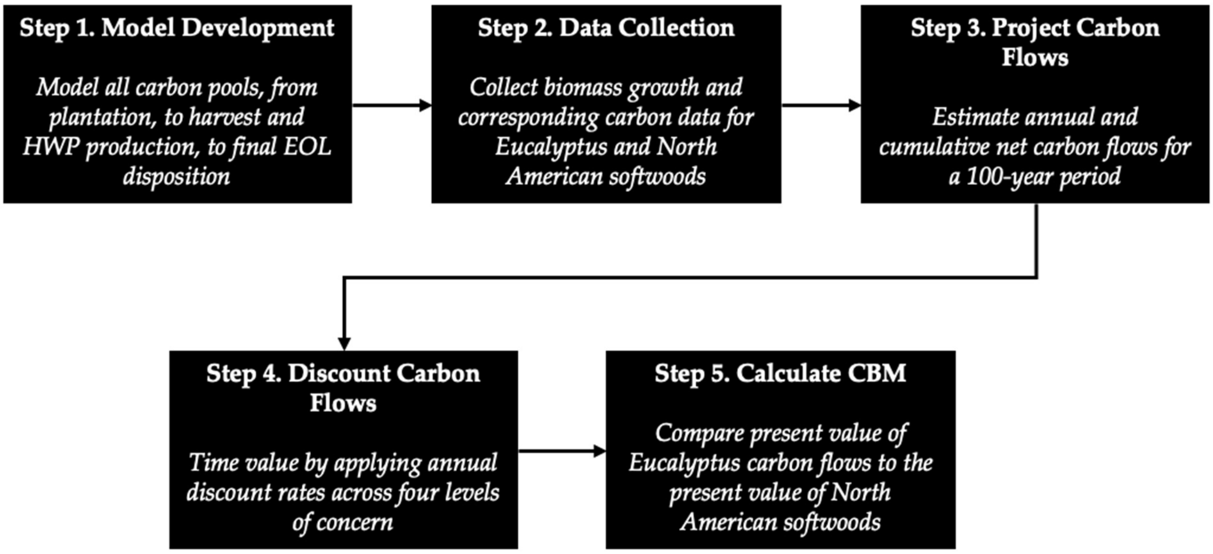


Figure 2. Flow diagram of analysis approach.

3. Results

3.1. Plantation-Level Cumulative Carbon Flows (Not Discounted)

The average undiscounted cumulative carbon flows for the four Eucalyptus species and the three softwood species at the plantation level until the year of harvest are shown in Figure 3. The Eucalyptus accumulates sequestered carbon per hectare meaningfully faster than the softwoods. By the ninth year, all four Eucalyptus species have accumulated more than 100 tons of C/ha. In contrast, the fastest US-grown coniferous species, Loblolly pine, does not accumulate 100 tons C/ha until year 17. The largest-growing US softwood, Douglas fir, does not accumulate 100 tons C/ha until year 28, which is three times as long as the slowest of the Eucalyptus species. The third commercial wood species, Ponderosa Pine, does not reach 100 tons C/ha by the 100th year. Agnostic of the subsequent carbon pools (harvest and HWP production), it is clear at the plantation level that there is a near-term and, in some cases, an absolute carbon advantage to fast-growing Eucalyptus over slow-growing softwoods.

