THE GREENHOUSE GAS IMPACTS OF BURNING POST-HARVEST DEBRIS PILES ON VANCOUVER ISLAND, BC

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ABSTRACT

It is increasingly important to identify climate change mitigation opportunities at different scales within all sectors. Avoiding burning of post-harvest debris piles may be a viable regional-scale mitigation strategy within the forestry sector. I used the Carbon Budget Model of the Canadian Forest Sector to simulate alternate burning scenarios over 2008-2050 and greenhouse gas (GHG) consequences over 2008-2250. The results show that the delayed release of carbon (through decomposition rather than burning) provides a benefit that persists for decades to centuries. Burning debris also releases a fraction of the stored carbon as CH_4 and releases N_2O, both of which are more powerful GHGs than CO_2. The quantity, form and timing of GHGs released are all critical components to address when evaluating the net climate impact of human activities. When applied across a large landscape over several decades, avoiding debris burning makes a meaningful contribution to a regional mitigation portfolio.

Keywords: carbon; greenhouse gases; mitigation strategies; slash burning; debris piles; forest management.

EXECUTIVE SUMMARY

The evidence corroborating human-induced global climate change is unequivocal. Consequently, it is increasingly important to identify opportunities for climate change mitigation within all sectors of human activity. Within the forest sector, there are many activities with the potential to increase sinks for carbon sequestration or decrease sources of greenhouse gas (GHG) emissions. Burning post-harvest debris, for example, results in an immediate release of GHGs to the atmosphere and therefore avoiding slash burning may be a viable GHG mitigation strategy. My research examines the GHG impact of burning debris piles on central Vancouver Island, with particular attention to the duration of these impacts.

The Strathcona Timber Supply Area (TSA) provides a case study to examine the cumulative impacts of burning post-harvest debris piles across a large landscape and over multiple decades. I use the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to simulate scenarios applying alternate potential levels of burning across the landscape to determine the GHG impacts of burning over 2008-2050. The results show that by 2050 a strategy of avoiding burning in the Strathcona TSA during the simulated management period would make a modest but certainly not insignificant contribution to the regional climate change mitigation portfolio. I then investigate the GHG consequences

over the following 200 years to assess the longevity of the cumulative GHG benefits observed in 2050.

A misconception that I have commonly encountered is the idea that the net GHG effect of burning over the long term is simply zero. This somewhat cursory interpretation is based on the assumption that although slash burning results in a large immediate release of carbon to the atmosphere, the benefit of avoiding this release is short-lived because, had it not been burned, the debris would eventually release the same amount of carbon through decomposition, and therefore the net GHG benefit must be zero. However, my research shows that there are two important GHG benefits of avoided slash burning that this simple assessment does not consider. First, while the delayed release of carbon is inherently a temporary benefit, a significant proportion of the benefit persists for many decades and even centuries. Current policy in BC considers any mitigation benefit that lasts greater than 100 years to be “permanent”. Second, burning debris releases a small fraction of the carbon as CH_4 and the additional, non-carbon GHG N_2O, both of which are more powerful GHGs than CO_2. Even though the same amount of carbon will eventually be released to the atmosphere either way, the climate impact of burning debris will be greater than allowing it to decompose (as measured in terms of CO_2-equivalents), and this difference is a permanent impact. Both the quantity of GHGs released and the form in which they are released are critical components in assessing the net climate impact of human activities. These results are highly relevant because an accurate quantification of the GHG impact of slash burning is necessary in order to

evaluate avoided slash burning as a potential mitigation or carbon offset strategy. Accounting for the temporary component of the net impact as an offset could over- or underestimate the long-term benefits of avoided slash burning depending on the offset system design. The duration of temporary impacts is an important attribute – carbon that is stored temporarily for a few years and carbon that is stored temporarily for decades or centuries should not be treated as equivalent. My research suggests that subdividing temporary mitigation impacts into more specific categories of impact based on their actual longevity may be beneficial.

DEDICATION

To Emily Clough, who has provided unfailing love, support and encouragement throughout this entire experience, with the occasional dose of perspective when it was most needed. Thank you for always being there – through the fun parts, the stressful parts, the exciting parts, the overwhelming parts, the interesting parts, the frustrating parts, the awesome parts, and the boring parts – always providing companionship and balance.

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1: INTRODUCTION

1.1 Climate Change and the Role of Forest Management

The evidence supporting human-induced global climate change is "unequivocal" (IPCC, 2007; Solomon et al., 2007). Little debate remains that global climate is changing and that this phenomenon is primarily attributable to human activities. The most recent assessment report of Intergovernmental Panel on Climate Change (IPCC) asserts that it is "extremely likely" (95% probability) that anthropogenic forcings have resulted in significant net global warming over the past 250 years (IPCC, 2007; Solomon et al., 2007). The debate has shifted to determining what society can and should do about climate change (Mathews, 2007). Consequently, assessing all human activities in terms of their contribution to or mitigation of anthropogenic climate change is becoming increasingly important (Kurz, 2007). Forest management is one such activity and likely one of importance.

Forests have a critical role to play in strategies to mitigate emissions because forests have the greatest potential of all terrestrial biomes to store and cycle carbon (Dixon et al., 1994; Murray et al., 2000; Binkley et al., 2002; Nabuurs et al., 2007; Wayburn et al., 2007). Forests ecosystems comprise the majority of terrestrial carbon, comprising up to 80% of all aboveground carbon stocks and 40% of all belowground carbon stocks (Dixon and Turner, 1991; Dixon et al., 1994). Globally, forests are the most expandable long-term carbon sink (Dixon et al., 1994), yet the forest sector is currently the second largest carbon source (Stern, 2006). Forest management activities can therefore provide critical opportunities for increasing carbon sequestration and mitigating greenhouse gas (GHG) emissions (Nabuurs et al., 2007).

In response to growing awareness of climate change, forest and land managers are interested in evaluating – and are under increasing pressure to demonstrate – the carbon impact of forest management activities on their landscape (Kurz et al., 2002). Many forest management activities are potentially useful for maintaining or increasing carbon sequestration, protecting existing carbon stocks, or reducing GHG emissions. Avoiding or reducing the burning of residual debris after harvesting a forested area, as examined in this project, is one such action. This stand-level mitigation approach avoids the immediate emissions of GHGs to the atmosphere produced by burning such debris. The IPCC states that strategies that avoid or reduce activities that would otherwise result in immediate emissions from existing carbon stocks achieve the greatest short-term gains (Nabuurs et al., 2007). Furthermore, even stand-level operational activities may offer substantial contributions to regional, provincial or national carbon budgets because small changes can be significant when aggregated over large landscapes (Kurz et al., 2002; Colombo et al., 2005).

In my research, I focus on the management outcomes related to carbon; however, carbon is only one objective among a diverse set of potential objectives for forest management. The objectives of forest management in North America have evolved in depth and complexity over the past century (Bengston, 1994;

Bettinger and Chung, 2004; Wang, 2004). Early management focused solely on efficient timber supply, but over time forest management has expanded to increasingly include other potential objectives such as recreation, hunting, fishing, scenic values, wilderness areas, wildlife habitat, water, and other non-timber resources (e.g. Nash, 1990; Bengston, 1994; Bettinger and Chung, 2004). With an increasing understanding of ecosystem services and appreciation for the intrinsic value of ecosystems, ecosystem-based management and its variants have also become common management goals (e.g. Bengston, 1994; Grumbine, 1994; Yaffee, 1998; BC Ministry of Natural Resource Operations, 2010).

By the 1990s, managing for carbon sequestration was an important new emphasis (King, 1993; Turner et al., 1995). Carbon sequestration and the maintenance of terrestrial carbon storage pools are now recognized as pertinent management objectives. Nevertheless, it is critical to acknowledge that the newer management objectives do not supersede those preceding them – all of these objectives are still relevant. Forest managers and scientists have merely broadened their definition of sustainable forest management; diverse societal values are embedded in forests, and management is frequently structured around multiple social, economic, and ecological performance goals (Government of British Columbia, 2002; Baskent and Keles, 2008; BC Ministry of Forests, Mines and Lands, 2010). Management to restore the “naturalness” of forests and increase carbon storage is often consonant with other habitat, biodiversity, and hydrology objectives, and may even increase mid- to long-term timber supply (Hoover et al., 2000; Wayburn et al., 2007). Carbon storage is yet another value of well-managed forests (Hoover et al., 2000; Baskent and Keles, 2008).

1.2 Forest Sector Strategies for Climate Change Mitigation

Within the forest sector, management actions with the objective of increasing sequestration or decreasing emissions should aim to protect or expand carbon stocks, maintain or enhance the function of existing carbon sinks, and reduce carbon sources (Dixon et al., 1994; Kurz et al., 2002). Fortunately, many potential management actions exist to achieve these objectives. The IPCC categorizes management actions within the forest sector into the broad strategies of maintaining or increasing: 1) forest area, 2) stand-level carbon density, 3) landscape-level carbon density, and 4) carbon stocks in forest products for long-term storage or product substitution (Nabuurs et al., 2007).

We can implement the first strategy through avoiding deforestation and increasing afforestation/reforestation of formerly forested lands (Dixon et al., 1994; Stinson and Freedman, 2001; Nabuurs et al., 2007; Gaboury et al., 2009). Reducing delays in the establishment of new stands, enhancing the growth rates of new or young stock, stocking stands at appropriate densities, or reducing prescribed burning can contribute to the second strategy (Kurz et al., 1998; Colombo et al., 2005; Nabuurs et al., 2007; Black et al., 2008). Protecting old-growth forests from conversion to managed forests, utilizing variable retention as a silvicultural strategy to maintain existing carbon stocks on a portion of the landscape, extending the rotation lengths for harvesting, or protecting against natural disturbances can achieve the third strategy’s goal of increasing landscape-level carbon density (Harmon et al., 1990, 1996a, 1996b; van Kooten et al., 1995; Kurz et al., 1998; Binkley et al., 2002; Harmon and Marks, 2002; Colombo et al., 2005; Wayburn et al., 2007; Kurz et al., 2008b). Finally, we can realize gains from the fourth strategy by manufacturing forest products with longer lifespans and using forest products to displace materials that are more emissions-intensive, including as direct substitutes for fossil fuels (IEA Bioenergy, 1998, 2005; Stinson and Freedman, 2001; Colombo et al., 2005; Petersen and Solberg, 2005; Gustavsson et al., 2006; Gustavsson and Sathre, 2006).

The IPCC further evaluates subcomponents of these broad classes in terms of the timing of both their impact and their costs (Nabuurs et al., 2007). This additional evaluation considers whether the impacts of a strategy will be immediate, gradual or delayed over a short- or long-term timeframe, whether the impacts will be one-time or on going, and the extent to which the impacts will be permanent. The type and scale of decision required to implement each strategy is also relevant to consider. Landscape-scale actions such as fire suppression likely require decisions at a regional scale. Stand-level actions will presumably be dependent on operational-level decisions, but may also require enabling regulations from higher authorities to be in place as well. The scale of decisions needed may influence the expediency with which a strategy can be implemented, independent of the temporal dynamics of the physical action. Presumably a mitigation strategy that is technically feasible and within the spectrum of currently permitted operational-level decisions will be easier and quicker to implement than one that requires revolutionary changes in landscape planning regulations or government policy.

Some forest management actions to increase carbon sequestration can also result in numerous secondary, non-climate benefits including sediment retention, erosion prevention/soil conservation, water infiltration, mitigation of floods and droughts, enhanced wildlife habitat, amenities, recreation opportunities, scenic values, and even increased future wood supply (Binkley et al., 2002; Wayburn et al., 2007; Baskent and Keles, 2008). Managing forests for carbon sequestration may simultaneously increase the health, productivity, diversity and resilience of terrestrial and aquatic ecosystems of the forest (Wayburn et al., 2007). However, some forest management actions aimed at achieving carbon objectives may conflict with other objectives. Successful management for carbon sequestration may sometimes come at the expense of delayed or forgone forest products and timber revenues (Baskent and Keles, 2008; Kurz et al., 2008b), and some of the methods to increase carbon sequestration within the forest ecosystem involve interference with natural ecological processes (e.g. fire suppression or intensive silviculture). The magnitude and direction of these secondary impacts will vary with each strategy and the circumstances under which a particular strategy is applied.

1.3 Burning of Post-harvest Debris

Burning is a major tool around the world for the management of forests, grasslands and agricultural areas (Levine, 1991). Globally, the most common applications of biomass burning include clearing land for agricultural development, maintaining agricultural lands through the burning of crop stubble, weeds and waste, generating heat or energy, and eliminating or reducing waste from forest harvesting (Andreae, 1991; Levine, 1991), which is the focus of my research. In BC, such burning of post-harvest debris makes a notable contribution to the annual GHG emissions associated with the forestry sector (Dymond and Spittlehouse 2009). I examine the GHG impacts of this management action in a single region in BC, as a case study to evaluate whether the intentional avoidance (or reduction) of such burning might represent an effective GHG mitigation strategy at a regional scale.

Post-harvest debris includes foliage, branches, tops, sub-merchantable trees, broken or defective boles, and other non-merchantable material remaining after the removal of all merchantable material. On Vancouver Island, forestry operations commonly leave a large portion of this harvest residue in large accumulations or piles. In this paper, I use the terms “slash” and “debris” interchangeably to refer to this post-harvest residue. Burning some of these slash piles (once conditions are appropriate for safe and effective burning) is a common practice on Vancouver Island (Baxter and Proteau, 2008; J. Andres, pers. comm.; B. McKerricher, pers. comm.) and across BC (FPB, 2008). Post-harvest debris piles are commonly considered a fire risk and therefore must be removed under BC’s Wildfire Act (Government of British Columbia, 2004) and Wildfire Regulation (Government of British Columbia, 2005). In my research I focus solely on the burning of piled debris and do not examine the practice of broadcast burning, where the debris to be burned is distributed across the cut block (i.e. not accumulated in piles prior to burning). Though once common, broadcast burning practice is rarely applied on the coast any more (Beese et al., 2006; J. Andres, pers. comm.). However, much of the relevant literature primarily on broadcast burning as there is a relative paucity of literature on pile burning in general and specifically for BC.

Burning of post-harvest debris in general, but broadcast burning especially, has historically been one of the most common tools for site preparation in many parts of the world, including BC (Burton, 1992). In BC, forest managers have commonly used prescribed fire for the following objectives (Feller, 1982):

1. reduction of fire hazard
2. facilitation of planting
3. improvement of environmental conditions for seedling establishment and growth
4. control of undesirable brush or regeneration
5. eradication of insects and disease
6. improvement of aesthetics
7. enhancement of browse or grazing potential
8. improvement of wildlife habitat, especially for ungulates

Managers and researchers have also used broadcast burning in ecological restoration to mimic the role of natural fire in fire-adapted ecosystems (Covington et al., 1997; Kranabetter and Macadam, 1998; Allen et al., 2002). However, even as of the early 1990s, the use of prescribed burning for site preparation (broadcast burning in particular) was decreasing due to concerns with cost, escaped fires, and air quality, which was reflected by corresponding changes in provincial policy and supported by the advancement of new alternatives (Burton, 1992).

A selection of feasible alternatives to the burning of post-harvest debris are available, though the suitability of any particular method is dependent on the specific landscape, harvesting methods and the objectives for which burning would have originally been used. Alternatives to open burning (broadcast or pile) include modifying harvest methods to reduce slash volume or concentrated accumulation, creating wildlife piles, dispersing debris, with or without breaking down material (e.g. crushing, shredding, mulching, grinding, etc.), increasing the utilization of secondary wood products such as chips, fuel pellets, ground fibre, cants, shingles, shake, firewood, or log salvage, employing alternative methods of vegetation control including herbicides, herbivores, grass seeding, mulches or other physical barriers around seedlings, prioritizing mechanical methods of site preparation, possibly still requiring a reduced level of piling and burning; or conducting no site preparation, which may require increased fertilization or additional silvicultural interventions later (Burton, 1992; Schnepf, 2006; FPInnovations, 2009). These alternatives apply across BC and are neither specific to nor even necessarily all applicable to the coast.

I do not explore specific alternatives to burning in my research but their existence underpins its relevance. Without any viable alternatives to the burning of slash piles, the proposition that avoided burning may be a practical strategy for reducing GHG emissions might have little policy or operational relevance. However, where slash pile burning is currently applied on the coast, the decision not to burn is often a relevant management alternative (B. McKerricher, pers. comm.). Even in circumstances where there are no reasonable alternatives to burning debris, it would still be beneficial to understand the potential GHG costs of this management activity either for offsetting its impacts elsewhere or simply increasing our knowledge of the GHG impacts of forest management activities. In general, there is a growing expectation for forest managers to evaluate the carbon implications of all activities against potential trade-offs, striving to balance carbon stocks and flows in a manner that best meets society's demands (Kurz, 2007).

The GHG implications of burning debris piles consist of four broad elements. First, the material in the pile that is combusted releases its carbon to the atmosphere immediately whereas it would otherwise release it only slowly through decomposition. To clarify, the material of interest is that which the burning would actually consume, as the fire will leave some unconsumed material that will then decompose over time. Second, a small portion of total emissions from the combustion of debris consists of GHGs that are much more powerful than carbon dioxide (CO_2). Third, using burning to reduce debris may increase the rate of successful regeneration or increase the area available for regeneration, thereby enhancing the strength of the future stock as a carbon sink. Fourth, reducing the volume of debris on the landscape may reduce the risk of future wildfires initiated in or propagated through the original setting that could possibly result in very large GHG emissions and the destruction of established carbon sinks if nearby stands are burned. If the relative impacts of the first two factors are sufficiently large and the impacts of the latter two factors are sufficiently small, then the avoidance of slash pile burning could be a feasible strategy for reducing emissions.

One of the distinct advantages of utilizing avoided or reduced slash pile burning as a potential climate mitigation strategy is that there are relatively low barriers to implementation. The act of not burning debris piles does not require advanced technology, complex institutions, or otherwise costly measures. Managers already choose not to burn piles in many cases for a variety of other reasons (i.e. not for climate mitigation; Burton, 1992; Schnepf, 2006; J. Andres, pers. comm., D. Tanner, pers. comm.), but a significant amount of burning is still performed in the Strathcona TSA in circumstances where burning is not absolutely necessary (B. McKerricher, pers. comm.). This situation presents opportunities for applying avoided burning as a mitigation strategy because in the absence of such a strategy this burning would continue to occur – the GHG impacts of avoided burning, if any, would truly be additional with respect to the status quo.

Aside from its carbon implications, the use of prescribed burning for site preparation has other ecological impacts. Prescribed burning can have impacts on soil organisms, structure, and chemistry, water quality, and site productivity (Feller, 1982, 1983). However, these ecological impacts can be positive or negative and are highly site-specific, varying with ecosystem, species, and burn characteristics (Feller, 1982, 1983). For example, one study found that in north-central BC, burned sites benefited the most by responding to burning with higher levels of productivity (Kranabetter and Macadam, 1998), but another study in northern Washington found that unburned sites benefited the most with significantly higher levels of advanced regeneration (Elman and Peterson, 2005). However, these studies as well as the literature in general focus predominantly on broadcast burning and there appears to be little or no literature that specifically examines the impacts of pile burning.

Conversely, the management choice not to burn post-harvest debris also has some important non-GHG impacts. As implicitly suggested above, two trade-offs that occur when debris is left unburned are that future regeneration (natural or assisted) may be impeded, and that the increased volume of unburned debris left on the landscape may increase the risk of future wildfires. Additional ecological, aesthetic, and health benefits are also associated with leaving harvest slash unburned. Residual woody material, especially coarse woody debris, provides numerous ecological benefits such as supplying organic matter and nutrient reserves, contributing to the stabilization and development of the forest floor and soil organic matter, influencing micro-topography and microclimate, offering structural characteristics that are useful for wildlife habitat, acting as refugia for organisms after the harvesting disturbance, and providing moisture storage (e.g. Caza, 1993 Marcot, 2002; Ucitel et al., 2003; Bunnell and Houde, 2010; Sullivan et al., 2011). Reducing the amount of smoke produced from burning generates both aesthetic and health benefits (e.g. McMahon, 1999; Core, 2001; Core and Peterson, 2001; Radke et al. 2001; Sandberg et al., 2002). Smoke management has been important objective in the management and regulation of burning in recent decades in North America (e.g. Burton, 1992;

Hardy et al., 2001; Sandberg et al., 2002), and air quality continues to be a chief concern associated with biomass burning in BC (e.g. BVLD AMS, 2006; Baxter and Proteau, 2008; Government of British Columbia, 2011). Furthermore, there may be economic benefits because burning can be costly but the net economic impact will depend on the specific alternatives applied. The secondary ecological, aesthetic, health, and economic impacts of burning or not burning are not explored in any greater depth in the present work.

The findings of my research will have relevance beyond the current study area of the Strathcona TSA because the use of prescribed fire as a management tool is very common almost wherever society actively manages forests. Throughout western North America, burning has been widely used as a management treatment after harvest (Feller, 1982). In the remainder of this paper, I use the terms “burning”, “slash/debris burning” and “pile burning” interchangeably to refer to the prescribed burning of slash piles and not broadcast burning. Where I address broadcast burning, I explicitly refer to it as such.

1.4 Climate Change Mitigation Targets and Strategies

Avoiding “dangerous anthropogenic interference” with the global climate system is the primary goal of climate policy (IPCC, 2007; Mignone et al., 2008). A common expression of this goal is the target of preventing average global temperature from increasing by more than 2°C (Weaver et al., 2007; Meinshausen et al., 2009; Zickfeld et al., 2009; O’Neill et al., 2010). However, due to uncertainties in the carbon cycle and climate response, climate modellers can only make probabilistic estimates of the level of cumulative global emissions corresponding with a specific temperature response (Weaver et al., 2007; Meinshausen et al., 2009; Zickfeld et al., 2009). Maintaining at least a 50% probability of keeping the rise in average global temperature to less than 2°C by 2100, requires reducing global emissions by 50-70% below current levels by 2050 (Mathews, 2007; Weaver et al., 2007; Meinshausen et al., 2009; O'Neill et al., 2010). Nevertheless, the 2°C threshold will eventually be broken even with emissions reductions of 90% (Weaver et al., 2007). Furthermore, if action is not begun immediately with major global-scale changes in place within 1-2 decades, the ultimate goal of stabilizing the climate at pre-industrial levels will no longer be attainable and catastrophic outcomes will be much more likely to occur (Mathews, 2007; Mignone et al., 2008; Vaughan et al., 2009). Early, rapid initiation of mitigation strategies is more effective than relying on aggressive action after a period of delay (Vaughan et al., 2009).

