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Review

Carbon Cycling, Climate Regulation, and Disturbances in Canadian Forests: Scientific Principles for Management

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Abstract: Canadian forests are often perceived as pristine and among the last remaining wilderness, but the majority of them are officially managed and undergo direct land use, mostly for wood harvest. This land use has modified their functions and properties, often inadvertently (e.g., age structure) but sometimes purposefully (e.g., fire suppression). Based on a review of the literature pertaining to carbon cycling, climate regulation, and disturbances from logging, fire, and insect outbreaks, we propose five scientific principles relevant for Canadian managed forests. Among these, a principle we wish to highlight is the need to properly account for the management-related fossil fuel emissions, because they will affect the global carbon cycle and climate for millennia unless massive atmospheric carbon dioxide removal becomes a reality. We also use these five principles to address questions of current interest to research scientists, forest managers, and policy makers. Our review focusses on total ecosystem carbon storage and various mechanisms through which forests affect climate, in particular albedo and aerosols forcings—including how disturbances influence all these elements—but also touches on other ecosystem goods and services. Our review underscores the importance of conducting >100-year time horizon studies of carbon cycling, climate regulation, and disturbances in Canadian managed forests.

Keywords: forest management; carbon; climate; wood harvest; fire; insect outbreaks; albedo; aerosols; net emissions; Canada

1. Introduction

Land use change and its consequences are most apparent when accompanied by major transformations of land cover, for example the conversion of forest to cropland or the replacement of natural vegetation with human-made surfaces. Yet land use change does not always involve land cover change [1]. Globally, the most widespread type of "land management change" (*i.e.*, the use of land by humans, without changing the land cover) occurs in forests; indeed only one fourth of the total forested area is not currently affected by human use [1]. Non-deforestation wood harvest is usually the main objective of forest management and has been occurring worldwide for centuries, often affecting the same area repeatedly [2,3]. This direct use of forests for timber extraction goes along with inadvertent consequences, of which we are increasingly becoming aware. Even without permanent land cover change, the transition from wild to managed forests modifies carbon storage and climate-relevant land surface properties like albedo through altered age structure and species composition, among others [4,5]. Managed forests also undergo temporary land cover change, because harvesting mature stands triggers a process of natural succession among different vegetation types, with a delay of years to decades before recovering back to a closed-canopy forest [6,7].

Canadian forests, particularly in the boreal region, are often perceived as being largely intact due to low population density, an overall small proportion of forest cleared for agriculture or urban settings, and the high share (~65%) of the forested area found in unfragmented blocks covering at least 1 Mha [8–10]. Although not inaccurate, this perspective is incomplete: excluding the Arctic ecozones, more than one fourth of Canada's landmass is within 500 m of human access or activity; outside the boreal region, less than 45% of the forested area is found in unfragmented blocks covering at least 50,000 ha; and even in the boreal region, more than 60% of the timber productive area has already been logged at least once [8,11,12]. These features result mainly from wood harvest and associated forest roads, but also from other ubiquitous activities like mining, oil and gas exploration and exploitation, hydroelectric power generation, agriculture, and hunting/fishing/trapping [13–16]. More than 40 years ago, the increasing northward human pressure led Hare and Ritchie [17] to state that "(p)*erhaps within the next decade—and certainly within what is left of this century—the Boreal forest of North America* (...) *will be massively altered by economic invasion*". One thing is sure: even though most of Canada's pre-European settlement forests are still covered by trees, human land use does occur over millions of hectares within them.

The purpose of this review is to: (1) propose scientific principles related to carbon cycling and climate regulation in the context of the major disturbances happening in Canadian managed forests (CMF); and (2) apply these principles to specific questions raised by human use of these forests. Carbon cycling and climate regulation are indeed major CMF ecosystem functions, and these functions are strongly influenced by disturbances that are anthropogenic (*i.e.*, logging) or partly under human control despite being mostly natural (*i.e.*, fire suppression and insect outbreak management) [18–24]. Note that our objective is not to review the expected impacts of climate change, including droughts; for these, we refer readers to previous publications [25–30]. We rather address the consequences stemming from land use in CMF, in the context of ongoing climate change that should require both mitigation and adaptation measures. We also exclude from our review the aquatic ecosystems that are embedded within CMF, even though they play a role in carbon cycling and are affected by land use, as well as the urban forests that provide various benefits to the ~80% of Canadians living in urban settings [31–36].

In the following section, we better define what CMF consist of, outline their human use history, present the ecosystems goods and services they provide, and discuss the role played by logging, fire, and insect outbreaks. In the third section, we discuss five principles that reflect the most important aspects of our current understanding of carbon cycling, climate regulation, and disturbances in CMF. In the fourth section, we use these principles to address four questions of current interest regarding the management of Canadian forests.

2. Overview of Canadian Managed Forests

The exact definition of CMF ultimately rests upon a two-step procedure: (1) "forests" are defined as areas of at least 1 ha with the potential to develop crown closure of 25% or more and a tree height of 5 m or more; and (2) the "managed" portions of these forests consist of lands under management for wood harvest, protected from natural disturbances when judged appropriate, or set aside for conservation purposes [37,38]. In other words, the managed forests of Canada correspond to tree-covered areas for which various decisions need to be made and implemented, through long-term planning (e.g., harvesting schedules) or short-term responses (e.g., fire suppression). CMF are spatially well correlated with areas exhibiting the highest proportion of tree cover (based on [39]), are generally located away from the Hudson Bay, and go much further north in western than in eastern Canada (Figure 1). Approximately 230 of the 350 Mha of Canadian forests are currently managed following the definition described above (*i.e.*, not only for wood harvest), which corresponds to the definition of managed forest used for the reporting of greenhouse gas emissions to the United Nations Framework Convention on Climate Change (UNFCCC) [37,38]. Given that almost two thirds of the CMF fall within the boreal region, our review particularly reflects the characteristics of these forests [24]. Note that CMF extent is not fixed permanently, but can change through time (e.g., northward expansion of wood harvest in eastern Canada).

Canadian forests are relatively young due to the dramatic influence of the most recent glaciation. Indeed, the country was almost entirely ice-covered during the Last Glacial Maximum (LGM), about 21,000 years ago. Plant species re-colonized the territory at different rhythms following the ice sheet retreat, and it was not until about 5000 years ago that the vegetation domains and assemblages became similar to the contemporaneous ones, albeit with changes still ongoing at the time of European settlement [40]. Today, Canada is mostly covered by coniferous forests (~70% of the treed area, consisting mostly of *Picea* genus, followed by *Pinus*, *Abies*, and other genera), along with mixedwood (~20% of the area) and deciduous forests (~10% of the area, consisting mostly of *Populus* genus, followed by *Betula*, *Acer*, and other genera) [41].

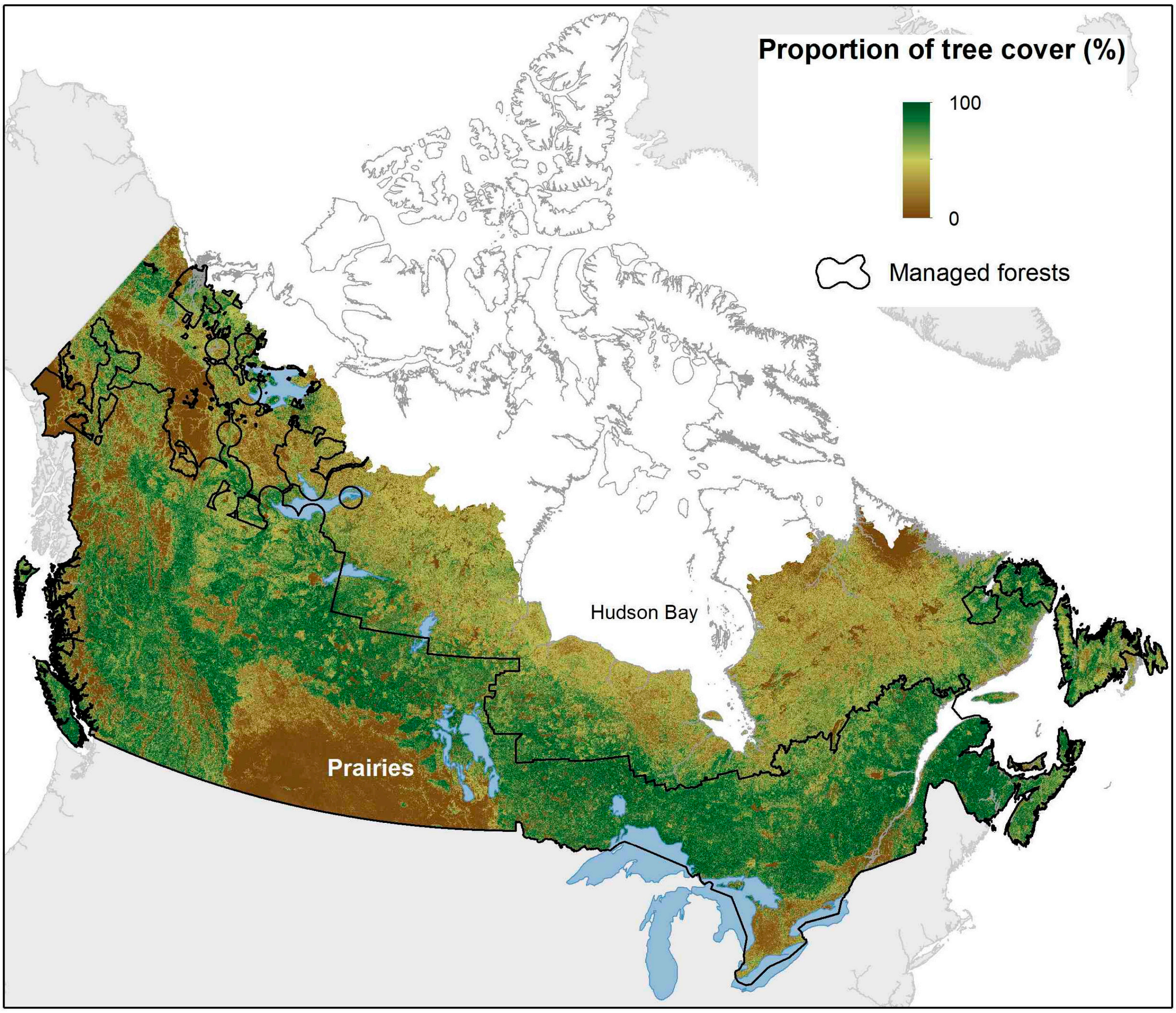

Figure 1. Current extent of the managed forests within Canada (see text for definitions), along with the percentage of tree cover estimated for year 2001 (based on [39]).

The older paradigm of pre-European pristine forests barely affected by Aboriginal people over thousands of years is giving way to a more nuanced view in which resource extraction, the use of fire to modify landscape attributes, and cascading impacts from the possibly human-driven megafauna extinction resulted in substantial impacts across Canada [15,42]. European settlers then affected Canadian forests mainly through agriculture and wood harvest, starting along the St. Lawrence river in the 17th century and progressively moving west across the country [2,43]. By the 19th century, commercial wood harvest had begun in boreal forests [11]. North of the Canadian Prairies, the conversion of the boreal forest southern fringe to agriculture, including cattle ranching, became important in the late 19th and early 20th centuries [2,13,15,43,44]. Some parts of this region still witness high rates of agriculture-driven deforestation, partly offset by high rates of land abandonment [13,45]. For Canada as a whole, however, the mean loss of forests to agriculture has been less than 0.02% annually since 1990 [38]. Activities related to the oil and gas sector, hydroelectric power generation, and mining have become more widespread in Canadian forests over the 20th century [15,16]. These activities do not lead to major deforestation, but require various linear features (road networks, pipelines, seismic lines, railways, and power lines) that fragment forests and influence much more land than the area they cover [8,12,15,16,38,46]. Other less prominent activities related to resource extraction also provide goods and income to Canadians [14,38,47]. In particular, the extraction of non-timber forest products (NTFP) is important and shows an interesting growth potential. Besides the emblematic maple syrup with sales of 350 million Canadian dollars in 2011, NTFP include various food items (e.g., mushrooms), ornamental (e.g., flowers) and transformed (e.g., essential oils) products, and even health and personal care products (e.g., paclitaxel, a cancer-fighting molecule) [38,48,49]. Estimates of the current NTFP sales across Canada are few and uncertain, but the ~500–600 different products could give rise to a billion-dollar industry and create tens of thousands of jobs in rural regions [48,49]. In addition to resource extraction, CMF provide many regulating and supporting services like carbon sequestration, climate regulation, primary production, flood control, and water quality [16,18–21,37,50,51]. The CMF cultural services go beyond recreational activities and include a strong sense of identity. Although many Canadians have not felled a single tree in their lifetime, the historical habit of "going up north" to lumber camps during wintertime still looms large in the country's psyche, as reflected by traditional songs, legends, and poems that remain popular [52–54].

Fire and insect outbreaks are part of the natural dynamics of CMF, especially in the boreal region, and the vegetation succession process they trigger explains the "mosaic of patches" structure of forests [55–59]. The wood harvest performed through clear-cutting over more than 90% of the logged area leads to further stand replacement and forest patchiness [60]. Together, these disturbances explain the surprising results from a recent study by Hansen *et al.* [61]: between 2000 and 2005, Canada was the country with the second highest *gross* forest cover loss, both in absolute and relative terms (the latter being restricted to countries with >100 Mha of forest). The *net* forest cover loss was however very small, because in Canada actual deforestation is rare and most of the disturbed stands are allowed to regenerate back to forests [62]. Nevertheless, fire, insect outbreaks, and wood harvest result in ever-changing spatial patterns of stand age, as well as forest cover gains and losses, across CMF [63,64]. The areas disturbed by fire and moderate to severe insect outbreaks in all Canadian forests since the 1980s have been estimated at ~2 Mha/yr and ~18 Mha/yr, respectively, but with major interannual fluctuations [60]. Typically fire predominates in the west and insects in the east, except for the exceptional mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) outbreak that is still ongoing in western Canada [18,37,38,65,66]. Although often grouped together as "natural disturbances", fire and insect outbreaks differ markedly. Insects are much more selective than fire in the tree species and age classes they attack, and their outbreaks are often synchronized over larger areas and can be relatively periodic [65]. Whereas the so-called "forest insect pests" target live trees only, the direct fire-induced carbon emissions come on average at ~85% from dead carbon pools in Canada [37,67]. And while fires in CMF caused direct carbon emissions of 23 Tg·C/yr on average from 1990 to 2008, insect outbreaks do not directly remove carbon from forests, but rather entail growth losses and transfers from live biomass to in-forest dead carbon pools [37]. As the insect-killed trees progressively decompose, the carbon they contain is emitted to the atmosphere at a pace that depends upon the environmental (temperature, moisture, *etc.*) conditions, with some carbon potentially ending up in soils for thousands of years [6,7,68–70]. Contrary to fire and insect outbreaks, wood harvest in CMF does not fluctuate much from one year to another: starting at roughly 0.3 Mha/yr in the 1920s, the area harvested annually increased more or less steadily up to ~1 Mha/yr during 1995–2005, decreasing quickly since then to levels below 0.7 Mha/yr [18,37,38,60].