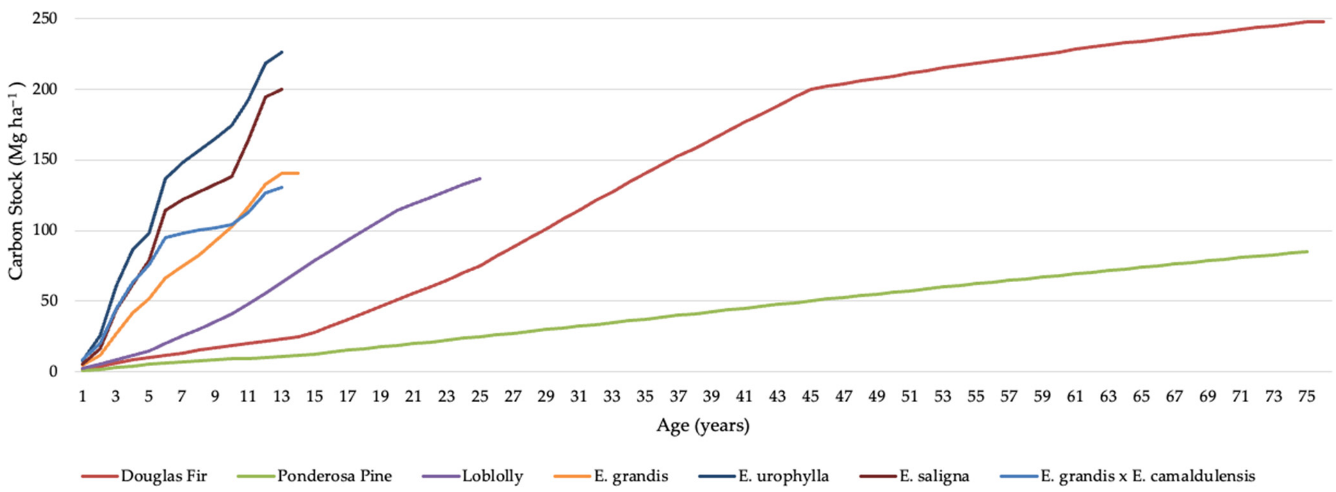
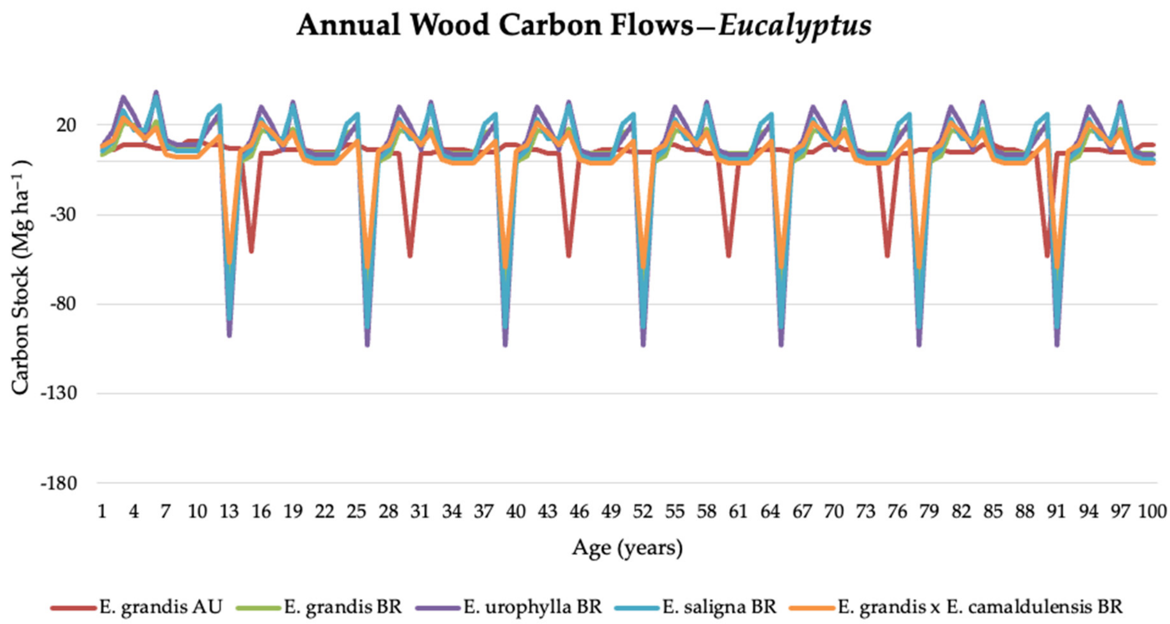


Figure 3. Accumulated carbon during the growth periods for all wood species, averaged across the locations.

