Environmental Research Letters

LETTER • **OPEN ACCESS**

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To cite this article: Mark E Harmon 2019 *Environ. Res. Lett.* **14** 065008

Environmental Research Letters

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OPEN ACCESS

RECEIVED
12 May 2017

REVISED
7 March 2019

ACCEPTED FOR PUBLICATION
1 May 2019

PUBLISHED
21 June 2019

LETTER

Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions

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Keywords: forest sector, carbon storage, forest management, climate mitigation, forest ecosystems

Supplementary material for this article is available online

Abstract

Substitution of wood for more fossil carbon intensive building materials has been projected to result in major climate mitigation benefits often exceeding those of the forests themselves. A reexamination of the fundamental assumptions underlying these projections indicates long-term mitigation benefits related to product substitution may have been overestimated 2- to 100-fold. This suggests that while product substitution has limited climate mitigation benefits, to be effective the value and duration of the fossil carbon displacement, the longevity of buildings, and the nature of the forest supplying building materials must be considered.

Introduction

Forest ecosystems represent important stores of global terrestrial carbon and are the focus of possible climate mitigation strategies [1–3]. Along with that stored in forest ecosystems, carbon can be stored in wood products in-use and after disposal [4, 5]. Another way forests could mitigate climate change is through product substitution, a process whereby products from the forest substitute for others (i.e. concrete and steel) which, if used, would result in more fossil carbon release to the atmosphere [6–16]. While wood-based building materials generally embody less fossil-derived energy in their manufacture than steel and concrete, resulting in a net displacement of fossil carbon, its effectiveness as a climate mitigation strategy depends on the amount of carbon displaced and its duration. Current estimates of climate mitigation benefits of product substitution are generally based on three critical, often unstated assumptions: (1) the carbon displacement value remains constant [8–16], (2) the displacement is permanent and therefore of infinite duration [12–16] which implies no losses via cross-sector leakage, and (3) there is no relationship between building longevity and substitution longevity [10]. Below, each of these assumptions is reviewed.

Although most analyses of product substitution benefits implicitly assume a constant displacement value over time [8–16], it is subject to change. Schlamadinger and Marland [12] hypothesized energy substitution displacement values increase over time because of increased efficiencies. For product substitution, I hypothesize it will likely move in the opposite direction for three reasons. First, changing manufacturing methods impact embodied energy: for example, as long as it is available, the addition of fly ash could lead to a 22%–38% reduction in embodied energy required for concrete reducing the displacement value [17]. At the same time, increased processing of wood to create materials suitable for taller buildings (e.g. cross laminated timbers) would likely lead to a lower displacement value given laminated beams have 63%–83% more embodied energy than sawn softwoods [9, 17]. Second, the increases in energy efficiency hypothesized by [12] related to rising energy costs and recycling [9, 18, 19] and as noted by [8, 16] would also result in a decrease in product substitution displacement because the key relationship involves the difference in emissions and not the ratio as in energy substitution [20] (see supplemental information is available online at stacks.iop.org/ERL/14/065008/mmedia for detailed analysis of the displacement formula). Finally, changing the mix of fossil fuels used to generate energy can also substantially change the amount of carbon released per unit energy consumed and if natural gas continues to increase relative to coal, as has been observed [21], then the displacement value would likely decline in the future. The same is true if non-fossil energy sources such as solar, wind, or hydropower are increasingly used as projected [22].

One possible mechanism leading to permanent displacement is that fossil carbon not used by the building sector is also not used in any other sector in the future. However, this seems unlikely given carbon leakage [20, 23–25]. While the rate of product substitution-related leakage is difficult to estimate (in part because the form and location of the fossil carbon is not specifically known), it is unlikely to be zero given fossil carbon-based fuels are expected to be depleted in the next 107–235 years [26, 27] (see supplemental information). Even if these depletion time estimates are off by centuries, the duration of the displacement is not infinite and the claim that 'saved fossil emissions are forever' [12] is untenable. I hypothesize that without a mechanism to prevent its use, that fossil carbon displaced by product substitution will gradually be released by other sectors and will not be excluded from depletion as implied by [10, 12].

The key assumption of no relationship between product longevity and product substitution longevity has been asserted [10], but not fully explained. If there always is a preference for non-wood building materials, then avoiding their use avoids fossil carbon emissions, hence the displacement would continue to accumulate [20]. However, if wood is preferred then the use of wood does not necessarily increase cumulative displacement [20]. Despite differences in regional preferences for wood [28], most if not all assessments of product substitution tacitly assume wood is not preferred and that preferences never change. As a consequence, the product substitution store never saturates and implying there is no negative feedback in the net cumulative displacement. In all other forest-related carbon pools, a negative feedback exists between pool size and output (i.e. they are donor controlled systems): the larger the pool size, the larger the output flow. This causes these pools to saturate in time as long as the input remains constant. It is striking that this behavior is true for wood products, but not for product substitution (see supplemental information). In [12] product and energy substitution are treated the same. However, I believe they are quite different. In the case of energy, once energy is used it does not have a lifespan or store per se. However, in the case of wood products when the product lifespan is exceeded it has to be replaced with either wood-based or some other materials. If it is the former, the fossil carbon displacement continues, but does not necessarily increase [20] (see supplemental information). If it is the latter, the fossil carbon that was displaced is released to the atmosphere [20]. I therefore hypothesize that when wood is or becomes the preferred building material the product substitution pool has a negative feedback directly related to building longevity.

The objective of this study is a sensitivity analysis of these three assumptions and their impact on projected climate mitigation benefits. In addition to examining each assumption separately, I examined how they might work together to determine whether product substitution carbon benefits eventually become as large relative to the forest ecosystem and harvested materials as previous analyzes suggest [10–15]. To perform this analysis I used a relatively simple landscape model assuming an idealized, regulated system and focused on conditions in which product substitution benefits would be highest (i.e. clear-cut harvest, high manufacturing efficiency, and maximum use of products in buildings). The cases examined are therefore illustrative of the kinds of behavior the assumptions create, but not an exhaustive analysis of all forest ecosystems, management or manufacturing systems. Nor does the analysis try to identify the most likely values of displacement factors, carbon leakage, or product lifespans: e.g. [29, 30].

Methods

Each of the three assumptions was examined individually and then jointly for three contrasting initial conditions using a simple landscape model[1] that tracks the stores for the live, dead, and soil carbon pools in the forest ecosystem, the products in use and disposal, and the virtual carbon stores associated with product substitution. Each of these pools was modeled as a simple input–output, donor controlled sub-model following first order dynamics in which the output was regulated by a rate-constant describing the fraction lost per year. For product substitution, the fossil carbon displaced was the input, and losses were associated with use of fossil carbon by other sectors (hereafter called leakage losses) and those associated with the replacement of wooden buildings (hereafter called replacement losses). All simulations were conducted for a 300 year period as in [8] using a 50 year harvest cycle.

Displacement decline

In this set of simulations I assumed no losses associated with leakage or building replacement. The initial displacement value of 2.1 Mg C per 1 Mg C wood use [20] was reduced by 25%, 50% and 100% over either a 25, 50, or 100 year period. The 100% decline represents the possibility that fossil carbon will be completely replaced as a source of energy in the location of manufacture. As a control, the displacement value was assumed to not decline.

[1] A more complete description of the model and parameters are available as supplemental information online.

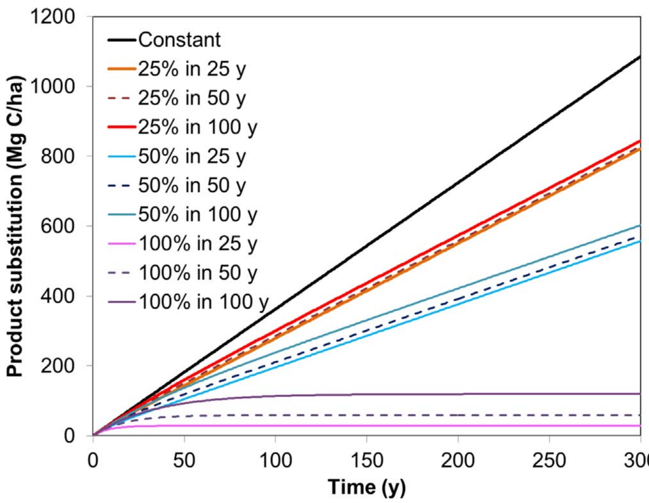

Figure 1. Accumulation of product substitution carbon when displacement is reduced 25%–100% over a 25–100 year period for a 50 year clear-cut harvest interval. For these simulations losses via leakage and replacement were zero[3].

Leakage losses

In this set of simulations I assumed the displacement value remained 2.1 Mg C per 1 Mg C wood use and there were no losses associated with building replacement. To examine the sensitivity of substitution benefits to cross-sector leakage, I simulated five possible scenarios: (1) no leakage, (2) 12%, (3) 6%, (4) 3%, (5) 1.5%, (6) 0.75, and (7) 0.375% yr^{-1}. In these scenarios leakage via other sectors was assumed to be continuous and not a one-time phenomenon. While expressed as a constant percentage lost per year, these values imply depletion times ranging between 25 and 800 years, which are 71%–340% of the currently estimated range of 35–235 years [26, 27].

Replacement losses

In this set of simulations I assumed the displacement value remained 2.1 Mg C per 1 Mg C wood use and there were no losses associated with cross-sector leakage. I varied the average building life-span to be 25, 50, 100, and 200 years, which bracket current estimates[2]. To provide a comparison to past studies, I reduced replacement losses to zero since this parameterization mimics the consequences of assuming no relationship between building longevity and product substitution longevity (see supplemental information).

Overall effect

To assess the overall effect of product substitution assumptions I examined a clear-cut system for three possible initial conditions: (1) an old-field planted to a production forest, (2) a production forest that originated from an old-growth forest landscape that began conversion 100 years ago, and (3) an old-growth forest converted to a production forest. In each case I assumed that 65% of the live carbon would be harvested, that 75% of that harvest would be converted into buildings. To explore the sensitivity of the assumptions on their overall impact I used the displacement and leakage loss parameter values that gave the minimum, median, and maximum effect based on the earlier simulations. In the case of replacement losses, I assumed an average building lifespan of either 50 years, 100 years, or an infinite number of years. The various combinations resulted in 47 simulations per initial condition. The model parameterization was based on a productive forest in the Pacific Northwest, a major source of wood building materials and US carbon stores [31].

[2] Estimates of housing longevity are highly variable with exponential rate-constants ranging from 0.0069/y to 0.03/y [12–16]. In some cases building longevity has been modeled as a step function, with rapid losses after 80 years [10–11]. These estimates give an average lifespan or turnover time of 33–144 years. I explored a range of 25 to 200 years to bracket this uncertainty. Note that the average lifespan is not the same as the maximum lifespan of buildings: for an average lifespan of 50 years, the maximum lifespan would be over 230 years.

Results

Displacement decline

There was a direct relationship to the total product substitution virtual store and the degree displacement declined, although the faster the decline in the displacement, the lower the final value (figure 1). For example, a 25% decline in 25, 50, and 100 years led to a final reduction in the product substitution virtual store of 24.3%, 23.6%, and 22.3%, respectively. This suggests that while the timing of the decline had an effect, the major response was to the level. The product substitution virtual store saturated only for the cases in which displacement went to zero and even if this took 100 years, product substitution stores estimates at 300 years were reduced by ≈89%.