Over 1990–2008, harvest has directly removed about twice as much carbon from CMF than fire and transferred almost as much carbon from live biomass to in-forest dead carbon pools as fire and insects combined, despite affecting a smaller area [37].

3. Five Scientific Principles Relevant for Forest Management

We critically reviewed the literature related to carbon cycling, climate regulation, and disturbances to propose five scientific principles that we consider fundamental to the management of CMF. We believe these principles should facilitate the application of the existing knowledge to specific management questions. The first three principles deal mostly with carbon cycling, whereas the last two principles address a broader suite of processes. In general, we only accounted for the carbon dioxide (CO_2) component of the carbon cycle. This simplification is more consequential for fire, which emits dozens of non-CO_2 carbon-containing chemical species [71]. Yet the overwhelming majority of the carbon emitted ends up as CO_2, because roughly 90% of the carbon monoxide (CO) is quickly transformed to CO_2 and 50%–100% of the methane (CH_4) eventually gets oxidized to CO_2 [72,73].

3.1. The Disturbance Regime, not a Single Disturbance Event, Modulates Long-Term Carbon Storage

Disturbances are, by definition, discrete events having noticeable impacts on ecosystem functions and properties [74]. Presenting disturbances as catastrophes that threaten forests seems normal, especially for CMF where the return interval between two events is often more than a century. Yet CMF are well-adapted and resilient to the fire and insect disturbances that have been affecting them for hundreds of years, so that the forest itself, and often the same tree species, regenerate naturally afterwards [46,75–78]. Since CMF consist of hundreds of thousands of forest stands, each with its own time since the last disturbance, looking at disturbance regimes over the entire landscape, particularly the long-term "average" return interval and severity, is more appropriate than considering a single event over a given area [74,79–81].

For a stable disturbance regime and climate, carbon losses from recently disturbed stands will be offset by carbon gains in older regrowing stands [80,81]. The resulting landscape-level equilibrium in carbon storage is lower than it would be in the absence of disturbances; further, it is only an approximate equilibrium due to: (1) the high interannual variability in the occurrence of disturbance events; (2) the spatial variability in stand productivity and carbon storage across the landscape; and (3) the fact that disturbance regimes are never perfectly stable [18,29,30,37,76]. The resulting fluctuations can modify the total carbon storage for decades, but usually fade away in the long term. For example, affected forests should recover over the coming decades from the receding MPB outbreak, so that the end-of-century CMF carbon storage will rather depend upon future disturbance rates and climate-driven changes to forest properties [22,29,66,82]. Besides the frequency of disturbances, the severity of events influences long-term landscape-level equilibrium by removing more or less carbon each time [81,83,84]. Moreover, disturbance severity sometimes modifies forest composition: severe fires can temporarily favour trembling aspen (*Populus tremuloides*) over black spruce (*Picea mariana*), while repeated defoliation of deciduous trees by gypsy moth (*Lymantria disspar*) can be beneficial for coniferous trees [85–87].

A few caveats about the possible importance of a single disturbance event are warranted. First, eddy covariance data suggest that undisturbed stands can remain carbon sinks for centuries, in contradiction with the traditional hypothesis of perfect carbon balance for old stands [88–90]. As a result, a disturbed forest stand might never "catch up" with the total amount of carbon it would have had if left undisturbed. This consideration is however rather theoretical for the CMF as a whole, because overall the net carbon accumulation for >100-year stands in Canada is small, especially in boreal forests, and can even be negative in some years [89,90]. Second, a single disturbance could in principle trigger an irreversible shift to non-forest conditions even under a forest-suitable climate [91]. The documented cases of such alternative stable states in Canadian forests, however, actually involve two events (insect–fire or fire–fire) in rapid succession, with the trees regenerating after the first event still being immature when the second event occurred [92,93]. Other documented cases of large-scale post-disturbance forest regeneration failure originate from remnant forests that established under a different climate centuries ago [94].

In summary, although isolated disturbance events can have local legacies, the overall carbon budget of CMF on centennial timescales is rather modulated by the landscape-level disturbance regime. Consequently, sustained increases in disturbance rate ultimately matter more for the ongoing climate change than spectacular, but anomalous (statistically speaking), events. Unfortunately, detecting regime changes is difficult in practice due to the high stochasticity of natural disturbances [95].

3.2. Disturbance-Driven net Carbon Emissions can Differ Substantially from the Gross Emissions

Among the three disturbances discussed heretofore, fire is probably the one whose carbon emissions have been investigated the most. Both globally and in Canada, studies have often considered mainly, if not exclusively, the combustion-driven emissions [18,37,67,71,96–99]. While relevant, these gross emissions are misused when compared directly to fossil fuel emissions because they provide an incomplete picture. The net carbon emissions from fire go indeed beyond what is actually combusted, and must account for the changes in decomposition (including the vegetation that was killed, but not combusted, by fire) and productivity (including the major emissions offset from post-fire vegetation regrowth) [100]. For example, the global net fire emissions over the 20th century were approximately only half of the gross emissions over the same period [101]. For stable fire regimes, the gross fire CO_2 emissions should eventually be perfectly offset, on average, by the other fire-caused fluxes [102]. These ideas, as well as the notion that most of the net emissions occur in the first few decades following a fire regime shift, are supported by simulations in a fully coupled climate–carbon model [103,104]. In the case of northern North America, we note that the increase in fire disturbance towards the end of the 20th century has led to a net decrease in forest carbon storage, reversing the previous sink effect that had itself resulted from less frequent fires [18,105–107].

Like fire, the net changes in forest carbon resulting from wood harvest include not only the carbon directly removed from the ecosystem, but also the fluxes from the decomposing wood debris and the regrowing vegetation. In Canada at least, these post-disturbance stand-level carbon fluxes are similar for both disturbance types: an initial carbon source reversing after ~10–20 years to a sink, which peaks before age 80 and decreases progressively [89,90,108]. Globally, the gross carbon sources and sinks resulting from wood harvest are much higher than the ones for deforestation/afforestation, but the opposite is true for the net emissions [109]. Since net emissions from constant wood harvest would fluctuate around zero in the long run, the global increase in net emissions from 1850 reflects the increasing amount of wood harvest [110]. Despite these conceptual similarities, one fundamental difference exists between fire and wood harvest: the carbon directly removed from the forest is immediately transferred to the atmosphere by fire, but can be stored for decades or centuries following wood harvest [109,110]. The stock of harvested wood products (HWP) coming from CMF (which are partly still in use, partly decomposing in landfills) has been growing steadily since the beginning of the 20th century [111,112]. Although the HWP stock was less than 2% of the CMF total ecosystem carbon 25 years ago, the absolute increase since then has been roughly an order of magnitude greater for the former than for the latter [37,111,112]. The management of HWP stocks has therefore a role to play in climate change mitigation, which is reflected in the Intergovernmental Panel on Climate Change (IPCC) new accounting rules on the explicit reporting of HWP changes [24,113].

The situation is markedly different for insect disturbances: since there is no direct carbon removal in the short term, the issue resides in estimating the long-term net impact on carbon storage. Three observations emerge from the literature. First, forests can recover very quickly from single-year light to moderate defoliation events and are hardly impacted by bark beetles during the endemic phase [108,114–117]. Second, many analyses have looked at timber or aboveground carbon only, providing limited insight into the impacts on ecosystem carbon storage [118–122]. Third, the recent eddy covariance studies of the net carbon balance following major insect outbreaks are still very short (*i.e.*, a few years) compared with the recovery dynamics (*i.e.*, various decades when mortality occurs) [108,123–125]. From the few modelling studies in or close to the CMF, we suggest the following generalizations for severe outbreaks: (1) the carbon loss is substantially lower for the total ecosystem than for biomass (or timber) alone, in relative and absolute terms; and (2) more severe outbreaks result in greater temporal changes (*i.e.*, higher carbon source, followed by higher carbon sink) [66,84,87,126,127].

In summary, the distinction between gross and net emissions is necessary to adequately appreciate the consequences of fire or wood harvest on carbon cycling. For both disturbances, the net emissions are usually much lower than the gross emissions, due to the carbon uptake from the regrowing vegetation, and come mostly from changes in the disturbance regime. For insect outbreaks, research has often been dedicated to the impacts from a single outbreak on timber only, so the consequences of actual insect disturbance regimes on the total carbon storage remain poorly quantified. To our knowledge, only one study has looked at the impacts from repeated outbreaks on ecosystem carbon in North America [87].

3.3. Even If Initially Beneficial, Mitigation Strategies Requiring Repeated Fossil Fuel Emissions can Become Detrimental over the Climatically-Relevant Millennial Time Horizon

People studying or managing CMF are used to thinking over decennial and centennial timescales, because the fire return interval is over a century across most of the territory and the typical logging rotation is around 70–120 years [128,129]. Yet these time horizons are still too short for some analyses related to the ongoing anthropogenic climate change. Of the ~500–2000 Pg·C of anthropogenic CO_2 emissions projected to happen during the 21st century, ~15%–40% will still be in the atmosphere after 1000 years and ~10%–20% after 10,000 years—unless massive atmospheric CO_2 removal becomes a reality [130–133]. The global surface temperature will increase linearly with the cumulative emissions and will then decline very slowly, if at all, for thousands of years following emissions cessation [131,134–137]. Today's fossil fuel CO_2 emissions will thus impact the global carbon cycle and climate on a millennial time horizon.

Note that the focus on CO_2 is warranted since the global warming and cooling impacts from non-CO_2 agents almost cancel each other, both for contemporaneous and projected climate forcing [138,139].

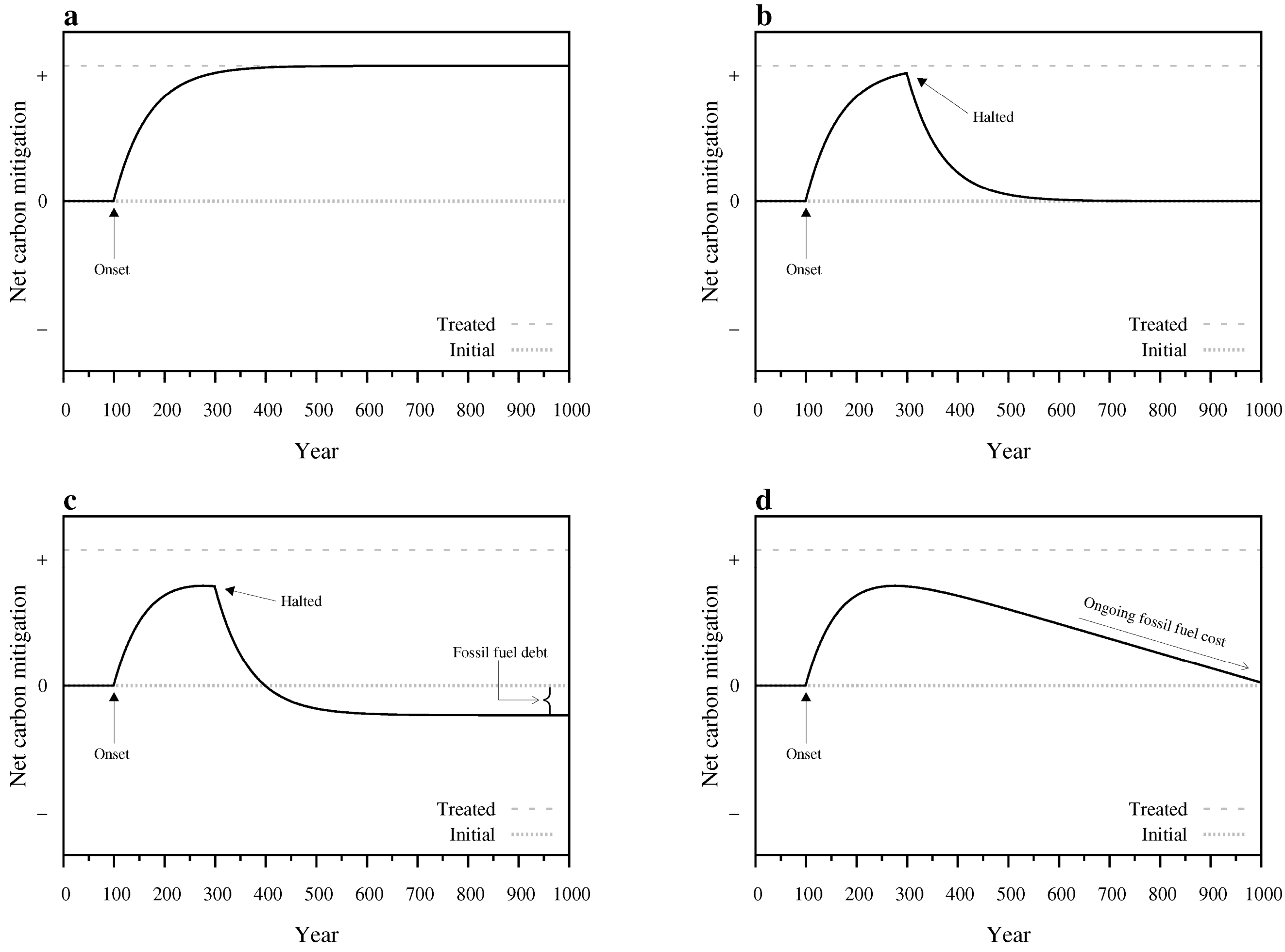

Figure 2. Net carbon mitigation from a treatment increasing forest carbon storage, based on realistic values for Canadian managed forests (CMF). The dotted gray line gives the initial landscape-level equilibrium carbon, whereas the dashed gray line gives the landscape-level equilibrium carbon with the treatment effect. (**a**) The treatment started in year 100 and was maintained perpetually. The results account for the forest landscape only; (**b**) The treatment started in year 100 and was halted in year 300. The results account for the forest landscape only; (**c**) The treatment started in year 100 and was halted in year 300. The results now also account for the fossil fuel emissions incurred; (**d**) The treatment 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 1021.

Current emissions from the Canadian forest sector are noticeably lower than they have been during the 1990s and early 2000s, due to decreased total production and a lower share of fossil fuels in the energy mix [38]. Greenhouse gases emissions in 2005 were estimated at 53 Tg·CO_2eq (CO_2 equivalents), with 48% from direct and indirect energy use at wood processing facilities, 46% from CH_4 emissions from wood products decomposing in landfills, and 6% from transportation [112]. The previous numbers do not include the fuel consumed during wood harvest itself and other forest management activities (e.g., airplanes used for fire suppression). These additional management-related emissions were considered small enough to be left unquantified in the NCASI (2007) study [112], yet accounting for them may sometimes be essential in order to adequately assess the benefits from mitigation strategies.