The scale and urgency of these mitigation targets necessitates large-scale strategies that are immediately implementable. Pacala and Socolow (2004) argue that society could solve the "carbon and climate problem" of the next 50 years by using a portfolio of "stabilization wedges”. Each wedge represents a 1 Gt C/year reduction by 2054 based on a set of technologies or approaches to reduce carbon emissions that is technically feasible today and has already been demonstrated on an industrial scale. Stabilizing emissions over the next 50 years by scaling up current technology would keep the long-term goal of stabilizing atmospheric CO_2 at less than double pre-industrial levels within reach, but the large reductions required in the second half of the century to actually meet that goal would still require advanced technologies that will need to be developed in the next few decades (Pacala and Socolow, 2004). Another approach outlines a seven-step strategy, comprising innovative global initiatives and new institutions, to reduce global emissions by 70% by 2050 (Mathews, 2007). Mathews (2007) designed these steps to be self-financing and reliant only upon existing technology. However, even when relying only on current technology it seems that global-scale initiatives will inevitably encounter delays – when published, it had been suggested that this seven step package could be undertaken at a global level by 2010 (Mathews, 2007).

If large-scale mitigation strategies will commonly face some degree of delay, there may then be an important role for small-scale mitigation strategies that, although smaller, are implementable immediately. Strategies with immediate or early benefits might represent the leading edge of larger "wedges" or stand-alone actions that can help offset the costs of delays in starting greater initiatives. Either way, the maximum benefit will likely occur when efforts directed towards smaller, immediate actions operate in parallel to the advancement of the larger, global-scale initiatives ultimately necessary to meet these ambitious targets, rather than diverting attention and resources.

Even with delays in major action, society can still achieve its long-term stabilization targets with aggressive mitigation once action begins to compensate for the delay (Vaughan et al., 2009). However, this approach might result in "transient peaks" in atmospheric CO_2 and possibly temperature that could temporarily exceed long-term targets. The chance of such an overshoot and its duration increase as the delay in action lengthens. This risk is especially concerning in the context of climatic “tipping points” (Vaughan et al., 2009). This concern may suggest that a role exists even for strategies that are known to only have temporary mitigation impacts on a sub-century scale. Such strategies might only make a small contribution to achieving long-term targets but might contribute to reducing peaks that could exceed critical atmospheric thresholds in the interim.

The question of whether or not temporary carbon storage or emissions mitigation can contribute meaningfully towards climate change mitigation has been debated in the literature (e.g. Dutschke, 2003; Herzog et al., 2003; Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008). The answer to this question is affected by many assumptions about timelines, economic discount rates, the value of carbon over time, particular measures of climate change used and their corresponding measures of mitigation success, the range of benefits considered, other confounding policy decisions, and structural differences among specific actions. No definitive answer exists, but many authors (e.g. Chomitz, 1998; Marland et al., 2001; Herzog et al., 2003; Dornburg and Marland, 2008; Fearnside, 2008) conclude that, for reasons beyond the example hypothesized above, even carbon sinks that are known to be temporary have value in the context of climate change mitigation. However, temporary mitigation actions should be explicitly recognized as such and not consume resources otherwise destined for permanent mitigation strategies. In my research, I discuss the actual benefit of temporary impacts only in theoretical terms but do not examine it in depth.

1.5 Current Research Project

Avoiding the burning of debris piles is one potential action within forest management that might reduce GHG emissions. This action is a fine-scale, stand-level strategy that generates both permanent and temporary GHG benefits. However, avoided slash burning is also an action that is currently feasible and initiated by operational-level decisions, and is therefore executable on a short time scale with immediate impacts.

In this research, I evaluate whether avoiding burning post-harvest debris piles could be an effective strategy for reducing GHG emissions in a timber harvesting land base (THLB). I focus on a case study in the Strathcona Timber Supply Area (TSA) on Vancouver Island, British Columbia (BC). My overall objective in this project is to determine the medium- and long-term GHG impacts of the burning of post-harvest debris piles from 2008 to 2050, while explicitly considering the duration of those GHG impacts. The majority of this impact is only temporary in nature, resulting from the difference between the immediate release of carbon from burning relative to the prolonged release of carbon that would have occurred had the burned material been left to decompose instead, a discrepancy that slowly dissipates over time. However, a portion of the total GHG impact of burning slash piles represents a permanent impact, resulting from differences between combustion and decomposition in terms of the molecular forms of emissions.

I simulate the GHG impacts of burning debris piles across a real landscape, with heterogeneous forest composition and long-term harvesting patterns that are in a state of transition. The results from my research are thus situated within the context of broader patterns of change on the landscape, including large decreases in the allowable annual cut (AAC) over time, a shifting balance between the harvest of old-growth and second-growth stands, and year-to-year variability in the annual volume harvested. The outputs of my simulations are therefore somewhat more convoluted than those that might result from the simulation of a theoretical stand or landscape without these complicating factors. However, this complexity strengthens the relevance of my results because I examine the impacts of slash pile burning over a real landscape undergoing realistic shifts in management.

2: METHODS

2.1 Study Area

I focussed on the Strathcona TSA, located within the Campbell River Forest District, in coastal BC, Canada. I chose this study area in the context of larger series of proposed investigations within the Campbell River Forest District, which has a long history of industrial logging, a large human footprint in the forest, a history of using slash burning, a more recent history of carbon related research, and good quality inventory data (C. Dymond, pers. comm.; K. Lertzman, pers. comm.). The Strathcona TSA spans north-central Vancouver Island and extends to include a portion of the mainland coast (**Figure 1**). The TSA is composed of three distinct subunits or "timber supply blocks": the Kyuquot block on the west coast, the Sayward block on the east coast, and the Loughborough block on the mainland. The Strathcona TSA includes the communities of Campbell River, Courtenay, Comox, Cumberland, Gold River, Tahsis, Zeballos, Sayward, and Kyuquot, and the territorial interests of fourteen First Nations. The Strathcona TSA covers approximately 407,000 ha, including 347,000 ha of productive forest area, of which approximately 160,000 ha are considered available for harvesting (BC Ministry of Forests and Range, 2004).

The high degree of topographic and climatic variation within the Strathcona TSA has produced an area that is ecologically rich and diverse. The TSA provides habitat for 300 species of migratory and resident birds, 45 species of mammals, and 13 species of amphibians, including 15 red-listed species (endangered or threatened) and 35 blue-listed species (vulnerable) (BC Ministry of Forests and Range, 2004). The region is characterized as a “mosaic of wet, mountainous terrain dissected by streams and rivers, many of which create estuaries as they enter the ocean” (BC Ministry of Forests and Range, 2004).

Within the Biogeoclimatic Ecosystem Classification (BEC) system (Meidinger and Pojar, 1991), the Strathcona TSA includes Coastal Western Hemlock (CWH), Mountain Hemlock (MH), and Alpine Tundra (AT) zones. The dominant BEC zone is CWH, which comprises 99% of the THLB. Three CWH variants constitute 75% of the THLB – CWHvm1 (45%), CWHxm2 (20%), and CWHvh1 (11%) (BC Ministry of Forests and Range, 2004). The submontane very wet maritime variant (CWHvm1) is characterized by a “wet, humid climate with cool summers and mild winters featuring relatively little snow” with high but variable precipitation and long growing seasons, and is dominated by western hemlock (*Tsuga heterophylla*) and amabilis fir (*Abies amabilis*) with minor amounts of western redcedar (*Thuja plicata*) (Green and Klinka, 1994). The very dry maritime subzone (CWHxm) is characterized by “warm, dry summers and moist, a mild winters with relatively little snowfall” with long growing seasons and frequent water deficits, and is dominated by Douglas-fir (*Pseudotsuga menziesii*), accompanied by western hemlock and lesser amounts of western redcedar (Green and Klinka, 1994). The southern very wet hypermaritime variant (CWHvh1) is characterized by a cool climate with widely variable precipitation but very little snowfall and is dominated by western hemlock, accompanied by amabilis fir, western redcedar, and lesser amounts of yellow-cedar (*Callitropsis nootkatensis*, formerly *Chamaecyparis nootkatensis*; Little et al., 2004) (Green and Klinka, 1994).

Industrial logging started around the 1880s in the eastern portions of the TSA (present day Loughborough and Sayward Supply Blocks) (J. Andres, pers. comm.). Logging operations were at first limited to areas accessible by water but gradually expanded inland, peaking in this area during the 1930s (J. Andres, pers. comm.). Logging in the western portion of the TSA (present day Kyuquot Supply Block) did not begin until the 1960s, limited by poor accessibility, but increased substantially until its peak in the 1980s/90s when the AAC began to be reduced for the entire TSA and logging operations began to gradually shift back to second-growth stands reaching maturity in the Sayward Supply Block (J. Andres, pers. comm.). When the Strathcona TSA was established in 1986, the AAC was set at 1.65 million cubic metres. The AAC increased to its maximum of 1.69 million cubic metres in 1992 and has decreased since then to its current level of 1.22 million cubic metres (effective August 1, 2005) (Snetsinger, 2005).

The total population of the Comox and Strathcona Regional Districts in 2009 was 110,282. The Comox-Strathcona Regional District (which subdivided into the two regions above in 2008) is similar in geographic extent to the Strathcona TSA, including all the same communities plus an additional 8,000-10,000 people in non-incorporated areas that do not fall within the TSA. The regional population has increased approximately 10.1% from its recent low in 2001 that followed a 3.8% decline during 1997 to 2001 (BC Statistics, 2009a). As of 2005, the regional income dependency on forestry was 14%, with the public sector accounting for 26% and tourism accounting for 6% (BC Statistics, 2009b).

2.2 Carbon Budget Model

I used the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, version 1.1) (Kull et al., 2007; Kurz et al., 2009; Natural Resources Canada, 2009). The CBM-CFS3 is an empirically based, data-driven model that simulates forest carbon dynamics at the stand- or landscape-scale. The model first uses forest inventory data to derive carbon stocks, then growth and yield data along with user-defined information on disturbances to simulate carbon within the forest ecosystem dynamically. The model keeps track of carbon stocks in five live biomass “pools” and nine dead organic matter (DOM) and soil pools, tracking transfers of carbon among these pools and removals of carbon to the atmosphere. This “one inventory plus change” approach allows the examination of future scenarios based on the effect of disturbance events and major ecological processes. For each species in a particular eco-zone, volume-to-biomass expansion factors, turnover rates within each pool, and decomposition rates are taken from a national database of ecological parameters used by the CBM-CFS3. The model is compliant with the guidelines of the Intergovernmental Panel on Climate Change (IPCC) for methods of carbon estimation and it meets the requirements under the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol (Kull et al., 2007; Kurz et al., 2009).

The CBM-CFS3 has evolved through two decades of improvement and advancement (Kurz et al., 1992; Kurz et al., 1995; Kurz and Apps, 1999; Kurz et al., 2002; Kull et al., 2007; Kurz et al., 2009). This model has been used to investigate the carbon budget implications of many forest management issues and disturbance types at different scales. Recently, the model has been used to quantify the impact of the mountain pine beetle outbreak in BC on the province's carbon budget (Kurz et al., 2008a), to reconstruct the historic carbon budget of a Vancouver Island landscape converted from old-growth to managed forests (Trofymow et al., 2008), and to evaluate the sensitivity the carbon budget of Canada's managed forests to the risk of natural disturbances, in preparation for Canada's decision whether or not to include forest management under its obligations to the Kyoto Protocol (Kurz et al., 2008b).

The CBM-CFS3 model represents the impact that a disturbance will have on carbon pools by a "disturbance matrix". Every unique disturbance type needs its own disturbance matrix that describes all the transfers of carbon among carbon pools that occur when the disturbance takes place. The matrix expresses transfers in terms of the proportion of carbon in each pool that is transferred to other particular pools.

For the present analyses, I used the "clearcut harvesting without salvage" disturbance matrix in the CBM-CFS3 to represent the management action of applying clearcut harvesting with no subsequent debris treatment (i.e. no burning). The "clearcut with slash-burn" disturbance matrix was originally developed as hybrid between the practices of piling and burning debris and broadcast burning debris, in order to represent the mixed occurrence of these two practices across large landscapes (C. Dymond, pers. comm.). Consequently, this default disturbance matrix is not an ideal representation of piling and burning where only the one practice applies. On the coast, very little broadcast burning is performed anymore (J. Andres, pers. comm.). Common practice within the Canadian Forest Service's (CFS) Carbon Accounting Team has been to implement the piling and burning of slash as a two-step process, by first applying the "clearcut harvesting without salvage" disturbance matrix to the target area, then subsequently applying the "clearcut with slash-burn" disturbance matrix (C. Dymond, pers. comm.). This has the effect of decreasing the proportion of the biomass that is consumed by burning and immediately released to the atmosphere from the merchantable, foliage, sub-merchantable, and other pools, but increasing the proportion of the biomass that is consumed in the coarse roots pool. The CFS Carbon Accounting Team has applied this approach in its research projects, considering it an improvement in the representation of piling and burning of post-harvest debris in CBM-CFS3 simulations (C. Dymond, pers. comm.). I have followed a similar approach in my research, except that I have consolidated these two disturbance matrices into a single disturbance matrix in order to apply it in a single step for streamlined computation (**Table 1**). Other than the modified approach used to simulate clearcut harvesting with piling and burning of slash, the simulations were run utilizing the default ecological parameters in the CBM-CFS3 for the Pacific Maritime ecozone.

2.3 Data

2.3.1 Inventory Data, Growth & Yield Data and THLB Definition

I acquired forest inventory data from the Vegetation Resources Inventory (VRI) database and growth and yield data (i.e. yield over time) from the Variable Density Yield Prediction (VDYP) Model from the Forest Analysis and Inventory Branch of the BC Ministry of Forests and Range (Q. Li, pers. comm.). The VRI database projects inventory data to January 1, 2008. The VRI data for the entire TSA contains 41,203 stand records, of which 34,385 have associated growth and yield data ("growth curves") from the VDYP model. The growth and yield dataset contained 24,263 unique growth curves for the TSA, each representing a different stand type.

The CBM-CFS3 model (Kull et al., 2007; Kurz et al., 2009) requires users to specify classifier values to define unique stand types so that similar stands can be aggregated and associated with a single growth curve. I developed a classification system for stand types to decrease computational complexity by reducing the number of unique stand types while attempting to maintain variation within the data. To define stand type, I used six initial classifiers: leading species and percent coverage, the second most dominant species and percent coverage, site index, and BEC zone. The species coverage variables used intervals of 5%. The site index variable used intervals of two units up to a level of 48. This classification resulted in 3830 unique stand types within the study area.

I also explored classification schemes using other permutations of the same variables, evaluating them by comparing the variation among the individual growth curves aggregated into a single growth curve for the resultant stand type. I chose the present scheme as a balance between improving computability and maintaining ecological complexity. Although I also examined classification schemes using the three most dominant species, using the two leading species to classify stand types offered sufficient precision. In most cases, the first and second species dominate the stand composition. The combined coverage of the two leading species exceeds 75% in 95% of all stands, and exceeds 80% in over 90% of all stands.

I reduced the data for the entire TSA to a subset representing the Timber Harvesting Land-base (THLB). The THLB is defined as “crown forest land within the timber supply area where timber harvesting is considered both acceptable and economically feasible, given objectives for all relevant forest values, existing timber quality, market values and applicable technology” (BC Ministry of Forests and Range, 2004). The on-the-ground delineation of the THLB is thus variable over time as the forest and management objectives change. The current specification of the THLB, acquired from the Forest Analysis and Inventory Branch of the B.C. Ministry of Forests, is based on the most recent information available and includes 143,668 ha (Q. Li, pers. comm.).

I created consolidated growth and yield curves for 1662 of the 3830 unique stand types (as defined above) by calculating the area-weighted average of the growth curves of all of the stands within each stand type. I compared the variation among the constituent growth curves and the resultant growth curve as part of the assessment of different stand type classification systems, though I do not describe these results any further. The remaining 2168 stand types only have a single occurrence and therefore I simply used the original growth curve associated with each particular stand and did not need to consolidate multiple growth curves. For the stand types with a singular occurrence, 32 of the associated growth curves had no actual data for volume and were removed, resulting in a final data set of 3798 unique growth curves. I excluded stands with no trees or no site index in their inventory record, or no growth curve associated with their stand type from further analysis. In total, I excluded 8718 ha due to incomplete data.

The final data set used for simulations contains 9124 stands covering 134,950 ha, or 84.1% of the THLB as reported in the TSR (BC Ministry of Forests and Range, 2004). These data contain 3798 unique stand types, as per the classifiers described above, each associated with a single growth curve. I further stratified the forest inventory into old- and second-growth stands, defining stands greater than 125 years old (as of the inventory date, January 1, 2008) as old-growth stands, as per the definition used in the TSR (BC Ministry of Forests and Range, 2004). Forest of this age may only represent “older forest” rather than “old-growth forest”, as the structural and ecological complexity of true old-growth forest is likely not achieved until these forests have reached at least 180-200 years old (K. Lertzman, pers. comm.); however, the definition of old-growth from the TSR (i.e. greater than 125 years old) is used here for consistency. Such old-growth stands constitute 80.0% of the total THLB area simulated. The CBM-CFS3 model requires specification of the most recent disturbance to have affected each stand; however, the inventory contains relatively sparse data on the last disturbance type for each stand. I have assumed that the last disturbance was clearcut harvesting for second-growth stands, whereas the last disturbance was stand-replacing fire for old-growth stands.

2.3.2 Forest Harvesting Schedule

I developed a single harvesting schedule, common to all simulations, specifying which stands to harvest in each year of the study period. A harvest schedule is a required input for the CBM-CFS3. By using a common schedule for all simulations, the pattern and timing of harvesting is the same among all of the scenarios simulated and therefore I can attribute the differences between scenarios to the differences between the post-harvesting practices that each scenario represents. I developed this common harvest schedule based on the total volume harvested, the old-growth proportion of the harvest volume, and criteria for the minimum harvest age.

I modelled the annual harvest volume and the proportional contribution of volume from old-growth stands after the “base case” in the Strathcona TSR (BC Ministry of Forests and Range, 2004). The base case represents one potential timber supply trajectory based on current management practices that accounts for short- to long-term goals and constraints within the TSA. The analyses in the TSR use the base case scenario as a common baseline against which to compare changes in assumptions about management practices, underlying data, and other constraints. However, the TSR base case is not a forecast of actual harvest levels since AAC is only determined for periods of approximately five years at a time. I adjusted the harvest volume upwards to reflect the fact that the final determination of AAC for the current period was higher than that of the base case. I adjusted the old-growth proportion of the harvest downwards to reflect the fact that old-growth stands currently represent approximately 70% of total harvested volume, whereas they represent 100% of the harvested volume for the first decade of the base case (BC Ministry of Forests and Range, 2007). Each stand becomes eligible for harvest once its growth rate has reached at least 95% of its maximum annual increment and its merchantable volume has exceeded 350m^3/ha, as per the specifications used in the TSR (BC Ministry of Forests and Range, 2004). However, these criteria only determine eligibility but do not specify the timing of actual harvest, which may occur many years after a stand reaches its minimum eligible age.

I used the “relative oldest first” rule to select stands for harvesting in each year, which specifies that the harvest order is prioritized based on the age of each stand relative to the minimum age at which it became eligible for harvesting. For each stand selected for harvesting, 85% of the total volume was counted toward the annual volume targets, matching the default parameters used in the CBM-CFS3 to specify the proportion of merchantable material that is transferred to the forest products pool when harvesting occurs. Stands would then be selected for harvest in the order of their relative age until the annual harvest volumes (as stratified by old- and second-growth proportions) were as close to the target volumes as possible without exceeding them. I did not subdivide or re-order stands to achieve the annual volume targets more precisely. Since I used the same harvest schedule across all scenarios, the resulting deviations from the target volumes are not critical. The final schedule results in approximately 42.7 million m^3 being harvested over 50 years. I developed a 50-year harvest schedule but only utilized the first 43 years in the present simulations. The average annual area harvested is 1396 ha with an average volume of 612 m^3/ha. These values are slightly lower than the TSR base case but still comparable (BC Ministry of Forests and Range, 2004).

2.3.3 Estimates of Burning

It was not possible to acquire accurate and definitive data on the extent to which the practice of piling and burning post-harvest debris currently occurs across the Strathcona TSA. The Annual Reports of the Ministry of Forests report the area treated each year by burning for site preparation, but from 1994 onward they do not separately account for different types of prescribed burning (BC Ministry of Forests and Range, 2009). Prior to 1994, the reports differentiate among alternate forms of burning, though broadcast burning was the dominant method, comprising over 82% of all area burned for site preparation during 1981 to 1993 (BC Ministry of Forests and Range, 2009). However, these values are only reported by Forest Region and not by TSA or even Forest District. Therefore, the only estimates from these reports are the annual averages for the entire Coast Forest Region, and the regional averages may not necessarily be representative of the Strathcona TSA specifically. The values in recent years reflect lower levels of total burning (predominantly broadcast burning) than the estimates of pile burning specific to the Strathcona TSA (from Ministry of Forests staff within the Campbell River Forest District). The Forest Practices Board (2008) anecdotally documents the burning of debris piles for the purposes of waste disposal and fire hazard abatement; however, based on the professionals and experts I consulted with, the extent to which burning for these purposes is captured by the statistics on site preparation as reported in the Annual Reports is unclear.

In place of data, I developed broad estimates of the level of burning within the study area based on consultations with staff from the Ministry of Forests who had experience and knowledge specific to practices in the Strathcona TSA. I intended these estimates to at least capture the broad range of variation in the application of this practice across space and time. The actual area subject to the piling of debris and the volume of debris actually burned within each piled area are both highly variable, depending on many factors such as stand type, harvest method, topography, remoteness, local climate characteristics, and other factors. The relative influence of each of these factors varies over time and among locations within the TSA; it is impossible to know how they will actually vary over the next several decades. Although these estimates are a simplification of a complex reality, they provide an approximation of how much burning could realistically continue to occur within the Strathcona TSA. The goal is to provide reasonable estimates that capture the current range of variability and will plausibly contain the future business-as-usual levels of burning.

