Supplementary Information

1. Conceptual Model for Figure 2

We represented the annual dynamics of the landscape-level mean forest carbon $C_{for}(t)$ (in kg·C/m^2) through the following equation:

$$C_{for}(t+1) = C_{for}(t) - C_{for}(t)/\tau_{for} + (NPP - H - F) \times \Delta t \tag{S1}$$

where τ_{for} is the mean carbon residence time in the absence of disturbances (in years; *i.e.*, $C_{for}(t)/\tau_{for}$ is the heterotrophic respiration), NPP is the net primary productivity, H is the yearly carbon removal from wood harvest, F is the yearly carbon removal from fires (all in kg·C/m^2/yr), and $\Delta t = 1$ year.

Since we were interested in the long-term equilibrium values, we used constant average values for NPP, H, F, and τ_{for}. We note that while F varies a lot from one year to another in Canadian managed forests (CMF), H, NPP, and heterotrophic respiration had coefficient of variation of only 8.9%, 0.6%, and 0.5%, respectively, over the 1990–2008 period [1]. Although CMF were not in perfect carbon equilibrium, the absolute changes in total carbon storage from 1990 to 2008 were very small: less than 0.1% between any two consecutive years and less than 0.005% for the whole period [1]. The recent carbon stocks and fluxes in CMF thus provided us with appropriate values for our first-order analysis. From Stinson *et al.* [1], we directly extracted the following mean values (all in kg·C/m^2/yr): $NPP = 0.352$, $H = 0.020$, and $F = 0.010$. We estimated the value of τ_{for} through the following equation derived from Equation (S1), where C_{for-eq} is the equilibrium carbon storage:

$$\tau_{for} = C_{for-eq}/(NPP - H - F) \tag{S2}$$

Based on the current mean carbon storage of 22.0 kg·C/m^2 in CMF [1], we obtained a value of $\tau_{for} = 68.3$ years.

1.1. Figure 2a

We assumed that the landscape was initially in the equilibrium condition described above. Then, at year 100, a treatment was applied over the entire landscape in order to increase its carbon storage. Increases in total ecosystem carbon of 11% have been estimated in CMF for nitrogen fertilization of trembling aspen (*Populus tremuloides*) [2], which is the tree species most responsive to nitrogen fertilization in boreal forests of North America [3]. A recent detailed study about CMF carbon mitigation potential also assumed that silvicultural treatments could increase stand biomass growth by 6%–20% for a period of 10–35 years [4]. Based on these numbers, an increase of ∼10% for the equilibrium carbon storage appears reasonable.

We therefore simulated the effect of the treatment by increasing NPP by 10%, assuming that the harvest level H remained the same. If fire frequency does not change, the higher landscape-level carbon storage should in principle lead to slightly higher average fire removals (F). We neglected this very small adjustment, thereby slightly overestimating the increase in equilibrium carbon storage (which strengthens the main outcomes from our analysis). Starting from year 100, we used the new NPP value in Equation (S1), along with the initial condition $C(t = 0) = C(t = 100) = C_{for-eq} = 22.0$ kg·C/m^2.

As shown in Figure 2a, the landscape then progressively reached its new equilibrium carbon amount of 24.4 kg·C/m^2, which is 11% higher than the initial value of 22.0 kg·C/m^2.

1.2. Figure 2b

In Figure 2b, we assumed that the treatment was permanently halted in year 300. At this point, the landscape had almost reached the new C_{for-eq} value of 24.4 kg·C/m^2. After stopping the treatment, the landscape progressively resumed to its initial C_{for-eq} value of 22.0 kg·C/m^2.

1.3. Figure 2c

In Figure 2c, we presented the same onset and halting of the treatment on years 100 and 300, respectively, but further accounted for the fossil fuel emissions required in order to perform the treatment. In the case of treatments performed to lower the amount of forest fuel for fire management, the fossil fuel emissions correspond to 1%–3% of the aboveground carbon stock [5]. We took the middle value of 2% and combined it with average aboveground carbon stock of 12 kg·C/m^2 in CMF [1], leading to fossil fuel emissions of 0.24 kg·C/m^2 for the treatment. Assuming that the treatment is performed only once during the stand rotation and using the average stand age of 92 years in CMF [1], we ended up with annual fossil fuel emissions of 0.0026 kg·C/m^2/yr for years 100 to 299 inclusively.