Management actions are often considered to be carbon-beneficial if, over one stand rotation, the resulting increase in forest carbon is greater than the associated fossil fuel emissions. Although usually necessary, this criterion is not always sufficient. Another key question is whether the increase in forest carbon will persist if the treatment is not repeated over the next rotations. In the affirmative, for example following afforestation in a region with forest-suitable climate, the usual assessment based on a single rotation is conceptually appropriate. In the negative, however, the purported carbon mitigation strategy could become detrimental over the relevant millennial time horizon. We developed a simple model of landscape-level forest carbon dynamics to illustrate this concept (Figure 2; see Supplementary Material for more details). We assumed that the forest carbon was initially in equilibrium. Then, a specific treatment increasing net primary productivity was initiated. Following the treatment onset, the landscape progressively reached a higher equilibrium carbon storage (Figure 2a) because the stand-level increase in productivity was only *maintained*, not *augmented*, each time the treatment was repeated. Assuming that the treatment was halted later on, the forest then resumed to its initial equilibrium (Figure 2b). When accounting for the fossil fuel emissions incurred to perform the treatment, the net carbon mitigation from this onset-and-halt pattern consequently resulted in a "fossil fuel debt" (Figure 2c). In fact, even when the treatment was perpetually repeated, the net carbon mitigation progressively shifted from positive to negative due to the ongoing fossil fuel emissions required (Figure 2d). The outcomes were similar for an analysis of a mitigation strategy based on the transfer of forest carbon to HWP having a longer carbon residence time than the forest itself (see Supplementary Material). In both cases, the net carbon mitigation eventually becomes negative unless: (1) fossil fuel emissions are not required, from the beginning (onset-and-halt pattern) or soon enough (maintained perpetually); or (2) the emissions are offset by a greater amount of forest or HWP carbon ending up in pools with a millennial residence time, or are actually negative due to the substitution of HWP for energy-intensive products [113].

In summary, the anthropogenic perturbations to the carbon cycle and climate from fossil fuel emissions have millennial timescales and must be considered as such. Analyses of forest-related carbon mitigation strategies that span only a few decades to centuries might therefore be short-sighted and counter-productive, especially when the gains happen upfront and the costs are recurrent.

3.4. Climate Regulation goes Beyond Carbon Cycling, for Disturbed and Undisturbed Forests

The substantial amount of carbon stored within CMF (currently estimated at ~50 Pg·C) and the focus put by the UNFCCC on greenhouse gases have fostered research on carbon cycling in the region [37,113]. Nonetheless, CMF influence the climate through many other processes. The process most studied over the past fifteen years is arguably the decrease in albedo when trees are present, especially when they mask underlying snow. This albedo decrease implies that the Earth conserves a higher amount of the incoming solar radiation, resulting in a global warming effect [20,21,23,140,141]. Various modelling experiments have concluded that, for the entire boreal region, this warming effect is stronger than the associated cooling effect from increased carbon storage by forests; hence large-scale boreal deforestation (afforestation) would actually cool (warm) the climate, contrary to the carbon-based expectation [142–145]. These idealized studies are informative, but do not answer questions about realistic forest cover changes. Afforestation of the CMF areas that have actually been deforested could result in net climate cooling (although barely noticeable), because deforestation has happened preferentially in areas with relatively high carbon content and low snow cover [146–148]. On the other hand, the albedo cooling may be greater than the carbon warming following the loss of closed-canopy forest that happened in northeastern CMF due to repeated fires [93]. The role of albedo change is also relevant in the much more common case of natural disturbances followed by forest regeneration. Both fires and the current MPB outbreak have been estimated to result in net climate cooling, although the analysis was limited to 14 years for the MPB [149,150]. Since the net climatic impact is a small residual between the larger carbon and albedo effects, which are uncertain themselves, each of the previous outcomes can be debated. Implicit assumptions also play a major role; for example: (1) the outcome might depend on the particular tree species used for afforestation; or (2) the albedo effect should loose strength in the future, and may already be doing so, due to warming-induced shortening of snow-cover duration [23,151,152]. More studies are needed before one can arrive at a more robust conclusion, but there is no doubt that the albedo effect has to be accounted for in CMF.

Besides albedo, differences in surface roughness and canopy conductance among vegetation types control the land–atmosphere exchanges of energy and water over CMF [141,153,154]. The land-surface properties determine not only the net radiation absorbed, but also how this net amount is partitioned among various fluxes. By creating patches with very different turbulent fluxes of sensible and latent heat, fire can modify mesoscale circulation over boreal forests, which may in turn influence the location of future fire events [155,156]. Changes in turbulent fluxes are not considered to be traditional "forcings" since they do not directly alter Earth's radiative balance, yet they affect surface temperature [141,157]. Moreover, modified turbulent fluxes can actually lead to climate forcing through changes in cloud cover [158]. Studies about the net impact from vegetation changes within Canada on cloud cover are unfortunately limited and provide contradictory evidence [20,145,154].

But the most important influence of CMF on climate may actually occur through aerosols. Different aerosol species give rise to various forcings, the most important being the direct radiative effect and the cloud-mediated indirect effect that involves many processes [159]. Despite giving rise to a strong net cooling that may offset the warming from non-CO_2 well-mixed greenhouse gases, anthropogenic aerosol forcings remain poorly understood [139]. For natural aerosols, even the emissions are highly uncertain, with estimates spanning more than two orders of magnitude for some sources [159,160]. Heretofore, studies on the climatic impacts from vegetation-related aerosols have focussed on fire and biogenic volatile organic compounds (BVOC).

Fire emits various aerosols that have major climate impacts despite their small share of the total emissions and their short atmospheric lifetime [71,159]. While most climatic impacts from a single pulse of fire aerosols would vanish within a day to a few weeks, recurring pulses result in a non-zero "average" climate forcing that depends upon the fire regime [139,159]. Global-scale studies concluded that: (1) all current biomass burning may have a negligible, or even negative, impact on global temperature due to the net cooling from fire-emitted aerosols; and (2) future changes in non-deforestation fires could lead to a small warming or substantial cooling, depending upon the highly uncertain strength of the cloud-mediated effect [103,161–163]. On the other hand, a recent study simulating additional processes concluded that fire aerosols might have a net warming impact [164]. Despite these uncertainties, the current evidence points towards a net cooling from boreal forest fires because studies looking at this question did not include aerosol-related cooling [149,150]. We note that fire also increases the atmospheric concentration of non-CO_2 greenhouse gases like CH_4, but the resulting effect on climate is noticeably smaller than the one from aerosols [162,163].

Globally, vegetation emits dozens of BVOC that can lead to the subsequent formation of secondary organic aerosols [159,165]. Vegetation composition strongly influences aerosols formation over CMF, because BVOC emission factors vary by orders of magnitude among boreal plant types [165]. BVOC-derived secondary organic aerosols cool the climate through radiative and cloud albedo (one of the cloud-mediated processes) effects, globally and over CMF [160]. The cloud albedo forcing is estimated to be particularly large over boreal forests during summer [160]. Kulmala *et al.* [166] hypothesized a decade ago that this forcing might constitute a negative feedback to climate warming, whereby higher temperature increases BVOC emissions and cloud albedo. Although this negative feedback appears negligible globally, its strength is likely much higher over boreal forests due to cleaner background conditions [167]. BVOC also have climatic impacts that could be modified through warming-induced changes in insect herbivory or plant phenology, but these impacts have not been quantified yet [168–170].

In summary, climate regulation by CMF is multifaceted, both for disturbed and undisturbed conditions. In particular, surface albedo and aerosols can predominate over carbon cycling in some circumstances. The role of albedo in northern forests is well recognized and has been validated by empirical-based studies [171,172]. Although the existence and importance of aerosols climatic impacts are established, their actual forcing remains elusive. Given the undergoing discovery of basic mechanisms, the strong non-linear dependence of aerosols forcing on background atmospheric pollution, and the wide inter-model range of results for the processes already represented, we should not expect conclusive results soon, especially for natural aerosols [173–177].

3.5. Wood Harvest Cannot Perfectly Emulate Natural Disturbances

The idea that wood harvest should aim to emulate natural disturbances in forests where they frequently occur was proposed a few decades ago to foster sustainable forestry, particularly for maintaining biodiversity and ecosystem functions [46,178]. This natural disturbance-based management approach rests upon the "coarse filter" concept, which promotes the conservation of a wide array of habitats across the landscape instead of focussing on individual species, and recognizes the essential role of disturbance regimes characterized by a range of variability in the frequency, severity, and size of individual events [46,178]. However, wood harvest differs fundamentally from natural disturbances in many aspects and cannot be simply substituted for them.

At the stand level, the most obvious difference between wood harvest and natural disturbances resides in the direct removal of organic matter. Fire directly removes less than half of the carbon contained in the trees it kills [37,97,99]. On the other hand, the purpose of wood harvest is to move carbon, particularly the stems, out of the forest. Regarding soil carbon, the situation is the opposite in CMF: most direct fire emissions usually come from soil and dead organic matter, whereas current logging practices aim to minimize soil disturbance [37,46,67]. Overall, wood harvest directly removes from CMF ~1.3 time more carbon than fire on a per-area (of disturbance) basis [37]. Moreover, the impacts from fire *vs.* wood harvest on the availability of nutrients differ substantially for nitrogen, calcium, and magnesium, and are even opposite for phosphorus [179]. The decreased availability of nitrogen and phosphorus following logging *vs.* fire is greater for whole-tree harvest, possibly enough to reduce tree growth [46,180]. Although insect outbreaks can result in nutrient losses through leaching, the actual impacts are often much smaller than for stand-replacing disturbances, especially for nitrogen in unsaturated soils like the CMF ones [181–184]. Concerning biodiversity, post-disturbance differences between burned and logged stands are complex. Species richness or diversity is often higher following logging rather than fire for the first harvest rotation in CMF, but results from Europe suggest the opposite for subsequent rotations [46]. Communities of birds, arthropods, and plants have been observed to differ considerably for the first few years after the disturbance, but much less after a decade; nevertheless, the across-stands post-disturbance variability in community composition is systematically higher for fire than for logging [46]. In the case of wood harvest, some of the variability in community composition might result from planting *vs.* natural regeneration [185]. Although alternative logging techniques (e.g., partial harvesting instead of complete clear-cutting) can decrease the stand-level differences between wood harvest and natural disturbances, they cannot completely erase them [46,178].

Other major differences arise at the landscape level. Even for the same average disturbance rate, the age-class distribution differs between the two disturbance types because humans, contrary to fire, systematically avoid the younger stands and often target the oldest ones. In eastern CMF, the current age-class distribution of a >1.5 Mha landscape has thus been shown to lie completely outside the fire-induced natural range of variability, even though mechanized logging started less than 40 years ago in that region [186]. Past logging in CMF is further considered to have decreased the abundance of coniferous species and reduced pre-existing altitudinal gradients in vegetation composition [187]. Wood harvest also alters the spatial structure of the landscape, resulting in a higher number of smaller-sized patches [46,57]. Such differences in spatial structure can modify the disturbance regime from the eastern spruce budworm (*Choristoneura fumiferana* Clemens), a major periodic defoliator of CMF needleleaf trees [188]. These landscape-level disparities in habitat features (age classes, fragmentation, and spatial structure) between wood harvest and natural disturbances are not systematically detrimental for biodiversity. For example, the higher proportion of very young stands is beneficial for moose (*Alces alces*) and its predators [59]. On the other hand, a strong decrease in very old stands is dramatic for species requiring vast expanses of such habitat. The iconic woodland caribou (*Rangifer tarandus caribou*) has been performing a continent-wide northward retreat, very likely in response to the logging wave from the south [46,189]. Today, one of the five Canadian populations of woodland caribou is listed as endangered, while two others, including the most widespread one, are listed as threatened [190]. Very large fire years also decrease suitable habitat for woodland caribou, but extirpation seems to be driven primarily by wood harvest and the loss of historical habitat is greater in regions with a longer forestry history [59,189,190].

Wood harvest involves further aspects that have no analog in unmanaged forests. First, road networks built for forestry operations result in a semi-permanent loss of vegetation cover, highly fragment the landscape, constitute favourable corridors for the propagation of exotic species, and alter animal behaviour, among others [8,12,46]. Estimates of the area deforested for forest roads vary from ~0.3% to ~2% of the harvested area, but roads influence a much greater area of CMF than they occupy [38,191]. Second, forest management aims to remove a fairly constant amount of wood out of CMF each year, whereas interannual gross fire emissions vary by more than one order of magnitude [37,67]. Implementing "pulsed" wood harvests might therefore seem desirable in order to better emulate the effect of natural disturbances, but also entails potential disadvantages, particularly if a large fire year occurs shortly after a wood harvest pulse [59].

In summary, natural disturbance-based management should be pursued in order to mitigate the detrimental consequences from wood harvest, but we must recognize that the fundamental differences between logging and natural disturbances prevent us from fully achieving its goal [46,57,178].

4. Application to Specific Management Issues

We now use the five previous principles (summarized in Table 1) to address four management issues of current interest. Both the questions and responses are for the specific context of CMF and, despite the many caveats involved, we forced ourselves to propose a clear "yes" or "no" answer to each question—albeit with qualifications in some cases.

Table 1. Five scientific principles relevant for Canadian managed forests.

Code	Principle
P1	The disturbance regime, not a single disturbance event, modulates long-term carbon storage
P2	Disturbance-driven net carbon emissions can differ substantially from the gross emissions
P3	Even if initially beneficial, mitigation strategies requiring repeated fossil fuel emissions can become detrimental over the climatically-relevant millennial time horizon
P4	Climate regulation goes beyond carbon cycling, for disturbed and undisturbed forests
P5	Wood harvest cannot perfectly emulate natural disturbances

4.1. Should We Suppress Natural Disturbances to Mitigate Climate Change? No

Natural disturbances are expected to generally increase in or close to the CMF over the coming decades and centuries (see [24,30] for boreal-focussed reviews). Suppressing natural disturbances is sometimes mentioned as a climate change mitigation strategy, the idea being to increase landscape-level carbon storage through the reduction of disturbance frequency and/or severity, in accordance with P1 [113,192]. We do not, however, support this strategy in CMF, mainly for two reasons.