2.4 Analysis Framework

2.4.1 Time Period of Analysis

The primary period for the analysis is 2008 to 2050. The VRI database projects the inventory data to January 1, 2008, making 2008 year 1 of the simulation. The year 2050 is an important focal point within the context of climate change research and policy. This date is a common benchmark for predicting impacts of climate change, evaluating alternative emissions scenarios and mitigation strategies, and setting mid-term GHG reduction targets (Pacala and Socolow, 2004; Nabuurs et al., 2007; Solomon et al., 2007; Weaver et al., 2007; G8, 2008; Government of British Columbia, 2008a; Government of Canada, 2009). Mid-century targets provide a critical bridge between near-term targets (e.g. Kyoto commitment period, 2008-2012) and long-term targets (e.g. 100-200 year stabilization goals), providing guidance and clearer policy signals for decision-makers while maintaining long-term climate policy options (O'Neill et al., 2006, 2010). Climate modellers have also found that emissions in the year 2050 are important determinants of long-term climate outcomes (Weaver et al., 2007; Meinshausen et al., 2009; O'Neill et al., 2010).

2.4.2 Primary Scenarios

I explored the impacts of debris pile burning through four basic scenarios, representing the GHG impact of low, moderate, high, and very high levels of burning applied across the landscape. To isolate the impact directly attributable to the particular level of burning, I calculated the difference between the results of the simulation of that particular level of burning simulation and the results of the simulation of the baseline where zero burning occurs in order to determine the GHG impacts of each burning scenario. That is, I simulated the impact of each burning scenario, but expressed this impact as the relative difference between the simulation of that burning scenario and the baseline simulation with no burning.

Each burning simulation substantially simplifies the variable manner in which burning is applied across the landscape. I modelled the application of debris pile burning as an all-or-nothing treatment. That is, in each burning simulation, a proportion of the total area of harvested stands is harvested via “clearcutting with debris pile burning” and the remaining area is harvested by “clearcutting”, with no burning of any debris. The precise levels of burning actually applied across the Strathcona TSA are variable both spatially and temporally. Reducing this complex variation to a single definitive value is difficult task; although these scenarios aim to encompass the plausible current and future variability, they represent a substantial simplification of a dynamic reality.

In the zero burning simulation, all stands are harvested by clearcut and no debris is burned. I used this simulation as the baseline against which I compared the simulations of the four different levels of burning to determine the relative impact of each burning scenario. I developed the first three burning scenarios based on the rough estimates provided by staff in the Ministry of Forests on the proportion of harvested stands subject to piling, the proportions of piles that are piled at the roadside, the proportion of blocks subject to at least some burning, and the proportion of roadside piles burned, with all estimates stratified by old-and second-growth status. I further transformed these estimates were into a range of estimates that would specify the proportion of harvested stands subject to piling and burning in a world in which the practice of piling and burning is applied in the all-or-nothing manner described above.

In the low burning scenario, 3% of the old-growth area harvested and 6% of the second-growth area harvested are subject to debris pile burning. In the moderate burning scenario, the area subject to burning is 4.5% of old-growth harvest and 9% of second-growth harvest; and in the high burning scenario, burning is applied in 6% of the harvested old-growth and 12% of the harvested second-growth (**Table 2**). I designed these three burning scenarios (i.e. low, moderate and high) to encompass variability within practices currently and over the past decade. I presented the resultant scenarios back to the same staff at the Ministry of Forests to confirm that these scenarios were a reasonable characterization of the average level of piling and burning across the TSA.

These burning scenarios appear to affect a larger area on the landscape than is reported for total burning (all methods of burning, but predominantly broadcast burning) in the Ministry of Forests Annual Reports for 2000 onwards (BC Ministry of Forests and Range, 2009). When I applied the low burning scenario to the Strathcona TSA, I found that the annual area subject to piling and burning was similar to the amounts reported for total burning in the 2000s in terms of absolute area and was slightly larger in terms of the percentage of the total area harvested. When I applied the moderate and high burning scenarios to the Strathcona TSA, I found that the area affected was higher than the amounts reported for total burning in the 2000s but similar to the amounts reported for the 1990s, both in terms of absolute area and as a percentage of the total area harvested. However, the Annual Reports only describe statistics for the Coast Forest Region as a whole, thus representing average values for the entire coast of BC. Direct estimates for either the Campbell River Forest District or the Strathcona TSA are not possible from these reports except by rough interpolation. Therefore, the Annual Reports have a limited ability to validate these scenarios but do offer some assurance that these estimates are not entirely unreasonable.

I added a fourth scenario, designated as “very high”, in which the area subject to debris pile burning is 1.5 times greater than the high burning scenario (**Table 2**). The purpose of the very high burning scenario was to expand the range of burning scenarios considered with a level of burning that, while well outside the current range, has not been unprecedented over the past few decades. When I applied the very high burning scenario to the Strathcona TSA, I found that the annual area subject to piling and burning was similar to the amounts reported for total burning in the 1980s across the Coast Forest Region in terms of the percentage of the total area harvested – before whole-tree-to-roadside harvesting became common practice (C. Dymond, per. comm.).

In a scenario where “clearcut with debris pile burning” is applied to X% of the harvested area, the scenario was implemented by applying the treatment to X% of every stand that is harvested rather than simulating repeated Monte Carlo runs selecting X% of the harvested stands (by area) each time. This approach greatly reduces the number of simulations needed while still capturing the variation present across the landscape. The ultimate result should be the same as the long run average of many simulation runs in which all stands being harvested were equally eligible candidates for the application of debris pile burning, as is the assumption in this project.

2.4.3 Long-run Analyses

I conducted further analyses to determine the long-term impact over the subsequent two centuries of the slash pile burning applied up to 2050. If some portion of the cumulative GHG impacts of burning is only temporary in duration, reflecting the difference between immediate and delayed emissions, then assessing the timeframe over which those diminishing, temporary impacts exist is important. I determined the long-term effect of the burning of slash piles from 2008 to 2050 by extending each of the burning scenarios and the zero burning baseline by an additional 200 years after 2050, but with no further harvesting or burning. This design allowed me to isolate the long-term impacts of the 43 years of applying slash pile burning across the landscape (2008-2050) from the confounding factors of additional harvesting and burning that might actually occur on the landscape. The results of these analyses thus demonstrate the degree to which the impacts of this particular practice over this particular period will persist or change over the following 200 years.

2.4.4 Sensitivity Analyses

I conducted a sensitivity analysis to assess how robust the results are to potential regeneration delays due to the physical footprint of unburned debris piles. The space that piled slash occupies may reduce the area available for regenerating stock or otherwise impede planting. Increasing the amount of space available for planting new stock and increasing the overall regeneration potential of the site is commonly part of the rationale for piling and burning debris. If the regeneration of the new stand is constrained either spatially or temporally because of leaving unburned debris, this will reduce the carbon sink function of the new growing stock by reducing the number of young trees sequestering carbon as they grow. Such a reduction or delay in the uptake of carbon may offset some of the potential carbon gains initially achieved by avoiding burning (i.e. delaying the release of carbon and avoiding methane (CH_4) and nitrous oxide (N_2O) emissions from combustion). The magnitude of this potential effect on the overall GHG impact of avoiding debris burning is therefore important to quantify.

Research quantifying the impact that leaving unpiled or unburned debris may have on the regeneration potential of a site is limited. In north eastern Ontario, one study estimated that debris piles, if left unburned, would cover four to seven percent of the harvested land and that this portion of the harvested area might experience regeneration delays of 10 to 30 years (Luke et al., 1993). Although these estimates will vary hugely depending on the amount of original debris, which varies with forest type, forest age, and utilization rates, and on decomposition rates, comparable estimates of the impact in coastal BC are simply lacking. Instead, I gathered information from several foresters with extensive experience within the Strathcona TSA.

The information I was able to find suggests, unsurprisingly, that the reality in the Strathcona TSA is quite different from that of northern Ontario. A cumulative physical footprint for slash piles of even 4-5% of the cut block area is much larger than is ever observed in the TSA, except for one particularly extraordinary case (D. Tanner, pers. comm.). Two licensees operating within the TSA similarly estimated that the total physical footprint of slash piles within a cut-block might commonly be around 1% (J. Andres, pers. comm.). Piles that are at least 30 years old and only partially degraded are commonly encountered, implying that 30 years may be toward the lower bound of a potential effect, but empirical data are unavailable because the longevity of unburned slash piles is not tracked (D. Tanner, pers. comm.; B. Beese, pers. comm.). Furthermore, the size and longevity of a pile as a physical structure is not necessarily an accurate proxy for the degree to which it may impede the establishment and growth of the new stock. As the pile breaks down, seedlings may establish themselves in small openings along the edge of the pile or on nurse logs sooner than change in the overall structure and footprint of a pile becomes apparent. Young trees surrounding the pile may actually benefit from increased resources, either directly from the release of nutrients from debris or indirectly from reduced competition for light and water in this artificial gap (B. McKerricher, pers. comm.; D. Tanner, pers. comm.). Even if piles last 30 to 50 years with only moderate degradation, it is unknown whether natural regeneration on the pile site would be delayed in equal measure. It may be unrealistic therefore to assume that regeneration is delayed by 50 years just because the coarse components of the pile have lasted that long.

Based on such information, the potential negative impact that unburned piles might have on the establishment of a new stand does not appear to be an actual concern in the Strathcona TSA. Within the TSA, unburned piles almost never impede the ability to plant cut-blocks to their target density – successful planting is possible wherever harvesting occurred (D. Tanner, pers. comm.). The presence of unburned slash (whether piled or not) may make planting more difficult, but it is always possible to find enough planting spots to achieve fully stocked stands (D. Tanner, pers. comm.). The abatement of fire risk is always the basis for the decision to burn the piles that accumulate at the roadside; the practices forester I spoke with could only recall one exceptional case when part of the rationale for burning was a concern about plantable space and the ability to fully restock the block (D. Tanner, pers. comm.).

Even though the information gathered suggests that the presence of unburned debris piles does not have a meaningful influence on the ability to fully stock harvested areas, I still performed a sensitivity analysis on this factor. In other landscapes, this effect is important and it is still a potential influence in the present study area, if only in theory. Determining how sensitive the results from this study are to this effect, if in fact it actually exists, is therefore still relevant. The sensitivity analysis tests the impacts of four different permutations of a partial regeneration delay on the moderate burning scenario. These regeneration delays represent the failure to fully replant harvested stands that would have otherwise been cleared by slash burning and therefore fully plantable. I only tested the sensitivity of the moderate burning scenario. The regeneration delays I tested were combinations of both the length of the delay and the area affected. I tested delays of 30 and 50 years, affecting 1% and 2% of the area that would have otherwise been piled and burned. The area affected is a percentage of the area that would be eligible for burning in a particular scenario, not a percentage of the total area harvested. For example, if 5% of the harvested area is subject to clearcut with slash burning, then 1% of that 5% might experience a regeneration delay if burning was not done (i.e. 0.05% of the harvested area). I do not account for the possibility of delayed regeneration or under stocking on the 95% of the harvested area that is not subject to debris burning because the effect would be identical across all scenarios, occurring independently of any decision regarding slash burning. In my research project, this effect is only important to explicitly include where there is a possible difference between a burning simulation and the zero burning baseline (i.e. on the proportion of the harvested area subject to slash burning in each scenario). I implemented this sensitivity analysis by incorporating these partial regeneration delays into the zero burning simulation against which I compare the moderate burning simulation to determine the relative GHG impacts of the moderate burning scenario.

2.4.5 Factors Excluded

I have excluded from consideration all factors that I expected to have an identical impact across all scenarios (i.e. regardless of the area subject to piling and burning) from the analyses. For example, natural disturbances have not been included in these analyses because I have assumed that such processes would affect all scenarios equally. These excluded elements affect the accuracy of the absolute measures of the carbon stocks and fluxes in any particular scenario, but not the relative measures between scenarios because the missing elements are those that would be identical in all scenarios and therefore exhibit relative differences of zero even if they were included in the analyses. One factor that is excluded but could have an important effect on the relative GHG impacts of avoided slash burning is the potentially increased risk of wildfire directly associated with relative differences in the amount of unburned debris left on the landscape in each scenario. This only concerns the possibility of fire that is a direct consequence of the application of different treatments among scenarios and does not refer to the background rate for natural wildfire that would occur equally in all scenarios regardless of their treatment. I could not evaluate the incremental fire risk from leaving additional unburned debris on the landscape in my research but I explore its relevance in the discussion.

2.5 Determination of GHG Impacts

2.5.1 Basic Carbon Dynamics of Slash Pile Burning

In simple terms, when a slash pile burns, the fire consumes much but not all of the debris in the pile and leaves a portion of the debris unconsumed after the fire. The combustion produces emissions of various GHGs, whereas the debris not consumed by the fire will decompose over time, slowly losing its carbon to the atmosphere as $CO_{2.}$ However, if the pile does not burn, then all of the debris will eventually decompose. Therefore, the fate of the debris that escapes consumption by the fire during a slash pile fire is the same in either case and is of little interest in the present investigation because it does not differ between the alternate actions (i.e. burning and not burning). When evaluating the GHG impacts of burning slash piles relative to not burning them, the portion of the debris of interest is that which combusts if the pile burns but decomposes if the pile does not burn.

The conceptual illustration in **Figure 2** shows the two potential fates of the carbon in this portion of the debris that would be fully combusted, depending on whether the slash pile actually burns or decomposes. If burning occurs, the debris releases its carbon to the atmosphere immediately as CO_2, carbon monoxide (CO), and CH_4. In addition to these carbon-based GHGs, burning the debris also produces a small amount of N_2O, a much more powerful GHG. However, if burning does not occur, then the debris only releases its carbon slowly over time through decomposition as CO_2. The net GHG impact of burning the slash is the difference between the total GHG emissions resulting from burning and those still resulting in the absence of burning, measured in terms of carbon dioxide equivalents (CO_2-e).

A portion of this net difference is likely to be only temporary in nature because it reflects the difference between the carbon released thus far through decomposition of the debris and the carbon that the debris will eventually release once it fully decomposes (**Figure 2**). However, even once the debris releases all of its carbon through decomposition, the total GHG impact (i.e. tons CO_2) will still not be as high as the slash burning alternative that includes the release of more powerful GHGs. This portion of the net difference between the two alternatives will be a permanent difference because once the debris releases all of its carbon through decomposition, it cannot release more carbon and it cannot change the molecular form of the carbon already released.

2.5.2 Quantifying the GHG Impacts of Slash Pile Burning

The key outputs from the CBM-CFS3 used to evaluate the impact of debris pile burning are the changes in the total carbon stocks over the analysis timeframe, the net annual carbon flux from the ecosystem to the atmosphere, and the amount of GHGs released from burning debris. When examining the carbon budget of a landscape, the two basic attributes analysed are carbon stocks and carbon fluxes. Stocks are the measure of the amount of carbon contained in a particular pool(s) at a particular time. If total carbon stocks are increasing over time, the landscape is a carbon sink, but if total carbon stocks are decreasing over time, the landscape is a carbon source. Fluxes are the transfers or flows of carbon among pools or between pools and the atmosphere. If the net carbon flux from the landscape to the atmosphere is positive, then the landscape is a carbon source.

One of the metrics most commonly reported is total ecosystem carbon, which is the sum of all the carbon stocks in all living biomass and dead organic matter pools for the landscape at a particular time. This metric represents an aggregate measure both across carbon pools but also across time, because current carbon stocks are the product of the processes, disturbances and transfers in all previous years. The impact of a particular burning scenario can be determined by comparing the total ecosystem carbon stocks of that scenario with the baseline simulation in which zero debris burning occurs. Relative to the absolute measure of the total ecosystem carbon, the divergence between any burning scenario and the baseline appears insignificant – harvesting only disturbs approximately 1% of the THLB each year and only a small percentage of the harvested area is subject to slash burning in any given scenario. Each year of the simulation, the vast majority (over 99%) of the total carbon stocks across the landscape are subject to identical changes irrespective of the scenario chosen. Therefore, I examine the relative differences between each burning scenario and the baseline simulation to isolate the difference in carbon stocks that is attributable to the level of slash burning applied. The difference between the carbon stocks of a burning scenario and the zero burning baseline in a particular year illustrates the cumulative impact of applying the practice of burning over all the previous years.

Total annual ecosystem carbon flux is the net transfer of carbon between the atmosphere, terrestrial ecosystem carbon pools (living biomass, DOM and soil), and losses to the Forest Products Sector over a single year. Following Stinson et al. (2011), I refer to this flux as the “net GHG balance” in the calculations below. Since both the CBM-CFS3 model and this research are forest-based, the convention is to consider a net increase of carbon in the forest ecosystem as a positive flux. The flux of carbon from terrestrial pools to the atmosphere is measured either in terms of amount of carbon, while ignoring the molecular form of the carbon released, or in terms of GHGs, accounting for the specific carbon-based GHGs released as well as including non-carbon GHGs. When biomass burns, the carbon transferred to the atmosphere is released as CO_2, CO and CH_4. The global warming potential (GWP) of CH_4 is substantially larger than that of CO_2, meaning emissions of CH_4 will have a disproportionately larger contribution to global warming than an equivalent amount of carbon emitted in the form of CO_2. Combustion also releases N_2O, a non-carbon GHG with an even larger GWP, though in much smaller amounts. I use the term "GHG emissions" to refer collectively to the amount of CO_2, CO, CH_4, and N_2O emitted to the atmosphere, converted to CO_2-e according to their GWP values. I use the term "carbon emissions" to refer only to the amount of carbon released to the atmosphere without including N_2O or accounting for differences in GWP among carbon-based GHGs.

The net GHG impact of the action of burning is the relative difference between the net GHG balance for a burning simulation and that of the zero burning baseline. I calculated this difference between the two potential trajectories for the landscape (i.e. either burning year after year or completely avoiding burning year after year) in terms of both annual and cumulative impacts. The annual impact is the difference between the GHG balances of the burning and the non-burning trajectories as measured in Year y and the cumulative impact is the sum of those annual impacts up to Year y (**Eq. 1**). In this section, I provide a simple definition the parameters below the equation in which they first appear but provide more detailed explanations of each new parameter in the text.

[**Eq. 1**] $$Net\ Cumulative\ GHG\ Impact_y = \sum_{i=1}^{y} Net\ Annual\ GHG\ Impact_i$$

y year of measurement
i initial year of period of analysis

The annual impact represents the difference between the emissions from combustion of debris in the burning simulation and the emissions from decomposition of debris in the non-burning simulation that actually occurs in a particular year. However, whereas the emissions from burning in a particular year are independent of previous years, the emissions from decomposition are not. Since the emissions from burning are immediate, the emissions from combustion in a particular year in the burning simulation solely reflect the burning performed in that same year. Since the emissions from decomposition occur slowly over many years, the emissions due to decomposition in a particular year in the non-burning simulation reflect the initial decomposition of the debris not burned in that year as well as continued decomposition of the unburned debris still remaining from previous years of avoided burning. Ultimately, the cumulative GHG impact is the measure of greatest interest. After engaging in burning year after year over the landscape, the most important question is, “what has the overall impact of these continuous years of burning been up to Year y”. The impact in one particular year of the difference between a sequence of years with burning and a sequence of years with no burning is not as important as the cumulative impact of all of the previous years in the sequence up to that particular year. However, I calculated the cumulative impact by first calculating the annual impacts.

The net annual impact of burning is the relative difference between the net GHG balance for a burning simulation and that of the zero burning baseline (**Eq. 2**). As shown in **Eq. 3**, the net GHG balance (INV_{GHG}) equals the net ecosystem exchange (NEE_{GHG}) plus the carbon losses to the forest products sector (C_HWP) (Stinson et al., 2011). NEE_{GHG} represents the net transfer of carbon and non-carbon GHGs between the atmosphere and terrestrial pools, in terms GHG emissions. C_HWP_{GHG} represents the export of carbon from terrestrial pools to harvested wood products, converted to CO_2-e. In this project, I applied the same level of harvesting to all simulations, therefore C_HWP_{GHG} is identical among all simulations and I can simplify **Eq. 2** to **Eq. 4**.

[**Eq. 2**] $$Net\ Annual\ GHG\ Impact_{GHG\ y} = INV_{GHG\ b\ y} - INV_{GHG\ b=0\ y}$$

INV	net GHG balance
GHG	measured in terms of GHG emissions
b	burning simulation
b=0	non-burning simulation

[**Eq. 3**] $$INV_{GHG\ y} = NEE_{GHG\ y} + C\_HWP_{GHG\ y}$$

INV	net GHG balance
NEE	net ecosystem exchange
C_HWP	carbon losses to the forest sector

[**Eq. 4**] $$Net\ Annual\ GHG\ Impact_{GHG\ y} = NEE_{GHG\ b\ y} - NEE_{GHG\ b=0\ y}$$

NEE_{GHG} represents the net result of various transfers among terrestrial pools and between these terrestrial pools and the atmosphere. Many of these components of NEE_{GHG} are identical among all of the burning and non-burning simulations in my study and therefore I factored them out. The live biomass pools in both the burning and non-burning simulations are identical as they are subject to precisely the same patterns of harvest and regeneration and, as discussed in Section 2.5.4, I did not simulate natural disturbances. I therefore determined the net annual GHG impact by examining only the emissions from the DOM and soil pools in the two simulations, as shown in **Eq. 5** in terms of GHG emissions and in **Eq. 6** in terms of carbon emissions. I calculated the carbon emissions from DOM and soil pools ($DOMSoilFlux_C$) for a particular year as the difference between the carbon stock for those pools in the current year and that of the previous year (**Eq. 7** for the burning simulation, **Eq. 8** for the non-burning simulation), using the CBM-CFS3 output on carbon stocks over time.

