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Gibson, Andy and Pomponi, Francesco orcid.org/0000-0003-3132-2523 (2025) The Impact of Forest Management Success Rates on the Net Carbon Benefits of Using Timber in Construction. Sustainability. 1919. ISSN 2071-1050

https://doi.org/10.3390/su17051919

sustainability

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The Impact of Forest Management Success Rates on the Net Carbon Benefits of Using Timber in Construction

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Abstract: The climate emergency calls for carbon drawdown to be applied at scale to offset the 'hard to abate' emission reductions that threaten Net Zero. The use of biogenic materials in construction promises benefits in terms of low embodied carbon (EC), but timber harvested today only sequestered atmospheric carbon (AC) in the *past*. A reduction in *future* AC concentration is only possible from today, and harvesting timber harms a forest's ability to sequester carbon in the future, unless a level of afforestation can be guaranteed. Current Whole Life Carbon (WLC) assessment methodologies confuse the perceived value of past sequestration, making it seem equivalent to EC, or implying a guarantee of future AC. This study seeks to connect these two opposing elements by finding a forest management 'success' value (F_S) at which harvesting losses are outweighed by future sequestration, and a net benefit (in future AC terms) can be justifiably claimed. The research proposes a measure of forestry success (a standard established in terms of net sequestration per hectare) and cumulatively offsets losses through harvest against additional drawdown achieved in a well-managed forest. The results show that current boreal forest management regimes do not guarantee a net benefit, but that only modest improvements from a contemporary baseline would be required to see a net benefit by 2050. Recommendations are made to establish a carbon-focused standard for forestry management to replace current binary sustainability accreditations.

Keywords: timber; construction; forestry; carbon; sequestration; afforestation

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Academic Editor: Jim Lynch

Received: 25 October 2024
Revised: 8 January 2025
Accepted: 11 February 2025
Published: 24 February 2025

Citation: Gibson, A.; Pomponi, F. The Impact of Forest Management Success Rates on the Net Carbon Benefits of Using Timber in Construction. *Sustainability* **2025**, *17*, 1919. https://doi.org/10.3390/su17051919

1. Introduction

Recent years have seen records being repeatedly surpassed in areas being monitored as indicators of global climate warming [1–3]. The link between rising temperatures and the concentration of greenhouse gases (GHGs) in the atmosphere is now clear [4]. Lowering atmospheric carbon (AC) is considered essential to avoiding the worst effects of climate change, leading to growing consensus around policies intending to achieve Net Zero by 2050, and for human activity to become carbon negative by the end of this century [5]. (The term 'atmospheric carbon' is used here as an umbrella term to refer to GHGs as they exist in the atmospheric part of the global carbon flux model, as a simplification. It is agreed that the aim of reducing the impacts of climate change requires a reduction in the concentration of GHGs in the atmosphere, and a reduction in the net passage of GHGs into it. The real effects of each GHG on radiative forcing (the mechanism by which they affect global warming), and the timescales over which this happens, are understood to be complex, and an equivalence between fluxes into and out of the atmosphere over time should not be assumed). However, it is recognized that some sources of carbon emissions are of such value to mankind, or to equity of access to power (especially in the developing world), that eradicating them entirely in this period is unrealistic. It is, therefore, necessary to begin to roll out methods of carbon capture and storage (CCS) at scale over the coming decades to offset these 'hard-to-abate' emissions [6].

Carbon sequestering processes exist in a variety of natural systems and leveraging some of these is the subject of much research [4]. Knowledge of soil management, carbon fluxes in the biosphere, and fast-growing plant species is improving, leading to an increase in the development of nature-based material alternatives. Construction—one of the most extractive and carbon-intensive parts of human activity [7]—is starting to embrace the use of such materials in a wide variety of applications.

The use of timber in construction has a very long history—it is perhaps one of the very oldest building materials—but throughout that period it has been a largely extractive and linear process. As with almost all materials employed in construction today, building with timber relies on removing material from the environment and using it in a structure, where it remains for the life cycle of that component. Circular economy principles seek to promote ways for timber (and, indeed, all materials) to be recycled or re-used in some way at the end of their life. For biogenic materials, this opportunity to prolong carbon storage should be embraced. However, the carbon that was sequestered by these plants as they grew happened entirely in the past for all but the very fastest growing species, so no impact on present or future atmospheric carbon can be assumed. Whilst storing past-sequestered carbon into the long term is desirable, the value of this sequestration in the context of future atmospheric carbon is not assured.

1.1. Creating a Link Between Timber and the Forest of the Future

As timber is extracted to create 'harvested wood products' (HWPs), the source forest's ability to sequester carbon into the future is reduced. These losses are in addition to the degradation of biological material, natural habitats, water management and other social and natural capital aspects. In forests deemed to be 'sustainable', replanting programs are audited to ensure that some or all of these losses are replenished, but the extent to which this happens is unclear. Forest management standards (such as FSC [8] and PEFC [9]) are binary in this regard, and do not *grade* the extent to which a replenishment protocol succeeds in replacing this sequestration potential, or even bringing new trees to maturity.

Promotors of timber as a construction material refer to the carbon storage potential as one of the benefits but ignore this lack of clarity about the future sequestration potential, which—in relation to future atmospheric carbon—is arguably much more important. The current UK standard set out by the Royal Institute of Chartered Surveyors (RICS) allows for the value of past sequestered carbon to be offset against embodied carbon (EC) [10] (The term 'embodied carbon' is used here as a simplification of the total net amount of GHGs' passage to the atmosphere assessed as being directly attributable to the creation and installation of the product being considered. This is normally presented as a total mass of equivalent CO_2 gas (tons of "CO_2e"). This is not to be confused with the amount of atmospheric carbon that is thought to have been extracted *from* the atmosphere by that material, by photosynthesis or other chemical process (sequestered carbon, SC)), leading some *cradle-to-gate* (A1-A4) life cycle assessments (LCAs) to report timber as a low-, zero- or even negative-carbon product. This implies that past sequestration equates to contemporary and future emissions. It is argued that this concept is flawed [11] and inappropriately leads specifiers to believe that (a) those two cancelling values are equivalent (they are not, in the context of the climate crisis [12]) and (b) that any loss of future sequestration potential (directly caused by HWP harvesting) can be ignored.