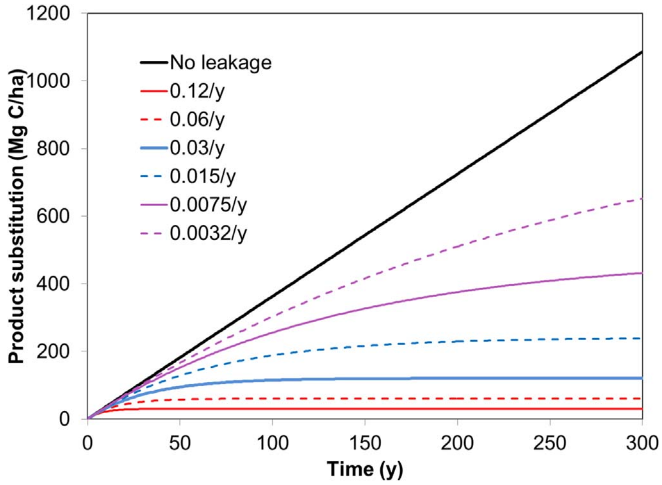

Figure 2. Accumulation of product substitution carbon when the time for displacement to be lost via leakage varies from 25 to 800 years for a 50 year clear-cut harvest interval. Displacement was assumed constant and replacement losses zero[3].

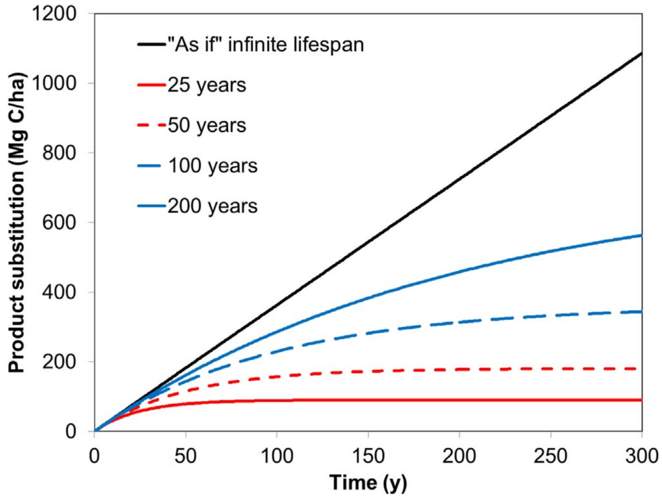

Figure 3. Accumulation of product substitution carbon when the average longevity of building varies for a 50 year clear-cut harvest interval. For these simulations displacement was constant and there were no leakage losses[3].

Leakage losses

Regardless of the time required for cross-sector leakage to occur, this process substantially limited the product substitution virtual store relative to the case without leakage (figure 2). With a leakage as low as 0.375% yr^{-1} (≈one-third the current estimate of the minimum depletion rate [27]) the store at 300 years was ≈40% lower than when there was no leakage. If the leakage rate-constant was 12% yr^{-1}, then ≈97% less would be stored relative to the no leakage scenario. Moreover, if the current range of depletion times (i.e. 35–235 years) is correct, then cross-sector leakage would reduce the estimates by 78%–96%. This indicates that leakage via other sectors may substantially undermine any attempt to displace fossil carbon using product substitution.

Replacement losses

For an average building longevity of 50 years the product substitution store at 300 years was ≈17% of that of the case in which product substitution behaved as if it had infinite lifespan (figure 3). Even when average building lifespan was 200 years, this store at 300 years was ≈52% that of when product substitutions behaved as if they had an infinite lifespan. This indicates that assuming no relationship between product substitution lifespan and building lifespan overestimates benefits.

Overall effect

Product substitution, estimated using past assumptions regarding displacement decline, leakage, and relationship to building longevity, increased for each initial condition; increasing the most when old-growth forests were harvested (figure 4). When alternative assumptions about product substitution were used, the shape of the product substitution accumulation curve varied: generally increasing for the old-field conversion to an asymptote, decreasing or increasing

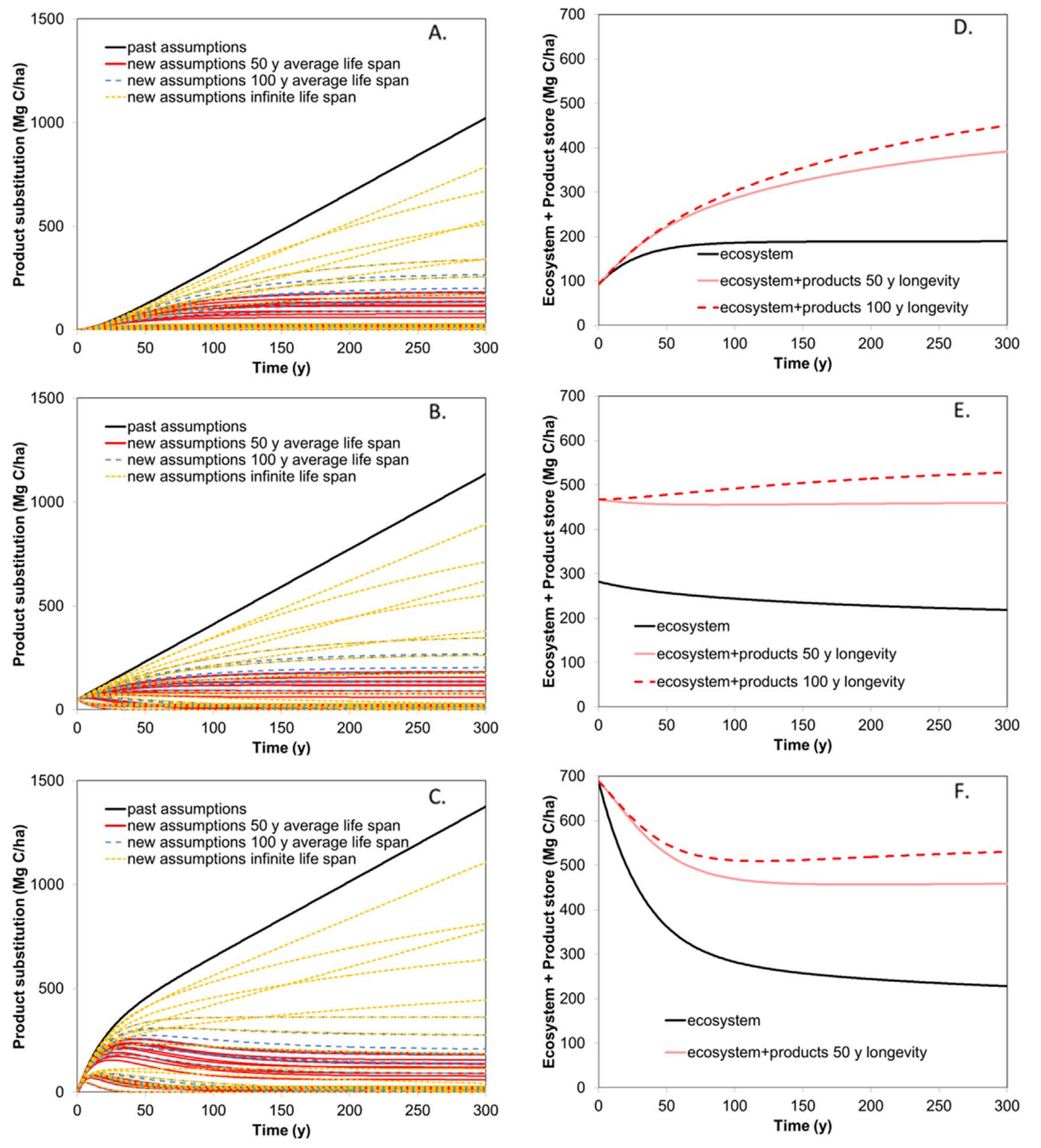

Figure 4. Accumulation of ecosystem, products in-use and disposed, and product substitution carbon stores for a 50 year clear-cut harvest interval in the Pacific Northwest for three possible scenarios: a plantation forest established on an agricultural field (A), (D); a production forest system that is continued (B), (E); an old-growth forest replaced by a forest plantation (C), (F). For past assumptions there was no decline in displacement value, there was no leakage, and buildings were assumed to have an infinite lifespan[3,4].

to an asymptote for the plantation system depending on replacement assumptions, and for most combinations reaching a peak at 10–40 years for the old-growth forest converted to a plantation scenario. This analysis indicates that to increase the overall amount of carbon stored in the system, that conversions of old-growth forests in the Pacific Northwest to plantations should be avoided, whereas creation of plantations on old-fields should be encouraged. Moreover, existing plantation systems are unlikely to increase their carbon stores unless building longevity is substantially increased (figure 4(e)).

Regardless of the initial conditions, product substitution was lower when alternative assumptions regarding displacement decline, leakage, and relationship to building lifespan were used, ranging from virtually zero to 80% of the past assumptions at year 300 depending on the parameter values assumed (tables S-2 to S-4). At the very least this suggests product substitution estimates are extremely uncertain. However, 85% of the 141 combinations examined were <50% than currently estimated. Those few exceeding 50% involved the assumption that substitution replacement losses were zero (i.e. an infinite lifespan) and had either an unrealistically low rate of

[3] See figures S-7 to S-10 for detailed view of the first 50 years.

[4] See supplemental text and figure for similar results for a productive Southeastern US forest.

leakage (i.e. less than one-third that indicated by the maximum depletion time) or a minimal decline in displacement. Moreover, although past assumptions would indicate product substitution forms a large share of carbon stores at year 300 (74%–80% depending on the initial conditions), 90% of the alternative combinations examined indicated it was less than 50%. The combinations in which product substitution stores comprise the majority share of stores assumed an infinite lifespan and either minimal displacement decline or extremely low cross-sector leakage rates (tables S-2 to S-4).

Discussion

Past analyses suggest product substitution benefits at the landscape level continue to increase at a constant rate into the future [6–16]. Moreover, they imply that while a carbon debt can be created in some situations (e.g. harvest of primary forests), that this debt is eventually paid back via product substitution [10, 12, 32]. While I examined only a few illustrative cases, in the case of product substitution, these debts would not be paid back if the displacement declines or there are losses via cross-sector leakage or related to product replacement. That is because negative feedbacks associated with losses can prevent product substitution from accumulating forever. These negative feedbacks could exist regardless of the forest ecosystem, the harvest system, and the efficiency of processing harvests into products as well as the proportion allocated to buildings. Thus, while I did not examine the effect on a wide range of ecosystems, or alternative harvest systems, or systems in which buildings are minor faction of harvested carbon, these underlying relationships would not be altered for these new situations[4].

The assumption that the product substitution benefit has no losses (e.g. [10]) results in at least two sets of untenable predictions: (1) if fossil fuel carbon is stored each time a wooden building is constructed, then theoretically it would be possible for fossil fuel carbon to be stored long after this carbon has been depleted by other sectors; hence this assumption may violate the conservation of mass; (2) this assumption also views the following as the same: (a) harvest that completely replaces wood building losses, (b) harvest that does not replace wood building losses, (c) harvest that exceeds wood building losses leading to more wood buildings, and (d) wood buildings that are not replaced. These cases clearly differ [20] (see supplemental information). This assumption also introduces a logical inconsistency: products appear to have different lifespans depending on whether their direct carbon (finite) or substitution carbon (infinite) effects are being considered (figure S-4).

Although displacement decline over time influences the accumulation of product substitution benefits, its effect is smaller than leakage or replacement losses. In contrast, leakage loss has as dramatic effect as longevity even if it occurs at a very slow rate implying the effect of product substitution is to delay eventual fossil carbon release, but not to stop it altogether. This may be important because it buys time, but this is not the same as the displaced fossil carbon never being released as suggested by [10, 12].

Collectively the past assumptions commonly used to assess the mitigation benefits of product substitution lead to a carbon pool that does not saturate causing the product substitution pool to eventually exceed the carbon stores in the forest ecosystem and in the associated wood products. Moreover, because there are no losses from the products substitution pool, its highest rate of increase occurs for the harvest interval providing the highest yield, typically a very young age relative to the forest ecosystem carbon maximum [32]. With no relationship to building longevity, there is no relationship to the size of the wood products pool despite the fact that more wooden buildings would imply more success in displacing fossil carbon. Finally, this set of assumptions makes product substitution benefits relatively insensitive to the initial conditions of the forest ecosystem because product substitution benefits always increase over time.