The equation describing the full carbon balance of the forest landscape and the associated fossil fuel emissions was then:

$$C_{full}(t+1) = \Big[C_{for}(t) - C_{for}(t)/\tau_{for} + (NPP - H - F) \times \Delta t\Big] - \Big[FFE \times \Delta t\Big] \tag{S3}$$

where FFE are the annual fossil fuel emissions normalized per unit of forest landscape area (0.0026 kg·C/m^2/yr for years 100 to 299 inclusively, zero the rest of the time) and the other symbols are as in Equation (S1). As was the case in Figure 2b, NPP was increased by 10% in year 100 and then resumed to its initial value in year 300. While the forest landscape itself progressively returned to its initial C_{for-eq} value of 22.0 kg·C/m^2 after the treatment was halted, the net carbon mitigation was negative due to the "fossil fuel debt" incurred during the 200 years over which the treatment was applied. Note that the value we used for FFE is likely conservative compared to nitrogen fertilization, for which the fossil fuel cost of nitrogen production alone was estimated at 0.104 kg·C/m^2 for aspen stands with a rotation length of 30 years [2], thereby resulting in $FFE = 0.0035$ kg·C/m^2/yr.

1.4. Figure 2d

In Figure 2d, the treatment and the related fossil fuel emissions were rather permanently maintained. Equation (S3) was therefore used with the initial values up to year 100, when NPP was permanently increased by 10% and FFE changed from 0.0 to 0.0026 kg·C/m^2/yr. While the forest landscape itself progressively reached its new C_{for-eq} value of 24.4 kg·C/m^2 after the treatment onset, the "ongoing fossil fuel cost" reduced year after year the net carbon mitigation, which became negative in year 1021.

1.5. Discussion

This conceptual model does not account for the fact that CMF are comprised of individual stands with a finite rotation length, NPP and τ_{for} values varying with stand age [6]. Accounting for the existence of individual stands would have led to different transient behaviours, but the main qualitative features (*i.e.*, shifts between different equilibrium conditions and cumulative impacts from fossil fuel emissions) would have remained the same. Furthermore, some consequences from a stand-based landscape-level model would partly offset each other. For example, the treatment would likely be implemented progressively across the stands, thereby slowing the change in carbon storage towards its new landscape-level equilibrium. On the other hand, the finite lifetime of stands implies that the new landscape-level equilibrium would be reached in a finite amount of time, contrary to the infinite time required with Equation (S1).

Each panel from Figure 2 presents a different outcome. The first outcome is expected: following the onset of a treatment increasing productivity, carbon storage over the landscape progressively reaches a new equilibrium value—but does not keep increasing forever (Figure 2a). The second outcome (*i.e.*, the landscape carbon storage resumes to its initial equilibrium value after the treatment is stopped; Figure 2b) is also intuitive, as long as the treatment does not have any positive and permanent legacy effect. This assumption is reasonable for thinning, but may appear questionable for fertilization because the nutrients applied do not instantaneously disappear from the ecosystem once the treatment is stopped. Yet a strong legacy effect on ecosystem carbon storage is unlikely because, at least in the case of nitrogen, the increase in stand growth is often of short duration, higher nutrient content generally promotes decomposition (*i.e.*, decreasing τ_{for}), and the amount of fertilizers remaining in the ecosystem progressively decreases through leaching and other losses [3,7,8]. The third outcome then naturally follows: the fossil fuel emissions incurred during the treatment lead to a net "fossil fuel debt" (Figure 2c), which increases with the treatment duration. The fourth outcome requires a long-term perspective: the "ongoing fossil fuel cost" eventually results in a net negative carbon mitigation, even though the fossil fuel emissions over a single rotation are small compared to the increase in equilibrium carbon storage (Figure 2d).