1.2. Building a Case for Timber

Taking the approach that timber has a net carbon benefit, using the above rationale, is common in the grey literature of the structural timber industry, which—as shown—is not strictly legitimate. What would be required to claim a net benefit is an assurance that the source forest has applied a management regime that provides true additionality in terms of new sequestration, less losses from harvesting. This could be through such techniques such as mixed speciation, amended thinning policies, targeted fertilizer application and amended ages of thinning and harvesting. These techniques are becoming more widely understood in the literature [13–15].

This study seeks to show whether this case can be built, by establishing ways to measure carbon sequestration potential for a spectrum of forest management behaviors and then testing this against harvest demands to see if a level can be found where a net benefit emerges.

2. Materials and Methods

To achieve the specific research intent—to arrive at fixed values and/or estimates for constants and variables in the relationship between HWP use and the drivers for different atmospheric carbon outcomes—a literature review was carried out for each value. Three UK building archetypes were used as models for how uptake in timber as a primary construction material could affect demand, and then sequestration potential. These were chosen as being those with the most opportunity to see growth in the coming decades, namely, low-rise domestic housing [LRD], archetype 1; multi-story residential [MSD], archetype 2; and multi-story non-residential [MSN], archetype 3.

To model the results of changes in behavior, it was necessary to both evaluate current baseline data and to estimate or predict the way values might change in the future. These steps were performed as follows:

2.1. Baseline Data

A baseline was found by identifying values for the following constants:

- Predictions for additional new-build floor areas of each of the three UK building archetypes, across the study period, in m^2 per year [A_{LRD}, A_{MSD} and A_{MSN}];
- Predictions for quantities of structural timber consumption in a 'business-as-usual' scenario, in tons per m^2 of new built floor [$T_{LRD\text{-}0}$, $T_{MSD\text{-}0}$ and $T_{MSN\text{-}0}$];
- Assessment of current proportions (%) of each archetype that currently employ mass timber [$P_{LRD\text{-}0}$, $P_{MSD\text{-}0}$ and $P_{MSN\text{-}0}$];
- Evaluation of expected yield in a commercial forest growing structural timber, in tons per hectare [Y_0]^3;
- Evaluation of the baseline carbon sequestration deemed to be lost by harvesting mature structural, product-ready trees. When evaluating sources, care was taken to avoid confusion with losses from generalized deforestation, as this would be inappropriate to the felling of selected mature trees that have a limited future sequestration potential (data for these values were taken from studies primarily looking at well-established boreal forests in Canada and Scandinavia, with low species diversity. This was deemed appropriate as (1) these areas are regarded as having some of the most well-understood forest management practices in the boreal forest zones, and (2) this is where the UK is currently most likely to import structural timber from). Value in tons CO_2e per hectare per year ($tCO_2e/ha/yr$), [$C_{T\text{-}0}$].

Then, these were applied to the following equation:

$$C_{LOSS} = \frac{U}{Y_0} \times C_{T-0} \tag{1}$$

where utilization [U], in $tons_{HWP}$, is found by

$$\begin{aligned} U = (A_{LRD} \times T_{LRD-0} \times P_{LRD-0}) + (A_{MSD} \times T_{MSD-0} \times P_{MSD-0}) \\ +(A_{MSN} \times T_{MSN-0} \times P_{MSN-0}) \end{aligned} \tag{2}$$

where P_{LRD-0}, P_{MSD-0} and P_{MSN-0} are the current baseline proportion of buildings using this material approach in each archetype.

C_{LOSS} resulted from this, in tons CO_2e for each year of the study period. This represented the lost ability for that forested area to consume carbon across the study period. The studies from which these sequestration data were drawn included an understanding of how natural and artificial processes affect the net sequestration potential of a stand, and only studies where a low-intervention baseline was found were used.

A 'growth curve' was applied to account for variability in a tree's sequestration potential across its lifetime. It was assumed that harvesting would happen during its peak flow, before sequestration tails off. This should not be confused with any carbon lost to the atmosphere in the natural management of that forested area. This is to be accounted for in the notional $C_{T\text{-}0}$ value found in the literature. To map these data over time, the annual data were shown accumulating year-on-year.

2.2. Comparison Data

Once a baseline was established, data were collated that show the effects of changes in the application of efforts to improve outcomes in forestry. Higher growth-to-maturity yields are more likely to generate better future sequestration [16], and using data about when trees are most likely to take in carbon, in their life cycle, optimal stock management can be established. In the studies reviewed, varying interventions were tested (as listed in Section 1.2) and the best current estimate for maximized yield in carbon terms was found.

An index of 'forest success' ([F_S], in the range 0 to 1) was developed using data extracted from the literature, and this allowed the calculation of outcomes for a range of variable index values. A notional forest managing to bring an optimal number of secondary trees to maturity through their most carbon-extracting periods of growth, over the study period, was deemed to be "100% successful" (i.e., a F_S value of 1). Then, it was necessary to establish a value for that optimum carbon extraction (F_S = 1) for a given forest [$C_{T\text{-}MAX}$], in tons CO_2e per hectare per year. A 'business as usual' value for F_S was then found from [$C_{T\text{-}0}/C_{T\text{-}MAX}$]. The notional prediction for maximum future sequestration that can be reasonably connected to the harvesting of wood product, followed by the successful management of trees to maturity, was then be found by

$$C_{SEQ} = \frac{U}{Y_0} \times C_{T-MAX} \times F_S \tag{3}$$

C_{SEQ} resulted from this, in tons CO_2e for each year. This represented the maximum predicted sequestration from a forested area replanted and managed as a direct result of the prior harvesting. This can be found for varying values of success from low to high (e.g., baseline, 60%, 80% and 100%). Note that both the notional carbon loss and the expected sequestration are directly connected to the consumption of HWP (utilization, [U]). While the loss amounts added each year happen only once, the sequestration values for each year's new plantation continue to sequester over time, so these annual elements are accumulated on top of the prior year's accumulated sequestration.