The alternative set of assumptions explored here suggests that the highest overall climate mitigation may not necessarily be achieved by maximizing the harvest yield using short rotation forestry [33]. Moreover, if product substitution is the primary climate mitigation strategy, wood building materials need to keep their carbon advantage by maintaining or increasing their displacement value. This suggests that while wood can be used in buildings taller than the general current practice, this may have less mitigation value than anticipated if these materials embody more fossil energy than current wood-based materials. Given the strong potential relationship between building and product substitution longevity, increasing the life-span of buildings or reusing building materials could potentially help meet future demand and increase mitigation benefits. Without a policy to assure that fossil carbon displaced by one sector is not used by another sector, product substitution benefits could be quite limited. While it is unlikely any policy could completely eliminate cross-sector leakage, designating long-term reserves might delay releases until their climate impacts are reduced to acceptable levels.

Conclusions

Despite its general and limited nature, this sensitivity analysis found that product substitution benefits have likely been overestimated for many scenarios and are generally smaller than those related to the forest ecosystem and their derived products. This new analysis suggests that if product substitution is to be used as part of a climate mitigation strategy, then more attention will have to be paid to maintaining the amount of carbon displaced, reducing the rate of carbon cross-sector leakage, and increasing the longevity of buildings. This new analysis also suggests that the best strategy for forest-related climate mitigation for an important timber region, the Pacific Northwest, is largely determined by the initial conditions of the management system. Afforestation leads to an increase in carbon stores in the ecosystem, wood products, and substitution benefits for many decades. On existing production forests, substitution benefits could be maintained by continuing the current system or increased by harvesting more (but only as long as ecosystem carbon stores do not decline) and/or increasing the longevity of buildings. Conversion of older, high carbon stores forests to short rotation plantations would over the long-term likely lead to more carbon being added to the atmosphere despite some of the harvested carbon being stored and production substitution occurring [33].

Acknowledgments

This research was funded by the Kaye and Ward Richardson endowment to the College of Forestry, Oregon State University and grant from the National Science Foundation (DEB-0823380 and DEB-1440409) to the Andrews LTER. I thank Drs Darius Adams, Thomas C Maness and the anonymous reviewers for their valuable insights.

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SUPPLEMENTARY INFORMATION

Changes in the Displacement Value

Although past studies have used a constant displacement factor as a simplifying assumption, it is highly unlikely that its value remains constant over time. More research is needed to determine past and to project future trends, but as a starting point I hypothesize that multiple factors would lead the displacement factor for product substitution to decline over time in part because of energy use and manufacturing changes, but also in part because of the mathematical relationship behind the calculation of the displacement factor.

As defined by Sathre and O'Connor [20] the displacement factor is the ratio of difference in fossil carbon use between non-wood and wood products used and the difference in wood used:

$DF = (Cfossil_{non\text{-}wood} - Cfossil_{wood})/(Wood\ Use_{non\text{-}wood} - Wood\ Use_{wood})$

Where DF is the displacement factor used to calculate the input to product substitution virtual stores and $Cfossil_i$ is the amount of fossil carbon used for product *i*. In the case of concrete and steel (non-wood) versus wood the displacment factor usually a positive number [9,20]. This equation can be simplied by assuming the difference in wood use is constant and set to 1 Mg C:

$DF = (Cfossil_{non\text{-}wood} - Cfossil_{wood})$

This reveals that the crucial relationship is a difference and not a ratio as in energy substitution.

If the source of fossil energy (e.g., coal to natural gas) changes over time one must account for these differences. Assuming a constant amount of energy is needed in the manufacturing process, then using a less carbon-rich energy source for both products leads the displacement factor to decline. For example, if coal was completely replaced by natural gas as the fossil energy source, and we assume that natural gas has half the carbon per unit energy, then half the fossil carbon would be used in manufacturing and the equation becomes:

$0.5\ DF = 0.5\ Cfossil_{non\text{-}wood} - 0.5\ Cfossil_{wood}$

Therefore the displacement factor would be halved. The same is true if non-fossil energy sources are used. This is important because if fossil energy is eventually phased out completely at some point in time, the displacement factor would also become zero at that time. In contrast, if the displacement factor truly is constant as has been generally assumed, then this result could never happen. Although these examples assume similar changes in energy source between products, the results would be similar even if no fossil energy was used to manufacture wood products. Suppose no fossil energy was used to manufacture wood products and the replacement of coal by natural gas only occurs in non-wood products. The equation then becomes:

$0.5\ DF = 0.5\ Cfossil_{non\text{-}wood} - 0$

indicating that the displacement factor still would be halved if this energy source conversion occurred.

Increases in manufacturing efficiencies relative to energy would also cause a decline in the displacement factor and this seems likely given the economic and environmental impetus to use energy more efficiently and to use less carbon, respectively [8,16]. This is why the changes for energy substitution hypothesized by [12] would lead to a decline in the product substitution displacement factor and not an increase.

Finally, use of wood framing in taller structures may require use of wood-based materials that require more energy to manufacture [17]. In contrast, non-wood products (i.e., concrete and steel versus wood) can already be put to these uses without increasing embodied energy. If the fossil energy source and efficiency of energy capture are the same in the manufacture of both kinds of products, then the displacement factor would decline in this scenario as well because the difference would become smaller.

Effect of altering the initial displacement factor and allocation to buildings.

During the simulations used in this analysis I assumed that the initial displacement factor would be 2.1 MgC per 1 MgC of net wood used. However, the initial displacement factor varies considerably from study to study and among regions [20]. To simulate the optimal scenario for product substitution I also assumed all the manufacturing output was allocated to buildings. Both sets of assumptions influence the input to the products substitution store and hence the value of this store. To adjust the product substitution stores to reflect different assumptions about the initial displacement factor and allocation of manufacturing output to buildings one can multiply the results by the adjustment factor in Figure S-1. For example, if the initial displacement factor was instead 0.54 MgC per 1 MgC of net wood used as in [34], then the product substitution stores should ≈26% of the value I presented. This lower value would also influence the proportion of total stores comprised by product substitution by the same amount. Further, if the allocation of solid manufacturing output to buildings was 26% suggested by [29] instead of 100% I used, then the products substitution store would be reduced to 26% of the values I presented in this analysis (Figures 4 and S-4, Table S-2 to S-4). It should be noted that these adjustment factors influence neither the relative shape nor the timing, only the magnitude of the response.

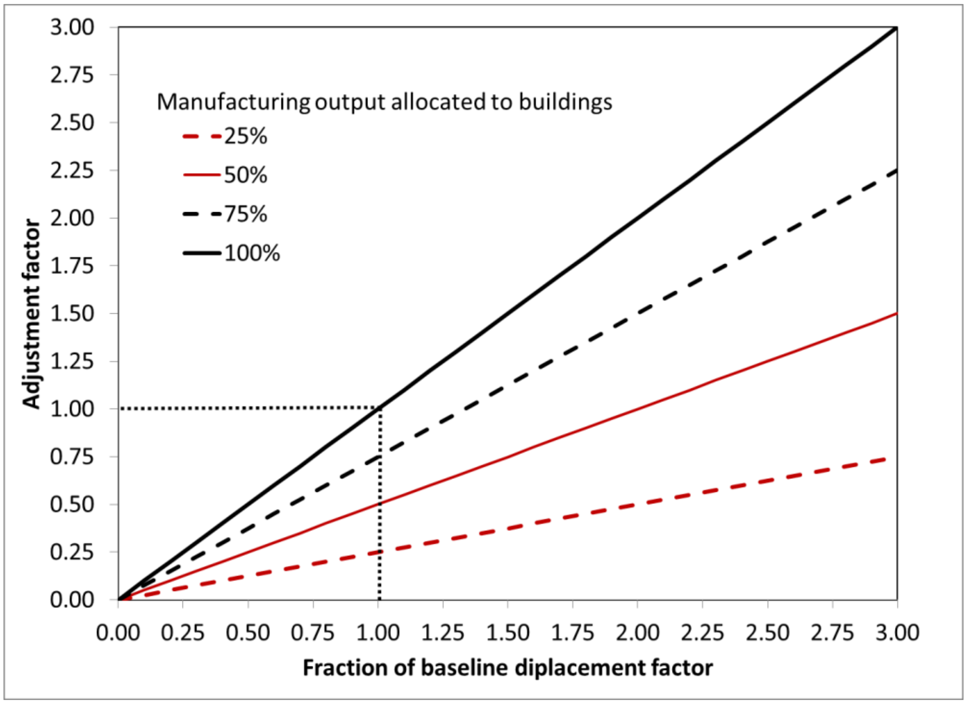

Figure S-1. Adjustment factors to alter the product substitution stores values if assumptions about the initial displacement factor and allocation of manufacturing output to buildings are altered. The dashed vertical and horizontal lines indicate an adjustment factor of 1, which represents an initial baseline displacement factor of 2.1 MgC per 1 MgC of net wood used and 100% allocation of manufacturing output to buildings.

Cross-sector leakage losses.

An assumption of past analyses of product substitution is that once the substitution occurs the displaced fossil carbon would not be used at any time in the future [10, 12, 15]. While that might be true within the building sector, it cannot possibly be true when all sectors using fossil energy are considered. In theory, when displacement occurs some fraction of fossil carbon is allocated to the substitution pool from the rest of the fossil fuel carbon pool. The former might be best thought of as a “virtual” pool of carbon that exists in some location and form. However, since its location and form cannot be completely specified, it is impossible to directly inventory and distinguish it from the other fossil fuel carbon. Moreover, there are no direct mechanisms to prevent use by other sectors. To eliminate (or even control) cross-sector leakage, the location and form of the product substitution related fossil fuel carbon would have to be identified and its use restricted (perhaps in a very long-term reserve). Otherwise, other sectors would have no way of “knowing” when they are drawing on the product substitution fossil fuel carbon store.

While the exact rate of cross-sector leakage has yet to be determined, it is unlikely be zero as tacitly assumed by [10, 12, 15]. It has been estimated that oil and natural gas will be depleted in 35-37 years and coal will be depleted in 107 years [26] implying an average rate of depletion of approximately 2.8 to 8.6% per year. Even if these estimates are low by a factor of two, the average depletion rate would be 1.5% to 4.3% per year. In a more recent production projection for Australia, Canada, China, USA by Mohr et al [27] fossil fuel reserves were estimated, depending on the scenario used, to become depleted in 135-235 years implying an average depletion rate of 1.3 to 2.2% per year. Switching to renewable energy sources has decreased the proportion of total energy generated from fossil carbon, however, this has not necessarily influenced overall fossil carbon use and depletion rates because total energy demand is expected to increase sufficiently to offset changes in energy sources [22]. This means that until fossil fuel use is globally ended that cross-sector leakage from the product substitution store is likely to occur. Moreover, because fossil carbon use has global consequences it is possible for the displacement factor to go to zero in the location of product manufacture and to still have cross-sector leakage globally. That is because fossil carbon use in the manufacturing sector is not necessarily collocated with use in other sectors (e.g., transport and heating).

To model cross-sector leakage at the landscape level I assumed that a constant fraction of the product substitution store was lost each year and used the range of fossil fuel carbon depletion rates as a guide as to the possible ranges in leakage rate-constant. While this simplified approach allows one to test the sensitivity of product substitution to cross-sector leakage, a more realistic estimate may come from a more global analysis of fossil carbon use in all sectors. For example, the leakage rate of product substitution carbon might be lower than fossil fuel depletion studies indicate if there are inefficiencies in finding and using the product substitution-related fossil carbon store. These inefficiencies would introduce a lag in fossil fuel carbon loss which would theoretically decrease the leakage loss as a positive function of the lag duration. However, this lag cannot exceed the estimated time required to deplete fossil fuel carbon because that implies that the fossil carbon related to product substitution is the most expensive and technologically hardest to find and extract. There is no reason to expect this to be true. Economic processes might lead to fossil fuel carbon related to product substitution to be used as fast as that related to other sectors. For example, if a large store of product substitution ”accumulates”, then its presence might push the relative price of fossil fuel carbon downward, leading to its eventual use unless other forces increase fossil carbon costs (e.g., either carbon tax or cap and trade) or use (e.g., regulations). In summary, while addressing lags and economic drivers would hopefully lead to a more realistic estimate of cross-sector leakage rates, it is unlikely these improvements would alter the underlying sensitivity of product substitution to the process of cross-sector leakage.