First, suppressing natural disturbances might actually contribute to climate warming (P4). For fire in CMF, the current understanding does point towards a net cooling effect [149,150]. The previous studies did not include all known aerosol-related impacts, but the evidence available suggests that fire-emitted aerosols would either further cool the climate or not warm it enough to change the outcome, while the possible post-fire reduction in BVOC-derived aerosol cooling appears much too small to play a substantial role [160–164]. Even when considering carbon cycling only, the net impacts from major changes in fire frequency are much smaller than suggested by the gross emissions (P2) [103,104]. Peatlands and permafrost, which store high amounts of carbon per unit area and were not included in the previous studies, might however be exceptions [193]. Unfortunately, current knowledge on the climate impact or net carbon emissions from insect outbreaks is limited, especially over repeated outbreaks.

Second, the cumulative fossil fuel emissions required to maintain suppression may eventually become higher than the potential increases in forest carbon storage (P3). Although this is highly speculative on a millennial timescale, one could hypothesize that early suppression of the recent MPB outbreak would have permanently prevented its crossing of the Rocky Mountains into the boreal forest, where it has been observed to successfully attack and reproduce in a new host [194]. But in general, suppression of natural disturbances would require repeated interventions instead of a single-time action. Furthermore, the actual feasibility and efficiency of sustained and large-scale disturbance suppression in North American forests are questionable [22,102,195–197]. If suppression were implemented and then had to be abandoned, the temporary increase in CMF carbon storage would progressively fade away (P1) and fossil fuel carbon would have been emitted in vain (P3). The previous discussion refers to traditional fire suppression or pest management activities, but not to the replacement of wood harvest planned well in advance with preemptive logging of stands "just before" a natural disturbance occurs. This hypothetical strategy should be beneficial from a carbon perspective, because it would increase CMF carbon storage without noticeably modifying management- and HWP-related emissions. Implementing such a strategy might be feasible for insect defoliators due to the relative periodicity and large-scale spatial synchrony of their outbreaks, but appears impossible for fire—which likely has a stronger net impact on CMF carbon storage—due to the dominant role of weather [37,65]. Finally, the strategy might be counter-productive when going beyond carbon cycling (see the previous paragraph), would involve other impacts on CMF (P5), and the resulting "pulsed" wood harvests would pose various challenges [59].

There can be valid reasons to suppress particular disturbance events, for example protecting people and property, conserving a particular habitat crucial for an endangered species, or securing the timber supply around a forest-dependent community. But climate mitigation does not justify an across-the-board suppression strategy in CMF, because it might be counter-productive and is not fail-safe.

4.2. Should We Salvage the Trees Killed by the Mountain Pine Beetle? Yes—But Only Some of Them

The recent MPB outbreak in western CMF has triggered a strong response from federal and provincial governments, which have together already committed around 2 billion Canadian dollars for various measures and have started to salvage some MPB-killed trees [198–200]. At the crudest level of analysis, salvage logging can simply "substitute" with MPB-killed trees the harvest that was originally planned elsewhere. These spared trees will then be available to replace the MPB-killed trees that should have been harvested later on. Such substitution does not entail an obvious long-term impact on carbon cycling (P1 and P2). While perfect substitution is impossible at the local scale in highly affected regions, it is roughly attainable over the entire province of British Columbia, where the bulk of mortality has occurred. Prior to the outbreak onset in the early 2000s, the average provincial harvest was around 74 Mm^3 of merchantable wood per year [60]. The most recent estimates project that, at the end of the outbreak, a total mortality of ~780 Mm^3 of merchantable wood will have happened over more than 20 years [201]. Given that MPB-killed trees can be used for many products in the solidwood, pulpwood, and firewood sectors if they are salvaged within a few years, there is thus room for a substantial amount of substitution [202,203]. Indeed, provincial-level wood harvest, both in area and in volume, has not systematically increased since the onset of salvage logging [60]. Salvaging might also have beneficial outcomes besides mitigating the short-term reduction of merchantable volume. By decreasing snagfall-induced nitrogen immobilization, salvaging could increase stand productivity ~10–50 years after mortality [84]. Avoiding massive decomposition of organic matter after MPB outbreaks may also prevent the degradation of drinking water quality measured in some water-treatment facilities in United

States, which likely resulted from the reaction between increased dissolved organic matter and water disinfection products [204]. Finally, lowering fire hazard is an oft-mentioned justification for salvaging, albeit not really supported by existing studies [205–207].

Yet we do not think that all MPB-killed trees should be salvaged, for four reasons. First and foremost, stands with enough secondary vegetation can achieve merchantable volumes within a few decades, a situation that may correspond to a majority of MPB-killed stands [208]. Avoiding systematic salvage will thus prevent all killed stands from reaching once again the age most susceptible to MPB attack at the same time, in ~80 years from now [209]. Second, salvaging all MPB-killed trees would almost certainly involve the construction of more extensive road networks, with the resulting negative impacts (P5). Third, the MPB-killed trees provide habitat for various species (P5) [210]. Fourth, we need more research on the climatic and ecological consequences of MPB outbreaks, involving various stand-level comparisons (*i.e.*, undisturbed forest, MPB attack without salvage, and MPB attack with salvage). Alternative interventions, like partial harvesting instead of the traditional clear-cutting, also show promises [125].

If the recent MPB outbreak was a one-time isolated event, the decision to salvage or not matters little for the long-term CMF carbon storage (P1) and other climate regulation processes (P4). (Temperature changes from short-term radiative forcing pulses also progressively fade away, as exemplified by major volcanic eruptions [139].) In such circumstances, the net climatic impact would rather be determined by the related fossil fuel emissions, in the forest itself (P3) but above all regarding the fate of the salvaged wood (P2). For the latter, the following considerations are relevant: (1) emissions per unit of wood processed are substantially higher for the pulpwood than the solidwood sector; (2) CH_4 emissions from paper decomposing in landfills were responsible for a third of all CO_2eq emissions from the Canadian forest sector in 2005; and (3) HWP can potentially be substituted for fossil fuels or energy-intensive products [111–113]. But if severe MPB or other bark beetle outbreaks become common in CMF, then the recurring dilemma on whether salvage log or harvest elsewhere will be consequential for carbon cycling and climate, hence the importance of undertaking the research previously suggested. Meanwhile, we can recommend that salvaging should give priority to stands without secondary structure and located close to existing forest roads.

4.3. Should We Try to Prevent Paludification? No

Paludification is the natural transformation of well-drained forest stands into peatlands, which can happen through the lateral expansion of a pre-existing peatland, the lack of drainage in topographic lows (edaphic paludification), or the accumulation of excessive soil organic matter following the establishment of *Sphagnum* spp. mosses (successional paludification) [211–213]. The last process is relatively common around the Hudson Bay (Figure 1), including in some portions of CMF where research on preventing paludification is ongoing because the lower timber productivity of paludified stands is considered detrimental from a forestry perspective [211,212]. While paludification is resilient to low-severity fires, high-severity fires consume the organic layer and lead to higher tree growth through increased nutrient availability, warmer soils, and enhanced drainage [211]. Similarly, disturbing the organic layer on purpose by summer clear-cutting without soil protection increases forest productivity [212].

Despite higher tree growth, preventing paludification likely goes against P2 due to the impact on soil carbon storage. Although there can be net carbon losses during the transition process and despite high spatial variability, paludification seems to increase total ecosystem carbon storage in the long run, possibly by a factor of roughly 4 [213,214]. Some authors have even suggested that paludification around the Hudson Bay could account for some of the missing terrestrial carbon sink [211]. In any case, the evidence available strongly suggests that paludification would result in substantially more carbon storage over centennial to millennial time horizons. A study on drained peatlands in Finland indicated that decreased CH_4 fluxes could cool the climate in the short term, but this effect stabilizes after a few decades whereas the concurrent CO_2 warming keeps increasing steadily after a century [215]. In fact, over climatically-relevant millennial timescales, the CO_2 effect seems to always be larger than the CH_4 effect for northern peatlands [216]. The decrease in leaf area index from forests to peatlands also suggest an additional cooling from increased albedo (P4), although this would need validation with data from the Hudson Bay region [214,215]. Of course, future carbon storage in peatlands could be threatened by climate-induced increase in fire severity, warming, and changes in hydrology [69,217]. But peatlands can also be resilient, and we consider that taking the bet of maintained carbon storage is preferable over almost certainly releasing more soil carbon than the more productive vegetation will sequester [218,219]. This is also a fail-safe approach, because halting the paludification process is much easier and faster than resuming it.

4.4. Should We Pursue Forest-Based Bioenergy? Yes—But with Limited Expectations and Only When Sufficiently Beneficial

A considerable body of research has addressed the potential contribution of forest-based bioenergy as a climate change mitigation strategy, as detailed in the latest IPCC reports [192,220]. Wood can indeed replace fossil fuels as a direct energy source (*i.e.*, through combustion) or following transformation into a second-generation biofuel (e.g., cellulosic ethanol). Here we discuss this strategy for CMF in the light of the previous principles. We refer readers to Lemprière *et al.* [113] and references therein for more details, especially for the boreal portion of CMF.

Bioenergy from afforested land could have a double positive impact, quickly increasing carbon storage both in vegetation and soil while reducing fossil fuel emissions [113,221–223]. As already mentioned, the albedo-induced warming from afforestation in Canada may be smaller than the associated carbon-induced cooling (P4) [146–148]. However, the resulting loss of agricultural production would likely lead to "indirect emissions" from land use change elsewhere in the world; the delay before the strategy provides a net climate gain would therefore be longer, especially if more primary tropical forests end up being cleared [224–226]. Moreover, we can question the permanence of afforestation projects north of the Prairies, where a substantial potential exists [13,43]. First, drought could cause permanent forest loss in this region and has already triggered massive tree mortality since the beginning of the century [25,27,28,30,227]. Second, frequent land use changes have historically occurred in the region, and climate change will likely entail future tensions between forestry and agriculture [13,44,45,228,229]. While not discarding the potential contribution of afforestation, we thus turn our attention to bioenergy from current forests.

Assuming that the extraction of wood for other products would stay the same, bioenergy would decrease the net carbon storage in CMF due to the increased rate of wood harvest (P1). Yet the cumulative benefit of fossil fuel substitution would eventually overwhelm this initial "carbon debt", *as* *long as* bioenergy does result in a net decrease of fossil fuel emissions over its entire life cycle (the reverse of P3; the situation is the opposite of the one illustrated in Figure 2) [113]. The higher albedo from reduced forest cover would cause a further cooling (P4), so that bioenergy could be more efficient when derived from CMF than from more productive forests with less snow cover [230]. Bioenergy coupled with carbon capture and storage looks particularly interesting since it can conceptually lead to net negative emissions, but the decrease in nutrient availability from repeated logging could become an issue, especially for whole-tree harvest (P5) [179,180,220]. Here again, a long-term perspective is required since nutrient depletion could take many rotations [231]. Fertilization can in principle compensate for nutrient losses, but involves emissions that must be subtracted from the climate benefits (P2) [113].

Bioenergy has a role to play in the global mitigation of climate change, but it faces ecological limits and is unlikely to meet even the current energy demand [220,232,233]. Despite the very large forested area per capita in the country, expectations should also be limited for CMF-based bioenergy because vegetation productivity is lower than in most other regions of the world [37,234]. Various studies have estimated that different "wastes" from Canadian forests could contribute ~3%–10% of the current national energy consumption, but roughly half of this bioenergy potential is already realized through the combustion of wood processing residues [113,235]. Additional wood harvest dedicated to bioenergy could substantially increase the total energy production, but may not be viable over many rotations. Such a strategy would also lead to a net negative carbon mitigation for decades at least, due to the slow growth of CMF and the lower carbon-based energy density of biomass compared to fossil fuels [113,236]. Other forest-based mitigation strategies can therefore be much more efficient over the coming decades [236]. Another key consideration is the extent to which bioenergy actually substitutes for, and not simply add to, fossil fuel energy consumption. This issue is beyond the scope of our review, but suffice it to say that per capita carbon emissions have slightly increased since 1960 despite the growth of renewable energies [237].

5. Conclusions

While recognizing the importance of various other changes, land use science has been particularly concerned heretofore with the most extreme instances—the loss of natural forests to agriculture and urban areas [238]. Although the consequences are less extreme, we must now come to grips with the fact that the vast majority of Earth's remaining forests are under direct human influence [1]. The overarching idea of our review is that even in Canada, despite an extensive tree cover and a very low population density, most of the forest is in fact being managed (Figure 1), and that this management (often, but not always, timber-oriented) has profoundly modified its functions and properties. Yet the changes to come may even be more severe, particularly in western CMF where cumulative impacts of forestry and oil and gas may remove virtually all old-growth stands over millions of hectares by the end of the century, even if "best practices" replace the current ones [239]. These detrimental effects are of course not the goal, but rather inadvertent consequences of the resource extraction we pursue in order to increase human well-being [51,238].

In this review, we aimed foremost at synthesizing the current understanding of carbon cycling, climate regulation, and logging, fire, and insect outbreak disturbances in CMF through five scientific principles (Table 1). We consider that these principles can guide research scientists, managers, and policy makers in their assessment of specific questions. We illustrated this by using various or all of these principles to analyze four complex questions related to land use in CMF, in order to propose relatively clear answers (Table 2). These answers are of course not definitive, but should be considered as well-informed default and generally fail-safe options awaiting more dedicated studies. While we believe in the guiding value of these principles, we acknowledge that they are not all-encompassing so that other considerations should prevail in some circumstances. For example, fire suppression is often socially desirable in CMF even though it likely contributes to climate warming.

Table 2. Proposed answers to questions of current interest in Canadian managed forests, based on the five scientific principles listed in Table 1.

Question	Proposed Answer
Should we suppress natural disturbances to mitigate climate change?	No
Should we salvage the trees killed by the mountain pine beetle?	Yes—but only some of them
Should we try to prevent paludification?	No
Should we pursue forest-based bioenergy?	Yes—but with limited expectations and only when sufficiently beneficial

One crucial observation emerging from our review is the relatively short-term focus of most large-scale studies dealing with carbon cycling, climate regulation, and disturbances in CMF. A 100-year analysis may look farsighted compared with most human endeavours, but for the vast majority of CMF it does not even cover two full rotations. And as far as global changes to the carbon cycle and climate are concerned, this is actually a short timescale compared with the millennial lifetime of fossil fuel-emitted CO_2. Many valid reasons justify such limited time horizons, including: (1) the short commitment periods (2008–2012 and 2013–2020) for the Kyoto Protocol developed under the UNFCCC; (2) the scarce empirical support for long-term results from ecosystem and forestry models, due to the limited time series and chronosequences currently available; and (3) the speculative nature of projections over centennial and millennial timescales. Unfortunately, yearly to decennial analyses risk fostering an inadequate focus on carbon fluxes instead of stocks [240]. Expanding the time horizon of CMF-related analyses is also needed since, as we have seen, severe short-term consequences from an isolated disturbance event usually disappear over time, whereas a mitigation strategy leading to a single up-front forest carbon benefit can eventually become detrimental if requiring repeated fossil fuel emissions (Figure 2).