True additionality, in tons CO_2e, was then found when the following equation returned a positive value:

$$C_{NET} = C_{SEQ} - C_{LOSS} \quad (4)$$

Values were found for these components and the analysis was conducted using a collection of tabulated calculations in the spreadsheet software Microsoft Excel, version 2501. A copy of the workbook can be found here: Data File. A typical calculation set for each archetype (three were mapped, plus "all"), forest success rate (four sample values were mapped) and conversion scenario (two limit states were mapped) used a cascading year-on-year table that gathered annual total sequestrations for each harvested forest area, and cumulative sequestrations from replanting, over the 25-year study period.

3. Parameters from the Literature

Values were found in the secondary data collection from the literature as follows (the full list of collected data, and their sources, can be found in the Appendix A):

3.1. Predicted Build Rates

Table 1 summarizes the results from reviews of the literature, where values were synthesized for each UK building archetype for additional floor areas likely to be added for each building archetype, in m^2 per year.

Table 1. Predicted build rates by archetype.

Area, by Archetype	Predicted Build Rate, m^2/yr
Low-rise domestic, A_{LRD}	6,000,000
Medium-rise domestic, A_{MSD}	2,200,000
Medium-rise non-residential, A_{MSN}	2,500,000
All archetypes combined, A_{ALL}	10,700,000

3.2. Timber Consumption

Table 2 summarizes the results from reviews of the literature, where estimates were made for the consumption of virgin timber, in kg per m^2 of new floor, in buildings where timber has become the principal structural material.

Table 2. Approximate consumption of timber by archetype.

Consumption, by Archetype	Consumption, kg/m^2
Low-rise domestic, $T_{LRD\text{-}0}$	30
Medium-rise domestic, $T_{MSD\text{-}0}$	120
Medium-rise non-residential, $T_{MSN\text{-}0}$	140

3.3. Conversion Estimates

Table 3 summarizes the estimates for baseline, showing them with the maximum notional conversion rates that were used in the analyses.

3.4. Other Values

Table 4 lists other values found. Key amongst these are the values for 'baseline' and 'maximum' sequestration deemed to be likely on the two extremes of our study parameters. The specifics of the studies used here are in Appendix A, Tables A8 and A9.

Table 3. Shares of new floor builds by archetype, baseline and maximum.

Archetype		Share of New Floor Builds
Low-rise domestic	Base., P_{LRD-0} Max., $P_{LRD-MAX}$	22% 100%
Medium-rise domestic	Base., P_{MSD-0} Max., $P_{MSD-MAX}$	3% 100%
Medium-rise non-residential	Base., P_{MSN-0} Max., $P_{MSN-MAX}$	3% 100%

Table 4. Other found values.

Value Name	Value Found
Fixed yield, Y_0 Baseline seq., $C_{(T-0)}$ Max. seq., $C_{(T-MAX)}$	61 t_{HWP}/ha 1.5 tCO_2e/ha 3.6 tCO_2e/ha

3.5. Forest Success Index

From the results of the findings for $C_{(T-0)}$ and $C_{(T-MAX)}$, above, the value "1" was set at 3.6 tons CO_2e per hectare annually. This puts baseline levels (1.5 tC/ha) at F_S = 0.416 on the index (see Figure 1).

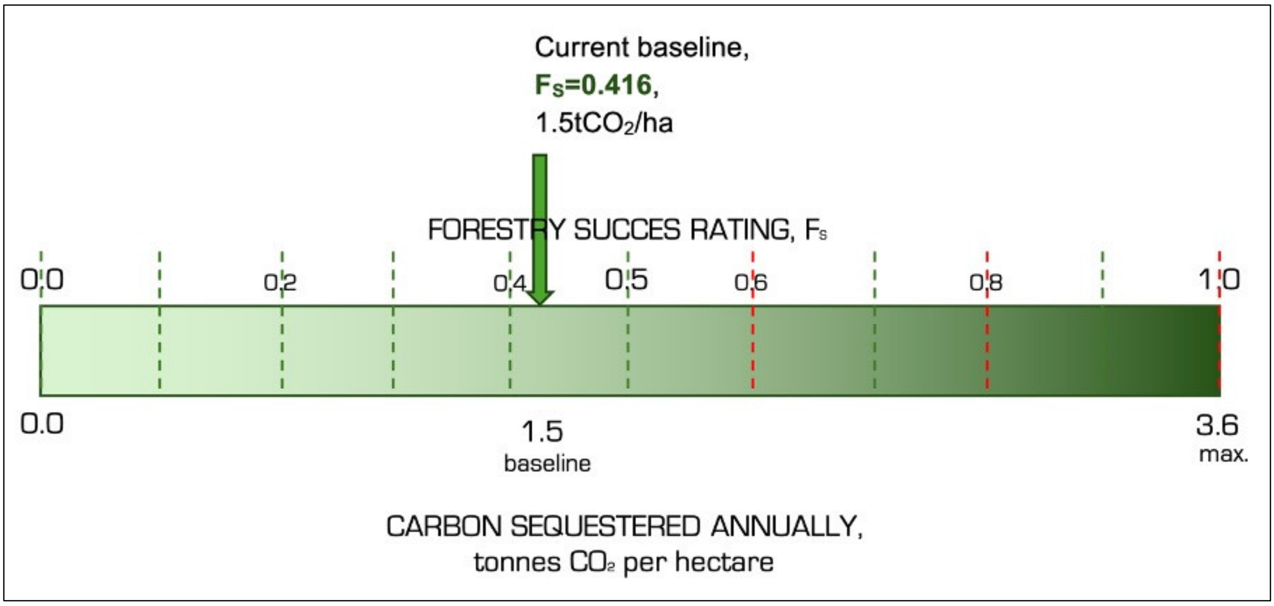

Figure 1. Establishment of forest success index, F_s. Arrow is shown at the baseline index level. Green dotted lines are gradations from 0.0 to 1.0, in increments of 0.1. Red dotted lines are the levels at which outcomes are tested in the research.