Creating a lag in fossil fuel carbon use could reduce climate impacts, but the degree would depend on the length of the lag time. It is unlikely that the lag time will greatly exceed the estimated depletion times. The fossil fuel carbon depletion times suggested by [26-27] are shorter than time scale at which the atmosphere responds [35]. This strongly indicates that any lag in fossil fuel carbon introduced by product substitution may be ineffective regards limiting climatic warming.

Product longevity and its relationship to product substitution longevity.

A key past assumption that strongly influences the accumulation of product substitution benefits is the lack of relationship between product longevity and product substitution longevity [7-16]. The reasoning and mathematics behind this assumption have not been fully explained, nor have their logical consequences been fully explored. Below I discuss each dimension of this aspect of product substitution.

Mathematically the assumption that product substitution is cumulative can be represented by:

$$Csub_t = Displacement_t + Csub_{t-1}$$

Where $Csub_t$ is the virtual carbon store associated with product substitution at time t and $Displacement_t$ is the amount of fossil carbon displaced at time t by wood product use. This relationship means the product substitution pool is only dependent on the input rate, lacks any negative feedback, and therefore never saturates (i.e., never reaches a limiting value). Moreover, the product substitution can never decline because there is no loss term. This temporal behavior is evident in many past analyzes of this topic [10-11, 15, 32].

Sathre and O'Connor [20] point out that the substitution benefit need not increase cumulatively. They state that for case in which wooden buildings are replaced by concrete and steel ones, the displacement factor would take on a negative sign, thus allowing the product substitution pool to decrease. They also suggest that when wood is the preferred building material and wood is used that the product substitution stores would not increase: replacing a wooden building with a wooden building when wood is preferred results in no net displacement. However, despite its ability to provide different temporal behaviors this approach does not appear to have been used (i.e., stores always increase regardless of initial conditions and preferences). Although allowing different temporal behaviors, the Sathre and O'Connor approach is problematical because it confounds inputs and losses to the product substitution pool thus creating a trifurcated system that either stays the same (zero input), gains (positive input) or loses carbon (negative input) (Figure S-2). Since this system is ambiguous concerning the initial substitution store, one must assume a value and while this could be zero, in some cases this initial value could result in negative stores of mass, something that is not possible. Therefore, in Figure S-2, I assumed for two of the cases that substitution stores had accumulated prior to year zero. Despite this alteration, it is still possible for product substitution stores to go negative if losses continue long enough because there is no negative feedback to prevent this behavior. This approach is also scale dependent in that it seems to pertain to a building or a cohort of buildings created at the same time. When buildings are created at different times then inputs and losses are potentially simultaneous; hence a framework in which simultaneous inputs and losses needs to be used. It might be possible to address this shortcoming by weighting the three possible values of input by the proportion of buildings with each value, but this would require predicting these proportions and how they evolve over time.

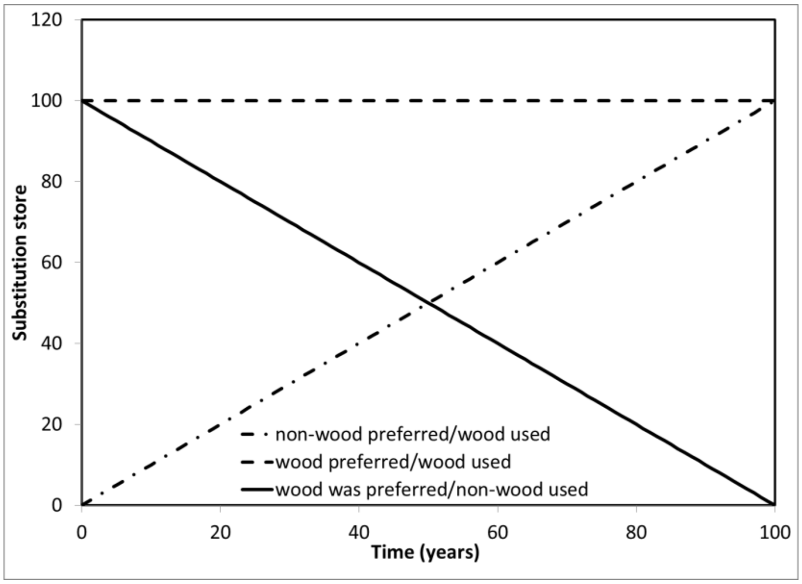

Figure S-2. An illustration of how Sathre and O'Connor's [20] framework would predict increasing, decreasing, and constant product substitution stores over time. To avoid the negative stores I assumed an initial store of 100 units for the case when wood was preferred, but then replaced by non-wood building materials. I also assumed that in the case in which wood is preferred and used, that the product substitution store had accumulated to 100 units in the past, but has no net input.

A more general, broader scale framework of substitution virtual stores would include the possibility of simultaneous inputs and losses. To account for possible losses the equation above would have to be modified to:

$Csub_t = Displacement_t + Csub_{t-1} - Loss_t$

Where $Loss_t$ is the loss at time t.

Intuitively, there should be a relationship with building longevity because it is when buildings are lost/replaced that decisions about replacement materials are made. Moreover, products that last longer should have the potential to displace fossil carbon longer and this should increase the substitution-related store of unused fossil carbon and vice versa. This implies a negative feedback that can be accounted for by making the loss term a function of the product substitution store at time t-1 and a rate-constant describing that loss ($k_{\text{replacement}}$):

$$\text{Loss}_t = k_{\text{replacement}} \, \text{Csub}_{t-1}$$

Since this loss term is associated with building replacement, it equals the sum of rate-constants used to define building longevity (e.g., combustion, decay, demolition). It should be noted that to create the no loss case one effectively has to set $k_{\text{replacement}}$ to zero and this implies an infinite building lifespan as far as product substitution is concerned. The negative feedback relationship also eliminates the possibility that product substitution stores can either have negative values or increase infinitely (Figure S-3).

Although not explicitly stated in prior studies, the steady accumulation without saturation of product substitution stores appears related to assumptions about preferences for wood versus non-wood materials. In the case in which non-wood products are always preferred, then the use of wood would repeatedly avoid the use of fossil fuel carbon and hence the product substitution benefit would cumulatively increase without saturation. However, as noted by [20] when wood is the preferred product one is essentially substituting wood with wood and no additional displacement of fossil fuel carbon occurs. This means that once wood becomes the preferred product that the product substitution store cannot increase. Given these relationships most, if not all, studies of product substitution benefits must have tacitly assumed that non-wood products

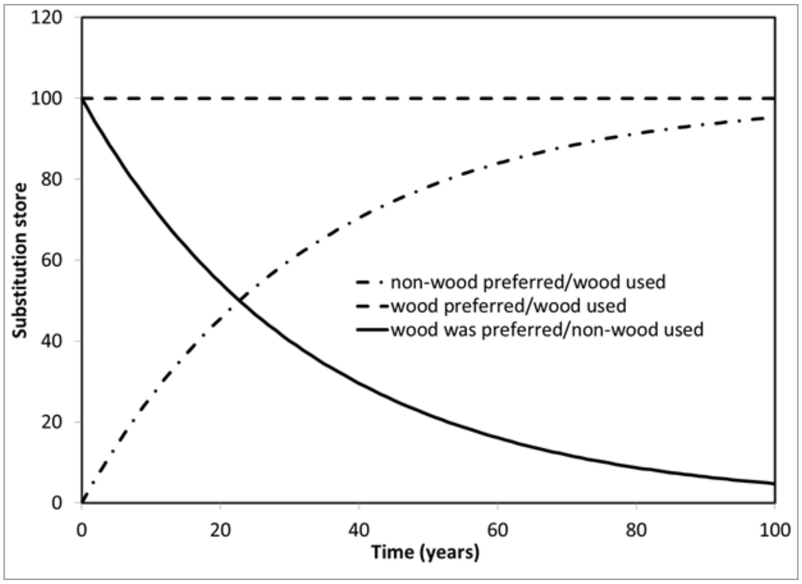

Figure S-3. An illustration of how an alternative framework using a negative feedback would be consistent with the framework suggested by [20] (Figure S-2). As with Figure S-2 I also assumed that in the case in which wood is preferred and used, that the product substitution store had accumulated to 100 units in the past, however it continues to have an input.

are always preferred given their assertion of cumulative, non-saturating stores. This is at odds with documented regional differences in wood versus non-wood products [28] and also assumes that preferences cannot change in the future. While assuming preferences do not change over time is convenient, it is at odds with research on preferences [36]. Realistic future projections of product substitution should therefore account for current as well as future preferences which, while difficult to predict, can at least be bracketed between two extremes: 1) no change in current preferences and 2) a progression toward a greater preference for wood. The latter can be implemented by creating a link between building longevity and product substitution longevity via the negative feedback described above. This relationship implies that once wooden building stores have reached their maximum, that preference for wood as a building material has been established, hence replacing wood with wood results in no net increase in product substitution consistent with [20]. In other words, the use of a negative feedback also reflects an evolution in the preference for wood as a building material.

There are number of serious conceptual problems with the original formulation of how the product substitution store changes over time which suggests a reformulation such as that using a negative feedback relationship is needed. Without a negative feedback relationship, the accumulation of the product substitution pool can never saturate; it can theoretically exceed the amount of fossil fuel carbon given enough time (particularly if the displacement factor is assumed constant). This suggests a potential for violation of the conservation of mass law which, while conceptually possible as a virtual store, undermines its practical meaning in terms of climate change because that depends on actual and not theoretical fluxes of carbon. As noted above, assuming no relationship between product longevity and product substitution longevity effectively means that product longevity is infinite (i.e., has no losses) when product substitution is considered; whereas it is finite (i.e., has losses) when the product is considered. This leads to a logical inconsistency in that product longevity varies depending on how a product is being considered (i.e., as a direct store of carbon versus as the driver of product substitution) (Figure S-4). It also leads to a situation in which current preferences for building material are ignored and does not allow these preferences to evolve over time.

These pitfalls are avoided if one incorporates a negative feedback relationship. In this case, when wood-based buildings (or parts) are completely replaced by wood-based buildings (or parts) the displacement of fossil carbon is continued but not increased. This is because the loss equals the input and therefore there is no net change in the product substitution store [20]. If on the other hand, a wood-based building is replaced by one constructed out or more energy intensive materials, then the at least some of the fossil fuel carbon originally displaced is released [20]. Without a relationship between product longevity and product substitution longevity, there is no clear mechanism by which fossil carbon can be released once it is displaced other than cross-sector leakage loss (which is also usually assumed to be zero). Moreover, without this relationship there also is no mechanism whereby alterations in product lifespan could lead to increases in product substitution because the rate of accumulation is fixed based solely on the input rate. It seems more reasonable that increasing the lifespan of wooden buildings would lead to additional displacement and additional product substitution benefits. It should be noted that these three cases assume that a wooden building that is lost one place within a region will be replaced by another building of some type in some location in the region (a general assumption of most if not all analyses on this topic). However, if a wooden building is removed and not replaced by another building within the region, then the product substitution store would remain constant unless there are other loss terms such as those associated with cross-sector leakage. This case differs from that of when a wooden building is replaced by a wooden building [20]. When replacement occurs leakage losses could be replaced via new inputs, whereas when the wooden building is not replaced the product substitution store would eventually go to zero because leakage losses are not replaced by new inputs.