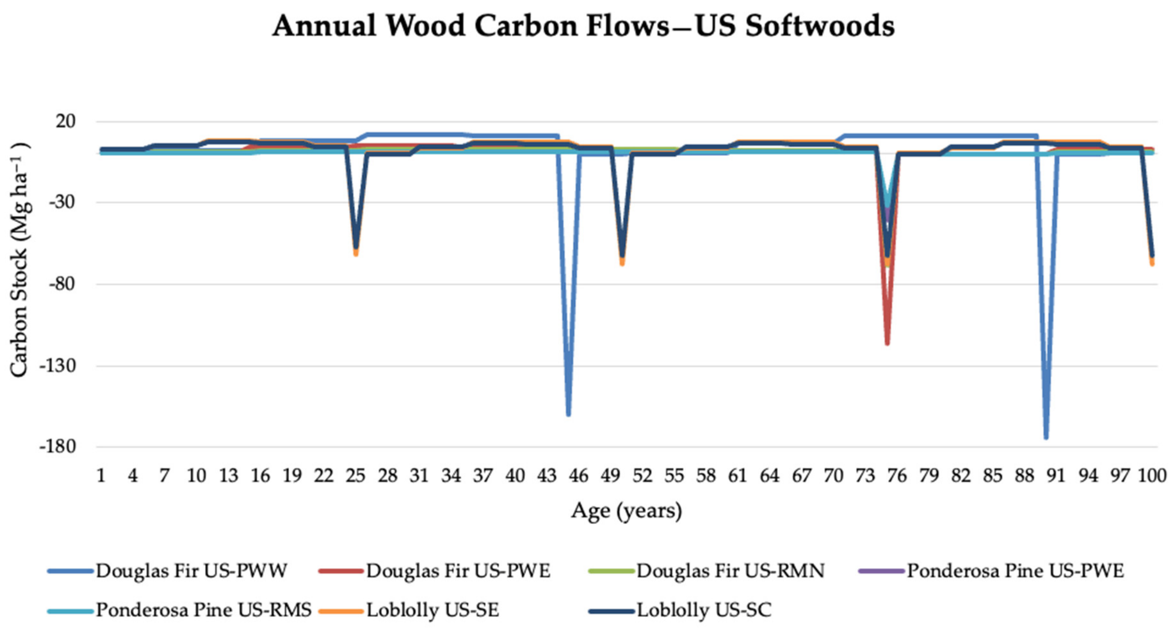
3.2. Total (Full Life Cycle)—Annual Carbon Flows (Undiscounted)

The net annual carbon flows for the Eucalyptus and softwoods, respectively, are presented in Figure 4a,b. For both Eucalyptus and the softwoods, when the lines are above zero, annual carbon sequestration occurs, and when the curve turns negative, the plantation's harvest waste reemits the sequestered carbon in the year following harvest. Taken together, Figure 4a,b highlight both the large difference in the rotation, or time to harvest, and the larger annual carbon flows for the Eucalyptus species than for the softwood species. Note that the Brazilian Eucalyptus growth data shown in Figure 4a were obtained from a single harvest cycle. The variability in growth year to year is responsible for the spikes in growth prior to harvest. Further research trials would help give more average data and potentially a smoother growth curve.



(**a**)

Figure 4. *Cont.*



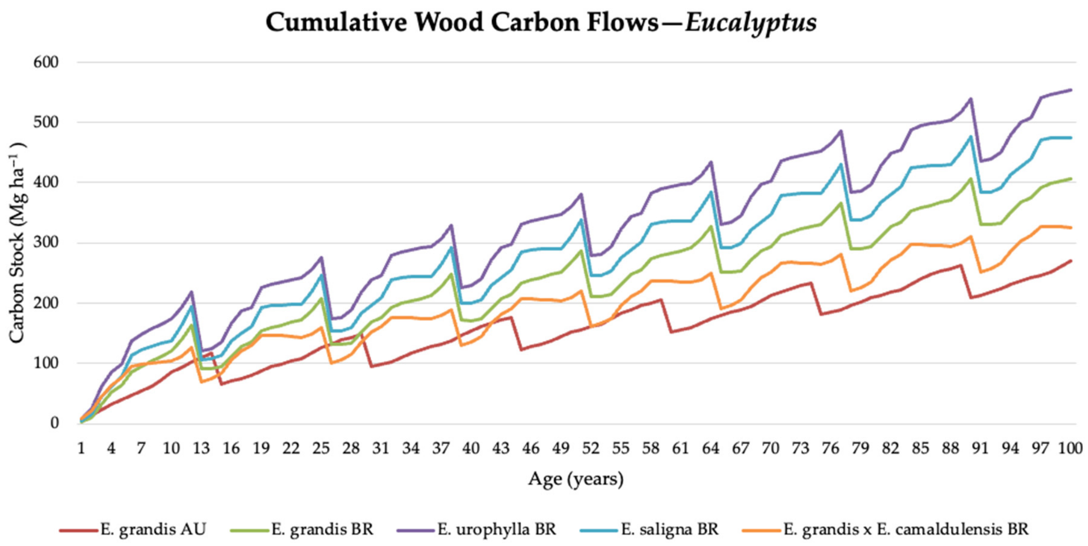
(**b**)

Figure 4. Net annual carbon flows for (**a**) five *Eucalyptus* species-location pairings and (**b**) seven softwood species-location pairings.