4. Results

Values were found in the secondary data collection from the literature, as follows:

4.1. Forest Success vs. Total Sequestration, over Time

Overall, the data indicate that a net benefit is possible, with enhanced activity in carbon-focused forestry. To show the relationships among forestry success rates, the cumulative sequestration was charted against the cumulative losses from harvesting over the same period. Having established that 'business as usual' sequestration in managed forests was around 41.6% of a theoretical 'maximum' (see Section 3.5), the data were extracted for sets of iterations of the chart for F_S = 0.42, F_S = 0.6, F_S = 0.8 and F_S = 1.0. The principal observation in this data set—with respect to the point at which net sequestration becomes positive—was that the data are not sensitive to the different archetypes being examined.

This is to be expected in iterations of the data where the variables affecting relative sequestration (versus losses) are the same. Absolute differences in the masses of carbon sequestered *do* vary significantly, and this is examined in Section 4.2. In Figure 2, relative sequestration is plotted over time with losses shown, for each UK building archetype, and for two limit state scenarios: 'business as usual' (BAU), where timber holds its current market share relative to RC and steel (charts (a), (c) and (e)); and 'Max. shift...', a condition in which all buildings of that archetype convert to timber frame or mass timber (MAX, charts (b), (d) and (f)). This second scenario is recognized as neither realistic nor desirable but is used here to demonstrate a limit state.

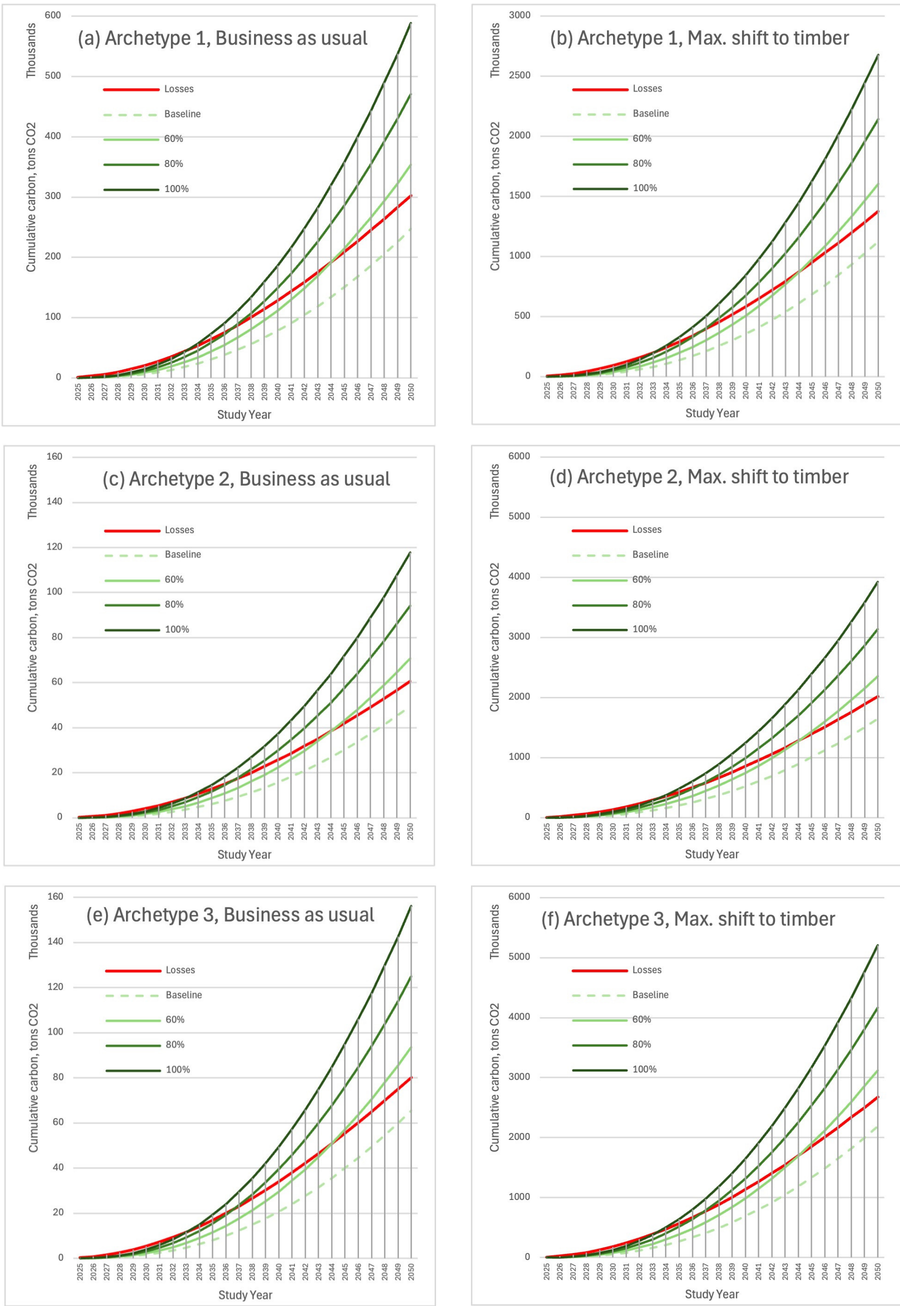

Figure 2. Sequestration vs. losses, in archetypes 1 to 3; BAU (**a**,**c**,**e**) and MAX (**b**,**d**,**f**).