Assuming that the treatment decreases τ_{for} instead of increasing NPP (or does both) would not challenge these conclusions. Using other values would of course modify the quantitative results, but not the qualitative outcomes. For example, assuming that FFE is 10 times smaller than the value we used would only postpone the time at which the continued treatment (Figure 2d) results in a net negative carbon mitigation, from year 1021 to year 9319. While the specific values clearly matter, the qualitative outcomes are imposed by the form of Equations (S1) and (S3). Challenges would thus stem from modifications to the fundamental assumptions underpinning the conceptual model, for example the two caveats mentioned in the main text. In the case of a treatment increasing forest productivity, we consider unlikely that a sufficient amount of forest carbon could end up being stored in pools with a millennial residence time.

2. Conceptual Model for Additional Harvested Wood Products

We now consider a different mitigation strategy that consists of increasing the harvest level in CMF and store this additional carbon in harvested wood products (HWP) with a longer residence time than the forest itself. We still represented the landscape-level mean forest carbon $C_{for}(t)$ by Equation (S1) with the same values for the different parameters, while the mean additional HWP carbon stock normalized per unit of forest landscape area, $C_{HWP}(t)$ (in kg·C/m^2), followed:

$$C_{HWP}(t+1) = C_{HWP}(t) - C_{HWP}(t)/\tau_{HWP} + IN \times \Delta t \tag{S4}$$

where τ_{HWP} is the carbon residence time in the additional HWP (in years), IN is the influx of carbon in the additional HWP (in kg·C/m^2/yr), and $\Delta t = 1$ year.

2.1. Figure SM.1a

We assumed once again that the forest landscape was initially in equilibrium, with a carbon storage of 22.0 kg·C/m^2, and that the mitigation strategy was implemented in year 100. We then implemented a sudden doubling of the harvest H from 0.02 to 0.04 kg·C/m^2/yr, with all the extra harvested carbon ending up as input (IN) to the additional HWP stock (*i.e.*, no waste from HWP processing) having a residence time of 100 years, *i.e.*, almost 50% higher than τ_{for}. Since the HWP stock considered was *additional* to the baseline, the initial condition we used was $C_{HWP}(t = 0) = C_{HWP}(t = 100) = 0$.

Doubling H in CMF would impact all the other forest carbon dynamics parameters in Equation (S1). (Since we were interested in the equilibrium storage, we neglected the transition period towards the new values as we did for Figure 2.) First, estimating the new NPP is difficult, because the value ultimately depends upon the combined effect of stand-level NPP variation with age and the landscape-level age-class structure [6]. Second, heterotrophic respiration is typically higher for a few years after a disturbance event and then becomes relatively stable [9,10]; hence, τ_{for} should decrease slightly due to the higher overall disturbance rate. Third, the smaller net forest carbon storage implies that F removal should become smaller. To account for all these modifications, we assumed that only half of the increased harvest became "effective" for the net forest carbon storage (*i.e.*, the effective value of H we used in Equation (S1) was 0.03 instead of 0.04 kg·C/m^2/yr, even though the value we used for IN in Equation (S4) was 0.02 kg·C/m^2/yr). This choice, as well as the no-waste assumption from HWP processing, likely overestimated the total (forest and HWP) carbon storage, thereby strengthening our main conclusions. Following the strategy onset, the combined storage in the forest and HWP progressively reached its new value of 23.3 kg·C/m^2, 6% higher than the initial equilibrium of 22.0 kg·C/m^2 (Figure SM.1a).

2.2. Figure SM.1b

In Figure SM.1b, we assumed that the strategy was permanently halted in year 300. Consequently, the combined carbon storage progressively resumed to its initial value of 22.0 kg·C/m^2.