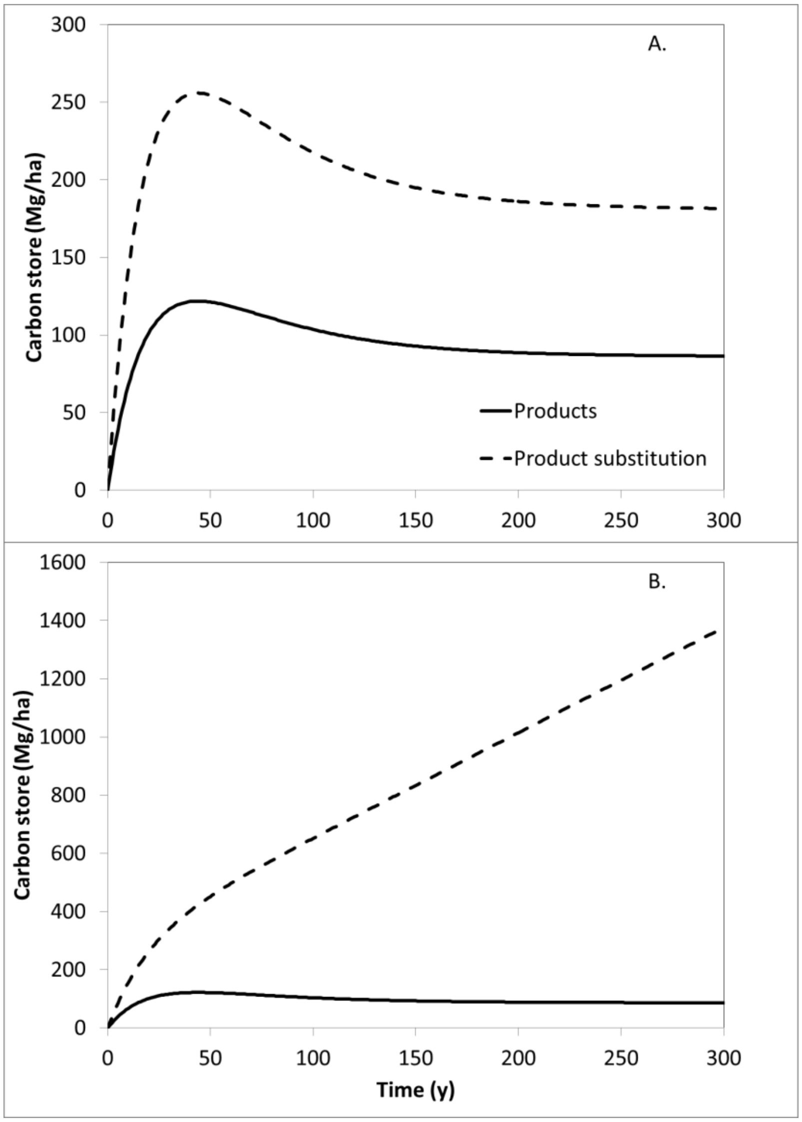

Figure S-4. Comparison of temporal patterns of carbon accumulation in products and product substitution when there is (A) and when there is not (B) a relationship between product and product substitution longevity. In these simulations the displacement factor was set to 2.1 MgC/MgC wood used. Note that in panel B product substitution acts as if it product longevity was infinite because it has no loss terms.

Modeling Methods

Carbon at the landscape level was modeled using a spreadsheet that tracked stores for the live, dead, and soil carbon pools in the forest ecosystem, the products in use and disposal, and the virtual stores associated with product substitution (Figure S-5). Each of these pools was modeled as a simple input-output, donor controlled sub-model following first order dynamics. For each pool j the net change in C stores each year was:

$$\Delta C_{jt} = I_{j\,t} - k_j\, C_{j\,t-1}$$

Where I_j t is the input in year t (Mg/ha/y), k_j is the rate-constant or proportion lost each year (per y), and $C_{j\,t-1}$ is the store of carbon in year t-1 (Mg/ha). The store in year t (C_{Jt}) was calculated as:

$$C_{jt} = \Delta C_{Jt} + C_{j\,t-1}$$

To simplify the model, I assumed that live carbon was primarily wood, clear-cut harvest was employed, that wood products consisted solely of buildings, and that disturbances such as insect outbreaks and wildfires did not occur. Input to the live carbon pool was based on the length of interval between harvests assuming that net primary production (NPP) increased with stand age as a natural growth function:

$$NPP_t = NPP_{max}\,(1 - \exp(-k_{NPP}\ t))$$

Where NPP_{max} for the Pacific Northwest was set to 5 Mg/ha/y and $-k_{NPP}$ was set to 0.15/y so that 95% of the maximum NPP was reached in 20 years (Table S1). This parameterization would mimic the temporal dynamics of productive forests in the Pacific Northwest, a major timber producing region [33]. For any interval T between harvests the average NPP and input to the live carbon pool at the landscape level was:

$NPP_T = I_{livet} = (\Sigma^{T}_{t=0} NPP_t)/T.$

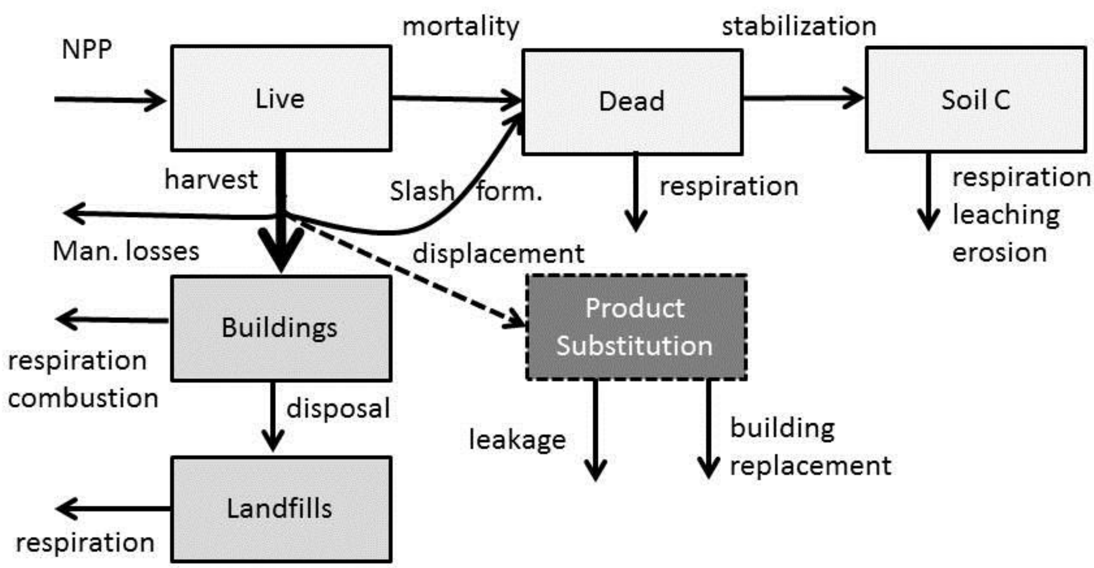

Figure S-5. Overview of the carbon pools and processes in the model used to examine product substitution-related assumptions. Ecosystem pools are indicated with light gray, those related to harvested carbon in medium gray, and those with product substitution dark gray. Live carbon influenced by harvest can be left as slash or manufactured into products used to create buildings with some losses. Creation of buildings leads to a virtual flow of carbon to the virtual product substitution pool via displacement (indicated by the dashed line). Note that carbon does not directly flow to the product substitution pool from the ecosystem, products, or landfill; rather it flows in from fossil carbon that is not used because of the substitution.

Table S1. Parameters used to simulate forests in the Pacific Northwest and southeastern US. The parameters were set to approximate the temporal dynamics and amount of carbon stored in these forest landscapes. One parameter value indicates the same value was used for both regions.

Parameter	Pacific Northwest		Southeastern US
NPP_{max}	5 Mg/ha/y		7.5 Mg/ha/y
k_{NPP}	0.15/y		0.30/y
$k_{mortality}$	0.01/y		0.03/y
$k_{harvest}$	0.0416/y		0.0921/y
F_{slash}		0.35	
$k_{decomposition}$	0.03/y		0.09
$k_{stabilization}$		0.005/y	
$k_{soil\ loss}$	0.005/y		0.0075/y
$F_{manufacturing\ loss}$		0.25	
$k_{building\ loss}$		0.01/y	
$k_{building\ disposal}$		0.01/y	
$k_{landfill}$		0.005/y	
$Displacement_{max}$		2.1 Mg C substitution/Mg C wood use	
$Displacement_{min}$		1.57 Mg C substitution/Mg C wood use	
$k_{displacement\ reduction}$		0.06/y	
$k_{leakage}$		0.06/y	

The loss of carbon from the live pool resulted from natural mortality ($k_{mortality}$) and harvest ($k_{harvest}$). The mortality parameter was based on an average live life-span of 100 years and that for harvest was the ratio of the amount of live carbon present at stand age T divided by T and the average live carbon store in stands ranging from age 0 to T. Inputs to dead carbon were 100% of mortality, but 35% of the felled carbon assuming that branch and coarse root wood was not removed (F_{slash}). The rate-constant controlling decomposition losses ($k_{decomposition}$) from the dead pool was parameterized based on an average residence time of 50 years (i.e., 0.02/y). The dead pool also lost carbon to the soil pool via carbon "stabilization" with assumption that 0.5% of the dead pools formed soil carbon each year ($k_{\text{stabilization}}$=0.005/y). Losses from the soil pool were not separated into those associated with respiration, leaching, and erosion, but the parameter controlling the sum of these losses was set to give soil carbon an average life-span of 200 y ($k_{\text{soil loss}}$=0.005/y). As parameterized, the old-growth store (688 Mg C/ha) is 11% higher than the 618 Mg C/ha estimated from field measurements by [37], but close to the average of 671 Mg C/ha reported by [38].

Inputs to wood products in use were based on the amount of carbon harvested deducting 35% for losses related to leaving branches and coarse roots in the ecosystem as slash (F_{slash}). I also assumed that there would be an additional 25% loss of carbon associated with wood product manufacturing ($F_{\text{manufacturing loss}}$) that needed to be deducted before carbon was added to the wood products pool. Wood products were assumed to have losses that were equally divided into those associated with decomposition and combustion ($k_{\text{building loss}}$= 0.01/y) and disposal ($k_{\text{building disposal}}$= 0.01/y). Carbon associated with building disposal was added to landfills in which the average life-span was assumed to be 200 y (k_{landfill}= 0.005/y). This would mean that 5% of the building carbon disposed of at time 0 would be present at time 600 y, reflecting the very low rates of decomposition in landfills.

The "virtual" stores of carbon associated with product substitution were modeled similarly to the other pools. However, while the other carbon pools have to obey conservation of mass, those associated with product substitution need not. Inputs to these pools were associated with the input to the wood products pool using a displacement factor that for the base scenario was assumed to be 2.1 Mg C substitution/1Mg C of wood used for buildings [20]. To account for the fact that the displacement factor might decline in the future, the initial value was decreased to a lower value in the future using a negative exponential function with an asymptote set by the lower value. There were two potential losses from the virtual product substitution carbon store: 1) use of unused fossil carbon by other sectors, termed leakage loss and 2) those associated with the replacement of wooden buildings, termed replacement losses. The rate-constant (k_{leakage}) used to account for cross-sector use of product substituted carbon was varied to reflect no loss (the current assumption) as well as 95% loss within 25, 50, 100, 200, 400, and 800 years which resulted in an annual loss of approximately 12, 6, 3, 1.5, 0.75, and 0.352%, respectively. Note that because leakage was modeled as a negative exponential function, 100% loss would take an infinite duration; therefore 95% was used to indicate the time when most of the fossil carbon would have been used by other sectors. To account for the losses associated with replacement of wooden buildings, I tied the rate-constant controlling this loss to the longevity of the buildings (i.e., $k_{\text{replacement}} = k_{\text{building loss}} + k_{\text{building disposal}}$). With this parameterization wooden buildings that replaced wooden buildings one to one would result in maintaining the product substitution store, whereas a lower rate of replacement of wood with wood leads to a loss of the product substitution store. Therefore, future wood harvests maintain the product substitution store, and substitution virtual stores only increase if the store of buildings increases. To replicate the results of previous studies, I set the replacement loss rate-constant to zero, which, in terms of the product substitution store acts as if the building had an infinite lifespan (Figure S-4).