Over the past decades, quantitative research about forests has progressively broadened its scope from pure timber through full carbon accounting to a larger suite of climate regulation mechanisms. While this is by itself a positive evolution, we would like to conclude on a cautionary note regarding the massive and purposeful climate engineering of CMF. The potential increase in global terrestrial carbon storage resides mostly in afforestation and represents only a fraction of the fossil fuel carbon that will be emitted by the end of this century [241,242]. Moreover, large-scale geoengineering projects involve major risks and create side effects since they differ from actual reductions in fossil fuel emissions [243,244]. Canadian managed forests are important actors in global carbon cycling and climate regulation, but their sole purpose should not be to mitigate anthropogenic climate change.

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Author Contributions

Jean-Sébastien Landry and Navin Ramankutty framed the review paper; Jean-Sébastien Landry further developed the specific ideas; Jean-Sébastien Landry wrote the paper with inputs from Navin Ramankutty.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Luyssaert, S.; Jammet, M.; Stoy, P.C.; Estel, S.; Pongratz, J.; Ceschia, E.; Churkina, G.; Don, A.; Erb, K.; Ferlicoq, M.; *et al.* Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Clim. Chang.* **2014**, *4*, 389–393.
2. Hurtt, G.C.; Frolking, S.; Fearon, M.G.; Moore, B.; Shevliakova, E.; Malyshev, S.; Pacala, S.W.; Houghton, R.A. The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Glob. Chang. Biol.* **2006**, *12*, 1208–1229.
3. Lawrence, P.J.; Feddema, J.J.; Bonan, G.B.; Meehl, G.A.; O'Neill, B.C.; Oleson, K.W.; Levis, S.; Lawrence, D.M.; Kluzek, E.; Lindsay, K.; *et al.* Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *J. Clim.* **2012**, *25*, 3071–3095.
4. Kurz, W.A.; Beukema, S.J.; Apps, M.J. Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. *Mitig. Adapt. Strateg. Glob. Chang.* **1998**, *2*, 405–421.
5. Otto, J.; Berveiller, D.; Bréon, F.M.; Delpierre, N.; Geppert, G.; Granier, A.; Jans, W.; Knohl, A.; Kuusk, A.; Longdoz, B.; *et al.* Forest summer albedo is sensitive to species and thinning: How should we account for this in Earth system models? *Biogeosciences* **2014**, *11*, 2411–2427.
6. Chapin, F.S.; Matson, P.A.; Mooney, H.A. *Principles of Terrestrial Ecosystem Ecology*; Springer: New York, NY, USA, 2002.
7. Bonan, G. *Ecological Climatology: Concepts and Applications*, 2nd ed.; Cambridge University Press: New York, NY, USA, 2008.
8. Smith, W., Lee, P., Eds. *Canada's Forests at a Crossroads: An Assessment in the Year 2000*; World Resource Institute: Washington, DC, USA, 2000.

9. Ellis, E.C.; Ramankutty, N. Putting people in the map: Anthropogenic biomes of the world. *Front. Ecol. Environ.* **2008**, *6*, 439–447.
10. Ruckstuhl, K.E.; Johnson, E.A.; Miyanishi, K. Introduction. The boreal forest and global change. *Phil. Trans. R. Soc. B* **2008**, *363*, 2243–2247.
11. Burton, P.J.; Messier, C.; Weetman, G.F.; Prepas, E.E.; Adamowicz, W.L.; Tittler, R. The current state of boreal forestry and the drive for change. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 1–40.
12. Lee, P.; Cheng, R. Human Access in Canada's Landscapes; Global Forest Watch Canada Bulletin, 2014. Available online: http://www.globalforestwatch.ca (accessed on 29 March 2014).
13. Hobson, K.A.; Bayne, E.M.; van Wilgenburg, S.L. Large-scale conversion of forest to agriculture in the boreal plains of Saskatchewan. *Conserv. Biol.* **2002**, *16*, 1530–1541.
14. Patriquin, M.N.; Parkins, J.R.; Stedman, R.C. Bringing home the bacon: Industry, employment, and income in boreal Canada. *For. Chron.* **2009**, *85*, 65–74.
15. Johnson, E.A.; Miyanishi, K. The boreal forest as a cultural landscape. *Ann. N. Y. Acad. Sci.* **2012**, *1249*, 151–165.
16. Brandt, J.P.; Flannigan, M.D.; Maynard, D.G.; Thompson, I.D.; Volney, W.J.A. An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environ. Rev.* **2013**, *21*, 207–226.
17. Hare, F.K.; Ritichie, J.C. The boreal bioclimates. *Geogr. Rev.* **1972**, *62*, 333–365.
18. Kurz, W.A.; Apps, M.J. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecol. Appl*. **1999**, *9*, 526–547.
19. Bhatti, J.S.; van Kooten, G.C.; Apps, M.J.; Laird, L.D.; Campbell, I.D.; Campbell, C.; Turetsky, M.R.; Yu, Z.; Banfield, E. Carbon balance and climate change in boreal forests. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 799–855.
20. Snyder, P.K.; Delire, C.; Foley, J.A. Evaluating the influence of different vegetation biomes on the global climate. *Clim. Dyn.* **2004**, *23*, 279–302.
21. Bonan, G.B. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* **2008**, *320*, 1444–1449.
22. Kurz, W.A.; Stinson, G.; Rampley, G.J.; Dymond, C.C.; Neilson, E.T. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 1551–1555.
23. Anderson, R.G.; Canadell, J.G.; Randerson, J.T.; Jackson, R.B.; Hungate, B.A.; Baldocchi, D.D.; Ban-Weiss, G.A.; Bonan, G.B.; Caldeira, K.; Cao, L.; *et al.* Biophysical considerations in forestry for climate protection. *Front. Ecol. Environ.* **2011**, *9*, 174–182.
24. Kurz, W.A.; Shaw, C.H.; Boisvenue, C.; Stinson, G.; Metsaranta, J.; Leckie, D.; Dyk, A.; Smyth, C.; Neilson, E.T. Carbon in Canada's boreal forest—A synthesis. *Environ. Rev.* **2013**, *21*, 260–292.
25. Hogg, E.H.; Hurdle, P.A. The aspen parkland in western Canada: A dry-climate analogue for the future boreal forest? *Water Air Soil Pollut.* **1995**, *82*, 391–400.
26. Flannigan, M.D.; Amiro, B.D.; Logan, K.A.; Stocks, B.J.; Wotton, B.M. Forest fires and climate change in the 21st century. *Mitig. Adapt. Strateg. Glob. Chang.* **2005**, *11*, 847–859.

27. Williamson, T.; Colombo, S.; Duinker, P.; Gray, P.; Hennessey, R.; Houle, D.; Johnston, M.; Ogden, A.; Spittlehouse, D. *Climate Change and Canada's Forests: From Impacts to Adaptation*; Natural Resources Canada and Sustainable Forest Management Network: Edmonton, AL, Canada, 2009.
28. Frelich, L.E.; Reich, P.B. Will environmental changes reinforce the impact of global warming on the prairie-forest border of central North America? *Front. Ecol. Environ.* **2010**, *8*, 371–378.
29. Metsaranta, J.M.; Kurz, W.A.; Neilson, E.T.; Stinson, G. Implications of future disturbance regimes on the carbon balance of Canada's managed forest (2010–2100). *Tellus B* **2010**, *62*, 719–728.
30. Price, D.T.; Alfaro, R.I.; Brown, K.J.; Flannigan, M.D.; Fleming, R.A.; Hogg, E.H.; Girardin, M.P.; Lakusta, T.; Johnston, M.; McKenney, D.W.; *et al.* Anticipating the consequences of climate change for Canada's boreal forest ecosystems. *Environ. Rev.* **2013**, *21*, 322–365.
31. Prepas, E.E.; Pinel-Alloul, B.; Steedman, R.J.; Planas, D.; Charette, T. Impacts of forest disturbance on boreal surface waters in Canada. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 369–393.
32. McGuire, A.D.; Anderson, L.G.; Christensen, T.R.; Dallimore, S.; Guo, L.; Hayes, D.J.; Heimann, M.; Lorenson, T.D.; MacDonald, R.W.; Roulet, N.T. Sensitivity of the carbon cycle in the Arctic to climate change. *Ecol. Monogr.* **2009**, *79*, 523–555.
33. Lehner, B.; Reidy Liermann, C.; Revenga, C.; Vörösmarty, C.; Fekete, B.; Crouzet, P.; Döll, P.; Endejan, M.; Frenken, K.; Magome, J.; *et al.* High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* **2011**, *9*, 494–502.
34. Raymond, P.A.; Hartmann, J.; Lauerwald, R.; Sobek, S.; McDonald, C.; Hoover, M.; Butman, D.; Striegl, R.; Mayorga, E.; Humborg, C.; *et al.* Global carbon dioxide emissions from inland waters. *Nature* **2013**, *503*, 355–359.
35. Regnier, P.; Friedlingstein, P.; Ciais, P.; Mackenzie, F.T.; Gruber, N.; Janssens, I.A.; Laruelle, G.G.; Lauerwald, R.; Luyssaert, S.; Andersson, A.J.; *et al.* Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nat. Geosci.* **2013**, *6*, 597–607.
36. Bardekjian, A. Compendium of Best Urban Forest Management Practices; Canadian Urban Forest Network, 2014. Available online: http://www.cufn.ca/#!best-urban-forest-management-practices/c1whv (accessed on 3 June 2014).
37. Stinson, G.; Kurz, W.A.; Smyth, C.E.; Neilson, E.T.; Dymond, C.C.; Metsaranta, J.M.; Boisvenue, C.; Rampley, G.J.; Li, Q.; White, T.M.; *et al.* An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Glob. Chang. Biol.* **2011**, *17*, 2227–2244.
38. Natural Resources Canada. *The State of Canada's Forests: Annual Report 2013*; Natural Resources Canada: Ottawa, ON, Canada, 2013.
39. Beaudoin, A.; Bernier, P.Y.; Guindon, L.; Villemaire, P.; Guo, X.J.; Stinson, G.; Bergeron, T.; Magnussen, S.; Hall, R.J. Mapping attributes of Canada's forests at moderate resolution through *k*NN and MODIS imagery. *Can. J. For. Res.* **2014**, *44*, 521–532.
40. Williams, J.W.; Shuman, B.N.; Webb, T.; Bartlein, P.J.; Leduc, P.L. Late-Quaternary vegetation dynamics in North America: Scaling from taxa to biomes. *Ecol. Monogr.* **2004**, *74*, 309–334.

41. Natural Resources Canada. Canada's National Forest Inventory; Natural Resources Canada: Victoria, BC, Canada, 2013. Available online: https://nfi.nfis.org/index.php (accessed on 5 June 2014).
42. Ellis, E.C.; Kaplan, J.O.; Fuller, D.Q.; Vavrus, S.; Klein Goldewijk, K.; Verburg, P.H. Used planet: A global history. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 7978–7985.
43. Ramankutty, N.; Foley, J.A. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Glob. Biogeochem. Cycles* **1999**, *13*, 997–1027.
44. Dore, M.; Kulshreshtha, S.; Johnston, M. An integrated economic-ecological analysis of land use decisions in forest-agriculture fringe regions of northern Saskatchewan. *Geogr. Environ. Model.* **2001**, *5*, 159–175.
45. Young, J.E.; Sánchez-Azofeifa, G.A.; Hannon, S.J.; Chapman, R. Trends in land cover change and isolation of protected areas at the interface of the southern boreal mixedwood and aspen parkland in Alberta, Canada. *For. Ecol. Manag.* **2006**, *230*, 151–161.
46. Haeussler, S.; Kneeshaw, D. Comparing forest management to natural processes. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 307–368.
47. Harvey, B.D.; Nguyen-Xuan, T.; Bergeron, Y.; Gauthier, S.; Leduc, A. Forest management planning based on natural disturbance and forest dynamics. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 395–432.
48. Turgeon, M. *Aperçu des produits forestiers non ligneux (PFNL)*; Ministère des Ressources naturelles, de la Faune et des Parcs: Québec, QC, Canada, 2003.
49. Lamérant, G.; Lebel, F.; Langlais, G.; Vézina, A. *Mise en valeur des produits Forestiers non ligneux*; Centre d'expertise sur les produits agroforestiers: La Pocatière, QC, Canada, 2008.
50. Adamowicz, W.L.; Burton, P.J. Sustainability and sustainable forest management. In *Towards Sustainable Management of the Boreal Forest*; Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L., Eds.; National Research Council of Canada: Ottawa, ON, Canada, 2003; pp. 41–64.
51. Shvidenko, A.; Barber, C.V.; Persson, R.; Gonzalez, P.; Hassan, R.; Lakyda, P.; McCallum, I.; Nilsson, S.; Pulhin, J.; van Rosenburg, B.; *et al.* Forest and woodland systems. In *Ecosystems and Human Well-Being: Current State and Trends, Volume 1—The Millennium Ecosystem Assessment Series*; Hassan, R., Scholes, R., Ash, N., Eds.; Island Press: Washington, DC, USA, 2005; pp. 585–621.
52. Anonymous. La Complainte du Saint-Maurice. In *C'est Un Monde* (Digi) [CD-ROM]; Fred Pellerin's Album, 2011; Disques Tempête, Catalog Number: TEM24027. Available online: http://www.archambault.ca/cest-un-monde-ACH003042804-fr-pr (accessed on 16 January 2015).
53. Beaugrand, H. *La Chasse Galerie: Légendes Canadiennes*; Beauchemin: Montréal, QC, Canada, 1900.
54. Desrochers, A. *Liminaire (Je suis un fils déchu de race surhumaine)*; À l'Ombre de l'Orford; Librairie d'Action canadienne-française: Montréal, QC, Canada, 1930.