Figure 3 collates all three archetypes into a single chart, again, for each scenario. Note that y-axis values have been adapted in each case to show how the curves are consistent across all archetypes and scenarios (albeit with varying absolute values).

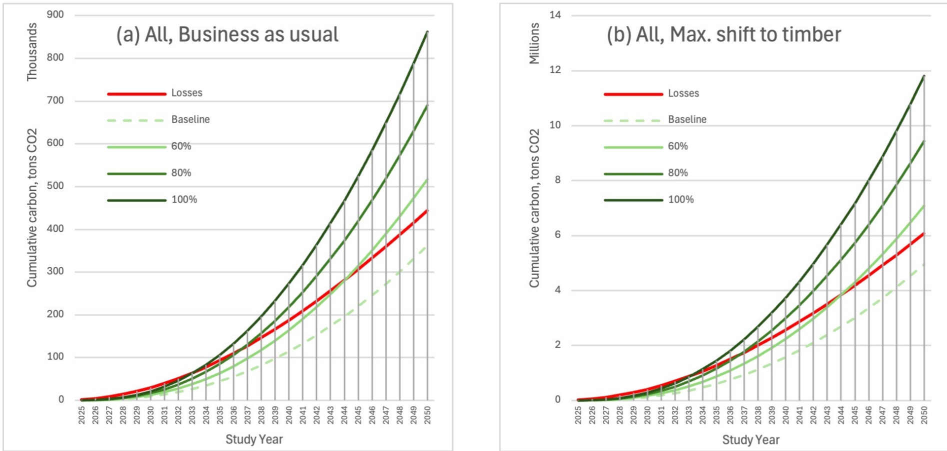

Figure 3. Sequestration vs. losses, all archetypes combined; BAU (**a**) and MAX (**b**).

In each case, the baseline rate of forest management ('business as usual' in that context) fails to show a net benefit over time. Improvement to F_S = 0.60 yields a net benefit by the end of the study period, but a value of F_S = 0.80 or better is required to give a more powerful and beneficial sequestration picture. Showing a net benefit by 2050 requires a value of at least F_S = 0.52 in any scenario of conversion, from BUA to MAX. Table 5 shows the study year in which carbon becomes net positive in all archetypes and scenarios, and this is shown in the charts in Figure 4.

Table 5. Study year in which CNET becomes positive.

Forest success index, F_S	F_S = 0.419	F_S = 0.60	F_S = 0.80	F_S = 1.00
Study year	(beyond the study period)	2044	2036	2033

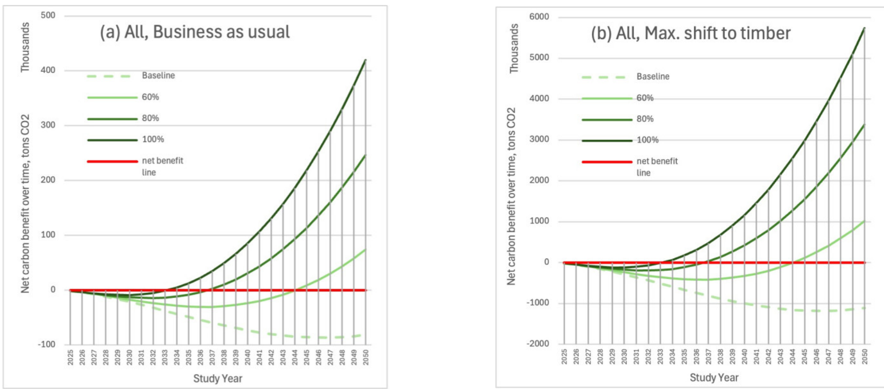

Figure 4. Timings of net benefits for four tested F_S values, for all archetypes combined; BAU (**a**) and MAX (**b**).

For all future states of uptake in timber use, for any archetype, a net sequestration benefit could happen as early as 2033. However, this would require forest management techniques to be improved immediately to provide maximum possible sequestration rates in a F_S = 1.00 scenario (sequestering ~3.6 tons CO_2 per hectare annually), which is neither feasible nor desirable, and exists here merely as a limit state demonstration of potential.

4.2. Total Sequestration by Archetype

Studying the rates of transfer within the three UK building archetypes offers an opportunity to evaluate absolute sequestration rates and total cumulative benefit values over the study period. It is acknowledged here that a 'MAX' conversion amount, for all archetypes, coinciding with immediate forest management rates of F_S = 1.00 is extremely unlikely, but they exist in the study as limit states for illustration. In such a scenario, the data show that 5.3 million tons of CO_2 could be additionally sequestered by this method alone in the years to 2050 (see Figure 5).