Compared to the softwoods, there is an apparent and sizable increase in carbon stock for the Eucalyptus, attributable to its fast growth and high productivity. No such visible increases in accumulated carbon can be seen for the softwoods. Over time, as is shown in the next section, these increases in stored carbon amount to substantial differences between the two fiber sources, with one clearly showing an advantage over the other.

3.3. Total (Full Life Cycle)—Cumulative Carbon Flows (Undiscounted)

The cumulative carbon flows for the Eucalyptus and softwoods, respectively, are presented in Figure 5a,b. For both Eucalyptus and the softwood species, the cumulative carbon captured grows annually until the downward reversal at the time of harvest waste emissions. The key difference between the two species groups is the short rotation and high yield of Eucalyptus species that enable them to more readily overcome the harvest-related emissions and, over time, end up with a much higher total accumulation of sequestered carbon (after including the conversion waste, HWP storage, and end-of-life treatment). Three of the five Eucalyptus species-location combinations exceed 200 Mt/ha by year 24. In contrast, only the first of the seven softwood combinations reaches 200 Mt/ha temporarily, and only at year 32. Conversely, at year 84, all five Eucalyptus datasets are above the 200 Mt/ha benchmark and two have reached 400 Mt/ha. The combination of fast growth and high productivity in the cumulative sequestered carbon of all five Eucalyptus datasets at the end of the 100-year period substantially exceeds any of the seven softwood datasets. The lowest-performing Eucalyptus species ends at the same level as the highest-performing softwood. The average total accumulation of carbon across the Eucalyptus projections is 406 Mt/ha compared to 138 Mt/ha for the softwoods, almost three times as much.



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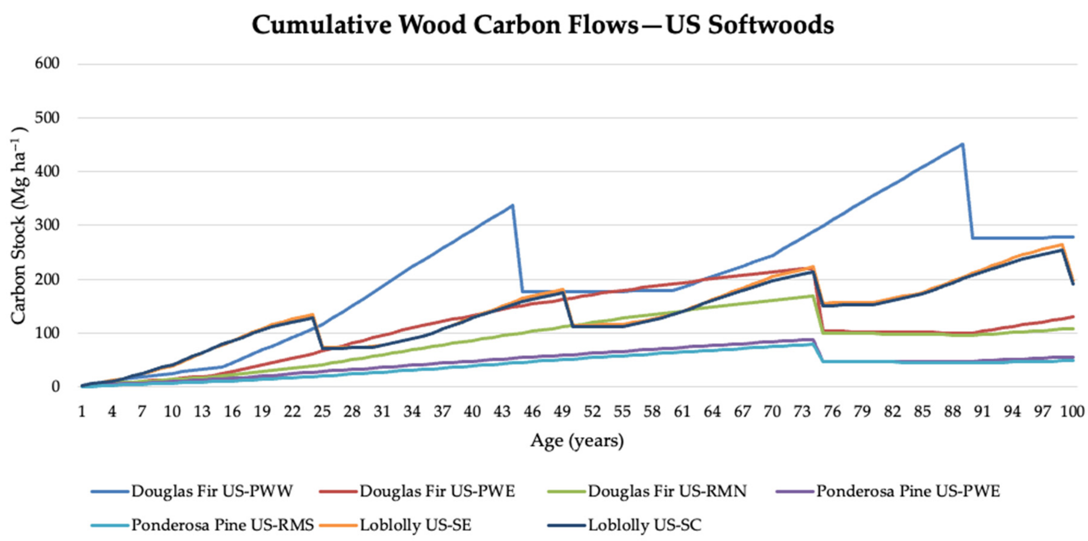