Analysis for Southeastern US

The southeastern US was also examined using the same assumptions regarding product substitution as for the Pacific Northwest. Relative to the Pacific Northwest, the southeastern forest landscape was assumed to be 50% more productive, recover NPP twice as fast and have higher mortality rates and losses from dead and soil pools (Table S1). In addition it was assumed that old-growth forests in the southeastern US would have half the NPP_{max} of plantation forests given the higher tree density and improved silvicultural practices such as fertilization of the latter [39-40]. Given the shorter period between harvests in the southeast than the Pacific Northwest, a 25 year rotation interval was used instead of a 50 year one.

The results for product substitution were quite similar to those for the Pacific Northwest, although there was even less sensitivity to initial conditions when past assumptions were used (Figure S-6). For all initial conditions and building longevities examined, product substitution at year 300 was ≈0 to 80% the value estimated using past assumptions. As in the Pacific Northwest, the majority of combinations predicted less than 50% the value currently estimated. The main distinction between regions is that conversion of lower productivity, understocked old-growth forests to plantations in the southeastern US may lead to a lower decrease in forest carbon stores than in the Pacific Northwest (i.e., the increase in productivity largely offsets the increase in losses caused by harvesting). Moreover, in the southeastern US, the stores that consistently increased over time involved wood products and landfills and in the case of old-growth conversion, this could lead to an overall increase in carbon stored in the forest sector.

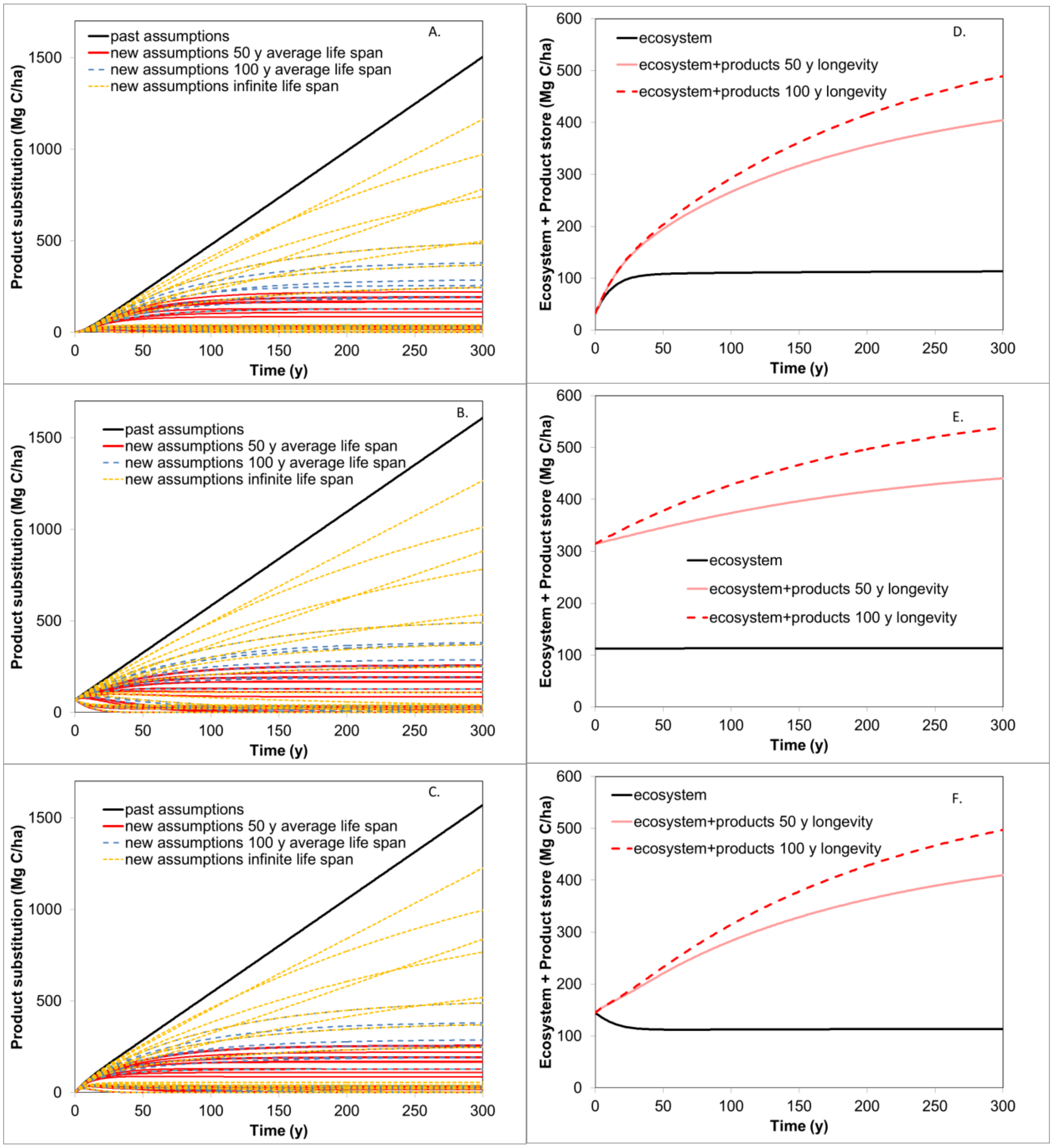

Figure S-6. Accumulation of ecosystem, products in-use and disposed and product substitution carbon stores for a 25 year clear-cut harvest interval in the southeastern US for three possible scenarios: a plantation forest established on an agricultural field (A, D); a production forest system that is continued (B, E); an old-growth forest replaced by a forest plantation (C, F). For past assumptions there was no reduction in displacement value, there was no leakage, and buildings were assumed to have an infinite lifespan.

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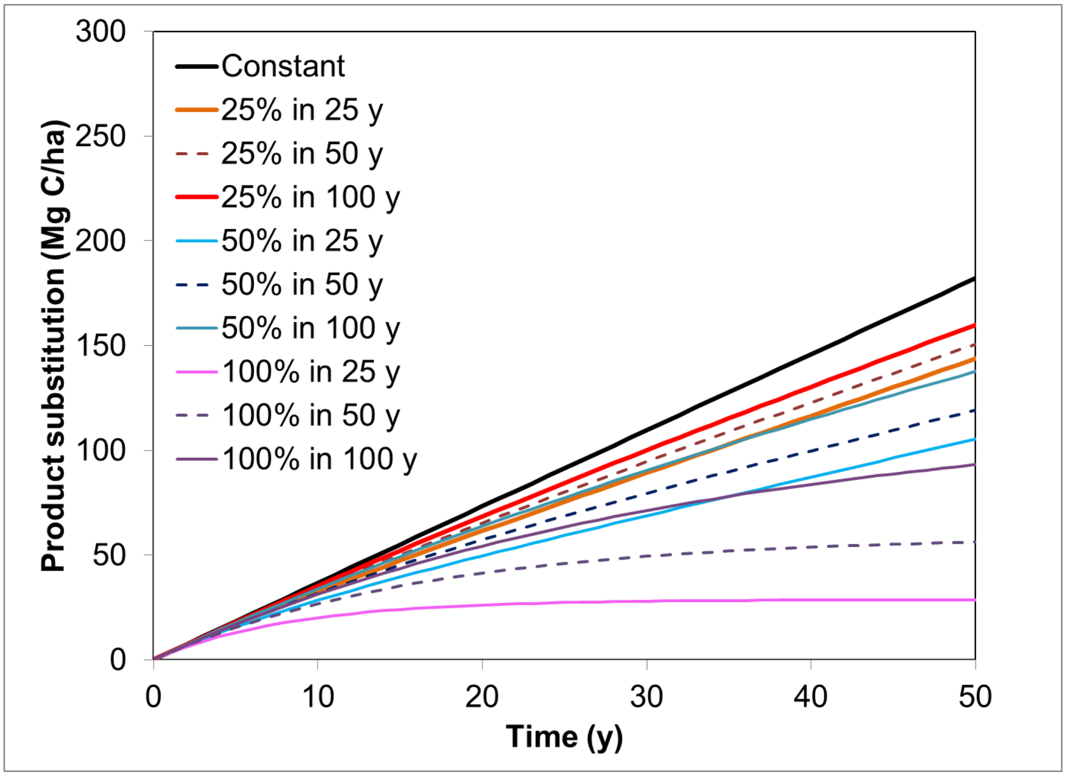


Figure S-7. Accumulation of product substitution carbon when displacement is reduced 25-100% over a 25-100 year period for a 50 year clear-cut harvest interval. For these simulations losses via leakage and replacement were assumed to be zero.

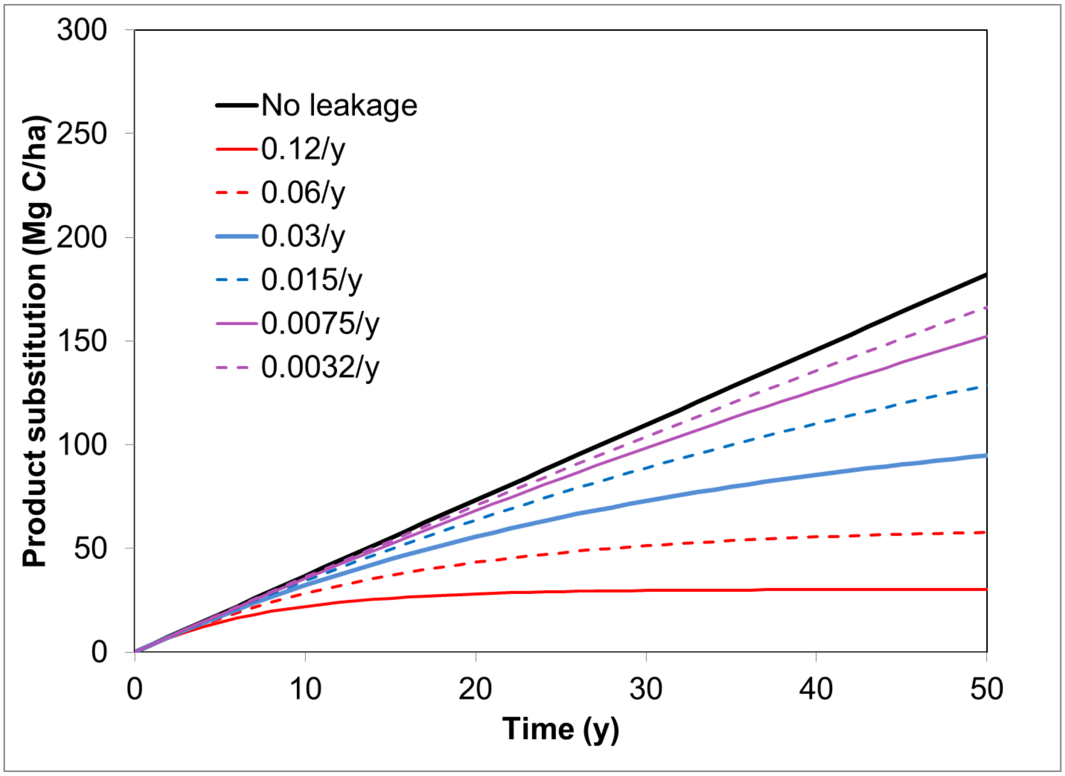


Figure S-8. Accumulation of product substitution carbon when the time for displacement to be lost via leakage varies from 25 to 800 years for a 50 year clear-cut harvest interval. Displacement was assumed constant and replacement losses zero.