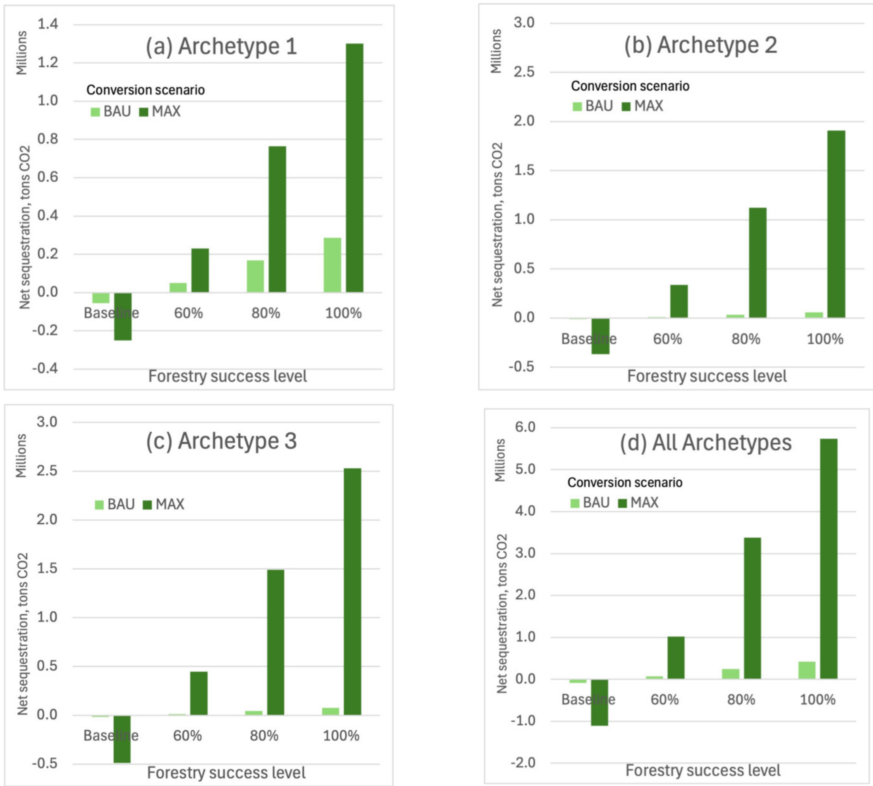

Figure 5. Absolute levels of total sequestration by 2050 for each archetype, each F_S standard, and each conversion scenario: (**a**) each F_S and conversion scenario for archetype 1; (**b**) each F_S and conversion scenario for archetype 2; (**c**) each F_S and conversion scenario for archetype 3; (**d**) each F_S and conversion scenario for all archetypes combined.

Applying pressure to pursuade substantial parts of each sector to convert to building in timber could create significant amounts of net sequestration potential. For F_S values above F_S = 0.52, all three archetypes benefit by impressive multiples. Table 6 shows the multiplying potential in each archetype. Treating maximum conversion as unlikely, even modest shifts in material use show a worthwhile benefit. Archetype 3 shows the most powerful results. Shifting from 3% to 34% market share by 2025, and holding steady at that level, would provide 10 times more sequestration potential overall. At F_S = 0.60 (a modest improvement on the baseline F_S), this equates to a new additional sequestration of 448,000 tons of CO_2 over 25 years. This is the equivalent of one year's emissions from nearly 100,000 petrol engine family cars [17].

Table 6. Multiplying potentials.

Archetype	1	2	3	All
Multiple of added sequestration by 2050 in a 'MAX' conversion scenario	3.5×	32.3×	32.3×	12.7×

However, as noted, any expectation of such a sudden shift is unrealistic, but in order to demonstrate real-world potential, this study finds that steadily adding annual growth up to 20% market share by 2050, at forestry management rates that reach F_S = 0.80 over the same time frame, would still garner approximately 230,000 tons of additional sequestration. It should also be noted that real rotation periods in forests managed for carbon are more likely to be in excess of 60 to 75 years, so—despite this study's period being limited to the 25 years up to 2050—the real impact of such actions can have long-lasting sequestration impacts.

It should be remembered, however, that at F_S rates under F_S = 0.52, extracting timber from even sustainably managed forests will have a net detriment on future sequestration and any increased shift toward building in timber in this scenario only makes this worse. This may not mean that such shifts are without justification, but in these cases, a claim of future atmospheric net benefit would not be possible.

5. Findings Discussed

It is found that there are levels of forest management that produce net-beneficial outcomes for carbon, when regenerative forestry is taken in isolation as a direct aftereffect of harvesting. When considered more broadly—to include the carbon stored in the long-life building stock, and the carbon saved by displacement effects—the argument for a measured move toward timber in construction is powerful. Findings in this study—which reinforce previous study findings—are supportive of the hypothesis that an augmented methodology for post-harvest forest management can be found that optimizes for carbon draw-down.

Furthermore, there are conclusions showing that forestry practices that do not maximize carbon management will lead to a reduction in the potential to claim net benefit, in some cases to zero. In these cases, a promoter of timber's selection in each use-case will need to be satisfied by just the carbon storage and displacement benefits alone and should avoid making suggestions that the selection is meaningfully 'carbon negative'. This was found particularly to be the case with typical values of sequestration likely to be happening in managed forests today. This implies that in such cases, there would be no additionality in the global balancing of GHG emission through an increased use of timber.

However, there remains a tension between the apparent climate benefit of increasing forest management techniques (for maximized sequestration behaviors) and the resultant availability and rotation times of roundwood stock in that forest. This means that perhaps there is a need to separate the following ideas:

1. The forest being there as a regenerative asset, replacing the lost carbon at initial felling, with intensive carbon-management processes;
2. The ability—or even requirement—of that forest to provide future rotations of roundwood supply, at rates previously assumed to be possible.

It should also be noted that—for all the talk of timber being important in the fight against climate change (which the results of this study further support)—the scale of the atmospheric carbon-concentration challenge must not be underestimated, and there should be no implication from this study that a mass switch to timber, and natural building materials in general, is a silver bullet to this problem. Even with all efforts directed towards maximizing draw-down, the global potential for sequestration is thought to be only 3.6 Gt CO_2e annually [18], whereas the gap highlighted by Friedman et al. [6] was thought to require as much as 5 to 10 Gt CO_2e of extraction.

As a renewable—and potentially regenerative—product, timber clearly offers several distinct benefits over non-renewable and high-EC materials, and this study presents proposals for changes to the way these are accounted for. But the modest nature of this future sequestration potential—whilst welcomed—may not be enough to justify a massive shift to timber, as the risk of land-use, water-stress and biodiversity impacts must be considered too. The recommendations that follow, therefore, focus on using this knowledge to promote a safe and measured increase in the use of timber in UK construction. This has been shown, by this study and others, to be entirely reasonable, and with multiple strands of justification.