[**Eq. 5**]

$$Net\ Annual\ GHG\ Impact_{GHG\ y} = DOMSoilFlux_{GHG\ b\ y} - DOMSoilFlux_{GHG\ b=0\ y}$$

DOMSoilFlux exchange of GHGs from DOM and soil pools to the atmosphere (includes combustion and decomposition emissions)

[**Eq. 6**]

$$Net\ Annual\ GHG\ Impact_{C\ y} = DOMSoilFlux_{C\ b\ y} - DOMSoilFlux_{C\ b=0\ y}$$

C measured in terms of carbon emissions

[**Eq. 7**]

$$DOMSoilFlux_{C\ b\ y} = DOMSoilCarbonStock_{C\ b\ y} - DOMSoilCarbonStock_{C\ b\ y-1}$$

DOMSoilStocks total carbon stock in all DOM and soil pools

[**Eq. 8**]

$$DOMSoilFlux_{C\ b=0\ y} = DOMSoilCarbonStock_{C\ b=0\ y} - DOMSoilCarbonStock_{C\ b=0\ y-1}$$

The annual carbon emissions from DOM and soil pools, as calculated above, arise from combustion and decomposition in the burning simulation (**Eq. 9**) and decomposition alone in the non-burning simulation (**Eq. 10**). The CBM-CFS3 reports the annual carbon emissions due to burning and therefore I used **Eq. 9** to determine the portion of the annual carbon emissions from DOM and soil pools due to decomposition of non-combusted debris in the burning simulation (i.e. *OtherDecomp*$_C$). In the non-burning simulation, I separated the carbon emissions due to the decomposition of debris that otherwise would have been combusted in the burning simulation (*DebrisDecomp*$_C$) from the carbon emissions due to the decomposition of debris that would be left as unburned debris in either simulation (*OtherDecomp*$_C$) in order to isolate the emissions that actually differ between burning and non-burning trajectories. I then used the value that I calculated above for *OtherDecomp*$_C$ in order to determine the value of *DebrisDecomp*$_C$). The *OtherDecomp*$_C$ emissions are equal in the two simulations because they represent decomposition emissions that occur in either simulation regardless of whether burning takes place, whereas *DebrisDecomp*$_C$ is incremental to those emissions because it represents emissions from the decomposition of the debris that is burned in the one simulation but left to unburned in the other.

[**Eq. 9**] $DOMSoilFlux_{C\ b\ y} = DebrisCombust_{C\ b\ y} + OtherDecomp_{C\ b\ y}$

$\text{DebrisCombust}_{C\ b\ y}$	combustion emissions from the debris burned in the burning simulation (i.e. burning and emissions both occur in Year y)
$\text{OtherDecomp}_{C\ b\ y}$	decomposition emissions released in Year y from other debris that remains unburned even in the burning simulation

[**Eq. 10**] $DOMSoilFlux_{C\ b=0\ y} = DebrisDecomp_{C\ b=0\ y} + OtherDecomp_{C\ b=0\ y}$

$\text{DebrisDecomp}_{C\ b=0\ y}$	decomposition emissions released in Year y from the debris that would have been combusted in the burning scenario in Year y or earlier (i.e. includes decomposition in Year y of residual unburned debris still remaining from avoided burning in previous years)
$\text{OtherDecomp}_{C\ b=0\ y}$	decomposition emissions released in Year y from other debris that remains unburned even in the burning simulation (i.e. emissions from debris that decomposes either way; $\text{OtherDecompReleased}_{C\ b=0\ y} = \text{OtherDecompReleased}_{C\ b=0\ y}$)

After removing all the components that are identical between a burning simulation and a non-burning simulation and focusing only on those elements which differ, I express the net annual GHG impact simply as the difference between the emissions from the combustion of debris in the burning simulation and the emission from the decomposition of the unburned debris in the non-burning scenario that would have otherwise been burned (**Eq. 11**, derived from substituting **Eqs. 9** and **10** into **Eq. 6**). By using **Eq. 11**, I do not consider the dynamics of debris that would be left to decompose in either of the simulations and instead I only consider the dynamics of the debris that burns in the burning simulation but decomposes in the non-burning simulation, which represents the only actual difference between the GHG impacts of the two simulations.

[**Eq. 11**] $Net\ Annual\ GHG\ Impact_{C\ y} = DebrisCombust_{C\ b\ y} - DebrisDecomp_{C\ b=0\ y}$

To determine the impact of combustion in terms of GHG emissions, I calculated the mass of each carbon-based gas emitted, added N_2O and accounted for the GWP of each GHG. The combustion emissions consist of CO_2, CO, CH_4, and N_2O; however, the CBM-CFS3 only reports emissions for the first three gases and only in terms of carbon emissions (**Eq. 12**). I converted the mass of carbon emitted in the form of each gas to the mass of each specific gas by using standard atomic weights (IUPAC, 2007). The CBM-CFS3 model does not track nitrogen cycling and therefore does not report the release of N_2O to the atmosphere from combustion. I calculated the emissions of N_2O as 0.00017 times the CO_2 emissions from burning, as per the CBM-CFS3 foundation paper (Kurz et al., 2009). I subsequently converted all emissions to the common unit of CO_2-e (**Eq. 13**) based on their 100-year GWP coefficients (**Table 2**), as reported in the IPCC Fourth Assessment Report (Solomon et al., 2007). Standard convention dictates using the 100-year GWP coefficients (e.g. Sambo, 2002; Dymond and Spittlehouse, 2009; Meinshausen et al., 2009). I assumed emissions of CO quickly convert to CO_2 (Kurz et al., 2009).

[**Eq. 12**] $DebrisCombust_{C\,b\,y} = CO_{2\,C\,b\,y} + CO_{C\,b\,y} + CH_{4\,C\,b\,y}$

[**Eq. 13**] $DebrisCombust_{GHG\,b\,y} = CO_{2\,GHG\,b\,y} + CO_{GHG\,b\,y} + CH_{4\,GHG\,b\,y} + N_2O_{GHG\,b\,y}$

I similarly converted the decomposition emissions of **Eq. 11** into units CO_2-e in order to express **Eq. 11** in terms of GHG emissions (**Eq. 14**). The

$DebrisCombust_{GHG}$ and $DebrisDecomp_{GHG}$ elements are key prerequisites to the determination of the permanent and temporary components of the net impact.

[**Eq. 14**]

$$Net\ Annual\ GHG\ Impact_{GHG\ y}=DebrisCombust_{GHG\ b\ y}-DebrisDecomp_{GHG\ b=0\ y}$$

As described earlier, when a single year of burning is performed, the carbon emissions that would eventually be released through decomposition of that debris should it be left unburned is equivalent to the carbon emissions released through its burning (i.e. when GWP and N_2O are not considered; **Eq. 15**). These two values are equivalent based on the underlying assumption embedded in the CBM-CFS3 model that eventually (maybe centuries or millennia) the carbon not released through burning will be released to the atmosphere via decomposition and slow soil processes. However, in every year, some of the debris that would have been combusted in the burning simulation actually decomposes (i.e. $DebrisDecomp_C$, **Eq. 10**). In **Eq. 16**, I define a delayed component of the eventual carbon emissions ($DebrisDecompDelayed_C$) as the difference between the decomposition emissions that will eventually result from the debris not burned in a particular year and those that actually occur in that year. However, although I attribute this delayed component to a particular year for accounting purposes, its determination is influenced by previous years because the decomposition emissions occurring in a particular year reflect one year’s worth of decomposition for the unburned debris (that would have been combusted in the burning simulation) from that year and previous years, whereas the eventual carbon emissions are based solely on that year’s unburned debris. That is, in terms of decomposition emissions, this annual metric reflects what actually occurs in a particular year (though affected by actions in previous years), rather than just decomposition that is associated with that year’s burning/avoided burning. Ultimately, the cumulative impacts, which are derived from the summation of these annual measures, are a more meaningful measure of the GHG impacts of burning over time than the GHG impacts attributed to a particular year. In order to compare decomposition to combustion, I converted the carbon emissions in **Eq. 16** to GHG emissions (**Eq. 17**), as described earlier.

[**Eq. 15**] $DebrisDecompEventual_{C\ b=0\ y} = DebrisCombust_{C\ b\ y}$

[**Eq. 16**] $DebrisDecompDelayed_{C\ b=0\ y} = DebrisDecompEventual_{C\ b=0\ y} - DebrisDecomp_{C\ b=0\ y}$

DebrisDecompDelayed	Emissions from decomposition of unburned debris that have not yet occurred but will eventually

[**Eq. 17**] $DebrisDecompDelayed_{GHG\ b=0\ y} = DebrisDecompEventual_{GHG\ b=0\ y} - DebrisDecomp_{GHG\ b=0\ y}$

Eqs. 14-**17** represent the critical components I used to calculate the permanent and temporary components of the net annual GHG impact of burning debris relative to leaving it to decompose. I defined the permanent GHG impact of burning as the difference between the GHG impact of the combustion of the unburned debris and the eventual GHG impact of the decomposition of that same debris (**Eq. 18**). I defined the temporary impact of burning as the delayed decomposition emissions or the difference between the total GHG emissions that will eventually result from the decomposition of the unburned debris and the GHG emissions from the unburned debris that has decomposed thus far (**Eq. 19**). As a check, **Eq. 20** confirms that the net annual GHG impact is the sum of the permanent and temporary GHG components of that impact, as determined using **Eqs**. **14**, **18** and **19**.

[**Eq. 18**]

$$Permanent\ GHG\ Impact_{GHG\ y} = DebrisCombust_{GHG\ b\ y} - DebrisDecompEventual_{GHG\ b=0\ y}$$

[**Eq. 19**]

$$Temporary\ GHG\ Impact_{GHG\ y} = DebrisDecompEventual_{GHG\ b=0\ y} - DebrisDecomp_{GHG\ b=0\ y} = DebrisDecompDelayed_{GHG\ b=0\ y}$$

[**Eq. 20**]

$$\begin{aligned} Permanent\ GHG\ Impact_{GHG\ y} + Temporary\ GHG\ Impact_{GHG\ y} \\ &= \left[DebrisCombust_{GHG\ b\ y} - DebrisDecompEventual_{GHG\ b=0\ y}\right] \\ &+ \left[DebrisDecompEventual_{GHG\ b=0\ y} - DebrisDecomp_{GHG\ b=0\ y}\right] \\ &= DebrisCombust_{GHG\ b\ y} - DebrisDecomp_{GHG\ b=0\ y} \\ &= Net\ Annual\ GHG\ Impact_{GHG\ y} \end{aligned}$$

3: RESULTS

3.1 Landscape Carbon Balance of the Strathcona TSA: the THLB in Context

This research focuses on actions applied within the THLB of the TSA, yet examining only the THLB would give an inaccurate picture of the carbon balance of the entire TSA landscape. Under a business-as-usual harvesting regime, the THLB alone is a carbon source of approximately 250,000-350,000 t C/yr over the period 2008-2023, decreasing to approximately 200,000-250,000 t C/yr over 2023-2050, but the THLB only accounts for approximately 46% of the total area of the TSA (**Figure 3**). The non-THLB portion of the TSA, accounting for the other 54% of the total TSA area, functions as a carbon sink that increases from approximately 125,000 t C/yr in 2008 to approximately 200,000 t C/yr by 2040. Thus, combining both the THLB and non-THLB source/sink factors, the entire TSA is a carbon source of approximately 150,000 t C/yr until the early 2020s, decreasing to less than 50,000 t C/yr by the early 2030s.

However, this is only a crude estimate of the carbon balance of the entire TSA as a managed ecosystem because: 1) as described earlier, I have not included natural disturbances in these analyses, and 2) I have applied the highly simplifying assumption used by the UNFCCC for accounting for harvested wood products (HWP) (IPCC, 2003). This assumption presumes that any harvested carbon transferred into HWP pools as new forest products is merely replacing an equivalent amount of carbon that older forest products reaching the end of their lives (e.g. decomposing or being combusted) are releasing from HWP pools, resulting in zero net change to HWP pools. If the inputs to HWP pools from forest harvesting are equivalent to the outputs from HWP pools to the atmosphere, then an accounting short cut is to represent harvested carbon as an immediate transfer to the atmosphere. This assumption thus conveniently avoids the necessity of tracking carbon within HWP pools. However, reality is rarely so simple and frequently the amount of carbon that new forest products are adding to the HWP pools actually exceeds the amount of carbon that products at the end of their lives are releasing from those pools, therefore violating this assumption (Apps et al., 1999; C. Dymond, pers. comm.). In the present case, approximately 40% of the harvested carbon likely represents an actual net increase in the total carbon that is stored in this long-term storage pool (i.e. after 100 years, the carbon will still be stored in products or landfills) (Dymond, *in prep*). **Figure 3** may therefore overestimate the degree to which the TSA is a carbon source and the TSA could be much closer to being carbon neutral, if not over the entire study period then perhaps during the latter half.

Accounting for the fate of carbon in harvested wood products would require analyses beyond the scope of this project. Such analyses require further modelling with assumptions about the lifespan of short- and long-term forest products and their end-of-life fate (e.g. aerobic decomposition, anaerobic decomposition in landfills and combustion all have very different GHG implications). My research explicitly focuses only on the effects of the particular management action of slash pile burning applied within the THLB portion of the TSA. However, examining the THLB and non-THLB components of the landscape carbon balance (i.e. **Figure 3**) does suggest that processes within the non-THLB make important contributions to achieving landscape objectives, such as achieving carbon neutrality across the entire managed forest landscape of the TSA. Given that I have not considered harvested wood products or natural disturbances that may result in loss of carbon from stored pools, these estimates of the landscape carbon balance of the entire TSA are unlikely to be quantitatively accurate, but the conclusions about the relative roles of the THLB and non-THLB portions of the landscape as sources or sinks are likely to be robust.

3.2 Forest Harvesting Schedule

The common harvesting schedule that I developed for all the scenario simulations starts with an initial AAC of approximately 1.2 million cubic metres (**Figure 4A**). In 2013, the annual harvest is reduced to approximately 1.0 million cubic metres and then further reduced in 2023 to its midterm level of approximately 0.8 million cubic metres. For 2012, the actual harvest volume that I simulated is substantially less than the target harvest level (i.e. used to guide construction of the schedule). This discrepancy is a product of the exceptional size of the next eligible forest polygon to be harvested and the rules used to select stands for harvesting, as described earlier. Harvesting the next stand in 2012 would have exceeded the annual target, though leaving it for the following year results in the 2012 volume being substantially less than the target.

Effectively this means that the reduction in annual harvest from 1.2 to 1.0 million cubic metres occurs one year earlier than I intended. In the harvesting schedule used, the proportion of the total annual harvested volume that is from old-growth stands is approximately 70% in 2008. Stepwise decreases occur in 2013, 2018, 2023, 2028, and 2038, reducing the old-growth percentage of the total harvested volume to 52%, 38%, 22%, 8%, and 4%, respectively.

Over the first few years approximately 1800 ha/yr are harvested (**Figure 4B**). There are large decreases in the area harvested corresponding with the large reductions in the overall volume of harvest. Medium-term levels fluctuate within 1100-1250ha/yr for almost 20 years before increasing to 1250-1500ha/yr. The increase in the area harvested observed in the last 10 years is attributable to a decline in the density of the stands being harvested; neither the overall harvest volume nor the proportional split between old-growth and second-growth changes in the last decade of the study period. The area harvested in 2050 is exceptionally high relative to the preceding decade as well as the following decade (not shown), which otherwise demonstrate a relatively consistent range. This anomalous value in the final study year is an artefact of the methodology by which I produced the forest harvesting schedule – it represents an outlier, but not the start of an upward trend. In the CBM-CFS3, the merchantable biomass transferred to the forest products pool represents the amount harvested in terms of tons of carbon. The initial harvest is approximately 300,000 t C/yr (**Figure 4C**). The amount harvested decreases to approximately 250,000 t C/yr by 2013 and to its medium-term range of roughly 200,000-225,000 t C/yr by 2023.

3.3 Burning Scenarios

Each burning scenario specifies a proportion of the total area harvested to which the approach of clearcut harvesting then burning of all debris piles will be applied, stratified by old- and second-growth. **Figure 5** illustrates the actual area of this treatment under each scenario. The remainder of the area harvested each year will also be clearcut but with no debris burning. Under the moderate burning scenario, for example, approximately 100 ha of the total area harvested per year are subject to the burning of debris following harvest. This value varies within a relatively consistent range until about 2040 when it begins to increase gradually, corresponding directly with the increase in total harvested area (i.e. **Figure 4B**). Even though the total annual area harvested decreases substantially over the first two decades, the same trend is not evident in the area treated with debris burning because of the increase in the area of second-growth forest that is harvested (which is subject to a higher proportion of burning). The two opposing factors appear to roughly balance each other. By the second half of the study period almost none of the area subject to burning occurs in old-growth stands, corresponding with the reduction of old-growth harvest to less than a tenth of the total harvest volume (**Figure 6**). The area of second-growth subject to burning continues to increase throughout the period of study.

3.4 Annual GHG Impacts (2008-2050)

The permanent component of the net annual GHG impact of burning post-harvest debris piles, relative to the baseline of zero burning, is shown for each scenario in **Figure 7A**. The permanent component is the impact attributable to the difference in CO_2-e between carbon released as multiple GHGs via combustion and the same quantity of carbon eventually released solely in the form of CO_2 via decomposition. The permanent component is directly proportional to the total GHG emissions from burning, though much smaller because non-CO_2 GHGs comprise only a small fraction of the total emissions from burning.

I show the temporary component of the net annual impact for each scenario, relative to the baseline of zero burning, in **Figure 7B**. The temporary component arises from the difference between the immediate release of carbon through burning and the slow release of carbon through decomposition. For each year, I calculated the annual impact based on the combustion and decomposition that occur in that year. However, the activities of previous years influence this annual measure because the decomposition that actually occurs in a particular year includes decomposition of both unburned debris from burning avoided in that year and unburned debris that remains from the burning avoided in previous years.

For any particular year of slash burning, the difference between the immediate and delayed release of carbon will be greatest immediately after burning. Over time, as the unburned material slowly decomposes, the magnitude of the temporary component of the total GHG impact decreases. However, **Figure 7B** represents the aggregate effect of multiple burning events over time, where each individual year of burning follows burning conducted in the previous year as well. For example, the temporary component of the impact specific to the burning applied in 2008 would decrease over time, as described above, but a similar signal that begins in 2009 and another one in each subsequent year confound this signal. However, the basic trend in which the magnitude of the temporary impact is largest initially and decreases over time is still evident in **Figure 7B**.

The net annual impact of each burning scenario represents the difference between the total annual GHG impact of a particular burning scenario and the total annual GHG impact of the baseline simulation with zero burning (**Figure 7C**). The net annual impact is also the sum of the permanent and temporary components in each year. In all scenarios, the annual impact of burning is largest initially, decreasing over the first two decades then stabilizing within a relatively consistent range over the latter two decades. The two substantial decreases in 2012 and 2023 coincide with the two large reductions in the overall harvest allowance.

The trend and patterns observed in the net annual GHG impact are predominantly influenced by the temporary component, which comprises the majority of the total impact (**Figure 7**). However, whereas the temporary component decreases over the period studied, the permanent component remains relatively constant and therefore makes up an increasing proportion of the total, rising from approximately one tenth initially to one quarter of the annual GHG impact by the 2040s. But this proportion is not explored in further detail because the results could not be meaningfully isolated to the events of a specific year.

For example, in Year 1, the temporary impact is the difference between the large immediate release of carbon through combustion (burning scenario) and the very small release of carbon through the decomposition of some of the unburned material (zero burning baseline). However, for a particular year within the study period, the zero burning baseline will have higher levels of carbon being released through decomposition due to the accumulation over previous years of unburned debris, all slowly decomposing. Therefore, the temporary component of the annual impact in Year X (**Figure 7**) reflects the portion of the total impact in that year that is inherently temporary, but it does not indicate how much of that is directly attributable to the actions of that particular year. However, the permanent component in Year X is directly attributable to the actions in that year because the release of carbon as non-CO_2 gases instead of CO_2 occurs only at the time of burning and does not have a time-delayed aspect.

During the last decade of the management period (2040-2050), the action of having burned debris since 2008 produces an additional annual GHG source of 4,690 t CO_2-e/yr, 7,035 t CO_2-e/yr, 9,380 t CO_2-e/yr, or 14,070 t CO_2-e/yr, for low, moderate, high, or very high burning scenarios, respectively. These values reflect the GHG emissions from combustion that are incremental to the emissions that would have otherwise occurred from the decomposition of the combusted debris. I report the average for 2040-2050 because 2050 itself is an anomalous year in the study, as described earlier. In each scenario, the temporary component comprises 76% of this average increase in the annual carbon source and the permanent component contributes the remaining 24%.

3.5 Cumulative GHG Impacts (2008-2050)

The permanent and temporary components of the cumulative GHG impact of burning post-harvest debris piles, relative to the zero burning baseline, are shown for each scenario in **Figure 8A, B**. The permanent component increases over the entire study period, which is a predictable effect of an annual permanent impact. However, the temporary component also continues to increase over the entire study period despite being inherently impermanent. As with the total annual carbon flux, the net cumulative GHG impact is dominated by the temporary component, which comprises the majority of the total impact (**Figure 8**). However, whereas the permanent component of the cumulative impact increases at a relatively constant rate over the period studied, the temporary component increases at a decreasing rate. Consequently, the proportional division between the temporary and permanent components of the cumulative impact changes over the study period. In 2008, the permanent component only comprises approximately 9% of the cumulative net GHG impact, but this increases to approximately 18% by 2050. The rate at which the cumulative impact changes over time reflects the annual impacts previously examined.

By 2050, the cumulative GHG impact of slash burning since 2008, relative to the zero burning baseline, is a carbon source of 248,211 t CO_2-e, 372,327 t CO_2-e, 496,421 t CO_2-e, or 744,629 t CO_2-e, for low, moderate, high, or very high burning scenarios, respectively (**Table 4**). The permanent component of these totals is 44,676 t CO_2-e, 67,018 t CO_2-e, 89,351 t CO_2-e, or 134,027 t CO_2-e, respectively. The temporary component of these totals is 203,536 t CO_2-e, 305,309 t CO_2-e, 407,070 t CO_2-e, or 610,602 t CO_2-e, respectively. The temporary component reflects the temporary storage of carbon in unburned material that has accumulated in the zero burning baseline relative to the burning scenario. This unburned debris is slowly releasing its carbon through decomposition. However, the longevity of this temporary impact spans a broad spectrum.

3.6 Long-run Impacts (2008-2250)

I ran simulations over a longer time frame (2008-2250) to explore the rate at which the cumulative temporary impacts of the 43 years (2008-2050) of slash burning examined above would slowly expire as the residual unburned slash in the zero burning baseline slowly decomposed. Put simply, the motivating question is, “how temporary are these ‘temporary’ impacts?” In the long-run simulations, all harvesting and burning activities cease after 2050 in all scenarios. From 2051 onwards, all scenarios experience identical disturbances and processes. Any differences are thus attributable to the differences in the levels of burning applied to each scenario during the 2008-2050 study period.