55. Bergeron, Y.; Leduc, A. Relationships between change in fire frequency and mortality due to spruce budworm outbreak in the southeastern Canadian boreal forest. *J. Veg. Sci.* **1998**, *9*, 492–500.
56. Malmström, C.M.; Raffa, K.F. Biotic disturbance agents in the boreal forest: Considerations for vegetation change models. *Glob. Chang. Biol.* **2000**, *6*, 35–48.
57. Chapin, F.S.; Callaghan, T.V.; Bergeron, Y.; Fukuda, M.; Johnstone, J.F.; Juday, G.; Zimov, S.A. Global change and the boreal forest: Thresholds, shifting states or gradual change? *Ambio* **2004**, *33*, 361–365.
58. Amiro, B.D.; Orchansky, A.L.; Barr, A.G.; Black, T.A.; Chambers, S.D.; Chapin, F.S.; Goulden, M.L.; Litvak, M.; Liu, H.P.; McCaughey, J.H.; *et al.* The effect of post-fire stand age on the boreal forest energy balance. *Agric. For. Meteorol.* **2006**, *140*, 41–50.
59. Bouchard, M.; Kneeshaw, D.; Bergeron, Y. Ecosystem management based on large-scale disturbance pulses: A case study from sub-boreal forests of western Quebec (Canada). *For. Ecol. Manag.* **2008**, *256*, 1734–1742.
60. Natural Resources Canada. National Forestry Database; Natural Resources Canada: Ottawa, CAP, Canada, 2014. Available online: http://nfdp.ccfm.org/index_e.php (accessed on 8 June 2014).
61. Hansen, M.C.; Stehman, S.V.; Potapov, P.V. Quantification of global gross forest cover loss. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 8650–8655.
62. Kurz, W.A. An ecosystem context for global gross forest cover loss estimates. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 9025–9026.
63. Chen, J.M.; Ju, W.; Cihlar, J.; Price, D.T.; Liu, J.; Chen, W.; Pan, J.; Black, A.; Barr, A. Spatial distribution of carbon sources and sinks in Canada's forests. *Tellus B* **2003**, *55*, 622–641.
64. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; *et al.* High-resolution global maps of 21st-century forest cover change. *Science* **2013**, *342*, 850–853.
65. Cooke, B.J.; Nealis, V.G.; Régnière, J. Insect defoliators as periodic disturbances in northern forest ecosystems. In *Plant Disturbance Ecology: The Process and the Response*; Johnson, E.A., Miyanishi, K., Eds.; Elsevier: Burlington, NL, USA, 2007; pp. 487–525.
66. Kurz, W.A.; Dymond, C.C.; Stinson, G.; Rampley, G.J.; Neilson, E.T.; Carroll, A.L.; Ebata, T.; Safranyik, L. Mountain pine beetle and forest carbon feedback to climate change. *Nature* **2008**, *452*, 987–990.
67. Amiro, B.D.; Todd, J.B.; Wotton, B.M.; Logan, K.A.; Flannigan, M.D.; Stocks, B.J.; Mason, J.A.; Martell, D.L.; Hirsch, K.G. Direct carbon emissions from Canadian forest fires, 1959–1999. *Can. J. For. Res.* **2001**, *31*, 512–525.
68. Schlesinger, W.H. Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature* **1990**, *348*, 232–234.
69. Davidson, E.A.; Janssens, I.A. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* **2006**, *440*, 165–173.
70. Schmidt, M.W.I.; Torn, M.S.; Abiven, S.; Dittmar, T.; Guggenberger, G.; Janssens, I.A.; Kleber, M.; Kögel-Knabner, I.; Lehmann, J.; Manning, D.A.C.; *et al.* Persistence of soil organic matter as an ecosystem property. *Nature* **2011**, *478*, 49–56.
71. Andreae, M.O.; Merlet, P. Emission of trace gases and aerosols from biomass burning. *Glob. Biogeochem. Cycles* **2001**, *15*, 955–966.

72. Ehhalt, D.; Prather, M.; Dentener, F.; Derwent, R.; Dlugokencky, E.; Holland, E.; Isaken, I.; Katima, J.; Kirchhoff, V.; Matson, P.; *et al.* Atmospheric chemistry and greenhouse gases. In *Climate Change 2001: The Scientific Basis*; Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., Eds.; Cambridge University Press: Cambridge, UK, 2001; pp. 239–288.
73. Boucher, O.; Friedlingstein, P.; Collins, B.; Shine, K.P. The indirect global warming potential and global temperature change potential due to methane oxidation. *Environ. Res. Lett*. **2009**, *4*, 044007.
74. Turner, M.G. Disturbance and landscape dynamics in a changing world. *Ecology* **2010**, *91*, 2833–2849.
75. Baskerville, G.L. Spruce budworm: Super silviculturist. *For. Chron.* **1975**, *51*, 138–140.
76. Bergeron, Y.; Cyr, D.; Girardin, M.P.; Carcaillet, C. Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: Collating climate model experiments with sedimentary charcoal data. *Int. J. Wildland Fire* **2010**, *19*, 1127–1139.
77. Boulanger, Y.; Arseneault, D.; Morin, H.; Jardon, Y.; Bertrand, P.; Dagneau, C. Dendrochronological reconstruction of spruce budworm (*Choristoneura fumiferana*) outbreaks in southern Quebec for the last 400 years. *Can. J. For. Res.* **2012**, *42*, 1264–1276.
78. Alfaro, R.I.; Berg, J.; Axelson, J. Periodicity of western spruce budworm in Southern British Columbia, Canada. *For. Ecol. Manag*. **2014**, *315*, 72–79.
79. Liu, S.; Bond-Lamberty, B.; Hicke, J.A.; Vargas, R.; Zhao, S.; Chen, J.; Edburg, S.L.; Hu, Y.; Liu, J.; McGuire, A.D.; *et al.* Simulating the impacts of disturbances on forest carbon cycling in North America: Processes, data, models, and challenges. *J. Geophys. Res.* **2011**, *116*, G00K08.
80. Luo, Y.; Weng, E. Dynamic disequilibrium of the terrestrial carbon cycle under global change. *Trends Ecol. Evol.* **2011**, *26*, 96–104.
81. Weng, E.; Luo, Y.; Wang, W.; Wang, H.; Hayes, D.J.; McGuire, A.D.; Hastings, A.; Schimel, D.S. Ecosystem carbon storage capacity as affected by disturbance regimes: A general theoretical model. *J. Geophys. Res.* **2012**, *117*, G03014.
82. Metsaranta, J.M.; Dymond, C.C.; Kurz, W.A.; Spittlehouse, D.L. Uncertainty of 21st century growing stocks and GHG balance of forests in British Columbia, Canada resulting from potential climate change impacts on ecosystem processes. *For. Ecol. Manag.* **2011**, *262*, 827–837.
83. O'Donnell, J.A.; Harden, J.W.; McGuire, A.D.; Kanevskiy, M.Z.; Jorgenson, M.T.; Xu, X. The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: Implications for post-thaw carbon loss. *Glob. Chang. Biol.* **2011**, *17*, 1461–1474.
84. Edburg, S.L.; Hicke, J.A.; Lawrence, D.M.; Thornton, P.E. Simulating coupled carbon and nitrogen dynamics following mountain pine beetle outbreaks in the western United States. *J. Geophys. Res.* **2011**, *116*, G04033.
85. Johnstone, J.F.; Chapin, F.S.; Hollingsworth, T.N.; Mack, M.C.; Romanovsky, V.; Turetsky, M. Fire, climate change, and forest resilience in interior Alaska. *Can. J. For. Res.* **2010**, *40*, 1302–1312.
86. Beck, P.S.; Goetz, S.J.; Mack, M.C.; Alexander, H.D.; Jin, Y.; Randerson, J.T.; Loranty, M.M. The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo. *Glob. Chang. Biol.* **2011**, *17*, 2853–2866.

87. Medvigy, D.; Clark, K.L.; Skowronski, N.S.; Schäfer, K.V.R. Simulated impacts of insect defoliation on forest carbon dynamics. *Environ. Res. Lett.* **2012**, *7*, 045703.
88. Luyssaert, S.; Schulze, E.D.; Börner, A.; Knohl, A.; Hessenmöller, D.; Law, B.E.; Ciais, P.; Grace, J. Old-growth forests as global carbon sinks. *Nature* **2008**, *455*, 213–215.
89. Goulden, M.L.; McMillan, A.M.S.; Winston, G.C.; Rocha, A.V.; Manies, K.L.; Harden, J.W.; Bond-Lamberty, B.P. Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. *Glob. Chang. Biol.* **2011**, *17*, 855–871.
90. Coursolle, C.; Margolis, H.A.; Giasson, M.A.; Bernier, P.Y.; Amiro, B.D.; Arain, M.A.; Barr, A.G.; Black, T.A.; Goulden, M.L.; McCaughey, J.H.; *et al.* Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests. *Agric. For. Meteorol.* **2012**, *165*, 136–148.
91. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591–596.
92. Jasinski, J.P.P.; Payette, S. The creation of alternative stable states in the southern boreal forest, Québec, Canada. *Ecol. Monogr.* **2005**, *75*, 561–583.
93. Bernier, P.Y.; Desjardins, R.L.; Karimi-Zindashty, Y.; Worth, D.; Beaudoin, A.; Luo, Y.; Wang, S. Boreal lichen woodlands: A possible negative feedback to climate change in eastern North America. *Agric. For. Meteorol.* **2011**, *151*, 521–528.
94. Payette, S.; Filion, L.; Delwaide, A. Spatially explicit fire-climate history of the boreal forest-tundra (eastern Canada) over the last 2000 years. *Phil. Trans. R. Soc. B* **2008**, *363*, 2301–2316.
95. Metsaranta, J.M. Potentially limited detectability of short-term changes in boreal fire regimes: A simulation study. *Int. J. Wildland Fire* **2010**, *19*, 1140–1146.
96. Ito, A.; Penner, J.E. Global estimates of biomass burning emissions based on satellite imagery for the year 2000. *J. Geophys. Res.* **2004**, *109*, D14S05.
97. Mouillot, F.; Narasimha, A.; Balkanski, Y.; Lamarque, J.F.; Field, C.B. Global carbon emissions from biomass burning in the 20th century. *Geophys. Res. Lett.* **2006**, *33*, L01801.
98. Thonicke, K.; Spessa, A.; Prentice, I.C.; Harrison, S.P.; Dong, L.; Carmona-Moreno, C. The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: Results from a process-based model. *Biogeosciences* **2010**, *7*, 1991–2011.
99. Van der Werf, G.R.; Randerson, J.T.; Giglio, L.; Collatz, G.J.; Mu, M.; Kasibhatla, P.S.; Morton, D.C.; DeFries, R.S.; Jin, Y.; van Leeuwen, T.T. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys.* **2010**, *10*, 11707–11735.
100. Seiler, W.; Crutzen, P.J. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Clim. Chang.* **1980**, *2*, 207–247.
101. Li, F.; Bond-Lamberty, B.; Levis, S. Quantifying the role of fire in the Earth system—Part 2: Impact on the net carbon balance of global terrestrial ecosystems for the 20th century. *Biogeosciences* **2014**, *11*, 1345–1360.
102. Loehman, R.A.; Reinhardt, E.; Riley, K.L. Wildland fire emissions, carbon, and climate: Seeing the forest and the trees—A cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. *For. Ecol. Manag.* **2014**, *317*, 9–19.
103. Landry, J.-S.; Matthews, H.D.; Ramankutty, N. Global carbon cycle and temperature impacts of future changes in fire regime. *Clim. Chang.* **2015**, submitted for publication.

104. Landry, J.-S. (McGill University, Montréal, QC, Canada); Matthews, H.D. (Concordia University, Montréal, QC, Canada). Unpublished work, 2015.
105. Balshi, M.S.; McGuire, A.D.; Zhuang, Q.; Melillo, J.; Kicklighter, D.W.; Kasischke, E.; Wirth, C.; Flannigan, M.; Harden, J.; Clein, J.S.; *et al.* The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. *J. Geophys. Res.* **2007**, *112*, G02029.
106. Bond-Lamberty, B.; Peckham, S.D.; Ahl, D.E.; Gower, S.T. Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* **2007**, *450*, 89–92.
107. Hayes, D.J.; McGuire, A.D.; Kicklighter, D.W.; Gurney, K.R.; Burnside, T.J.; Melillo, J.M. Is the northern high-latitude land-based CO_2 sink weakening? *Glob. Biogeochem. Cycles* **2011**, *25*, GB3018.
108. Amiro, B.D.; Barr, A.G.; Barr, J.G.; Black, T.A.; Bracho, R.; Brown, M.; Chen, J.; Clark, K.L.; Davis, K.J.; Desai, A.R.; *et al.* Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *J. Geophys. Res.* **2010**, *115*, G00K02.
109. Houghton, R.A.; House, J.I.; Pongratz, J.; van der Werf, G.R.; DeFries, R.S.; Hansen, M.C.; le Quéré, C.; Ramankutty, N. Carbon emissions from land use and land-cover change. *Biogeosciences* **2012**, *9*, 5125–5142.
110. Houghton, R.A. How well do we know the flux of CO_2 from land-use change? *Tellus B* **2010**, *62*, 337–351.
111. Apps, M.; Kurz, W.; Beukema, S.; Bhatti, J. Carbon budget of the Canadian forest product sector. *Environ. Sci. Policy* **1999**, *2*, 25–41.
112. National Council for Air and Stream Improvement, Inc. (NCASI). *The Greenhouse Gas and Carbon Profile of the Canadian Forest Products Industry*; NCASI: Research Triangle Park, CA, USA, 2007.
113. Lemprière, T.C.; Kurz, W.A.; Hogg, E.H.; Schmoll, C.; Rampley, G.J.; Yemshanov, D.; Mckenney, D.W.; Gilsenan, R.; Beatch, A.; Blain, D.; *et al.* Canadian boreal forests and climate change mitigation. *Environ. Rev.* **2013**, *21*, 293–321.
114. Safranyik, L.; Carroll, A.L. The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. In *The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine*; Safranyik, L., Wilson, B., Eds.; Natural Resources Canada: Victoria, BC, Canada, 2006; pp. 3–66.
115. Cook, B.D.; Bolstad, P.V.; Martin, J.G.; Heinsch, F.A.; Davis, J.K.; Wang, W.; Desai, A.R.; Teclaw, R.M. Using light-use and production efficiency models to predict photosynthesis and net carbon exchange during forest canopy disturbance. *Ecosystems* **2008**, *11*, 26–44.
116. Heliasz, M.; Johansson, T.; Lindroth, A.; Mölder, M.; Mastepanov, M.; Friborg, T.; Callaghan, T.V.; Christensen, T.R. Quantification of C uptake in subarctic birch forest after setback by an extreme insect outbreak. *Geophys. Res. Lett.* **2011**, *38*, L01704.
117. Gough, C.M.; Hardiman, B.S.; Nave, L.E.; Bohrer, G.; Maurer, K.D.; Vogel, C.S.; Nadelhoffer, K.J.; Curtis, P.S. Sustained carbon uptake and storage following moderate disturbance in a Great Lakes forest. *Ecol. Appl.* **2013**, *23*, 1202–1215.
118. Mattson, W.J.; Addy, N.D. Phytophagous insects as regulators of forest primary production. *Science* **1975**, *190*, 515–522.
119. Romme, W.H.; Knight, D.H.; Yavitt, J.B. Mountain pine beetle outbreaks in the Rocky Mountains: Regulators of primary productivity? *Am. Nat.* **1986**, *127*, 484–494.