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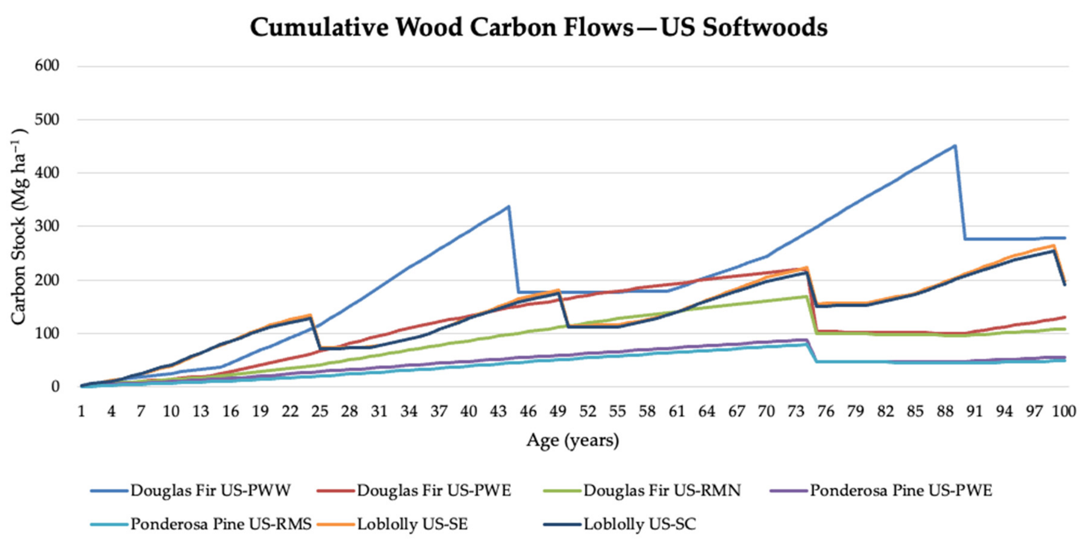

(**c**)

Figure 5. Cumulative net carbon flows for (**a**) five *Eucalyptus* species-location pairings, (**b**) seven softwoods species-location pairings, and (**c**) averages across all *Eucalyptus* and softwoods.

The simple average cumulative carbon flows for the combined Eucalyptus species as compared to the combined softwood species are shown in Figure 5c. By the end of the 100-year period, the average carbon stock of the Eucalyptus datasets is 2.8× higher than that of the US softwoods. It is the combination of both speed and productivity that results in these Eucalyptus examples showing the potential to be powerful biogenic carbon capture and storage solutions when used in the built environment. If the objective is to quickly decarbonize buildings, it is clear that Eucalyptus is a more effective mechanism than the softwoods commonly used in today's construction.

3.4. Carbon Benefit Multiples (Including Temporal Discounting and Scenarios)

To analyze varying degrees of concern about climate change, four different temporal discount rate scenarios are constructed that progressively weight higher levels of concern (zero, moderate, serious, and extreme) and thus higher discount rates. The resulting CBM for each scenario is a ratio of the present values after discounting the annual carbon flows for the Eucalyptus species compared to the softwood species. This results in a quantification of the relative benefit of Eucalyptus compared to the softwoods in capturing atmospheric carbon to be stored in durable building structures. The scenario-specific CMBs, shown in Figure 6, suggest that Eucalyptus can be 2.7 to 4.6 times more potent in decarbonizing buildings. In the "Modest" to "Extreme" comparisons, the overall effect of time valuing significantly lowers the absolute amounts of carbon sequestration for both Eucalyptus and softwoods. However, across the three "Modest" to "Extreme" levels of concern, the comparative CBM rises in favor of Eucalyptus as the level of concern about climate change (i.e., higher discount rates) increases, highlighting the impact of near-term carbon flows from Eucalyptus.

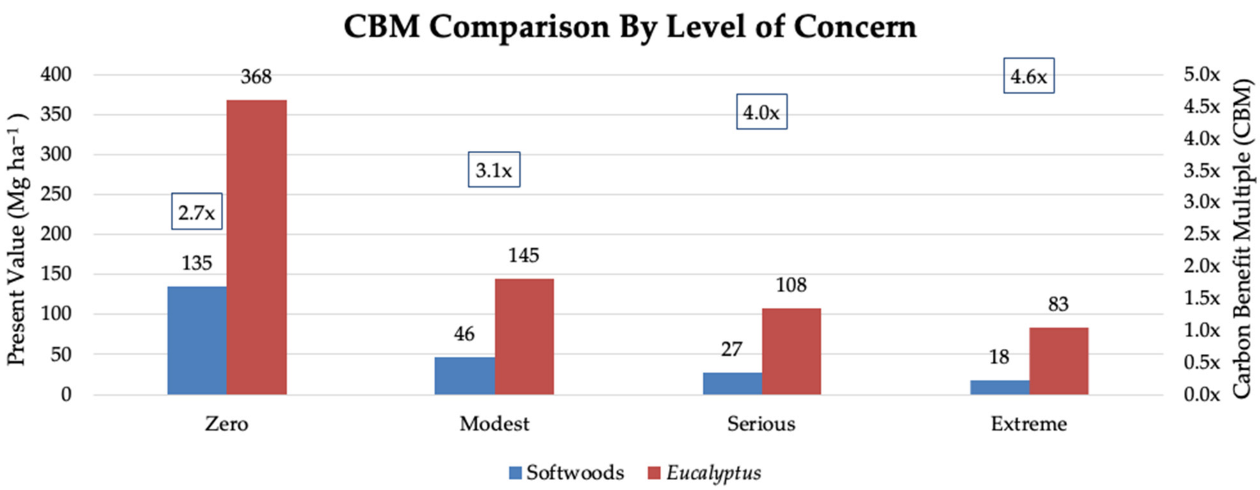

Figure 6. Carbon benefit multiple comparing the average of the five *Eucalyptus* carbon flows with the average of the seven softwood carbon flows across each of the four concern levels.