2.3. Figure SM.1c

In addition to the onset-and-halt pattern presented in Figure SM1.b, we further accounted for the fossil fuel emissions required to produce the additional HWP. We estimated these emissions based on various data for year 2005. That year, 87% of the total merchantable wood harvest volume in CMF went to the solidwood sector, a relatively stable fraction over the last decades [11]. We directly applied this fraction to the total carbon removed from CMF through wood harvest, which was 51 Tg·C in 2005 [1]. Neglecting waste, the total greenhouse gases emissions for the processing of solidwood in Canada that same year were 2.2 (direct emissions) + 1.9 (indirect emissions) Tg·CO_2eq, to which we added 87% of the transport-related emissions of 3.0 Tg·CO_2eq [12]. Given that more than 97% of the CO_2eq emissions for the different fuel types actually consisted of CO_2 [12], we neglected the other greenhouse gases and simply divided these emissions by 3.67 to transform them into C-based emissions. Based on the previous numbers, we estimated that transforming harvested wood into solidwood HWP required emissions corresponding to 4.1% of the total carbon removed from CMF. For a doubling of H, the additional annual fossil fuel emissions (FFE) were thus equal to 0.00082 kg·C/m^2.

The equation describing the full carbon balance of the forest, additional HWP, and associated fossil fuel emissions was then:

$$C_{full}(t+1) = \Big[C_{for}(t) - C_{for}(t)/\tau_{for} + (NPP - H - F) \times \Delta t\Big] + \Big[C_{HWP}(t) - C_{HWP}(t)/\tau_{HWP} + IN \times \Delta t\Big] - \Big[FFE \times \Delta t\Big] \quad \text{(S5)}$$

where the changes in H, IN, and FEE were applied for years 100 to 299 inclusively. While the forest landscape and the additional HWP carbon storage progressively returned to their initial equilibrium values of 22.0 and 0.0 kg·C/m^2, respectively, the net carbon mitigation after halting the treatment was negative due to the 200-year "fossil fuel debt" (Figure SM1.c).