120. MacLean, D.A.; Erdle, T.A.; MacKinnon, W.E.; Porter, K.B.; Beaton, K.P.; Cormier, G.; Morehouse, S.; Budd, M. The Spruce Budworm Decision Support System: Forest protection planning to sustain long-term wood supply. *Can. J. For. Res.* **2001**, *31*, 1742–1757.
121. Pfeifer, E.M.; Hicke, J.A.; Meddens, A.J.H. Observations and modeling of aboveground tree carbon stocks and fluxes following a bark beetle outbreak in the western United States. *Glob. Chang. Biol.* **2011**, *17*, 339–350.
122. Caldwell, M.K.; Hawbaker, T.J.; Briggs, J.S.; Cigan, P.W.; Stitt, S. Simulated impacts of mountain pine beetle and wildfire disturbances on forest vegetation composition and carbon stocks in the Southern Rocky Mountains. *Biogeosciences* **2013**, *10*, 8203–8222.
123. Clark, K.L.; Skowronski, N.; Hom, J. Invasive insects impact forest carbon dynamics. *Glob. Chang. Biol.* **2010**, *16*, 88–101.
124. Brown, M.G.; Black, T.A.; Nesic, Z.; Fredeen, A.L.; Foord, V.N.; Spittlehouse, D.L.; Bowler, R.; Burton, P.J.; Trofymow, J.A.; Grant, N.J.; *et al.* The carbon balance of two lodgepole pine stands recovering from mountain pine beetle attack in British Columbia. *Agric. For. Meteorol.* **2012**, *153*, 82–93.
125. Mathys, A.; Black, T.A.; Nesic, Z.; Nishio, G.; Brown, M.; Spittlehouse, D.L.; Fredeen, A.L.; Bowler, R.; Jassal, R.S.; Grant, N.J.; *et al.* Carbon balance of a partially harvested mixed conifer forest following mountain pine beetle attack and its comparison to a clear-cut. *Biogeosciences* **2013**, *10*, 5451–5463.
126. Dymond, C.C.; Neilson, E.T.; Stinson, G.; Porter, K.; MacLean, D.A.; Gray, D.R.; Campagna, M.; Kurz, W.A. Future spruce budworm outbreak may create a carbon source in eastern Canadian forests. *Ecosystems* **2010**, *13*, 917–931.
127. Hennigar, C.R.; MacLean, D.A. Spruce budworm and management effects on forest and wood product carbon for an inventory managed forest. *Can. J. For. Res.* **2010**, *40*, 1736–1750.
128. Harvey, B.D.; Leduc, A.; Gauthier, S.; Bergeron, Y. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. *For. Ecol. Manag.* **2002**, *155*, 369–385.
129. Stocks, B.J.; Mason, J.A.; Todd, J.B.; Bosch, E.M.; Wotton, B.M.; Amiro, B.D.; Flannigan, M.D.; Hirsch, K.G.; Logan, K.A.; Martell, D.L.; *et al.* Large forest fires in Canada, 1959–1997. *J. Geophys. Res.* **2002**, *107*, doi:10.1029/2001JD000484.
130. Archer, D.; Eby, M.; Brovkin, V.; Ridgwell, A.; Cao, L.; Mikolajewicz, U.; Caldeira, K.; Matsumoto, K.; Munhoven, G.; Montenegro, A.; Tokos, K. Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* **2009**, *37*, 117–134.
131. Eby, M.; Zickfeld, K.; Montenegro, A.; Archer, D.; Meissner, K.J.; Weaver, A.J. Lifetime of Anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations. *J. Clim.* **2009**, *22*, 2501–2511.
132. Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.F.; *et al.* The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5–31.

133. Joos, F.; Roth, R.; Fuglestvedt, J.S.; Peters, G.P.; Enting, I.G.; von Bloh, W.; Brovkin, V.; Burke, E.J.; Eby, M.; Edwards, N.R.; *et al.* Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmos. Chem. Phys.* **2013**, *13*, 2793–2825.
134. Matthews, H.D.; Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **2008**, *35*, L04705.
135. Matthews, H.D.; Gillett, N.P.; Stott, P.A.; Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **2009**, *459*, 829–832.
136. Gillett, N.P.; Arora, V.K.; Matthews, D.; Allen, M.R. Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. *J. Clim.* **2013**, *26*, 6844–6858.
137. Zickfeld, K.; Eby, M.; Weaver, A.J.; Alexander, K.; Crespin, E.; Edwards, N.R.; Eliseev, A.V.; Feulner, G.; Fichefet, T.; Forest, C.E.; *et al.* Long-term climate change commitment and reversibility: An EMIC intercomparison. *J. Clim.* **2013**, *26*, 5782–5809.
138. Collins, M.; Knutti, R.; Arblaster, J.; Dufresne, J.L.; Fichefet, T.; Friedlingstein, P.; Gao, X.; Gutowski, W.J.; Johns, T.; Krinner, G.; *et al.* Long-term Climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK/New York, NY, USA, 2013; pp. 1029–1136.
139. Myhre, G.; Shindell, D.; Bréon, F.M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.F.; Lee, D.; Mendoza, B.; *et al.* Anthropogenic and natural radiative forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK/New York, NY, USA, 2013; pp. 659–740.
140. Brovkin, V.; Raddatz, T.; Reick, C.H.; Claussen, M.; Gayler, V. Global biogeophysical interactions between forest and climate. *Geophys. Res. Lett.* **2009**, *36*, L07405.
141. Davin, E.L.; de Noblet-Ducoudré, N. Climatic impact of global-scale deforestation: Radiative *versus* nonradiative processes. *J. Clim.* **2010**, *23*, 97–112.
142. Betts, R.A. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* **2000**, *408*, 187–190.
143. Claussen, M.; Brovkin, V.; Ganopolski, A. Biogeophysical *versus* biogeochemical feedbacks of large-scale land cover change. *Geophys. Res. Lett.* **2001**, *28*, 1011–1014.
144. Bala, G.; Caldeira, K.; Wickett, M.; Phillips, T.J.; Lobell, D.B.; Delire, C.; Mirin, A. Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 6550–6555.
145. Bathiany, S.; Claussen, M.; Brovkin, V.; Raddatz, T.; Gayler, V. Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences* **2010**, *7*, 1383–1399.

146. Montenegro, A.; Eby, M.; Mu, Q.; Mulligan, M.; Weaver, A.J.; Wiebe, E.C.; Zhao, M. The net carbon drawdown of small scale afforestation from satellite observations. *Glob. Planet. Chang.* **2009**, *69*, 195–204.
147. Arora, V.K.; Montenegro, A. Small temperature benefits provided by realistic afforestation efforts. *Nat. Geosci*. **2011**, *4*, 514–518.
148. Pongratz, J.; Reick, C.H.; Raddatz, T.; Caldeira, K.; Claussen, M. Past land use decisions have increased mitigation potential of reforestation. *Geophys. Res. Lett.* **2011**, *38*, L15701.
149. Randerson, J.T.; Liu, H.; Flanner, M.G.; Chambers, S.D.; Jin, Y.; Hess, P.G.; Pfister, G.; Mack, M.C.; Treseder, K.K.; Welp, L.R.; *et al.* The impact of boreal forest fire on climate warming. *Science* **2006**, *314*, 1130–1132.
150. O'Halloran, T.L.; Law, B.E.; Goulden, M.L.; Wang, Z.; Barr, J.G.; Schaaf, C.; Brown, M.; Fuentes, J.D.; Göckede, M.; Black, A.; *et al.* Radiative forcing of natural forest disturbances. *Glob. Chang. Biol.* **2012**, *18*, 555–565.
151. Euskirchen, E.S.; McGuire, A.D.; Chapin, F.S. Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. *Glob. Chang. Biol.* **2007**, *13*, 2425–2438.
152. Price, D.T. (Natural Resources Canada, Edmonton, AB, Canada); Bernier, P.Y. (Natural Resources Canada, Ste-Foy, QC, Canada); Orchansky, A.L. (Micrometeorology consultant, Edmonton, AB, Canada); Wang, S. (Natural Resources Canada, Ottawa, ON, Canada); Li, J. (Natural Resources Canada, Ottawa, ON, Canada). Unpublished work, 2015.
153. Baldocchi, D.; Kelliher, F.M.; Black, T.A.; Jarvis, P. Climate and vegetation controls on boreal zone energy exchange. *Glob. Chang. Biol.* **2000**, *6*, 69–83.
154. Betts, A.K.; Desjardins, R.L.; Worth, D. Impact of agriculture, forest and cloud feedback on the surface energy budget in BOREAS. *Agric. For. Meteorol.* **2007**, *142*, 156–169.
155. Chambers, S.D.; Chapin, F.S. Fire effects on surface-atmosphere energy exchange in Alaskan black spruce ecosystems: Implications for feedbacks to regional climate. *J. Geophys. Res.* **2002**, doi:10.1029/2001JD000530.
156. Pielke, R.A.; Adegoke, J.; Beltrán-Przekurat, A.; Hiemstra, C.A.; Lin, J.; Nair, U.S.; Niyogi, D.; Nobis, T.E. An overview of regional land-use and land-cover impacts on rainfall. *Tellus B* **2007**, *59*, 587–601.
157. Pielke, R.A.; Marland, G.; Betts, R.A.; Chase, T.N.; Eastman, J.L.; Niles, J.O.; Niyogi, D.D.S.; Running, S.W. The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Phil. Trans. R. Soc. A* **2002**, *360*, 1705–1719.
158. Ban-Weiss, G.A.; Bala, G.; Cao, L.; Pongratz, J.; Caldeira, K. Climate forcing and response to idealized changes in surface latent and sensible heat. *Environ. Res. Lett.* **2011**, *6*, 034032.
159. Mahowald, N.; Ward, D.S.; Kloster, S.; Flanner, M.G.; Heald, C.L.; Heavens, N.G.; Hess, P.G.; Lamarque, J.F.; Chuang, P.Y. Aerosol impacts on climate and biogeochemistry. *Annu. Rev. Environ. Resour.* **2011**, *36*, 45–74.
160. Scott, C.E.; Rap, A.; Spracklen, D.V.; Forster, P.M.; Carslaw, K.S.; Mann, G.W.; Pringle, K.J.; Kivekäs, N.; Kulmala, M.; Lihavainen, H.; *et al.* The direct and indirect radiative effects of biogenic secondary organic aerosol. *Atmos. Chem. Phys.* **2014**, *14*, 447–470.

161. Jacobson, M.Z. The short-term cooling but long-term global warming due to biomass burning. *J. Clim.* **2004**, *17*, 2909–2926.
162. Unger, N.; Bond, T.C.; Wang, J.S.; Koch, D.M.; Menon, S.; Shindell, D.T.; Bauer, S. Attribution of climate forcing to economic sectors. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 3382–3387.
163. Ward, D.S.; Kloster, S.; Mahowald, N.M.; Rogers, B.M.; Randerson, J.T.; Hess, P.G. The changing radiative forcing of fires: Global model estimates for past, present and future. *Atmos. Chem. Phys.* **2012**, *12*, 10857–10886.
164. Jacobson, M.Z. Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects. *J. Geophys. Res. Atmos.* **2014**, *119*, 8980–9002.
165. Guenther, A.B.; Jiang, X.; Heald, C.L.; Sakulyanontvittaya, T.; Duhl, T.; Emmons, L.K.; Wang, X. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions. *Geosci. Model Dev.* **2012**, *5*, 1471–1492.
166. Kulmala, M.; Suni, T.; Lehtinen, K.E.J.; Dal Maso, M.; Boy, M.; Reissell, A.; Rannik, U.; Aalto, P.; Keronen, P.; Hakola, H.; *et al.* A new feedback mechanism linking forests, aerosols, and climate. *Atmos. Chem. Phys.* **2004**, *4*, 557–562.
167. Paasonen, P.; Asmi, A.; Petäjä, T.; Kajos, M.K.; Äijälä, M.; Junninen, H.; Holst, T.; Abbatt, J.P.D.; Arneth, A.; Birmili, W.; *et al.* Warming-induced increase in aerosol number concentration likely to moderate climate change. *Nat. Geosci.* **2013**, *6*, 438–442.
168. Peñuelas, J.; Ruthishauser, T.; Filella, I. Phenology feedbacks on climate change. *Science* **2009**, *324*, 887–888.
169. Arneth, A.; Niinemets, U. Induced BVOCs: How to bug our models? *Trends Plant Sci.* **2010**, *15*, 118–125.
170. Richardson, A.D.; Keenan, T.F.; Migliavacca, M.; Ryu, Y.; Sonnentag, O.; Toomey, M. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agric. For. Meteorol.* **2013**, *169*, 156–173.
171. Liu, Z.; Notaro, M.; Kutzbach, J.; Liu, N. Assessing global vegetation–climate feedbacks from observations. *J. Clim.* **2006**, *19*, 787–814.
172. Lee, X.; Goulden, M.L.; Hollinger, D.Y.; Barr, A.; Black, T.A.; Bohrer, G.; Bracho, R.; Drake, B.; Goldstein, A.; Gu, L.; *et al.* Observed increase in local cooling effect of deforestation at higher latitudes. *Nature* **2011**, *479*, 384–387.
173. Quaas, J.; Ming, Y.; Menon, S.; Takemura, T.; Wang, M.; Penner, J.E.; Gettelman, A.; Lohmann, U.; Bellouin, N.; Boucher, O.; *et al.* Aerosol indirect effects—General circulation model intercomparison and evaluation with satellite data. *Atmos. Chem. Phys.* **2009**, *9*, 8697–8717.
174. Carslaw, K.S.; Lee, L.A.; Reddington, C.L.; Pringle, K.J.; Rap, A.; Forster, P.M.; Mann, G.W.; Spracklen, D.V.; Woodhouse, M.T.; Regayre, L.A.; *et al.* Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature* **2013**, *503*, 67–71.
175. Spracklen, D.V.; Rap, A. Natural aerosol-climate feedbacks suppressed by anthropogenic aerosol. *Geophys. Res. Lett.* **2013**, *40*, 5316–5319.
176. Ehn, M.; Thornton, J.A.; Kleist, E.; Sipilä, M.; Junninen, H.; Pullinen, I.; Springer, M.; Rubach, F.; Tillmann, R.; Lee, B.; *et al.* A large source of low-volatility secondary organic aerosol. *Nature* **2014**, *506*, 476–479.