The objective of this study was to prove or disprove the hypothesis that *Eucalyptus* is a superior building material feedstock from a carbon storage standpoint compared to softwoods. The results above prove this thinking, showing positive CBMs for the comparison across all levels of time valuing (i.e., discounting). Even when observing only the total present value of carbon flows and not the comparative CBM metric, this conclusion can be drawn from the results in Figure 6.

3.5. Total (Full Life Cycle)—Cumulative Carbon Flows with Year 0 Harvest

The CBM framework was originally constructed to compare the potential of bamboo- vs. wood-based afforestation initiatives, and as such, sequestration was modeled over the period leading up to the harvest, following the carbon physically present in the HWP. In dynamic LCAs (DLCA), this so-called "backward-looking" approach is considered appropriate in cases where timber is harvested from forests planted as afforestation efforts [29,30]. Conversely, "forward-looking" approaches follow carbon sequestration after a harvest in which trees are planted to replace those that are harvested [31]. Because of its focus on fiber regrowth and the climate benefits of additional sequestration enabled by the harvest of timber with subsequent replanting, we also analyzed the carbon flows, setting the harvest at Year 0. The results of this second analysis are shown in Table 1. While this study does not use a DLCA method, the data highlight how the results can vary considerably between the two alternative approaches to the timing of sequestration.

Table 1. Average cumulative carbon stock (Mt ha^{-1}) across all *Eucalyptus* and softwood datasets at the end of the 100-year period for each of varying concern levels.

Species	Zero Concern	Modest Concern	Serious Concern	Extreme Concern
Eucalyptus	286	60	24	2
US Softwoods	72	−24	−51	−57

The impact of this "forward-looking" approach is that total carbon sequestration across all datasets and scenarios is lowered because of the upfront emissions event at the time of harvest. Instead of starting from zero and increasing, the starting point is a negative value, and over time, the follow-on sequestration must compensate. The result is that the present value of annual carbon flows from the US softwoods turns progressively negative for each increasing level of concern scenario, whereas the Eucalyptus remains positive across all levels of concern. Given the negative values, the CBM metric becomes less useful and is therefore not calculated in this analysis.

4. Discussion

The results of this study clearly prove that the working hypothesis is correct; *Eucalyptus*, when compared to commonly used North American softwoods, is a better building material from the perspective of carbon sequestration potential. We have shown that the key drivers of this superior carbon storage are (1) fast growth (shorter rotation cycles) and (2) high productivity (more biomass produced per unit of area). While *Eucalyptus* is not traditionally thought of as a feedstock for construction, the existing literature has shown it possesses the necessary mechanical properties to do so [11,32–34], and now, having demonstrated the improved carbon benefits, its structural use in buildings should be widely adopted. The broader implications of these findings and future research directions are discussed in the sections below.

4.1. Global Carbon Impact

To illustrate the potential impact that Eucalyptus can have when utilized for structural building materials, we examined how much atmospheric carbon can be removed and durably stored when increasing portions of existing Eucalyptus plantations are converted to longer rotation for use in construction. The total plantation area of Eucalyptus is estimated at 22.57 million hectares, making it the most widely planted broad-leaved forest species in the world [35]. The vast majority of Eucalyptus is managed on short rotations (4–7 years) for the production of pulpwood, charcoal, and firewood. We assessed extending these rotations for use in long-lived, high-value building products. Using the USFS model, the average cumulative value of the carbon flows (assuming a zero-discount rate) for the five Eucalyptus datasets is 698 Mt C ha^{-1} over a 100-year period. If a mere 2% of the existing plantations were converted (451,400 ha), 315 million Mt of carbon could be durably sequestered, translating to 1.16 billion Mt CO_2 eq, or over a gigatonne of CDR. Increasing the conversion rate to 10% increases the carbon stored to 1.58 billion Mt and carbon dioxide removed to 5.78 billion Mt. Notably, this analysis does not include any substitution or displacement benefits that could arise if the engineered structural Eucalyptus products replace high embodied carbon alternatives like cement and steel. Doing so would increase the carbon benefit projections substantially.