The cumulative temporary impact from burning applied during 2008-2050 decays slowly over the subsequent 200 years (2050-2250) (**Figure 9**). The cumulative temporary GHG impact is at its maximum in 2050 and then begins to decrease immediately once all harvesting and burning activity has stopped after 2050. After 2050, the cumulative temporary GHG impact decreases quickly but at a decreasing rate. By 2100 (50 years after the initial study period and the conclusion of all forest management activities), 37% of the cumulative temporary impact that existed in 2050 still remains (the same value applies to all scenarios). By 2150, a century after the initial study period, 23% of the cumulative temporary impact in 2050 remains. By 2250, approximately 12% of the impact in 2050 still exists and the rate of decrease is very slow. However, these data do not indicate how long it will take the temporary GHG impact to completely expire (i.e. return to zero, once the DOM and soil pools have finally released all of the carbon from the original unburned debris associated with the avoided burning). However, it does appear from additional, rough calculations that it would take many centuries for this to occur.

Separating the long-run results for the high burning scenario shown in **Figure 9** into individual pools illustrates how each of the DOM and soil pools contributes to the aggregate temporary impact (**Figure 10**). I only show DOM and soil pools because the live biomass pools are identical for all the scenarios. Comparing DOM and soil pools between the burning scenarios and the zero burning baseline reveals the cumulative amount of carbon in each DOM and soil pool that has been lost from the landscape as a result of burning. However, it is also possible to conceive these relative differences within each DOM or soil pool as effectively showing the amount of carbon that has “accumulated” in the zero burning baseline (relative to burning) and how this carbon is released over time as the debris inevitably decomposes. Although it reverses the convention used throughout the rest of this study, I use this second perspective for these data because its interpretation is much more intuitive.

Carbon increases in all the DOM and soil pools relative to the burning scenario from 2008-2050 (i.e. **Figure 10**). However, the carbon accumulated in unburned material in the “aboveground very fast” (litter), “aboveground fast” (branches, tops, other), and “medium” (coarse woody debris) pools begins to decrease immediately once harvesting and burning are stopped after 2050. The varying rates at which carbon decreases in each of these pools reflect the differences in the decomposition rate for the type of material associated with each pool. Decomposition of litter occurs relatively quickly and thus all the carbon accumulated by 2050 in the aboveground very fast pool is released within 41 years. Decomposition of coarse woody debris occurs relatively slowly and thus it takes 200 years for almost all (>99%) of the carbon accumulated by 2050 in the medium pool to be released. Carbon in the aboveground slow pool actually continues to increase after 2050 for 10 more years before beginning to decrease, albeit at an even slower rate than for the medium pool. Carbon continues to increase in the mineral soil pool for such an extended period (>100 years) that it does not at first appear to be responding at all to the 43 years of burning and the sudden halt after 2050. I have not presented the very fast belowground and fast belowground pools because their values are identical for all the scenarios and therefore the relative differences are zero.

Understanding the patterns observed in the aboveground slow and belowground slow pools requires a closer look at the structure of the CBM-CFS3 model, which specifies how carbon moves among pools. In the CBM-CFS3, carbon released from the aboveground very fast, aboveground fast, and medium pools is only partially released to the atmosphere (**Figure 11**). A portion of the carbon from these pools is actually transferred to the aboveground slow pool, which is then transferred very slowly to the soil pool where it will eventually be released to the atmosphere at an extremely slow rate. Kurz et al. (2009) report the transfer rates and proportions of carbon released to the atmosphere that the CBM-CFS3 applies.

The belowground slow pool continues to accumulate carbon over a long period of time (i.e. **Figure 10**), long after the period of harvesting and burning activity has stopped. This occurs because it slowly accumulates the portion of carbon from all of the more quickly decomposing pools not directly released back to the atmosphere. The belowground slow pool then releases this carbon only very slowly. The temporary component of the GHG impact of slash burning is truly temporary – all of the carbon in unburned debris that may have otherwise been released to the atmosphere immediately if burned will still ultimately be released to the atmosphere either way. However, this final equalization will only occur on a time scale of many centuries. The precise duration has not been simulated but calculations based on the magnitude of the belowground slow pool in 2250 and the decay rate specified in the CBM-CFS3 suggest that it would take many centuries for this accumulated carbon to be completely returned to the atmosphere (not shown). The permanent component of the cumulative GHG impact for each burning scenario neither increases nor decreases after 2050 – the cumulative permanent impact in 2250 is the same as it was in 2050 (not shown).

3.7 Sensitivity Analyses

I performed further simulations in order to determine how sensitive the primary results are to the potential reduction of plantable space by unburned debris piles, which could reduce and/or delay regeneration (and therefore carbon sequestration) on a portion of the harvested stand. Although it appears that this impact is not an issue on this particular landscape, I still tested it because it is a potentially confounding factor in principle and an important factor in other landscapes (e.g. Luke et al., 1993). The results up to 2050 for the cumulative temporary GHG impact are relatively insensitive to the levels of regeneration delay tested (**Figure 12**). The permanent impacts (not shown) remain unchanged because the same amount of debris is burned in either case. Over a 43-year study period, a 50-year delay is effectively the same as a permanent delay, but even then, the difference in the cumulative GHG impact at 2050 between the 30 year and 50 year effects is negligible. The alternate scenarios tested show relatively minor absolute effects and no change to the overall pattern observed. A partial regeneration delay of 50 years on 2% of the harvested area subject to burning in the moderate burning scenario (i.e. the maximum effect tested) reduces the cumulative net GHG impact in 2050 by approximately 26,000 tons CO_2-e. By comparison, changing the overall level of burning from the moderate burning scenario to the low burning scenario reduces the cumulative net GHG impact in 2050 by approximately 124,000 tons CO_2-e.

4: DISCUSSION

Burning post-harvest debris piles in the Strathcona TSA during 2008-2050 is a net source of GHG emissions to the atmosphere for all four burning scenarios simulated, both in absolute terms and relative to the baseline simulation in which zero burning occurs. The annual GHG impact of both the permanent and temporary components are both net GHG sources in each year of the study period of 2008-2050 and therefore the cumulative impact of each component increases over the entire study period. The cumulative temporary impacts of burning during 2008-2050 slowly decline post-2050, albeit over decades to centuries. In 2050, the cumulative GHG impact of the low, medium, high, and very high burning scenarios (relative to zero burning) are 248,211 t CO_2-e, 372,327 t CO_2-e, 496,421 t CO_2-e, and 744,629 t CO_2-e, respectively.

For each scenario, the permanent component comprises 18% of the cumulative GHG impact in 2050. However, approximately 19% of the total net GHG impact is comprised of impacts that, although inherently temporary, will persist at least 100 years after 2050. But because this measure is based on 100 years since the end of the management period, not 100 years since each burning event, the value of 19% underestimates the portion of temporary impacts that would actually be deemed “permanent” according to current regulations in BC (Government of British Columbia, 2008b).

4.1 Temporary GHG Impacts

4.1.1 Distinguishing Temporary and Permanent Impacts

This research illustrates two important and independent components of the total net GHG benefits that are realized from avoided slash burning. First, the delayed release of carbon, which is a temporary benefit because eventually the same amount of carbon will be released via decomposition as would have been released immediately through combustion. Second, the avoidance of releasing more powerful GHGs than CO_2, which is a permanent benefit because once carbon is released to the atmosphere as CO_2 the same carbon cannot be released again in another form. These temporary and permanent impacts both need to be accounted for in order to effectively assess of the overall GHG impacts of avoided slash burning or other potential mitigation actions. Some authors suggest that temporary carbon storage contributes no value towards climate mitigation efforts (e.g. Kirschbaum 2003, 2006), whereas others argue that temporary measures can provide a valuable contribution (e.g. Chomitz 1998; Dornburg and Marland 2008; Marland et al. 2001), but there is agreement that temporary and permanent impacts are unequivocally different. As my research demonstrates, treating them as equal would overestimate the overall impact of a particular action but discounting the temporary component entirely would clearly underestimate the impact over the timeframe of interest. If society is concerned with accurately assessing its potential climate mitigation success over different time frames, then both permanent and temporary impacts must be appropriately considered.

4.1.2 Key Characteristics of the Temporary Impact

The slow rate of decay for unburned debris produces two patterns observed in the temporary impact. First, the aggregate temporary storage of carbon actually increases over time when the act of avoiding burning occurs repeatedly over time and space. Avoiding burning over many years “adds” temporary carbon storage, relative to burning having occurred, to the system at a greater rate than the decay of existing temporary carbon storage from previous years of avoided burning. This pattern drives the important yet somewhat unintuitive result that the cumulative “temporary” impact of burning actually increases over the entire management period. By 2050, four decades of avoided burning for the moderate burning scenario result in an accumulation of 305,000 t CO_2-e of temporary sequestration. For the same scenario, the permanent benefit is only 67,000 t CO_2-e of non-CO_2 GHG emissions avoided by 2050. The aggregate effect on the entire landscape of avoided burning applied over many subsequent years is distinctly different from the pattern that one would observe from a single application of this treatment, where the large initial benefit of avoiding the release of GHGs will begin to decrease immediately as the unburned debris decomposes.

Second, not only has the cumulative amount of “temporary” sequestration increased by 2050, but a significant proportion of that temporary storage will also remain sequestered for many decades and even centuries. Approximately one quarter of the temporary impact (comprising 19% of the total impact) persists past 2150, 100 years after the end of the simulated management period. Of this one quarter of the temporary impact that lasts beyond 2150, approximately half persists for at least an additional 100 years. The threshold beyond which temporary carbon storage should be considered effectively permanent is a subject of considerable debate (e.g. Dutschke, 2003; Herzog et al., 2003; Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008) that will not be resolved here. Nevertheless, this portion of “temporary” carbon sequestration that lasts for greater than 200 years after the 43 years of this management action should surely be considered as effectively permanent relative to the timescales of primary interest today. This long-lived storage reflects carbon that has eventually transferred into the soil carbon pool, which has a very slow decay rate.

4.1.3 Distinguishing among Different Types of Temporary Impacts

The results presented above demonstrate that the timescale over which the temporary components of the total GHG impact exist varies greatly. In society’s assessment of the contribution of its activities to climate change, the difference between a temporary impact that expires within a few decades and one that may last centuries is an extremely relevant distinction. Given the timelines suggested as important to avoid dangerous climate change and the idea that the latter half of this century may see new advanced technologies and significant societal changes (e.g. Pacala and Socolow, 2004), there must be some temporal threshold beyond which “temporary” impacts could be considered effectively permanent with respect to our current concerns. Although one should be concerned about giving temporary and permanent impacts equal weight, the results of the my research show that completely excluding the temporary component from further consideration substantially underestimates the GHG impact of slash burning, and conversely, the mitigation potential of avoiding it. For these reasons, it seems prudent to further distinguish different “types” of temporary impact based on their anticipated life span.

For the purposes of subdividing the temporary component into more duration-specific classifications, I chose to use 100 and 200 years after the initial study period as convenient but still informative thresholds. The BC Emission Offset Regulation states that for the purposes of quantifying potential carbon offsets, any impact that lasts longer than 100 years is considered a permanent impact (Government of British Columbia, 2008b). However, the 100-year threshold used here is not an accurate representation of this criterion because it represents 100 years after the end of the study period rather than 100 years after each incidence of burning. The present implementation therefore underestimates the proportion of the impact that the regulation would actually deem to be “permanent”. The 200 year threshold is arbitrary but represents a point where 98% of the remaining temporary impact is due to the accumulation (relative to burning) of carbon in the slowly decaying DOM and soil pools, which will only release their carbon to the atmosphere over many centuries. Using these thresholds, I divide the temporary component into three subcomponents: 1) the “decadal temporary” impact that will persist from years to many decades, but less than a century; 2) the “centennial temporary” impact that will persist for at least a century but no longer than two centuries; and, 3) the “multi-centennial temporary” impact that will persist for greater than two centuries. In this study, I measure these durations from the end of the management period rather than from the year of each activity.

I show the relative contribution of each of these classes of temporary impact to the cumulative GHG impact in 2050 of slash burning from 2008 to 2050 in **Figure 13**. The graph shows that even though the decadal temporary subcomponent constitutes the majority of the cumulative temporary GHG impact in 2050, the centennial temporary and multi-centennial temporary subcomponents still represent a substantial contribution, especially relative to the magnitude of the permanent component. **Figure 14** represents the proportional contributions of the permanent component and the three temporary subcomponents to the cumulative net GHG impact in 2050. This chart illustrates that the combined impact of the centennial temporary and multi-centennial temporary subcomponents is approximately equal to the permanent component. In this particular case, this means that if one were to count any "temporary" impact that will last more than 100 years as equivalent to the permanent impact, then the reported impact of burning would effectively be double the amount reported when excluding all temporary impacts entirely. However, the specific proportions of the total temporary impact that fall within each class are sensitive to the temporal definition of each subcomponent, which may be arbitrary.

Although arbitrary, the thresholds applied illustrate the effect of distinguishing different "types" of temporary impacts that explicitly account for the actual duration of the impacts being considered. This seems particularly important when “temporary” impacts can range from years to centuries. Alternate thresholds may be equally valid and ultimately policy makers must decide upon definitive rules about what does and does not count as permanent. The present results simply show that temporary impacts exist across a spectrum – there are no definitive boundaries between short-term and long-term temporary impacts.

4.1.4 The Relevance of Temporary Impacts that are Effectively Permanent

This project demonstrates the need to distinguish among “temporary” carbon impacts of differing longevity. Temporary impacts exist over a very large spectrum and should not all be treated equally – long-term temporary impacts deserve consideration as a type of impact distinctly different from short-term temporary impacts. My research shows that the cumulative temporary benefit of avoided burning that contributes to targets in 2050 is approximately 4.6 times the size of the contribution of the permanent component of the total impact. Even by 2100, fifty years after the simulated management period, the temporary impact remaining is still slightly larger than the cumulative permanent impact.

Acknowledging this pattern means that the GHG benefit of avoided slash burning is actually much larger than would be indicated by an analysis that ignored temporary impacts. Although I do not explore alternative treatments or other potential uses of unburned slash, this observation indicates that removing unburned slash for other purposes (e.g. biomass fuel, mulch) would have a GHG cost that would not be accounted for in an assessment that discounted all temporary impacts. To treat this unburned biomass as short-lived sequestration assumed to fully release its carbon within years would be erroneous; some of the temporarily stored carbon will endure many decades to centuries. Any activity that removed this unburned biomass would be removing some carbon storage that was effectively permanent. It is therefore critical that any proposal to remove unburned slash from the landscape includes these “temporary” impacts in their life cycle analysis of GHG impacts, especially if the biomass is being removed for bio-energy, where demonstrating quantifiable GHG benefits is commonly a major component of its justification. This research shows that any superficial assessment that simply assumes that debris is carbon-neutral because the carbon will eventually be released to the atmosphere through decomposition should really ask the question, “carbon-neutral, but over what time scale?”

4.1.5 Potential Benefits of Short-term Temporary Impacts

Even the short-term temporary impacts may be beneficial to mitigation efforts, based on the premise that there is benefit even in merely postponing emissions. As described above, I classified short-term temporary impacts that persist less than 100 years as decadal temporary impacts. Some of potential benefits of temporary carbon sequestration or delayed GHG emissions include (Chomitz, 1998; Marland et al., 2001; Dutschke, 2003; Dornburg and Marland, 2008):

1. it postpones climate change;
2. adaptation within biotic systems may be improved with slower increases in temperature;
3. temporary mitigation may partially offset any initial warming pulse;
4. slowing the increase in damage lowers the present value of the costs of climate change;
5. delayed release of temporarily sequestered CO_2 will produce lower marginal damages;

6. it buys time for additional learning;
7. it buys time for technological progress;
8. it buys time for capital turnover;
9. abatement costs will be lower in the future;
10. it saves money for larger investments;
11. the aggregate effect of many temporary projects may be a net benefit over time;
12. some temporary sinks may actually turn out to be permanent; and,
13. a lower emissions path today helps preserve a wider range of future options.

If major, global action towards emissions mitigation is delayed by too long then the likelihood increases that there will be interim peaks in atmospheric CO_2 and global mean temperature that would exceed critical thresholds of Earth systems, even though aggressive mitigation might still be able to achieve long-term stabilization targets (Vaughan et al., 2009). Depending on the delay period and subsequent rate of mitigation, this “transient peak” could occur as early as 2100 (Vaughan et al., 2009). Mitigation actions that reduce emissions or increase sequestration over this period may therefore be beneficial even if these effects are not ultimately permanent. The short term or decadal temporary impacts of avoided slash burning over subsequent years are immediate and the cumulative impact increases over the four-decade study period to a relatively substantial level by 2050 (for a small, regional-scale action). By 2100, roughly a fifth of the cumulative decadal temporary impact in 2050 that will be gone by 2150 (the 100 year threshold) still exists. Hypothetically, if aggregated across a multitude of other actions with similar characteristics, this type of impact might be able to contribute to a temporary stopgap measure to reduce the magnitude of any interim overshoot resulting from the delay of larger, permanent mitigation strategies needed ultimately achieve the long-term stabilization goals.

Although inherently short-lived, a portion of the decadal temporary impacts of avoided burning will at least last beyond the next likely harvest on the same land (i.e. past a rotation age of between 50-100 years). When we harvest these stands again, debris pile burning may continue to be the status quo practice (i.e. in the absence of mitigation initiatives). If so, this strategy of avoiding burning could add new decadal temporary benefits to the residual decadal temporary benefits of the previous rotation. However, estimating this effect would require modelling over multiple rotations that is beyond the scope of this project. I also did not attempt to quantify the actual benefit that the decadal temporary impacts of avoided burning might have toward climate mitigation, though such analyses appear to be worthy of further investigation. There may be conditions in which even relatively short-lived carbon sequestration or emissions reductions might actually make a positive contribution to a mitigation portfolio, although such actions should not divert resources from larger, permanent mitigation efforts.

4.2 Sensitivities and Secondary Effects

4.2.1 Sensitivity to Critical Indirect Effects

To determine comprehensively the full GHG implications of any particular management action, potential changes to all carbon stocks and flows must be included, whether they are direct or indirect consequences of the activity of interest. Of the two, the direct consequences should be more easily identifiable. The indirect component may be much more complex because it may include carbon stocks and flows of processes that might superficially appear to be entirely natural processes. The underlying principle is that an assessment framework should account for the full impacts of an intentional management action but not for any truly unavoidable acts of nature. It is therefore critical to distinguish between truly natural processes and processes that have been modified in some indirect manner by the management action itself.

Hurteau and others provide a detailed example of this failure to recognize how the indirect effects of management may modify an otherwise natural risk profile (Hurteau et al., 2008; Hurteau and North, 2009; Wiedinmyer and Hurteau, 2010). They analyse forest management practices in the dry, fire-prone forests of the western United States. The simulations of Hurteau and others show that the practice of thinning for fuel reduction would have actually decreased the scale and severity of past wildfires and thus their corresponding GHG emissions. From the perspective of maximizing carbon storage or minimizing carbon emissions over time, it is likely thinning treatments are better than allowing fuels to accumulate in highly fire-prone areas (Daigle and Dymond, 2010). What have not yet been quantified in the scientific literature are the GHG consequences of the amount of area and frequency of repeated fuel treatments required given our limited knowledge of the future (C. Dymond, pers. comm.).

As described by Hurteau et al. (2008), the California Climate Action Registry Forest Sector Protocol considers thinning operations for the purpose of fuel treatment as a reduction in carbon storage in the forest relative to the baseline; however, if accumulated fuel results in a large wildfire with a large release of carbon to the atmosphere, this protocol simply considers the fire as an unavoidable act of nature and a new baseline is set for evaluating future management actions. Managers therefore have a disincentive (from a GHG perspective) to conduct such fuel treatments despite the likely GHG benefits of doing so. For this particular legislation, the incentives do not align with the desired outcomes because the framework fails to make the connection between intentional management actions (i.e. thinning) and their potential effect on natural processes or disturbances (i.e. fire risk).

In the previous example, the direct management intervention (i.e. thinning as a fuels treatment) is beneficial in the previous example, but in other cases, the intervention of interest might ultimately have a detrimental effect (e.g. fire suppression). Furthermore, even the specific relationship observed in these studies may not necessarily apply elsewhere. For example, research in the US Pacific Northwest found that where thinning was applied to forests in the west Cascades and Coast Range ecosystems, carbon storage over time was less than when thinning was not applied (Mitchell et al., 2009). However, the critical concept is that direct management interventions can indirectly modify on-going natural processes, and the analytical framework used for assessing the GHG impacts of management actions should incorporate these dynamics.

This concept manifests itself in my research insofar as leaving unburned slash may alter the dynamics of future growth or fire risk. The natural regeneration of a stand (or natural growth following planting) and the risk of natural wildfires cannot simply be excluded from the analysis as “natural” processes if their attributes have been indirectly modified by the increased presence of unburned debris piles on the landscape, which is the direct physical effect of the management action. These consequences should be considered in addition to the direct GHG impacts of avoided burning (i.e. the delayed release of carbon and the avoidance of CH_4 and N_2O).

In this project, I have acknowledged these potential indirect effects but I have only examined the impact on regeneration quantitatively. It appears that the potential regeneration consequences of leaving unburned debris piles are insignificant in this particular study area. However, I have only addressed the potential impact of avoided burning on future fire risk qualitatively in this project. This omission means that this assessment of the GHG implications of the avoided burning of debris piles falls short of a comprehensive analysis of the full spectrum of potential impacts over time. However, although a mix of natural disturbance regimes exist over the landscape, the fire risk across the study region is generally low (e.g. Wong et al., 2004). Although much of the landscape has a very low incidence of fire, a substantial Douglas-fir component in any particular stand provides evidence of a fire history, even if only low frequency (K. Lertzman, pers. comm.). Because the study landscape as a whole has a relatively low incidence of fire (e.g. Wong et al., 2004), I do not expect the implications of the exclusion I describe above to be critical, nor should they affect the key patterns I have reported concerning permanent and temporary GHG impacts. In Alberta, drier conditions and more frequent lightning-initiated fires make residual slash a more substantial fire hazard than for coastal BC; however, the number of fires involving slash in Alberta decreased over the past several decades and the area burned due to slash fires decreased markedly in the 1990s, despite increases in total wildfires (Baxter, 2002).