177. Rosenfeld, D.; Sherwood, S.; Wood, R.; Donner, L. Climate effects of aerosol-cloud interactions. *Science* **2014**, *343*, 379–380.
178. Drever, C.R.; Peterson, G.; Messier, C.; Bergeron, Y.; Flannigan, M. Can forest management based on natural disturbances maintain ecological resilience? *Can. J. For. Res.* **2006**, *36*, 2285–2299.
179. Maynard, D.G.; Paré, D.; Thiffault, E.; Lafleur, B.; Hogg, K.E.; Kishchuk, B. How do natural disturbances and human activities affect soils and tree nutrition and growth in the Canadian boreal forest? *Environ. Rev.* **2014**, *22*, 161–178.
180. Thiffault, E.; Hannam, K.D.; Paré, D.; Titus, B.D.; Hazlett, P.W.; Maynard, D.G.; Brais, S. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—A review. *Environ. Rev.* **2011**, *19*, 278–309.
181. Hunter, M.D. Insect population dynamics meets ecosystem ecology: Effects of herbivory on soil nutrient dynamics. *Agric. For. Entomol.* **2001**, *3*, 77–84.
182. Lovett, G.M.; Christenson, L.M.; Groffman, P.M.; Jones, C.G.; Hart, J.E.; Mitchell, M.J. Insect defoliation and nitrogen cycling in forests. *BioScience* **2002**, *52*, 335–341.
183. Mikkelson, K.M.; Bearup, L.A.; Maxwell, R.M.; Stednick, J.D.; McCray, J.E.; Sharp, J.O. Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects. *Biogeochemistry* **2013**, *115*, 1–21.
184. Rhoades, C.C.; McCutchan, J.H.; Cooper, L.A.; Clow, D.; Detmer, T.M.; Briggs, J.S.; Stednick, J.D.; Veblen, T.T.; Ertz, R.M.; Likens, G.E.; *et al.* Biogeochemistry of beetle-killed forests: Explaining a weak nitrate response. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 1756–1760.
185. Aubin, I.; Deshaies, O.; Cardou, F.; Sirois, L. Management legacy in the understory of North American mixed boreal regenerating stands. *For. Ecol. Manag.* **2014**, *320*, 129–137.
186. Cyr, D.; Gauthier, S.; Bergeron, Y.; Carcaillet, C. Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Front. Ecol. Environ.* **2009**, *7*, 519–524.
187. Boucher, Y.; Arseneault, D.; Sirois, L.; Blais, L. Logging pattern and landscape changes over the last century at the boreal and deciduous forest transition in Eastern Canada. *Landsc. Ecol.* **2009**, *24*, 171–184.
188. Robert, L.E.; Kneeshaw, D.; Sturtevant, B.R. Effects of forest management legacies on spruce budworm (*Choristoneura fumiferana*) outbreaks. *Can. J. For. Res.* **2012**, *42*, 463–475.
189. Vors, L.S.; Schaefer, J.A.; Pond, B.A.; Rodgers, A.R.; Patterson, B.R. Woodland caribou extirpation and anthropogenic landscape disturbance in Ontario. *J. Wildl. Manag.* **2007**, *71*, 1249–1256.
190. Parks Canada. Species at Risk: Woodland Caribou—Southern Mountain population; Parks Canada: Gatineau, QC, Canada, 2013. Available online: http://www.pc.gc.ca/eng/nature/eep-sar/itm3/eep-sar3caribou.aspx (accessed on June 21 2014).
191. Canadian Council of Forest Ministers. *Criteria and Indicators of Sustainable Forest Management in Canada: National Status 2005*; Canadian Council of Forest Ministers: Ottawa, ON, Canada, 2006.

192. Nabuurs, G.J.; Masera, O.; Andrasko, K.; Benitez-Ponce, P.; Boer, R.; Dutschke, M.; Elsiddig, E.; Ford-Robertson, J.; Frumhoff, P.; Karjalainen, T.; *et al.* Forestry. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK/New York, NY, USA, 2007, pp. 541–584.
193. Schuur, E.A.G.; Bockheim, J.; Canadell, J.G.; Euskirchen, E.; Field, C.B.; Goryachkin, S.V.; Hagemann, S.; Kuhry, P.; Lafleur, P.M.; Lee, H.; *et al.* Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience* **2008**, *58*, 701–714.
194. Cullingham, C.I.; Cooke, J.E.K.; Dang, S.; Davis, C.S.; Cooke, B.J.; Coltman, D.W. Mountain pine beetle host-range expansion threatens the boreal forest. *Mol. Ecol.* **2011**, *20*, 2157–2171.
195. Kurz, W.A.; Apps, M.J.; Stocks, B.J.; Volney, W.J.A. Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests. In *Biotic Feedbacks in the Global Climatic System: Will the Warming Feed the Warming?* Woodwell, G.M., Mackenzie, F.T., Eds.; Oxford University Press: New York, NY, USA, 1995; pp. 119–133.
196. Flannigan, M.D.; Stocks, B.J.; Turetsky, M.; Wotton, B.M. Impacts of climate change on fire activity and fire management in the circumboreal forest. *Glob. Chang. Biol.* **2009**, *15*, 549–560.
197. Campbell, J.L.; Harmon, M.E.; Mitchell, S.R. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? *Front. Ecol. Environ.* **2012**, *10*, 83–90.
198. British Columbia Ministry of Forests Lands and Natural Resources Operations. Mountain Pine Beetle: Frequently Asked Questions. 2008. Available online: http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/faq.htm (accessed on 23 June 2014).
199. Alberta Government. Alberta Provides $190 Million to Protect People, Forest Health. 2012. Available online: http://alberta.ca/release.cfm?xID=3255410908E23-B498–3802–40B7207AB7985E38 (accessed on 23 June 2014).
200. British Columbia Ministry of Forests Lands and Natural Resources Operations. Factsheet: Funding to Limit Impacts of Mountain Pine Beetle. 2013. Available online: http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/Fact Sheet - Forest Inventory - Oct 2013.pdf (accessed on 23 June 2014).
201. Walton, A. *Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak: Update of the Infestation Projection Based on the Provincial Aerial Overview Surveys of Forest Health Conducted from 1999 through 2012 and the BCMPB Model (Year 10)*; Ministry of Forests, Lands and Natural Resource Operations, British Columbia Government: Victoria, BC, Canada, 2013.
202. Byrne, T.; Stonestreet, C.; Peter, B. Characteristics and utilization of post-mountain pine beetle wood in solid wood products. In *The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine*; Safranyik, L., Wilson, B., Eds.; Natural Resources Canada: Victoria, BC, Canada, 2006; pp. 233–253.
203. Watson, P. Impact of the mountain pine beetle on pulp and papermaking. In *The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine*; Safranyik, L., Wilson, B., Eds.; Natural Resources Canada: Victoria, BC, Canada, 2006; pp. 255–275.
204. Mikkelson, K.M.; Dickenson, E.R.V.; Maxwell, R.M.; McCray, J.E.; Sharp, J.O. Water-quality impacts from climate-induced forest die-off. *Nat. Clim. Chang.* **2013**, *3*, 218–222.

205. Simard, M.; Romme, W.H.; Griffin, J.M.; Turner, M.G. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? *Ecol. Monogr.* **2011**, *81*, 3–24.
206. Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. Effects of bark beetle-caused tree mortality on wildfire. *For. Ecol. Manag.* **2012**, *271*, 81–90.
207. Harvey, B.J.; Donato, D.C.; Romme, W.H.; Turner, M.G. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. *Ecology* **2013**, *94*, 2475–2486.
208. Hawkins, C.D.; Dhar, A.; Balliet, N.A.; Runzer, K.D. Residual mature trees and secondary stand structure after mountain pine beetle attack in central British Columbia. *For. Ecol. Manag.* **2012**, *277*, 107–115.
209. Taylor, S.W.; Carroll, A.L.; Alfaro, R.I.; Safranyik, L. Forest, climate and mountain pine beetle outbreak dynamics in western Canada. In *The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine*; Safranyik, L., Wilson, B., Eds.; Natural Resources Canada: Victoria, BC, Canada, 2006; pp. 67–94.
210. Weed, A.S.; Ayres, M.P.; Hicke, J.A. Consequences of climate change for biotic disturbances in North American forests. *Ecol. Monogr.* **2013**, *83*, 441–470.
211. Simard, M.; Lecomte, N.; Bergeron, Y.; Bernier, P.Y.; Paré, D. Forest productivity decline caused by successional paludification of boreal soils. *Ecol. Appl.* **2007**, *17*, 1619–1637.
212. Lafleur, B.; Fenton, N.J.; Paré, D.; Simard, M.; Bergeron, Y. Contrasting effects of season and method of harvest on soil properties and the growth of black spruce regeneration in the boreal forested peatlands of eastern Canada. *Sylva Fenn.* **2010**, *44*, 799–813.
213. Pluchon, N.; Hugelius, G.; Kuusinen, N.; Kuhry, P. Recent paludification rates and effects on total ecosystem carbon storage in two boreal peatlands of Northeast European Russia. *Holocene* **2014**, doi:10.1177/0959683614523803.
214. Bhatti, J.S.; Errington, R.C.; Bauer, I.E.; Hurdle, P.A. Carbon stocks trends along forested peatland margins in central Saskatchewan. *Can. J. Soil Sci.* **2006**, *86*, 321–333.
215. Lohila, A.; Minkkinen, K.; Laine, J.; Savolainen, I.; Tuovinen, J.-P.; Korhonen, L.; Laurila, T.; Tietäväinen, H.; Laaksonen, A. Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *J. Geophys. Res.* **2010**, *115*, G04011.
216. Frolking, S.; Roulet, N.T. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Glob. Chang. Biol.* **2007**, *13*, 1079–1088.
217. Fenner, N.; Freeman, C. Drought-induced carbon loss in peatlands. *Nat. Geosci.* **2011**, *4*, 895–900.
218. Dise, N.B. Peatland response to global change. *Science* **2009**, *326*, 810–811.
219. Hommeltenberg, J.; Schmid, H.P.; Drösler, M.; Werle, P. Can a bog drained for forestry be a stronger carbon sink than a natural bog forest? *Biogeosciences* **2014**, *11*, 3477–3493.
220. Smith, P.; Bustamante, M.; Ahammad, H.; Clark, H.; Dong, H.; Elsiddig, E.A.; Haberl, H.; Harper, R.; House, J.; Jafari, M.; *et al.* Agriculture, forestry and other land use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., *et al.*, Eds.; Cambridge University Press: Cambridge, UK/New York, NY, USA, 2014; pp. 811–922.

221. Post, W.M.; Kwon, K.C. Soil carbon sequestration and land-use change: Processes and potential. *Glob. Chang. Biol.* **2000**, *6*, 317–327.
222. Lal, R. Forest soils and carbon sequestration. *For. Ecol. Manag*. **2005**, *220*, 242–258.
223. Li, D.; Niu, S.; Luo, Y. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: A meta-analysis. *New Phytol.* **2012**, *195*, 172–181.
224. Searchinger, T.; Heimlich, R.; Houghton, R.A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319*, 1238–1240.
225. Melillo, J.M.; Reilly, J.M.; Kicklighter, D.W.; Gurgel, A.C.; Cronin, T.W.; Paltsev, S.; Felzer, B.S.; Wang, X.; Sokolov, A.P.; Schlosser, C.A. Indirect emissions from biofuels: How important? *Science* **2009**, *326*, 1397–1399.
226. West, P.C.; Gibbs, H.K.; Monfreda, C.; Wagner, J.; Barford, C.C.; Carpenter, S.R.; Foley, J.A. Trading carbon for food: Global comparison of carbon stocks *vs.* crop yields on agricultural land. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19645–19648.
227. Michaelian, M.; Hogg, E.H.; Hall, R.J.; Arsenault, E. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Glob. Chang. Biol.* **2010**, *6*, 2084–2094.
228. Stennes, B.; Krcmar-Nozic, E.; van Kooten, G.C. Climate change and forestry: What policy for Canada? *Can. Public Policy* **1998**, *24*, S95–S104.
229. Krcmar, E.; van Kooten, G.C.; Vertinsky, I. Managing forest and marginal agricultural land for multiple tradeoffs: Compromising on economic, carbon and structural diversity objectives. *Ecol. Model.* **2005**, *185*, 451–468.
230. Cherubini, F.; Bright, R.M.; Strømman, A.H. Site-specific global warming potentials of biogenic CO_2 for bioenergy: Contributions from carbon fluxes and albedo dynamics. *Environ. Res. Lett.* **2012**, *7*, 045902.
231. Vadeboncoeur, M.A.; Hamburg, S.P.; Yanai, R.D.; Blum, J.D. Rates of sustainable forest harvest depend on rotation length and weathering of soil minerals. *For. Ecol. Manag.* **2014**, *318*, 194–205.
232. Smith, L.J.; Torn, M.S. Ecological limits to terrestrial biological carbon dioxide removal. *Clim. Chang.* **2013**, *118*, 89–103.
233. Slade, R.; Bauen, A.; Gross, R. Global bioenergy resources. *Nat. Clim. Chang.* **2014**, *4*, 99–105.
234. Beer, C.; Reichstein, M.; Tomelleri, E.; Ciais, P.; Jung, M.; Carvalhais, N.; Rödenbeck, C.; Arain, M.A.; Baldocchi, D.; Bonan, G.B.; *et al.* Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science* **2010**, *329*, 834–838.
235. Thiffault, E.; Paré, D.; Brais, S.; Titus, B.D. Intensive biomass removals and site productivity in Canada: A review of relevant issues. *For. Chron.* **2010**, *86*, 36–42.
236. Smyth, C.E.; Stinson, G.; Neilson, E.; Lemprière, T.C.; Hafer, M.; Rampley, G.J.; Kurz, W.A. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences* **2014**, *11*, 3515–3529.
237. Raupach, M.R.; Canadell, J.G.; le Quéré, C. Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction. *Biogeosciences* **2008**, *5*, 1601–1613.

238. Foley, J.A.; DeFries, R.S.; Asner, G.P.; Barford, C.; Bonan, G.B.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; *et al.* Global consequences of land use. *Science* **2005**, *309*, 570–574.
239. Schneider, R.R.; Stelfox, J.B.; Boutin, S.; Wasel, S. Managing the cumulative impacts of land uses in the western Canadian sedimentary basin: A modeling approach. *Conserv. Ecol.* **2003**, *7*, art8.
240. Schulze, E.D.; Wirth, C.; Heimann, M. Managing forests after Kyoto. *Science* **2000**, *289*, 2058–2059.
241. House, J.I.; Colin Prentice, I.; le Quere, C. Maximum impacts of future reforestation or deforestation on atmospheric CO_2. *Glob. Chang. Biol.* **2002**, *8*, 1047–1052.
242. Mackey, B.; Prentice, I.C.; Steffen, W.; House, J.I.; Lindenmayer, D.; Keith, H.; Berry, S. Untangling the confusion around land carbon science and climate change mitigation policy. *Nat. Clim. Chang.* **2013**, *3*, 552–557.
243. Robock, A. 20 reasons why geoengineering may be a bad idea. *Bull. At. Sci.* **2008**, *64*, 14–18.
244. Matthews, H.D.; Turner, S.E. Of mongooses and mitigation: Ecological analogues to geoengineering. *Environ. Res. Lett.* **2009**, *4*, 045105.