4.2. Land-Use Efficiency Comparison

While the analysis above demonstrates the building decarbonization benefits of Eucalyptus, the data for land-use efficiency suggests additional benefits. With significant increases in wood construction, the areas and quantities of additional wood harvested could be large. For example, if 10% of the world's new urban construction between 2010 and 2050 were wood-based, 50 Mha of secondary forest would be required [7]. This highlights the critical need to consider land-use efficiency as an additional criterion for evaluating potential biogenic fiber sources. From the USFS data, the average volume per hectare at the time of harvest across the seven softwood species-location pairings is 227 m^3/ha. The highest volume per ha of softwood came from Douglas fir in the Pacific Northwest, West (445 m^3/ha), while the lowest volume per ha came from Ponderosa Pine in the Rocky Mountains, South (69 m^3/ha). Conversely, the average volume per hectare at the age of 13.4 years across the four Brazilian Eucalyptus species-location pairings is 532 m^3/ha, with *E. urophylla* producing the most (612 m^3/ha) and *E. grandis* x camaldulensis producing the least (427 m^3/ha). Assuming the average amount of lumber with a specific gravity of 0.50 required for constructing a house frame is 17,146 kg, a total of 34.3 m^3 per house is needed [36]. An average Brazilian Eucalyptus plantation could generate 17 houses, whereas an average US softwood plantation could generate 6.6 houses. This means the fast-growing Eucalyptus is 134% more land-use efficient than the slow-growing alternative. Given that every hectare of land used to supply human consumption comes with a high "carbon opportunity cost", it is essential that we maximize production with the land we have already converted in order to limit future conversion of additional forests.

4.3. Transportation Impact on Carbon Flows

Because fast-growing biogenic fibers are typically found in the warmer tropic and subtropic climates, there will be a greater emissions impact from the logistics associated with transporting them from these regions to decarbonize buildings in other parts of the world. To assess this potential benefit reduction, we performed a simple carbon footprint analysis of the transportation associated with using materials in two different US regions (using US Census data to identify the areas with high amounts of new residential construction) that are sourced from within the US and Brazil. Using Simapro software and the ecoinvent database (version 3.9.1), we modeled the emissions resulting from three transit configurations: (1) Pacific Northwest softwood traveling to the Midwest or Southern US, (2) Southeastern softwood traveling to the Midwest or Southern US, and (3) Eucalyptus from southern Brazil sent to the US Midwest and South. The total CO_2eq transport results in Table 2 demonstrate that in the transit configurations where biogenic structural material travels long road distances within the US, the carbon impact per kg of material is higher than the scenarios where the material travels long distances that are principally oceanic (Brazil to US). This is due to the relatively higher carbon intensity of land transportation compared with oceanic transport. Still, the lowest carbon footprint will result from scenarios where the sourced material is used for buildings in the same region, but practically speaking, this is seldom the case.

Table 2. Total transportation distances and associated carbon impact for scenarios with different raw material origins and end destination locations.

Origin	Destination	Land (km)	Sea (km)	Total CO_2eq per kg Raw Material (kg)
Pacific Northwest US	Midwest US	3670	0	0.56
Pacific Northwest US	Southern US	3300	0	0.50
Southern Brazil	Southern US	1690	11,450	0.33
Southern Brazil	Midwest US	1415	11,450	0.29
Southeast US	Southern US	1610	0	0.24
Southeast US	Midwest US	1045	0	0.16

The above data show that the transport burden of sourcing South American wood for framing in US buildings can be less than the carbon footprint of transporting US-grown wood to a different region within the US. Even if *Eucalyptus* has a higher carbon transport burden when the *Eucalyptus* to softwood CBM is greater than 1, some or all of the transport carbon burden can be absorbed while still leaving the CBM greater than 1.

It is worth noting that there is a broader geographic mismatch between a sustainable wood supply and building stock demand at play. The majority of sustainable wood supplies today are located in North America and Europe, yet the biggest impact from future urban building development will not occur in these regions. There is, however, significant overlap with where *Eucalyptus* plantations are most prevalent and where concentrations and future growth of populations are. For example, the two most populous countries (China and India), both with more than 1 billion people and each representing nearly 18% of the world's population, are ranked second and third in terms of the total area under *Eucalyptus* cultivation, 20% and 17%, respectively [11]. Brazil, which has the largest proportion of *Eucalyptus* plantation area in the world (20%), is the seventh most populous country worldwide. Looking forward, Pakistan, which has 1% of the *Eucalyptus* plantation area, is projected to become the fifth most populated nation by 2050 [37]. This is yet another benefit of fast-growing, high-productivity fiber sources like *Eucalyptus*; they are more likely to be co-located where urbanization rates, and therefore new construction rates, are high, further increasing their potential to produce net-zero built environments.