4.2.2 Secondary Effects of Burning of Post-harvest Debris

Although carbon is the focus of this work, it is by no means the only objective of forest managers – it is one of many and neither replaces nor supersedes other objectives. Avoided burning may have other important consequences that I have not assessed in the current study. Retaining unburned debris offers ecological benefits (Marcot 2002; Bunnell and Houde, 2010). Reducing smoke emissions from burning provides the aesthetic and health benefits of improved air quality (Hardy et al., 2001; Sandberg et al., 2002). However, I did not explore the magnitude of these types of benefits as part of my research. The secondary costs of leaving debris piles unburned include a potential impediment to regeneration, which did not appear to be a concern in this case-study, and a potential increase in future fire hazard, which could not be assessed but is likely low in this case-study. Avoiding the burning of debris piles reduces expenses on the direct costs of burning, but the net cost would depend on the specific alternate actions taken. The role of mangers is to weigh these benefits and costs as they strive to balance a whole suite of objectives that include ecological, economic, social, and climate outcomes.

4.3 Extensions and Limitations

4.3.1 Comparison with Other Regional GHG Emissions

I compared selected results of this research to other regionally relevant GHG impacts to provide a frame of reference for assessing my results (**Table 5**). In 2050, the total cumulative GHG impact that will persist at least 100 years after the initial study period is 91,075 tons CO_2-e for the low burning scenario and 182,147 tons CO_2-e for the high burning scenario. I calculated these values as the sum of the permanent, multi-centennial temporary and centennial temporary cumulative impacts. The average GHG impact of ground-based forestry operations in western Canada is approximately 20,463 g CO_2-e per cubic metre harvested (20,418 g CO_2-e/m^3 when adjusted for updated GWP coefficients) (Sambo, 2002). Based on the cumulative harvest of 37.26 million m^3, the cumulative direct GHG impact of forestry operations within the Strathcona TSA from 2008-2050, as simulated in this study, would be approximately 761,000 t CO_2-e. The impacts of the low and high burning scenarios as described above thus represent 12% and 24% of the GHG impact of the total direct emissions from forestry operations over the same period. However, this calculation only provides a rough estimate because the GHG impact factor used applies to all of western Canada and assumes that all operations are ground-based (Sambo, 2002).

The 2007 Community Energy and Emissions Inventory reports provide a snapshot of the regional GHG budget against which to compare the present results (BC Ministry of Environment, 2010). The Comox and Strathcona Regional

Districts together cover an area very similar to the Strathcona TSA, providing an appropriate comparison. **Table 5** shows the equivalent impacts of the low and high burning scenarios, as described above, in terms of vehicles and residential energy use within the region. For example, the GHG impact of the low burning scenario is equivalent to an additional 636 small passenger cars (3.3% of the regional total) on the road from 2008-2050, or 1.9% of residential energy use over the same period. These comparisons illustrate that the cumulative impact of debris pile burning makes a non-trivial contribution to the regional GHG budget; consequently, avoiding such burning could make a noticeable contribution to a regional portfolio of strategies to mitigate climate change.

4.3.2 Potential for Avoided Burning as a Carbon Offset

A logical extension of this research would be to evaluate the potential for avoided slash burning to qualify as a carbon offset project. The focus of my research has only been to quantify the GHG impacts of slash pile burning and the mitigation potential of avoiding this activity across the landscape over time, but not to evaluate potential carbon offset credits from any individual action. However, this is a relevant issue and at first pass, it appears that projects reducing debris pile burning might satisfy some of the general criteria commonly used for assessing carbon offset projects. These criteria include confirmation that gains from the potential offset project are real and verifiable, permanent, additional, and will not be subject to leakage (Cathcart, 2000; Wayburn et al., 2007). The gains of avoiding debris pile burning can be verified through simulation modelling or field measurements. My research identifies the permanent component of the GHG impact, as well as the long-lived temporary components that regulators might consider as equivalent to permanent (e.g. Government of British Columbia, 2008b). Determining the additionality of any project to reduce debris pile burning would require a much more accurate forward-looking business-as-usual baseline, to verify that credit is truly additional and not awarded where burning would have been avoided for other reasons (i.e. changing practices, smoke reduction goals, or coarse woody debris management). Leakage over space will not be a concern because reduced debris pile burning in one area will not drive an increase in intentional burning elsewhere. However, accurately assessing both leakage over time and permanence would require explicit analysis of the extent to which additional unburned piles may increase the risk of wildfire and future GHG releases that could offset the estimated upfront gains.

4.3.3 Illustration of Broader Principles about Forests

The results from this research may also offer some insight into or confirmation of broader principles of forest ecology and forest management in general. Although a detailed exploration of this idea is beyond the current scope, a superficial examination reveals an overall pattern of particular interest. I examined the impacts of a relatively moderate operational change (burning versus not burning on a small fraction of the harvested landscape), yet these impacts persist over a very long period. In fact, a substantial portion of the impacts last beyond the expected timing of the next harvest and presumably these impacts could compound if managers maintained a similar strategy over multiple rotations. Consequently, this research demonstrates a case where there would be substantial, long lasting impacts from relatively non-intensive management activity. This overall pattern emphasizes that forest landscapes may indeed have long “memories”.

Additionally, it is important to remember that the DOM modelled in this research is not just carbon but serves many other important ecological roles, such as habitat, food, and nutrients (e.g. Harmon et al., 1986; Hagan and Grove, 1999). The focus of my work is decidedly on the carbon and GHG implications of debris pile burning, but the results simultaneously demonstrate an effect on the amount and longevity of DOM across the landscape (e.g. **Figures 9** and **10**), which is an integral component of the entire ecological system (e.g. Harmon et al., 1986; Caza, 1993; Hagan and Grove, 1999; Marcot, 2002; Bunnell and Houde, 2010). Although I have not explored such effects in this project, these observations at least suggest that the decision to perform or avoid the burning of debris piles will also have ecological consequences.

4.3.4 Comparability to Actual Levels of Slash Pile Burning

The burning scenarios used to characterize the current area to which piling and burning post-harvest debris is applied are simplistic representations of a very complex and dynamic reality. Each scenario uses rates of burning stratified only by forest age (old-/second-growth), but otherwise applied uniformly across the landscape and over time. In each year simulated, the area selected for pile burning is a cross-section of all harvested stands rather than targeting specific stands with particular attributes. In reality, the extent to which the burning of debris piles occurs is highly variable both spatially and temporally. The volume of debris piled and the proportion that will ultimately be burned will vary by stand and year based on many factors including: utilization levels (in turn influenced by species composition and age, site quality, timber quality, and current timber and pulp market conditions); proximity of cut-blocks to populations; local terrain; harvesting systems used; bucking methods employed; micro-climatic conditions; current regulations; current economic circumstances (for both markets and operators); and sometimes even the personal preferences of operators (Feller 1982; J. Andres, pers. comm.; B. McKerricher, pers. comm.; D. Tanner, pers. comm.). However, data on the precise extent of debris pile burning done were not available. Even with precise data on current levels of burning, it would still not be possible to know how the factors influencing the decision to burn will change over time. Instead, I designed the scenarios used to encompass the range of potential variation to achieve a reasonable representation of the average cumulative impact across the landscape over time rather than capture annual, stand-level variability.

4.3.5 Potential Effects of Climate Change

This research does not account for any potential effects of actual changes in climate on carbon dynamics over the study period. Researchers have already been observing significant impacts of climate change on Canada’s forests and they anticipate these impacts to be even more significant in the future (Lemprière et al., 2008; Williamson et al., 2009). Climate change may affect many different aspects of forest dynamics; however, I will only mention those impacts that may potentially influence the results of this research. The impacts of climate change on decomposition rates, wildfire risk, insect activity, and forest productivity could each potentially modify the present results by altering processes associated with additional unburned debris left on the landscape.

Temperature and moisture affect decomposition rates for woody debris, the forest floor and soil (Gholz et al., 2000). The CBM-CFS3 does not yet integrate precipitation and therefore temperature is the only climatic variable driving decay rates (Kull et al., 2007). By the end of the century, mean annual temperature is forecast to increase 2.8-3.7°C within the Pacific Forest Region (PFR), and annual precipitation is forecast to increase 65-107 mm (Lemprière et al., 2008). However, moisture availability is forecast to increase only slightly, by 0.3-0.8% (Lemprière et al., 2008). These predicted changes are based on average values modelled for 2071-2100, compare against average values for 1961-1990. If decomposition rates increase over the study period due to increasing temperature, the longevity of the temporary component of net GHG benefits could be reduced. Over the same period, the area affected by fire within the PFR is forecast to increase, with a low increase for the near term (2011-2040) and a high increase for the long term (2071-2100) (Lemprière et al., 2008). Although I did not model the impact that leaving additional unburned piles on the landscape could have on fire risk, I have discussed its importance. If the background fire risk increases substantially over the study period, then the importance of this factor and the magnitude of the potential consequences may also increase accordingly.

Within the PFR, climate change is forecast to result in a moderate increase in biotic activity in the near/medium term, with uncertain effects in the long term (Lemprière et al. 2008). However, the only situation that could potentially alter the present results is an insect (or pathogen) that is affected by changes in both climate and the quantity of dead wood available (i.e. the sole physical difference between the burning and non-burning simulations). As a hypothetical example, if an insect that benefited from these factors causes additional damage that modifies the carbon dynamics of other stands (e.g. tree mortality or reduced growth), part of that carbon cost might be attributable to the additional piles of unburned debris and therefore reduce the relative benefit of avoided slash burning over time. Increases in productivity due to climate change can only influence the current results if there are relative differences in the growing stock between burning scenarios and the non-burning baseline. However, as discussed earlier, the presence of additional unburned piles is not expected to affect the stocking of the new stand and therefore there would be no relative differences in growing stock. Regardless, average forest productivity in the PFR is not expected to change over this century, although there may be variation among individual species (Lemprière et al., 2008).

The results for 2050 are expected to have low to moderate sensitivity to climate change because of the relatively short period. The post-2050 results up to 2250 are expected to be much more sensitive to climate change. The extent of climate change over the next 250 years and its impacts on various ecological factors are extremely uncertain. Trofymow et al. (2008) suggest that the CBM-

CFS3 may be of limited use for simulating long-term time frames in the presence of climate change. However, because the present study examines relative differences between burning scenarios and a baseline simulation with no burning, the only climate change factors of immediate concern are impacts of decomposition rates, increased wildfire, and possibly some very specific types of biotic activity.

4.3.6 Applicability of Results beyond this Study

Although my research relates only to the burning of debris to remove accumulated "waste", both to prepare the site for regeneration and/or the abate the potentially increased fire risk, the intentional use of fire is also a common management tool in a wide variety of other settings. For example, some other purposes for which managers may use prescribed burning include, controlling invasive weeds (DiTomaso et al, 2006) or pathogens (Holzmueller et al., 2009), restoring and maintaining fire-dependent ecosystems (Switzer, 2011), preparing degraded ecosystems for replanting (Stanley et al., 2011), improving rangeland forage for grazing (Augustine et al., 2010), clearing forest for plantations (Simorangkir, 2007), or reducing fuel loads to mitigate the risk of high intensity wildfires (Vaillant et al., 2009), potentially with the explicit objective of reducing forest carbon emissions over time (Wiedinmyer and Hurteau, 2010). Additionally, managers have commonly used prescribed burning across BC and Canada for silvicultural purposes including site preparation, vegetation management, stand conversion, and stand rehabilitation, for the enhancement of wildlife habitat, and for the control of insects (Feller, 1982; Weber and Taylor, 1992).

The quantitative results of my research cannot be directly extrapolated to other regions or alternative uses of prescribed burning because the data, scenarios and parameterization of the CBM-CFS3 are specific to the Strathcona TSA. Other regions may consist of entirely different forest types and ecological processes. The scenarios I simulated would require modification in order to represent appropriately the intended purpose of prescribed burning and regional practices in alternate settings. The GHG impact of slash pile burning could be much larger in other landscapes where managers apply this treatment to a larger proportion of the harvested area, and differences in the volume of slash per area harvested or decomposition rates might further influence this difference. Additionally, the trade-offs embodied in the choice between status quo burning practices and alternative scenarios may be quite different in other situations. In fire-prone landscapes, the increased risk of wildfire associated with leaving unburned debris after harvest will likely be a much more critical factor. In such circumstances, a structured decision analysis would be beneficial to determine the level of burning at which reduced GHG emissions from burning less debris might outweigh the increased risk of large releases of GHG emissions from additional wildfires that would not have otherwise occurred. In other landscapes, the physical footprint of slash piles may actually reduce or delay regeneration of the subsequent stand (e.g. Luke et al., 1993). I deemed this particular trade-off not to be relevant in the current study area but evidently this conclusion does not hold everywhere. Conducting similar research to the present project in other regions would improve our understanding of how the GHG impacts of burning debris piles and the relative importance of these different factors vary across landscapes.

Even if the quantitative results of this study cannot be directly extrapolated to other areas, there are several qualitative conclusions that may be extendable to other situations, or at least warrant explicit consideration. First, it is both possible and informative to distinguish between the temporary and permanent GHG impacts of alternative actions. Second, the results of this approach may not correspond with simplistic *a priori* assumptions about those temporary and permanent impacts (e.g. that only permanent impacts should be considered and temporary impacts are not important or not relevant). Finally, such assumptions about temporary and permanent impacts may actually underestimate the long-term GHG implications of a particular action. These observations may apply to other potential mitigation actions that produce a mix of permanent and temporary GHG impacts.

4.3.7 Data and Model Limitations

Some of the known limitations of my research relate to data processing, the availability of precise baseline data, specific characteristics of the CBM-CFS3, and particular attributes of the study area. I used aggregate stand types and corresponding area-weighted aggregate growth curves to reduce computing complexity. However, an informal exploration revealed that large variation sometimes exists among the constituent growth curves of a single aggregate growth curve even though the stands have very similar stand composition (same leading and second species, with coverage of each particular species within 5%)

and site quality (SI values within the same 2 unit interval). However, the thousands of unique raw growth curves may give a somewhat exaggerated sense of precision since they are all derived algorithmically from a much smaller set of core growth curves used by the Ministry of Forests (C. Dymond, pers. comm.). The result is distinct growth curves for stands that differ by any margin at all, even if the difference is smaller than the likely sampling error of the attributes. For example, stands that only differ by 1% coverage in their fifth most dominant species have unique growth curves. Nevertheless, the present results should be evaluated against results using the raw growth curves to confirm whether the difference is significant.

The lack of readily available data on the extent to which piling and burning currently occurs within the Strathcona TSA made it impossible to establish a definitively accurate business-as-usual scenario. The extent of future burning is unknowable, but accurate knowledge of current and recent levels would provide a solid foundation for forecasting the business-as-usual trajectory. Instead, I performed the present analyses on a range of potential burning levels based on the estimates of experienced professionals, with the goal of encompassing a realistic range of variation.

There are particular aspects of the CBM-CFS3 that could be improved to more accurately characterize the volume, orientation and actual burning of post-harvest debris. The volume of debris left in each stand after harvest is calculated based on a proportional utilization factor developed from provincial averages. The implicit assumption is that this value is a reasonable approximation of actual utilization levels when applied to a large landscape, even though it may under-/overestimate the residual slash volume in individual stands. The Canadian Forest Service's Carbon Accounting Team is currently investigating the effect of different utilization levels across Canada and developing utilization parameters with greater regional specificity (C. Dymond, pers. comm.).

The present project specifies that unburned debris is left in piles; however, the CBM-CFS3 simulates decomposition processes based on the assumption that debris is left distributed across the setting. This difference in debris orientation means that the present study likely underestimates the temporary GHG benefit of avoided debris burning because unburned debris will actually decompose more slowly in piles than when distributed because it is drier when elevated off the forest floor (e.g. Laiho and Prescott, 2004). The disturbance matrix used in the CBM-CFS3 to represent slash pile burning when piles was originally designed as a hybrid between pile and broadcast burning that could be applied to large landscapes across which both practices were being applied, and therefore it does not entirely differentiate a pile burn from a broadcast burn. Consequently, this disturbance matrix may actually overestimate the amount of soil and forest floor burned and underestimate the amount of coarse woody debris burned (C. Dymond, pers. comm.).

The emissions factors (EF) used in the CBM-CFS3 to determine the proportion of emissions from burning released as different GHGs are based on research from boreal forests (Cofer et al., 1998; Kasischke and Bruhwiler, 2002; Kurz et al., 2009). However, the EFs used are within the range of similar estimates for temperate forests (US EPA, 1995), extra-tropical forests (Andreae and Metlet, 2001), and wildfires and burning of cleared forests globally (IPCC, 2003). However, for CH_4 in particular, the estimated EFs cover a wide range (0.42-1.50% of carbon released as CH_4), varying especially with assumptions about burning conditions. The CH_4 EF for the smouldering phase of burning can be 2-4 times as high as that of the flaming phase, and slash burning usually involves more smouldering than wildfires (Cofer et al., 1998; Kasischke and Bruhwiler, 2002; W. Kurz, pers. comm.). In the present research, approximately two thirds of the permanent GHG impact that I calculated is due to the CH_4 component of the combustion emissions. The only two GHGs in the combustion emissions that contribute to this permanent impact are CH_4 and N_2O because, as per the CBM-CFS3 foundation paper (Kurz et al., 2009), I assume that CO quickly converts to CO_2. When only considering these two components of the combustion emissions, approximately 96% (by mass) is CH_4 and only 4% is N_2O, but the GWP of N_2O is substantially higher than the GWP of CH_4 (**Table 3**). The calculation of the permanent impact should therefore be relatively sensitive to any changes in the assumption regarding the amount of CH_4 released during the combustion of debris. Adjusting the 1.0% CH_4 EF used in the CBM-CFS3 by 0.5% in either direction (within the range of values from the literature) would represent a 50% increase or decrease in the amount of CH_4 actually released during combustion and would likely change the permanent GHG impact that I calculated substantially.

5: CONCLUSION

Avoiding the burning of post-harvest debris piles throughout the THLB of the Strathcona TSA during 2008 to 2050 could contribute to regional climate mitigation. Further analyses are required to precisely quantify the GHG impacts of this strategy when applied to specific stands or management units.

This project demonstrates the value in utilizing small, operational-scale strategies such as the avoidance or reduction of slash pile burning. This strategy does not require new or untested methods, advanced technology or complex institutions, and should therefore be readily implementable. The GHG impacts are immediate – there are no delays in the effect or upfront GHG costs. This strategy has only a stand-level effect from its direct application, but the cumulative response across the THLB produces a more substantial landscape-level effect. Beyond its GHG implications, this tactic may also have other ecological, social and economic benefits. I have shown that a relatively basic management, action applied operationally at the stand-level, can have immediate and lasting GHG impacts that have the potential to make a noticeable contribution to a regional mitigation portfolio when repeated across the landscape.

A common but somewhat cursory interpretation of the impact of slash burning is that the benefit of avoiding the large immediate release of carbon to the atmosphere is short-lived because, had it not been burned, the debris would eventually release the same amount of carbon through decomposition and the net GHG benefit must therefore be zero. This interpretation is incorrect. The research presented here shows that such a simple explanation does not account for two important GHG benefits of avoided slash burning. First, while it is true that the delayed release of carbon is inherently a temporary benefit, a significant proportion of it persists many decades and even centuries. The duration of these temporary impacts is important – short-term temporary benefits that last only years and long-term temporary benefits that last centuries should not be treated as equivalent outcomes. Second, burning debris releases both a small fraction of the carbon as CH_4 and the additional non-carbon GHG N_2O, both of which are more powerful GHGs than carbon dioxide. Even though the same amount of carbon will eventually be released to the atmosphere either way, the climate impact of burning debris will be greater than allowing it to decompose, and this difference is a permanent impact. The quantity, form and timing of carbon released to the atmosphere are all critical in assessing the net climate impact of human activities.

This work illustrates that it is both possible and instructive to distinguish between the permanent and non-permanent components of the total GHG impact of a potential mitigation strategy. Any permanent avoidance of GHG emissions or sequestration of carbon is inarguably beneficial from a mitigation perspective, but the value of non-permanent GHG impacts has been a more contentious issue. When aggregated across the landscape, the temporary benefits of the delayed release of carbon in the present example continue to increase over the entire study period, demonstrating that a complete exclusion of all temporary benefits would understate the total GHG impact of this strategy. Even though the bulk of the carbon in temporary storage in 2050 is subsequently released to the atmosphere through decomposition over the following 100 years, a substantial portion in temporary storage pools persists even longer, suggesting that distinct types of temporary impact should be differentiated based on their longevity. From the perspective of climate change mitigation, delaying the release of carbon for years is not equivalent to delaying the release of carbon for centuries. The present analyses show that some of this temporary carbon storage lasts long enough to become effectively permanent with respect to society's current priorities regarding climate change. If we treat this quasi-permanent carbon stock as a permanent impact then it effectively increases the permanent GHG benefits of avoiding slash pile burning but also increases the permanent GHG benefits of leaving that unburned material in situ. Furthermore, although I only performed these simulations over a single rotation, a large proportion of the temporary carbon storage still exists when the following rotation would likely occur.

Beyond the GHG implications, the current results may even demonstrate broader principles within forest management. Compared with more aggressive management tools such as intensive silviculture or large-scale reduction of harvest, avoiding the burning of slash piles on the small proportion of the landscape over which managers currently practice such burning would have a relatively moderate impact. Yet the consequences of this action extend over a very long period and may even compound over multiple rotations – forest landscapes can have long memories. Furthermore, the “waste” debris retained when avoiding burning is not just carbon. The DOM left on the landscape has physical structure, organic content and water retention properties that serve important ecological functions. As this material decomposes over time and returns most of its carbon to the atmosphere and some of its carbon to the soil (which eventually returns to the atmosphere), it slowly returns other important nutrients to the ecosystem as well. Dead organic material retained on the landscape is not wasted.

Society is increasingly recognizing that climate change is occurring and will be one of the most critical issues facing humanity over the next century. Although climate change is fundamentally a fossil fuel problem, forest management activities can still make a significant contribution to mitigation portfolios, because forest managers are responsible for managing the largest of all terrestrial carbon stocks (Kurz, 2007). Avoiding the burning of post-harvest debris piles in the Strathcona TSA is one potential strategy, shown in this research to make a positive contribution at a regional scale to climate mitigation targets in 2050 and beyond.