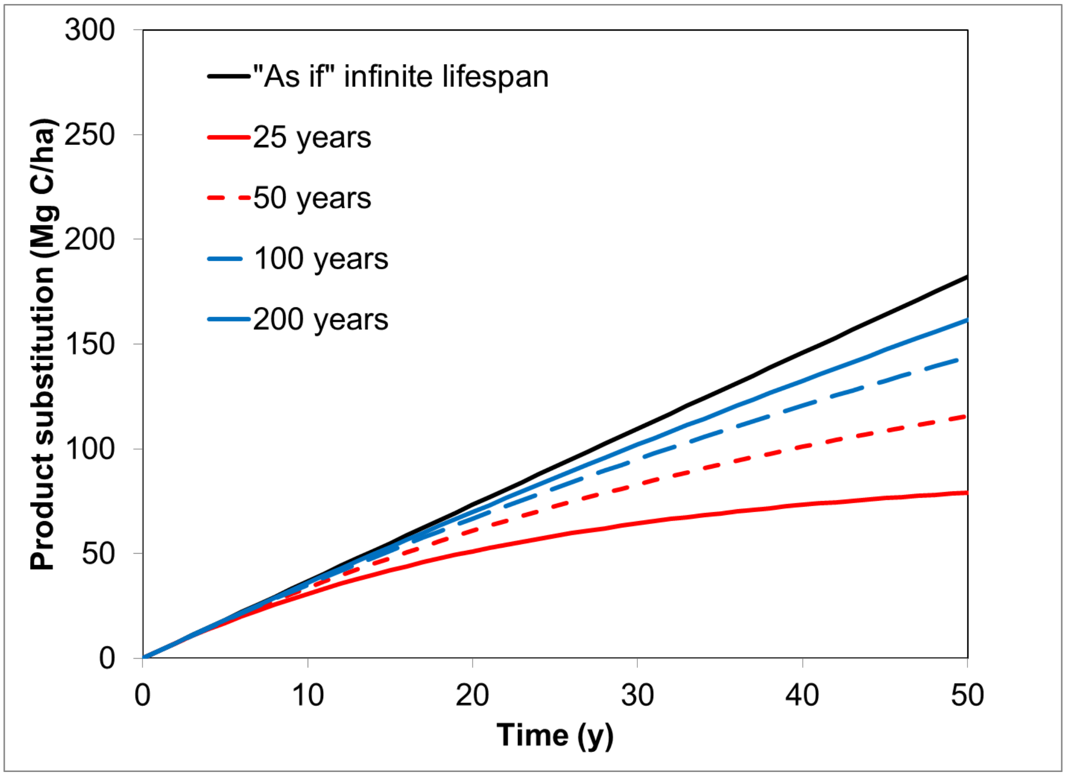
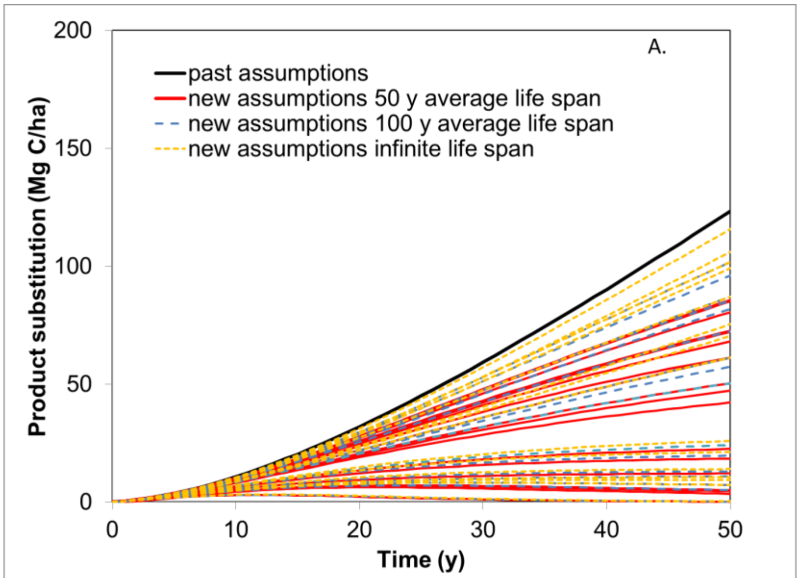


Figure S-9. Accumulation of product substitution carbon when the average longevity of building varies for a 50 year clear-cut harvest interval. For these simulations displacement was constant and there were no leakage losses.


A.
past assumptions
new assumptions 50 y average life span
new assumptions 100 y average life span
new assumptions infinite life span
Product substitution (Mg C/ha)
Time (y)
0
50
100
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200
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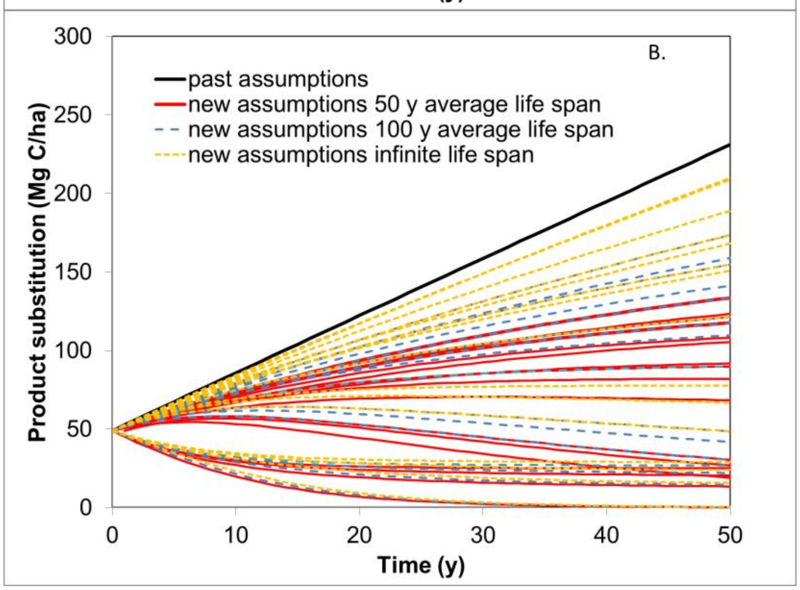
10
20
30
40
50


B.
past assumptions
new assumptions 50 y average life span
new assumptions 100 y average life span
new assumptions infinite life span
Product substitution (Mg C/ha)
Time (y)
0
50
100
150
200
250
300
0
10
20
30
40
50

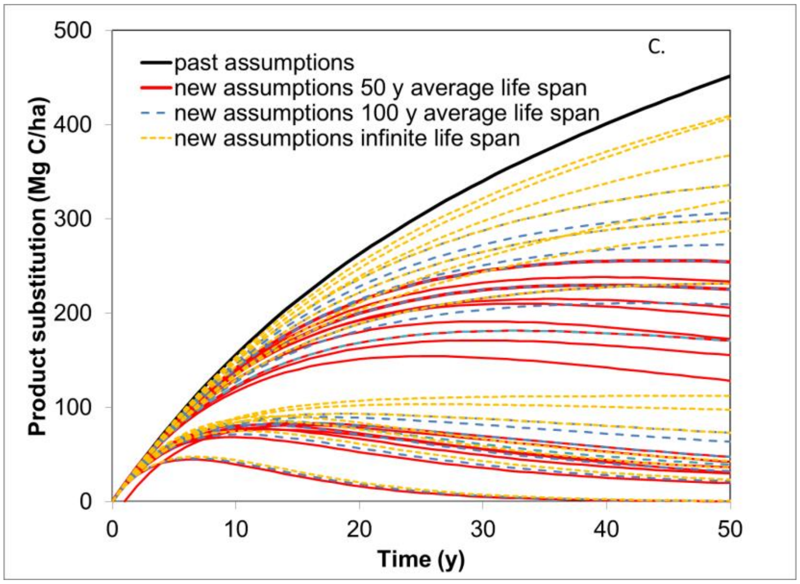


Figure S-10. Accumulation of ecosystem, products in-use and disposed, and product substitution carbon stores for a 50 year clear-cut harvest interval in the Pacific Northwest for three possible scenarios: a plantation forest established on an agricultural field (A); a production forest system that is continued (B); an old-growth forest replaced by a forest plantation (C). For past assumptions there was no decline in displacement value, there was no leakage, and buildings were assumed to have an infinite lifespan.

Table S-2. Fraction of maximum product substitution and fraction of total forest sector stores comprised of product substitution for combinations of parameter values used in Figure 4a (forest plantation established on old-field).

Treatments			fraction of maximum substitution			fraction of total stores		
Displacement decrease	Leakage rate	Average building life span	50 years	100 years	300 years[1]	50 years	100 years	300 years
	per year	years						
100% in 25 years	0.125	50 years	0.001	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.125	100 years	0.002	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.125	infinite years	0.002	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.01	50 years	0.029	0.003	0.000	0.016	0.003	0.000
100% in 25 years	0.00325	50 years	0.036	0.005	0.000	0.020	0.005	0.000
100% in 25 years	0	50 years	0.041	0.006	0.000	0.023	0.007	0.000
100% in 25 years	0.01	100 years	0.041	0.006	0.000	0.023	0.007	0.000
100% in 25 years	0	100 years	0.059	0.015	0.001	0.032	0.016	0.002
100% in 25 years	0.01	infinite years	0.059	0.015	0.001	0.032	0.016	0.002
100% in 25 years	0.00325	infinite years	0.075	0.027	0.004	0.041	0.029	0.012
100% in 25 years	0	infinite years	0.085	0.035	0.010	0.046	0.038	0.030
50% in 50 years	0.125	50 years	0.098	0.041	0.012	0.053	0.045	0.035
50% in 50 years	0.125	100 years	0.105	0.044	0.013	0.057	0.048	0.038
100% in 25 years	0.00325	100 years	0.089	0.040	0.013	0.048	0.044	0.038
50% in 50 years	0.125	infinite years	0.113	0.048	0.014	0.061	0.051	0.040
25% in 100 years	0.125	50 years	0.149	0.063	0.018	0.078	0.066	0.052
25% in 100 years	0.125	100 years	0.160	0.068	0.020	0.083	0.071	0.055
25% in 100 years	0.125	infinite years	0.172	0.048	0.021	0.089	0.076	0.060
None	0.125	50 years	0.183	0.083	0.024	0.094	0.085	0.068
None	0.125	100 years	0.195	0.089	0.026	0.100	0.091	0.072
None	0.125	infinite years	0.210	0.096	0.028	0.107	0.097	0.078
50% in 50 years	0.01	50 years	0.342	0.187	0.059	0.163	0.174	0.149

50% in 50 years	0.00325	50 years	0.383	0.225	0.075	0.179	0.202	0.183
50% in 50 years	0.01	100 years	0.409	0.252	0.088	0.189	0.221	0.208
50% in 50 years	0	50 years	0.409	0.252	0.088	0.189	0.221	0.208
25% in 100 years	0.01	50 years	0.496	0.283	0.088	0.220	0.242	0.209
25% in 100 years	0.00325	50 years	0.553	0.341	0.113	0.239	0.277	0.252
None	0.01	50 years	0.588	0.362	0.118	0.251	0.289	0.260
50% in 50 years	0.00325	100 years	0.465	0.318	0.131	0.209	0.264	0.280
25% in 100 years	0.01	100 years	0.587	0.379	0.132	0.251	0.299	0.283
25% in 100 years	0	50 years	0.587	0.379	0.132	0.251	0.299	0.283
None	0.00325	50 years	0.652	0.432	0.150	0.271	0.327	0.309
50% in 50 years	0	100 years	0.496	0.360	0.167	0.220	0.288	0.333
50% in 50 years	0.01	infinite years	0.496	0.360	0.167	0.220	0.288	0.333
None	0	50 years	0.692	0.480	0.176	0.283	0.351	0.344
None	0.01	100 years	0.692	0.480	0.176	0.283	0.351	0.344
25% in 100 years	0.00325	100 years	0.663	0.477	0.196	0.274	0.349	0.369
25% in 100 years	0	100 years	0.705	0.537	0.251	0.286	0.377	0.428
25% in 100 years	0.01	infinite years	0.705	0.537	0.251	0.286	0.377	0.428
None	0.00325	100 years	0.778	0.598	0.260	0.307	0.402	0.437
None	0	100 years	0.826	0.672	0.332	0.320	0.431	0.498
None	0.01	infinite years	0.826	0.672	0.332	0.320	0.431	0.498
50% in 50 years	0.00325	infinite years	0.570	0.476	0.333	0.245	0.349	0.498
25% in 100 years	0.00325	infinite years	0.805	0.705	0.499	0.314	0.442	0.598
50% in 50 years	0	infinite years	0.612	0.550	0.515	0.258	0.383	0.606
None	0.00325	infinite years	0.938	0.873	0.654	0.348	0.495	0.661
25% in 100 years	0	infinite years	0.859	0.812	0.770	0.329	0.477	0.697
none[2]	0[2]	infinite years[2]	1.000	1.000	1.000	0.363	0.530	0.749

1-Treatments ranked by value of fraction of maximum substitution value of 1023 MgC/ha at 300 years. The ecosystem and wood products stores at 300 years were 449 MgC/ha.