4.4. Additional Fast-Growing Fiber Sources

The present analysis demonstrates that five non-traditional Eucalyptus species-location combinations can be more beneficial in capturing and storing carbon than seven US softwood species-locations combinations. Other non-traditional species-location combinations, like Asian-grown Acacia [38,39], are candidates to be subsequently explored.

4.5. Limitations and Future Considerations

Despite the significant conclusions of this study, several limitations are acknowledged. First, the range of the data analyzed was species and location restricted, which may limit the generalizability of the results. If available, including more data from other regions, such as European-grown softwoods or Indian-grown Eucalyptus, could increase the robustness of the analysis. The types of fiber sources also varied between datasets; specifically, the USFS data contained a myriad of forest types and management intensities, whereas the Brazilian Eucalyptus data came from plantations with advanced breeding and silvicultural practices that are typically found in Brazil. This may have skewed the results, but it also supports the case to be made that increased investment in clonal selection and silvicultural practices (as has been done for several decades in Brazil) can produce relatively beneficial results. Second, the reliance on self-reported data from Brazilian plywood manufacturers pertaining to the rotation length for structural Eucalyptus products introduces potential biases and inaccuracies that could affect the outcomes. Third, with respect to the carbon flows from tree growth over a 100-year timeframe, we assume no change in the underlying growth rates and carbon sequestration capacity. However, studies have shown that with warming climates come changes in productivity, water availability, and soil degradation, which are not accounted for in this analysis [40]. Fourth, the validity of applying the USFS assumptions about the harvest and HWP production carbon efficiencies for the non-USFS sourced Eucalyptus species has also not been tested. Future research should aim to obtain more species and location-specific harvesting and manufacturing practices to more precisely compare the alternatives. Similarly, the analysis can be strengthened by using statistical data from multiple sources instead of relying solely on USFS data for the HWP service life and end-of-life allocations. Fifth, a more robust supply–demand transit analysis could provide deeper insights into the transportation impacts of sourcing fast-growing fibers for use in buildings outside of their local regions.

5. Conclusions

Given the outsized role that buildings have in generating greenhouse gas emissions, if the built sector does not achieve significant decarbonization, other CDR efforts will remain futile. The present work utilizes a time-discounted rational decision-making framework to test the hypothesis that fast-growing, high-productivity *Eucalyptus* offers superior carbon capture and storage benefits compared to the traditionally used softwoods used in North American buildings and, in fact, more closely resembles a similar opportunity with timber bamboo. The detailed analysis of system-wide carbon flows from numerous wood sources found that the earlier and faster biomass accumulation of Brazilian-grown *Eucalyptus* gave it a significant advantage in capturing and storing atmospheric carbon compared to US-grown softwoods, even after considering the differential carbon flow impacts from transportation. The time-discounted decision model that compared annual carbon flows produced the novel Carbon Benefit Multiple (CBM) metrics, which attempt to quantify the carbon sequestration benefits when choosing between alternative structural fibers. The *Eucalyptus* studied here produced a CBM of 2.7× to 4.6× when compared to the slow-growing North American softwoods, suggesting this category of trees can be prioritized as the preferred structural fiber to help decarbonize buildings. The findings underscore the significant potential of utilizing fast-growing and highly productive structural fibers in the construction sector to achieve substantial carbon removal and storage. The accelerated growth cycles allow for quicker accumulation of sequestered carbon to potentially lessen the risk of climate change tipping points. The high productivity permits a more efficient use of limited arable land to potentially address the emerging global land squeeze. Today, *Eucalyptus* is predominately used for short-lived or non-durable products like pulp and paper, but the more durable the harvested product is, the greater the CBM of the fiber source can be. This suggests that transitioning even small percentages of existing *Eucalyptus* plantations to higher-value, more durable end-use products, like building structures, could provide material benefits in climate change mitigation work. By demonstrating the superior carbon sequestration potential of fast-growing *Eucalyptus*, this study provides critical insights for decision-makers within the construction industry to choose the most effective materials for decarbonizing the built environment.

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