Pacala and Socolow (2004) argue that society could solve the carbon and climate problem of the next 50 years by using a portfolio of stabilization wedges, in which each wedge represents a set of technologies or approaches to reduce carbon emissions that are currently available and industrially feasible. Forest management represents one potential wedge in the portfolio (Pacala and Socolow, 2004). Nested within that mitigation wedge is a multitude of potential climate mitigation strategies within the forest sector at the global scale, the national scale, and all the way down to the local scale. On the one hand, the strategy of avoiding debris burning in the Strathcona TSA is just one action within all forest management options to increase carbon sequestration and reduce GHG emissions at the scale of the TSA, which is only one part of the Coast Forest Region, which is only one portion of BC, which is only one piece of the Canadian landscape, which only represents a fraction of the potential global contribution of forest management to climate mitigation, which will at most provide only one of the 10-20 global “stabilization wedges” necessary to reduce emissions by 2050 to a level where society at least maintains a chance of avoiding catastrophic climate change by the end of this century. On the other hand, it does have the potential to be one practical component of the complex solution required.

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FIGURES

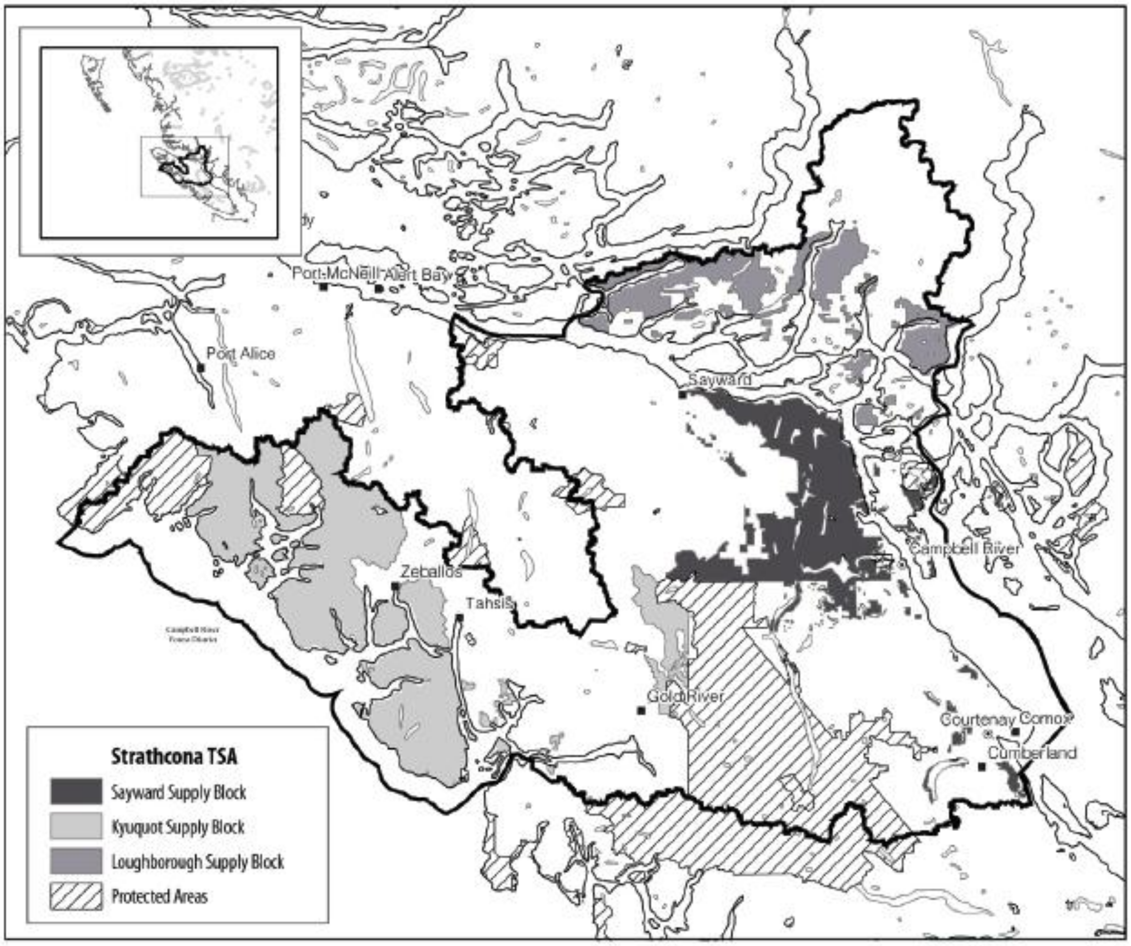

Figure 1. The Strathcona Timber Supply Area (TSA) on Vancouver Island, British Columbia. The map illustrates the location and extent of the three timber supply blocks – Kyuquot, Sayward, and Loughborough. The inset map shows the location of the Strathcona TSA relative to rest of coastal British Columbia.

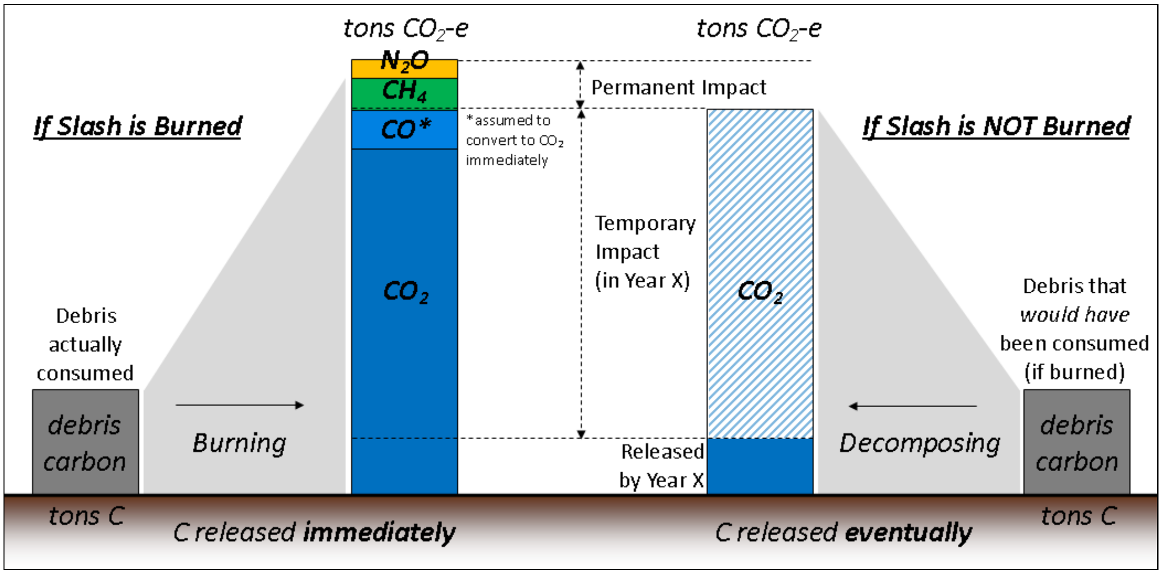

Figure 2. Conceptual illustration of the greenhouse gas (GHG) implications of either burning or not burning slash. The grey box on the left-hand side represents the amount of carbon stored in the debris that is actually released to the atmosphere during slash burning (i.e. it does not reflect the carbon of the debris in the pile that is not actually combusted). Burning releases this carbon immediately in the form of several GHGs (CO_2, CO, CH_4). In addition to the carbon-based GHGs, burning debris also emits N_2O to the atmosphere. From the right-hand side, if the same debris is not burned then decomposition releases this carbon slowly over time, but only in the form of CO_2. In any particular year, the total GHG impact of burning is the difference between the total emissions (in CO_2-equivalents) from burning and those that would result from decomposition even if burning had not occurred. The portion of this difference that simply represents the fact that the decomposing debris has not yet released all of the carbon that it eventually will is temporary. The portion of this difference that represents the discrepancy between releasing all of that carbon as CO_2 and releasing it as CO_2 plus stronger GHGs is permanent.

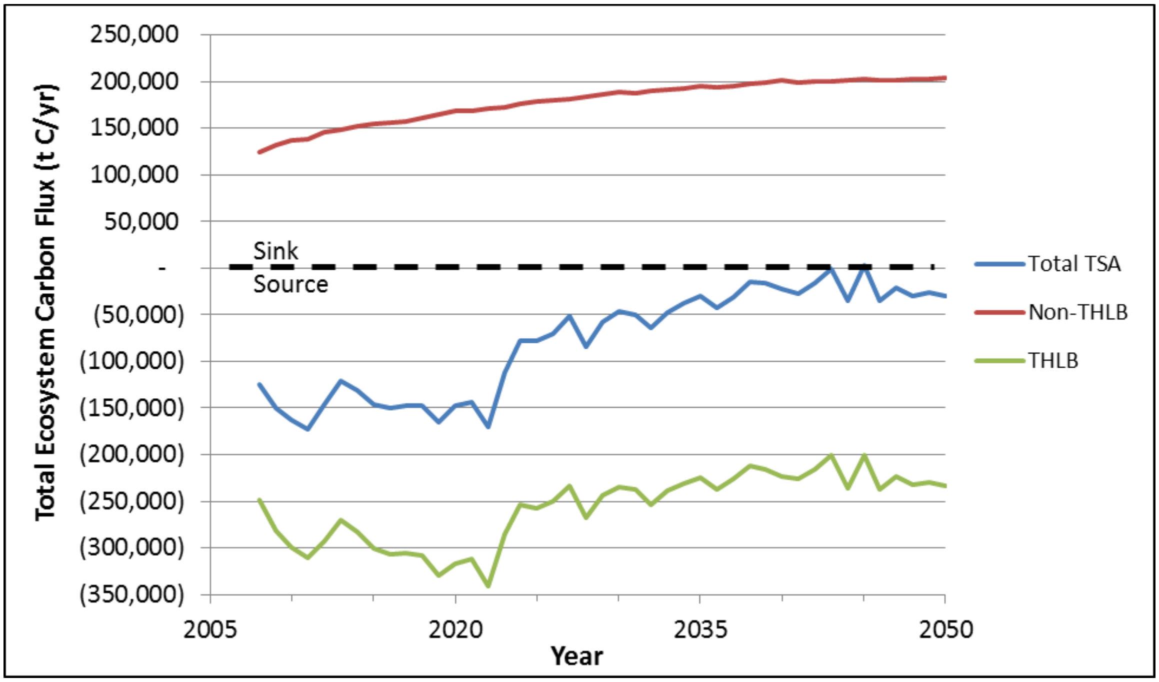

Figure 3. Total ecosystem carbon flux for the Strathcona TSA. This graph illustrates an approximate carbon balance of the Strathcona TSA from 2008 to 2050, distinguishing the contributions of the THLB and non-THLB portions of the landscape. This estimate is based on a simplified model of the landscape. Harvesting occurs according to a schedule based on the TSR “base case”; however, harvested wood products are assumed to be immediate emissions to the atmosphere (zero net addition to long-term storage) and natural disturbances are not included.

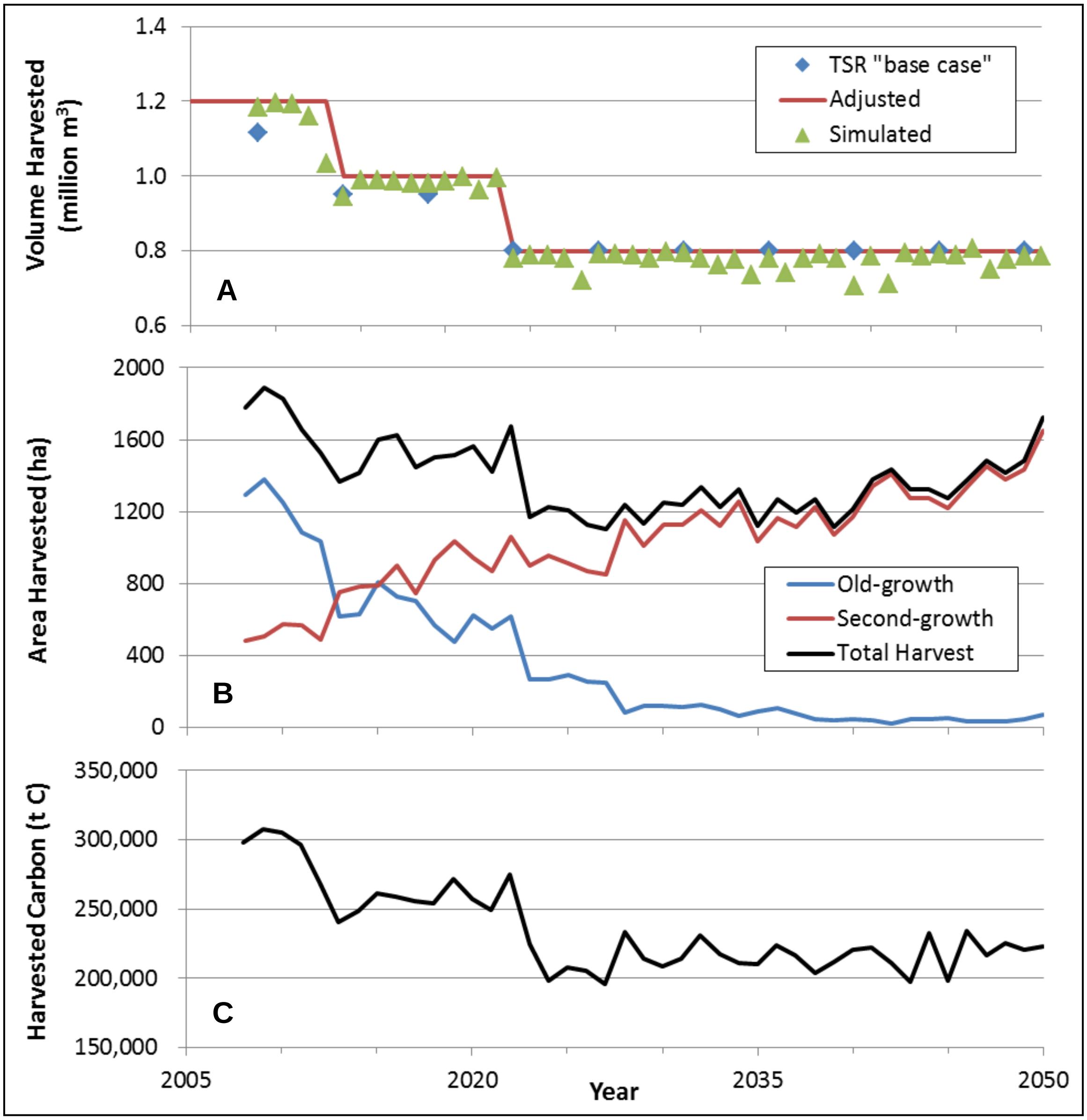

Figure 4. The common harvest schedule. **A**: The AAC forecast used as the basis for the common harvest schedule. The blue diamonds are the values extracted from the TSR "base case". The solid red line is an adjustment of those values to reflect the actual current AAC. The green triangles represent the final harvest levels used in the present simulations. **B**: Annual area harvested (2008-2050). The annual old-growth, second-growth and total area harvested within the Strathcona TSA over the study period. The abrupt increase in 2050 is an anomaly that is not representative of the level of harvest post-2050 (not shown), which is within a similar range as the 2040s. **C**: The annual amount of carbon harvested over the study period. This represents carbon transferred from the merchantable biomass pool to the forest products pool as the result of harvesting operations in each year.

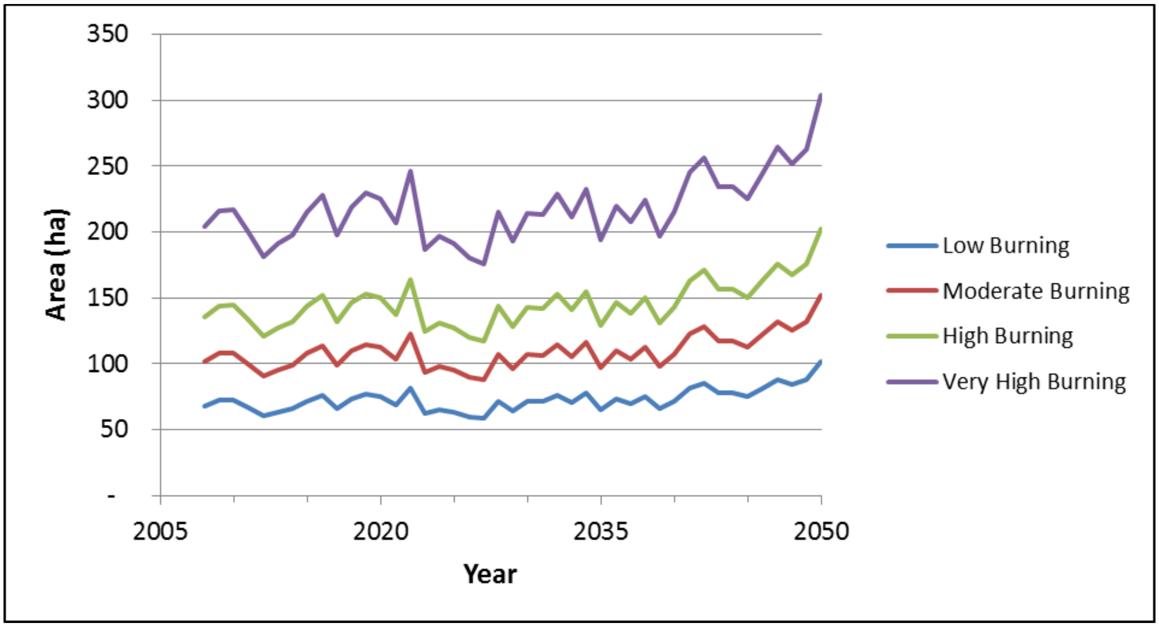

Figure 5. Area harvested and subsequently burned (2008-2050). The graph shows the annual area subject to the “clearcut with slash pile burning” treatment over the study period for each of the four burning scenarios. The remaining area harvested each year is subject to the “clearcut” treatment with no burning of debris. The particularly high values in 2050 are an anomaly within the longer record (not shown) and do not represent the beginning of a sharp upward trend.

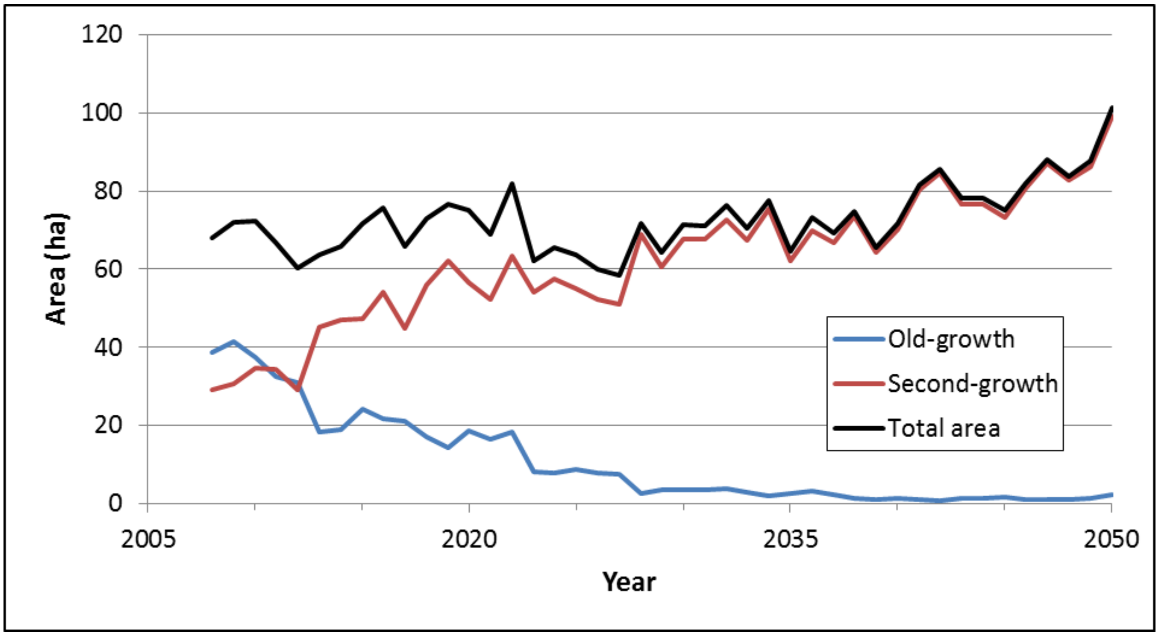

Figure 6. The area of old-growth and second-growth forest subject to the "clearcut with slash pile burning" treatment over the study period for the low burning scenario. The remaining area harvested each year is subject to the "clearcut" treatment with no burning of debris. The particularly high values in 2050 are an anomaly within the longer record (not shown) and do not represent the beginning of a sharp upward trend.

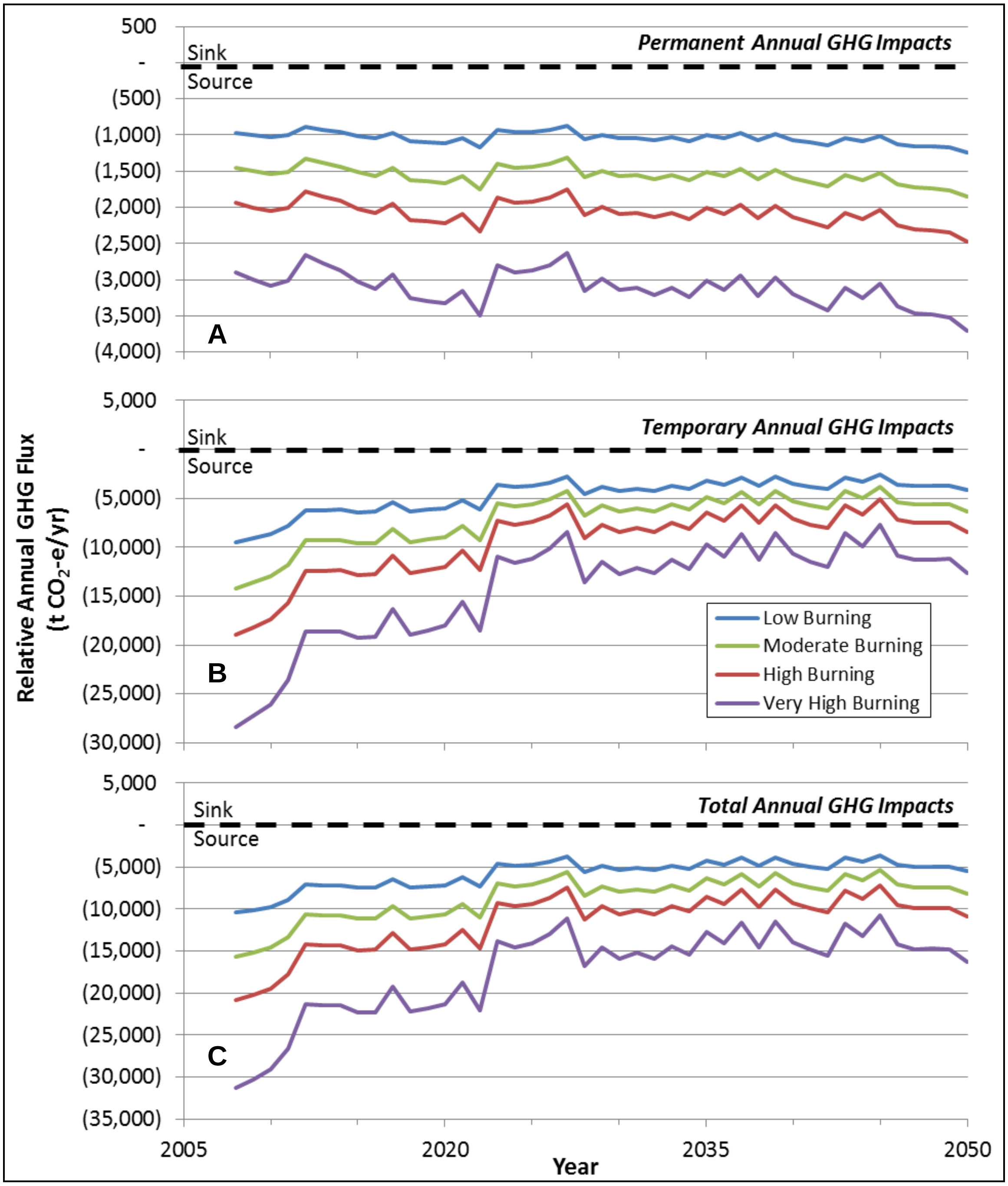

Figure 7. The annual GHG impact of burning debris piles, relative to the zero burning baseline, for each burning scenario. Negative flux values represent an emission of GHGs from the ecosystem to the atmosphere. **A**: The permanent component of the annual GHG impact. **B**: The temporary component of the annual GHG impact. **C**: The total annual GHG impact, which is the sum of the permanent and temporary components.