In processes where effects are compounded, early and significant actions create deeper impacts, as their value accumulates over time, so a common theme in the results is to act early, to gain as much benefit as possible. However, as has been discussed in this section already, immediate conversion to timber is going to be difficult in all archetypes, as is any significant change to the carbon impact in modern forestry techniques. This difficulty makes it even more important to apply any changes that can be made, as soon as possible, to maximize their impact. The outcomes of this study offer numerical indicators of the scale of effects that can be made for any given action, where this was previously difficult to establish. It is encouraging to see that even modest improvements from the current state can deliver better outcomes. Only slight improvements in forest management (for carbon benefit) offer the chance for timber promotors to do so in the knowledge that increases in market share will deliver truly additional future sequestration.

6. Conclusions and Recommendations

With the climate crisis increasing in threat and magnitude year after year, it is imperative to find every possible avenue that reduces current impacts and mitigates future ones. Using more timber in construction arguably offers such benefits: It is a lower carbon material than the alternatives it can replace (e.g., steel and concrete), thus reducing emissions now, and it is a carbon-storing material that can lead to future mitigation potential if the trees harvested for timber are successfully replaced with new trees that, by surviving to maturity, add to the net carbon stock of the forest.

While this works logically, its practical effectiveness depends on the success rates in forest management to see if and when the initial removal of trees for timber is eventually outweighed at a later date by a net carbon benefit. This paper has addressed this specific issue by focusing on three archetypes in the UK context where increasing levels of timber use are possible.

6.1. Recommendations

Having found that a net carbon benefit is indeed possible, with relatively modest improvements in forest management, the conclusions highlight several areas where action could be taken. The confusion over how carbon is accounted for in biogenic materials was found in the literature review to be at the heart of the issue surrounding claims made in this area. The findings of this study point to a need to state the case for when there truly is a net carbon benefit and make efforts to separate this from other ways in which carbon is measured in WLC analyses.

With specific reference to the conclusion that contemporary forest management methods (which may not optimize for carbon drawdown) are unlikely to be providing enough future sequestration to justify increased timber use by that measure alone, it is recommended that promoters of timber in construction act in the following ways:

- Avoid making this connection where it is now known to be untrue;
- Only focus on the long-term storage benefits in relation to past-sequestered carbon;
- Seek to build systems for connecting sourcing with carbon-optimized plantations.

6.1.1. Clarifications in Existing Methodologies

In the RICS's WLC methodology, taking past sequestration and binding it into the account as a negative, only for it to be added back later as a record of it being released back to atmosphere at end-of-life, introduces confusion around the notion of sequestration and what it means for timber's efficacy as a low carbon product. This has been shown in this study to invite the idea that future sequestration can also be connected to this. This can be likened to a jar of mixed currencies, where each one has its own real value, but the combination of values is inappropriate, and leads to a confused understanding of the total value in the jar.

Representations from the timber industry are already being made to RICS to extend the modeled building life well beyond the current 60-year benchmark, proposing that 120 years is more appropriate [19]. This would bring past-sequestered carbon into greater focus as a claimed value, as it would no longer be discounted at end-of-life and lead to even greater confusion in the accounting. If stored biogenic carbon were to be deducted from embodied carbon in this way, in almost all cases, this would show timber—inappropriately, it is found here—as being carbon negative. It is possible that this could become the case in life cycles as short as only 75 years.

As has been shown, any such rating could lead consumers to assume that a positive impact on current and future atmospheric carbon is tied in, when it remains unclear if this claim can be made in good faith without knowing more about how the source forests are being managed. It is recommended that the move to extend the study life for WLCs is coupled with a clarification strategy whereby stored biogenic carbon is highlighted as a separate and valid additional benefit, outside of the calculation for embodied carbon, and that future sequestration potential is found separately too. In this way, confusion over which specific area of carbon benefit is being claimed in WLCs will be reduced, and overall claims of the carbon benefits of building in timber can be strengthened by this multi-value approach.

6.1.2. A New Standard for Forest Management

Having established that a well-managed forest can make a variety of process changes that would enhance sequestration potential, the findings of the research call for a standard to be introduced such that forest management can be rated for efficacy in terms of optimized carbon sequestration. The two most common forestry standard schemes used in the UK (PEFC and FSC) are now decades old and were effective at establishing the 'Chain of Custody' methodology for source-checking consumed timber. At the introduction of these schemes, the intent was to make a binary adjudication over whether any given forest source could be deemed to be managed to a satisfactory standard, in sustainability terms.

The outcome of this research supports a move to a *graded* badging system for forestry standards whereby certification is based on annual carbon acquisition data. Forests making efforts to optimize for carbon draw-down can be graded as such. Ratings based on tons CO_2 per hectare can be used to score the forest against a benchmark. As data on the required benchmarks improve, periodic reassessments can rate a forest on how well it is performing against this standard. Environmental performance declarations (EPDs) currently using embodied carbon data for timber from given sources would then be able to state the forest management success grading alongside the embodied carbon value.

Consumers and specifiers would then be in no doubt as to the true efficacy of timber being selected for its carbon sequestering potential. Possibly, timber from better managed forests could even generate green premiums that work as incentives, similar to how organic agriculture yields produce that garners higher price points in the market.

The actual interventions being used in each case are not so important as to be stated in this grading system, as it is expected that the opportunities for carbon-specific improvements will be well known to each forest's managers. However, it is important to recognize that optimizing forests for carbon alone may lead to other impacts on water security and/or biodiversity, so grading a timber source for carbon impact alone may be inappropriate without reference to other impacts.