2-These assumptions are used in current estimates of product substitution stores.

Table S-3. Fraction of maximum product substitution and fraction of total forest sector stores comprised of product substitution for combinations of parameter values used in Figure 4b (established forest plantation continued into the future).

Treatments			fraction of maximum substitution			fraction of total stores		
Displacement decrease	Leakage rate	Average building life span	50 years	100 years	300 years[1]	50 years	100 years	300 years
	per year	years						
100% in 25 years	0.125	50 years	0.001	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.125	100 years	0.002	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.125	infinite years	0.002	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.01	50 years	0.029	0.003	0.000	0.016	0.003	0.000
100% in 25 years	0.00325	50 years	0.036	0.005	0.000	0.020	0.005	0.000
100% in 25 years	0	50 years	0.041	0.006	0.000	0.023	0.007	0.000
100% in 25 years	0.01	100 years	0.041	0.006	0.000	0.023	0.007	0.000
100% in 25 years	0	100 years	0.059	0.015	0.001	0.032	0.016	0.002
100% in 25 years	0.01	infinite years	0.059	0.015	0.001	0.032	0.016	0.002
100% in 25 years	0.00325	infinite years	0.075	0.027	0.004	0.041	0.029	0.012
100% in 25 years	0	infinite years	0.085	0.035	0.010	0.046	0.038	0.030
50% in 50 years	0.125	50 years	0.098	0.041	0.012	0.053	0.045	0.035
50% in 50 years	0.125	100 years	0.105	0.044	0.013	0.057	0.048	0.038
100% in 25 years	0.00325	100 years	0.089	0.040	0.013	0.048	0.044	0.038
50% in 50 years	0.125	infinite years	0.113	0.048	0.014	0.061	0.051	0.040
25% in 100 years	0.125	50 years	0.149	0.063	0.018	0.078	0.066	0.052
25% in 100 years	0.125	100 years	0.160	0.068	0.020	0.083	0.071	0.055
25% in 100 years	0.125	infinite years	0.172	0.048	0.021	0.089	0.076	0.060
None	0.125	50 years	0.183	0.083	0.024	0.094	0.085	0.068
None	0.125	100 years	0.195	0.089	0.026	0.100	0.091	0.072
None	0.125	infinite years	0.210	0.096	0.028	0.107	0.097	0.078
50% in 50 years	0.01	50 years	0.342	0.187	0.059	0.163	0.174	0.149
50% in 50 years	0.00325	50 years	0.383	0.225	0.075	0.179	0.202	0.183

50% in 50 years	0.01	100 years	0.409	0.252	0.088	0.189	0.221	0.208
50% in 50 years	0	50 years	0.409	0.252	0.088	0.189	0.221	0.208
25% in 100 years	0.01	50 years	0.496	0.283	0.088	0.220	0.242	0.209
25% in 100 years	0.00325	50 years	0.553	0.341	0.113	0.239	0.277	0.252
None	0.01	50 years	0.588	0.362	0.118	0.251	0.289	0.260
50% in 50 years	0.00325	100 years	0.465	0.318	0.131	0.209	0.264	0.280
25% in 100 years	0.01	100 years	0.587	0.379	0.132	0.251	0.299	0.283
25% in 100 years	0	50 years	0.587	0.379	0.132	0.251	0.299	0.283
None	0.00325	50 years	0.652	0.432	0.150	0.271	0.327	0.309
50% in 50 years	0	100 years	0.496	0.360	0.167	0.220	0.288	0.333
50% in 50 years	0.01	infinite years	0.496	0.360	0.167	0.220	0.288	0.333
None	0	50 years	0.692	0.480	0.176	0.283	0.351	0.344
None	0.01	100 years	0.692	0.480	0.176	0.283	0.351	0.344
25% in 100 years	0.00325	100 years	0.663	0.477	0.196	0.274	0.349	0.369
25% in 100 years	0	100 years	0.705	0.537	0.251	0.286	0.377	0.428
25% in 100 years	0.01	infinite years	0.705	0.537	0.251	0.286	0.377	0.428
None	0.00325	100 years	0.778	0.598	0.260	0.307	0.402	0.437
None	0	100 years	0.826	0.672	0.332	0.320	0.431	0.498
None	0.01	infinite years	0.826	0.672	0.332	0.320	0.431	0.498
50% in 50 years	0.00325	infinite years	0.570	0.476	0.333	0.245	0.349	0.498
25% in 100 years	0.00325	infinite years	0.805	0.705	0.499	0.314	0.442	0.598
50% in 50 years	0	infinite years	0.612	0.550	0.515	0.258	0.383	0.606
None	0.00325	infinite years	0.938	0.873	0.654	0.348	0.495	0.661
25% in 100 years	0	infinite years	0.859	0.812	0.770	0.329	0.477	0.697
none[2]	0[2]	infinite years[2]	1.000	1.000	1.000	0.363	0.530	0.749

1-Treatments ranked by value of fraction of maximum substitution value of 1135 Mg/ha at 300 years. The ecosystem and wood products stores at 300 years were 460 MgC/ha.

2-These assumptions are used in current estimates of product substitution stores.

Table S-4. Fraction of maximum product substitution and fraction of total forest sector stores comprised of product substitution for combinations of parameter values used in Figure 4c (forest plantation replacing old-growth forest).

Treatments			fraction of maximum substitution			fraction of total stores		
Displacement decrease	Leakage rate	Average building life span	50 years	100 years	300 years[1]	50 years	100 years	300 years
	per year	years						
100% in 25 years	0.125	50 years	0.001	0.000	0.000	0.001	0.000	0.000
100% in 25 years	0.125	100 years	0.001	0.000	0.000	0.003	0.000	0.000
100% in 25 years	0.125	infinite years	0.002	0.000	0.000	0.003	0.000	0.000
100% in 25 years	0.01	50 years	0.068	0.010	0.000	0.055	0.014	0.000
100% in 25 years	0.00325	50 years	0.091	0.020	0.000	0.073	0.026	0.000
100% in 25 years	0.01	100 years	0.105	0.027	0.000	0.180	0.061	0.001
100% in 25 years	0	50 years	0.105	0.027	0.000	0.083	0.036	0.001
100% in 25 years	0.00325	100 years	0.140	0.050	0.002	0.226	0.109	0.007
100% in 25 years	0	100 years	0.161	0.068	0.004	0.252	0.142	0.017
100% in 25 years	0.01	infinite years	0.161	0.068	0.004	0.252	0.142	0.017
50% in 50 years	0.125	50 years	0.044	0.020	0.009	0.036	0.027	0.026
50% in 50 years	0.125	100 years	0.048	0.021	0.010	0.090	0.050	0.038
50% in 50 years	0.125	infinite years	0.052	0.023	0.011	0.099	0.053	0.040
25% in 100 years	0.125	50 years	0.066	0.030	0.014	0.054	0.040	0.039
25% in 100 years	0.125	100 years	0.072	0.033	0.015	0.130	0.074	0.055
25% in 100 years	0.125	infinite years	0.079	0.023	0.016	0.141	0.079	0.060
None	0.125	50 years	0.080	0.040	0.018	0.064	0.052	0.052
None	0.125	100 years	0.087	0.043	0.019	0.154	0.094	0.072
None	0.125	infinite years	0.096	0.046	0.021	0.166	0.101	0.078
100% in 25 years	0.00325	infinite years	0.216	0.127	0.031	0.310	0.237	0.112
50% in 50 years	0.01	50 years	0.284	0.122	0.044	0.196	0.145	0.116
50% in 50 years	0.00325	50 years	0.344	0.164	0.057	0.228	0.186	0.146
25% in 100 years	0.01	50 years	0.382	0.178	0.066	0.247	0.199	0.165

50% in 50 years	0	50 years	0.378	0.192	0.066	0.245	0.211	0.166
50% in 50 years	0.01	100 years	0.378	0.192	0.066	0.441	0.320	0.210
100% in 25 years	0	infinite years	0.248	0.172	0.082	0.341	0.296	0.247
25% in 100 years	0.00325	50 years	0.456	0.236	0.085	0.281	0.247	0.204
None	0.01	50 years	0.436	0.222	0.088	0.272	0.235	0.208
25% in 100 years	0	50 years	0.499	0.275	0.099	0.300	0.276	0.230
25% in 100 years	0.01	100 years	0.499	0.275	0.099	0.510	0.402	0.285
50% in 50 years	0.00325	100 years	0.463	0.278	0.101	0.491	0.404	0.289
None	0.00325	50 years	0.517	0.289	0.113	0.308	0.287	0.254
None	0	50 years	0.564	0.334	0.132	0.326	0.317	0.284
None	0.01	100 years	0.564	0.334	0.132	0.540	0.449	0.346
50% in 50 years	0	100 years	0.513	0.337	0.135	0.517	0.452	0.352
50% in 50 years	0.01	infinite years	0.513	0.337	0.135	0.517	0.452	0.352
25% in 100 years	0.00325	100 years	0.604	0.388	0.151	0.557	0.487	0.378
None	0.00325	100 years	0.678	0.464	0.200	0.586	0.531	0.445
25% in 100 years	0	100 years	0.664	0.465	0.201	0.581	0.532	0.446
25% in 100 years	0.01	infinite years	0.664	0.465	0.201	0.581	0.532	0.446
None	0	100 years	0.744	0.552	0.263	0.608	0.574	0.513
None	0.01	infinite years	0.744	0.552	0.263	0.608	0.574	0.513
50% in 50 years	0.00325	infinite years	0.636	0.518	0.322	0.570	0.559	0.564
25% in 100 years	0.00325	infinite years	0.814	0.700	0.464	0.629	0.631	0.651
50% in 50 years	0	infinite years	0.708	0.646	0.569	0.596	0.612	0.696
None	0.00325	infinite years	0.907	0.817	0.589	0.654	0.666	0.703
25% in 100 years	0	infinite years	0.901	0.864	0.805	0.652	0.679	0.764
none[2]	0[2]	infinite years[2]	1.000	1.000	1.000	0.676	0.710	0.801

1-Treatments ranked by value of fraction of maximum substitution value of 1376 Mg/ha at 300 years. The ecosystem and wood products stores at 300 years were 458 MgC/ha.

2-These assumptions are used in current estimates of product substitution stores.