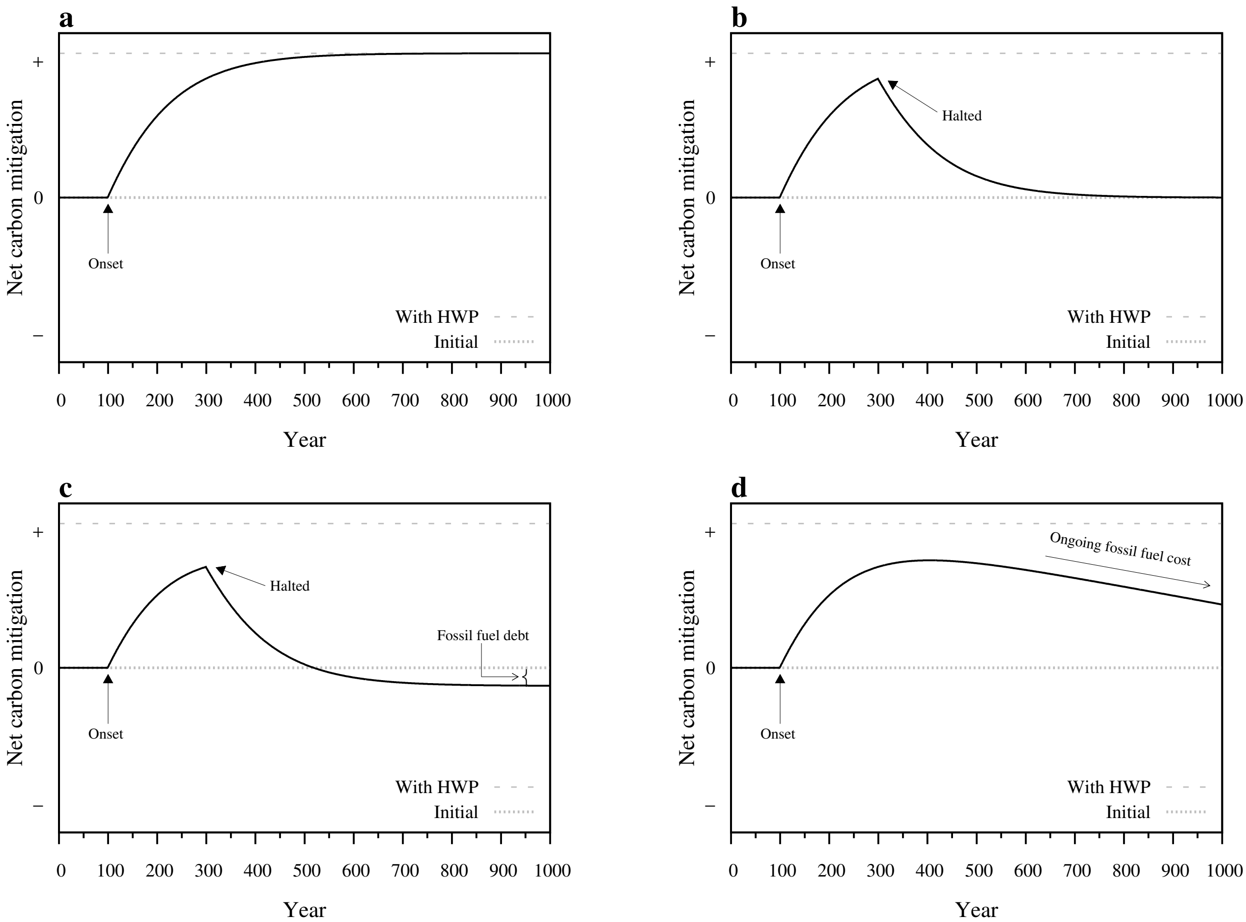
2.4. Figure SM.1d

In Figure SM.1d, the strategy was permanently maintained. While the combined carbon storage in the forest and additional HWP progressively reached its new equilibrium value of 23.3 kg·C/m^2, the "ongoing fossil fuel cost" progressively led to a net negative carbon mitigation, which happened in year 1705.

2.5. Discussion

The four outcomes from this strategy are basically the same as for the NPP-increasing treatment illustrated in Figure 2, but one important difference arises from the ultimate fate of HWP. The conceptual model we used assumed a single carbon residence time of 100 years for the additional HWP. Now, HWP carbon accounting in Canada considers that most HWP is eventually directed towards landfills, in which a fraction of the incoming carbon is assumed to remain forever [4]. Although the specific values are probably appropriate for yearly to decennial carbon accounting, a review of HWP decomposition in landfills concluded that "(...) *it is difficult to establish the ultimate extent of decomposition*" [13]. Nevertheless, evidence from the degradation of archaeological wood clearly establishes that some wood can remain stable for centuries to millennia in anaerobic conditions [14]. Contrary to the situation illustrated in Figure 2, the outcomes from this strategy could therefore be challenged with regards to the second caveat mentioned in the main text (*i.e.*, sufficient HWP carbon might end up being conserved in landfills over the climatically-relevant millennial timescale). Such an assessment would however need to also account for all the fossil fuel emissions related to the construction, operation, and maintenance (including post-closure) of landfills. The bottom line here is that an additional harvest from CMF directed towards HWP might end up in a net positive carbon mitigation—even when accounting for all the related fossil fuel emissions—due to the ultimate carbon storage in landfills, but not to the products in use *per se*.

Figure S1. Net carbon mitigation from a strategy transferring more forest carbon to an additional harvested wood products (HWP) pool with a 100-year residence time, based on realistic values for Canadian managed forests (CMF). The dotted gray line gives the initial equilibrium carbon, whereas the dashed gray line gives the new equilibrium carbon resulting from the additional HWP. **(a)** The strategy started in year 100 and was maintained perpetually. The results account for the forest and HWP only; **(b)** The strategy started in year 100 and was halted in year 300. The results account for the forest and HWP only; **(c)** The strategy started in year 100 and was halted in year 300. The results now also account for the fossil fuel emissions incurred; **(d)** The strategy started in year 100 and was maintained perpetually. The results now also account for the fossil fuel emissions incurred. Net carbon mitigation became negative in year 1705.



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