6.1.3. Developing a Tool

A visual tool that demonstrates the effects of changes in behavior, to help policy makers and specifiers understand the impacts of material selections, and the immediacy of actions is recommended. As part of the analysis of data carried out in this study, a dynamic set of output charts was developed using sliders to increase or decrease values and see how this affected total net sequestration over time, and how soon or late this happens. A demonstration is in the Supplementary Data File in this repository.

In its present form, it is possible to use the tool to see indications of the outcomes of behavior changes across a range of areas that were covered in this study. The results of early or late action, and minimal and maximum conversions of material uses within each archetype, can be seen, and in each case, the absolute sequestration value, the year in which the action becomes net beneficial and the annual carbon sequestration rate in the source forests required to achieve this are all estimated.

6.1.4. Future Research

It is recognized that a full analysis of primary data (required to arrive at more accurate values) is beyond the scope of this research design, and that this limits the applicability of the outcomes and the conclusions arrived at. It is, therefore, proposed that more accurate data are sought on the levels of sequestration that can be found in a current typical forest, and that which might be feasible in a 'maximum sequestration' operational scenario. In this way, the simplistic scheme applied herein, to evaluate forest management success ("F_S"), can be recalibrated and made more accurate. This would facilitate the modeling required to arrive at the graded badging scheme proposed above and provide even more reliable benchmarks for demonstrating true net carbon benefit.

The accuracy of predictions and—more importantly—the thresholds at which behaviors can claim true additionality will be improved if primary research is carried out to establish values arrived in the data collection. A future iteration of the tool discussed above would benefit from using these more accurate data points, as would the benchmarking used in the establishment of the grading system proposed in Section 6.1.2.

Supplementary Materials: The following supporting information can be downloaded at https://doi.org/10.6084/m9.figshare.28466180.v2.

Author Contributions: Conceptualization, A.G. and F.P.; methodology, A.G.; spreadsheet programming, A.G.; validation, F.P.; formal analysis, A.G.; investigation, A.G.; resources, A.G.; data curation, A.G.; writing—original draft preparation, A.G.; writing—review and editing, F.P.; visualization, A.G.; supervision, F.P.; project administration, A.G. and F.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was approved by the Ethics Committee of the University of Cambridge and deemed not applicable, for studies not involving humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are openly available in FigShare at https://doi.org/10.6084/m9.figshare.28466180.v2.

Acknowledgments: Kind support with conceptual rigor and industry expertise was provided by Colin Rose, University College London (UCL); Martha Godina, Elliott Wood; Charlie Law, Timber Development UK (TDUK); Andy Lietch, Confor; and Chris Gaze; Structural Timber Association (STA) and Future Homes Hub (FHH). Editing and review help was kindly provided by Morwenna Spear, University of Bangor. Our thanks to all.

Conflicts of Interest: Andy Gibson is a technical director in a timber frame panel manufacturing business and is active in the promotion of timber as a building material through work on committees within the Structural Timber Association, TDUK and the Future Homes Hub.

Appendix A

The data collected, and their sources, are as follows:

Table A1. Archetype 1 ([$_{LRD}$]) predicted floorspace addition.

Authors	Date	Synthesized Value Taken
Drewniok, Dunant, Allwood et al. [20]	2023	6.6 million m^2/yr, falling to 5.84 m
ONS [21]	2023	~12 million m^2/yr

Table A2. Archetype 2 ([$_{MSD}$]) predicted floorspace addition.

Authors	Date	Synthesized Value Taken
Drewniok, Dunant, Allwood et al. [20]	2023	2.5 million m^2/yr, falling to 2.16 m
NSC [22]	2022	3 million m^2/yr
ONS [21]	2023	~10 million m^2/yr

Table A3. Archetype 3 ([$_{MSN}$]) predicted floorspace addition.

Authors	Date	Synthesized Value Taken
Drewniok, Azevedo, Dunant et al. [23]	2023	2.5 million m^2/yr
NSC [22]	2022	3 million m^2/yr

Table A4. Relative material consumptions.

Material Forms	Material Intensity, kg/m^2		Carbon Intensity	
	2–5 Stories	6–10 Stories	Kg CO_2e/kg	Kg CO_2e/m^2
Concrete (solid floor)	470–485	485–515		60–75 [24]
Concrete (ribbed deck)	405–420	420–440		55–70 [24]
Hot rolled steel	55–65	65–75	1.41 [25]	78–106
Timber	30–35	35–45	0.19 [26]	6–9

Table A5. Material consumptions for mass timber, from Skullestad et al. [27].

No. of Stories	Typical Glulam and CLT Content Using Density 0.479 tons/m^3)
3	108
7	121

Table A6. Market share for timber as the principal material, from NSC [22] and Eurban [28].

Archetype	Current Market Share
(1) LRD	22%
(2) MSD	3%
(3) MSN	3%

Table A7. Baseline yield value, tons HWP.

Authors	Date	Synthesized Value Taken
Pyörälä et al. [29]	2014	58 tons per hectare
Baul et al. [30]	2017	69 tons per hectare
Hynynen et al. [31]	2015	58–64 tons per hectare

Table A8. Baseline sequestration [$C_{T\text{-}0}$], tons CO_2e.

Authors	Date	Synthesized Value Taken
Pyörälä et al. [29]	2014	1.3 tons per hectare
Kurz et al. [14]	2013	2.5 tons per hectare
Lindner et al. [15]	2014	2 tons per hectare

Table A9. Maximum sequestration targets [$C_{T\text{-}MAX}$], additional tons CO_2e.

Authors	Date	Synthesized Value Taken
Baul et al. [30]	2018	1.8 tons per hectare
Kurz et al. [14]	2013	1.5 tons per hectare
Lindner et al. [15]	2014	1 tons per hectare

Full explanations for the synthesis of each value used in the calculation can be found in the full study dissertation report, a copy of which is loaded into the dataset repository https://doi.org/10.6084/m9.figshare.28466180.v2.

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