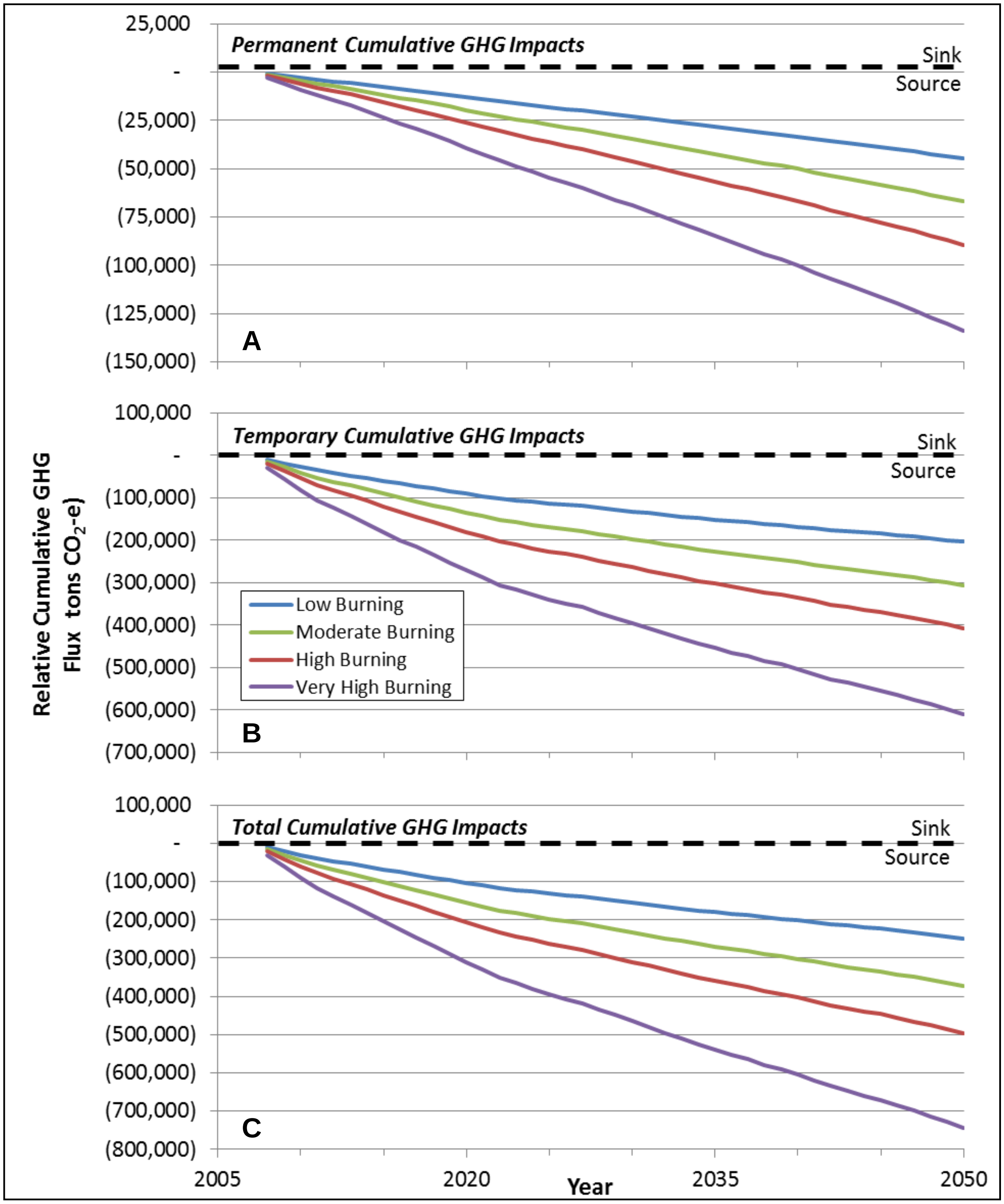

Figure 8. The cumulative GHG impact of burning debris piles, relative to the zero burning baseline, for each burning scenario. Negative flux values represent an emission of GHGs from the ecosystem to the atmosphere. **A**: The permanent component of the cumulative GHG impact. **B**: The temporary component of the cumulative GHG impact. **C**: The total cumulative GHG impact, which is the sum of the permanent and temporary components.

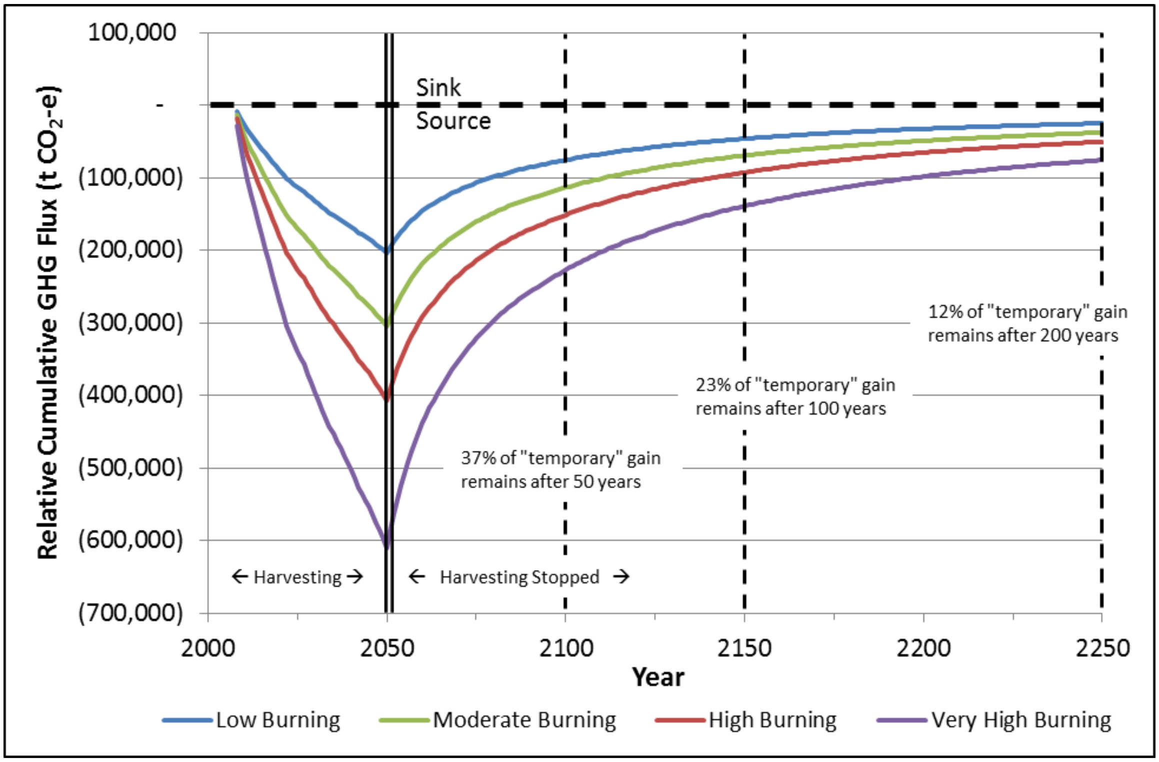

Figure 9. The GHG impacts of burning over the long-run (2050-2250). This graph shows the temporary component of the cumulative GHG impact of burning debris piles during the study period (2008-2050) over the subsequent 200 years. This figure is identical to **Figure 8B** up to 2050. During the initial period of management, the same level harvesting and slash pile burning is applied but management actions stopped after 2050 to observe how the temporary GHG impacts accumulated by 2050 change over a longer time frame. The values displayed for the percentage of the temporary gain remaining apply to all scenarios – the absolute measure of the cumulative temporary impact differs among scenarios, but the proportional decay of that impact follows the same pattern. Negative flux values represent an emission of GHGs from the ecosystem to the atmosphere.

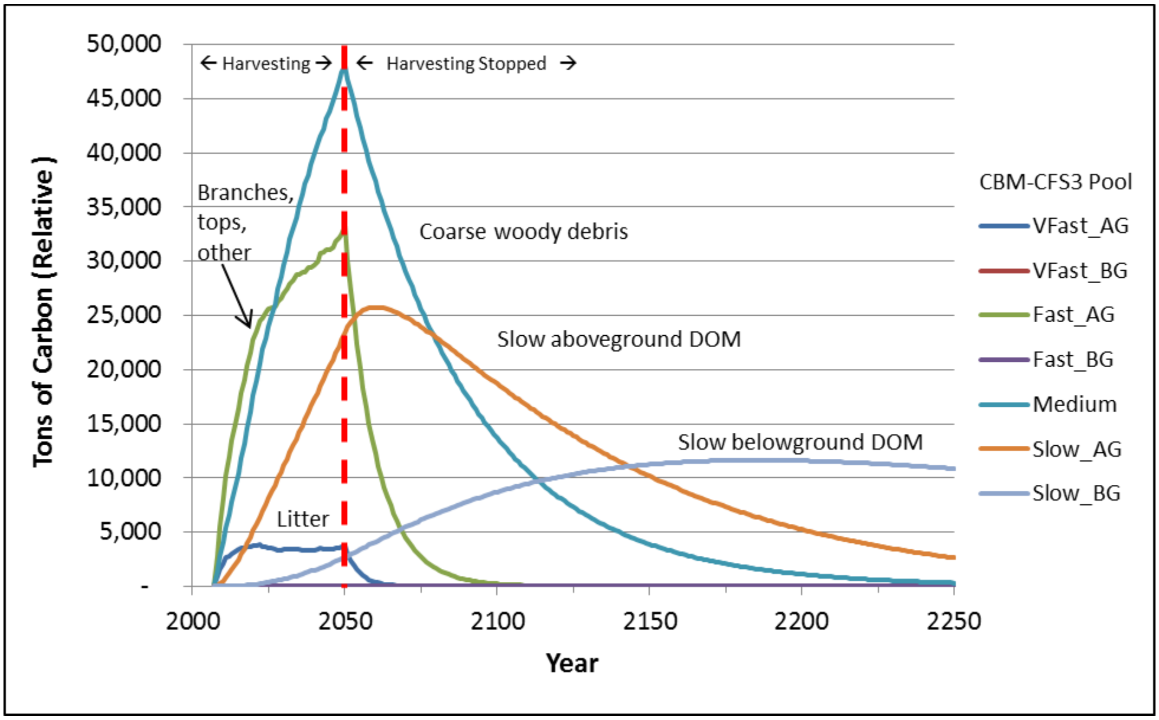

Figure 10. Accumulation and subsequent release of carbon in the DOM pools of the zero burning baseline, relative to the high burning scenario, during the study period (2008-2050) and over the following 200 years. For the zero burning baseline, this carbon storage is incremental to the high burning scenario (against which it is being compared) because the carbon would have otherwise been released immediately through burning. This figure represents a disaggregation of the high burning scenario as displayed in **Figure 9**; however, for a more intuitive interpretation, this figure presents the results as an accumulation relative to the zero burning baseline rather than as a loss relative to the burning scenario.

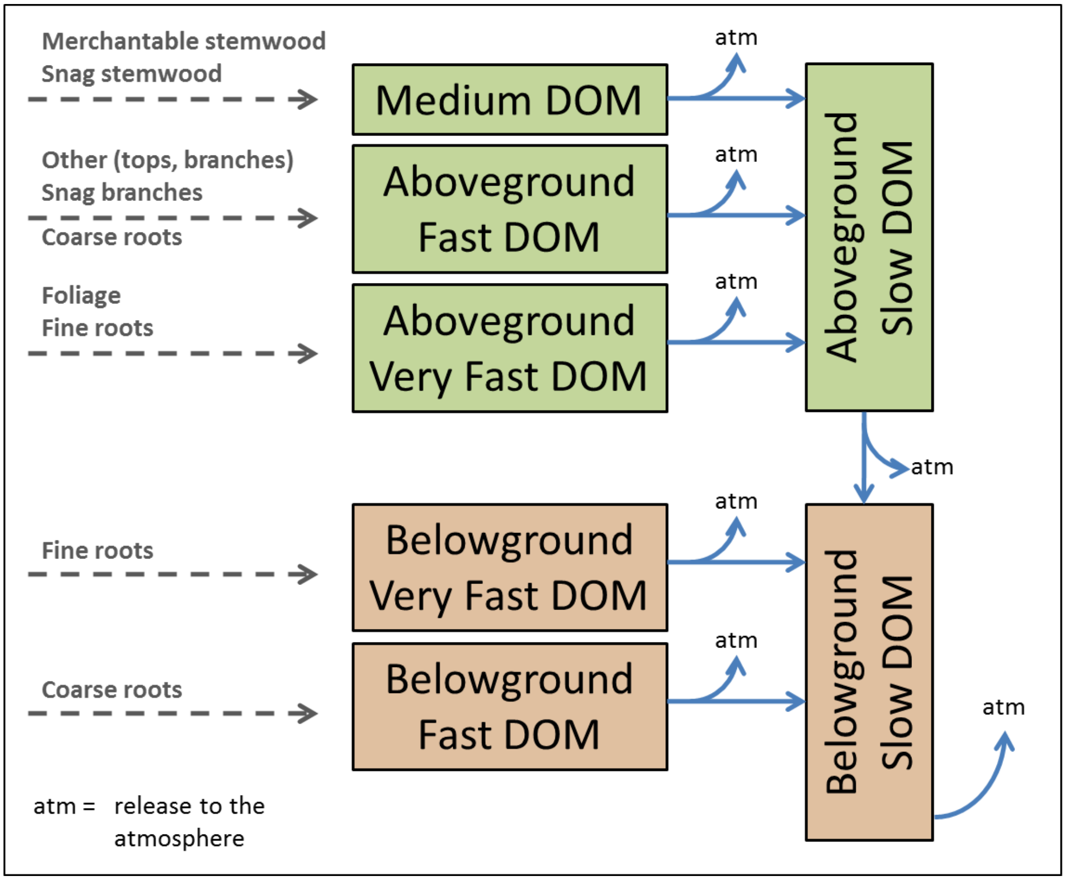

Figure 11. A diagram of the decomposition of the forest floor and soil as represented in CBM-CFS3. This diagram shows that a portion of all the carbon in DOM pools will eventually be transferred into the slow DOM pools, which play a critical role in the longevity of temporary carbon storage in the zero burning baseline that is incremental to alternate burning scenarios (e.g. **Figure 10**).

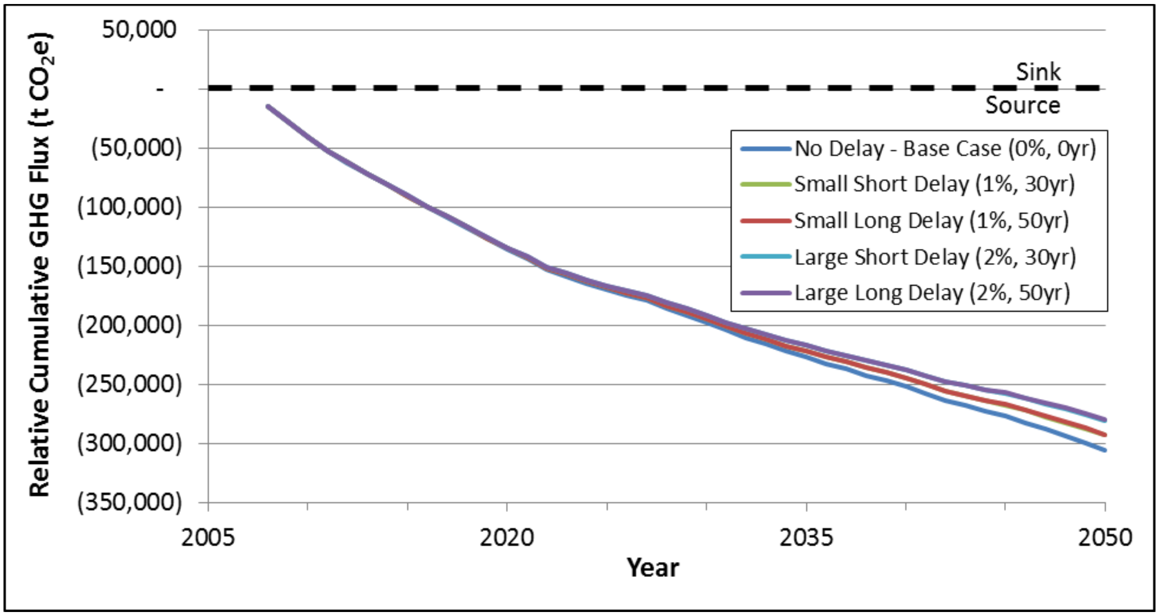

Figure 12. The effect of potential regeneration delays on the cumulative temporary GHG impacts of the moderate burning scenario, relative to zero burning. Regeneration delays do not affect the permanent component of the overall GHG impact because they have no impact on the release of non-CO2 GHGs from combustion. Each delay scenario is specified by two values. First, the size of the effect is expressed in terms of the percentage of the stand area subject to a delay in regeneration. Second, the duration of the effect is expressed in terms of the number of years before regeneration will occur on that particular portion of the stand. Negative flux values represent an emission of GHGs from the ecosystem to the atmosphere.

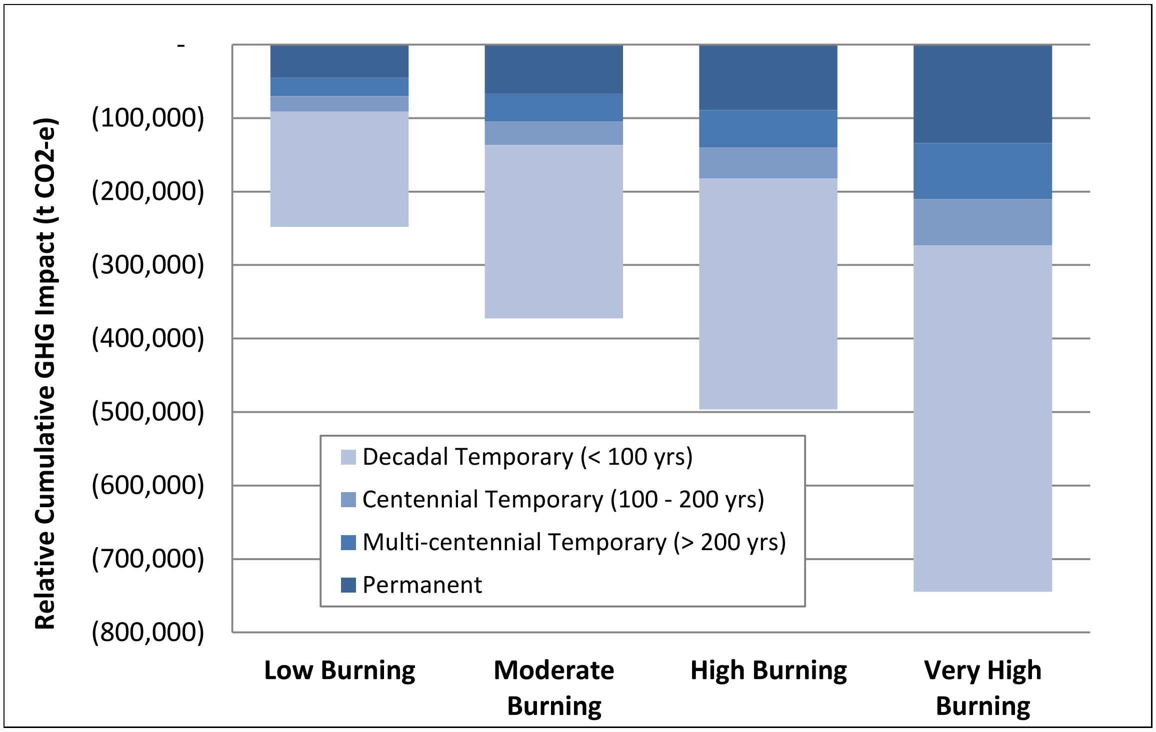

Figure 13. The cumulative GHG impact in 2050 of burning debris piles during 2008-2050 for each burning scenario, relative to the zero burning baseline. Subcomponents of the total impact are differentiated by their longevity past 2050. In particular, the temporary component of the cumulative GHG impact has been subdivided into different “types” of temporary impacts based on the duration of those impacts: decadal temporary impacts are those that will expire prior to 2150; centennial temporary impacts are those that will persist beyond 2150 but will expire prior to 2250; multi-centennial temporary impacts are those that will persist beyond 2250, 200 years after the end of the period in which the management actions were applied. Negative flux values represent an emission of GHGs from the ecosystem to the atmosphere.

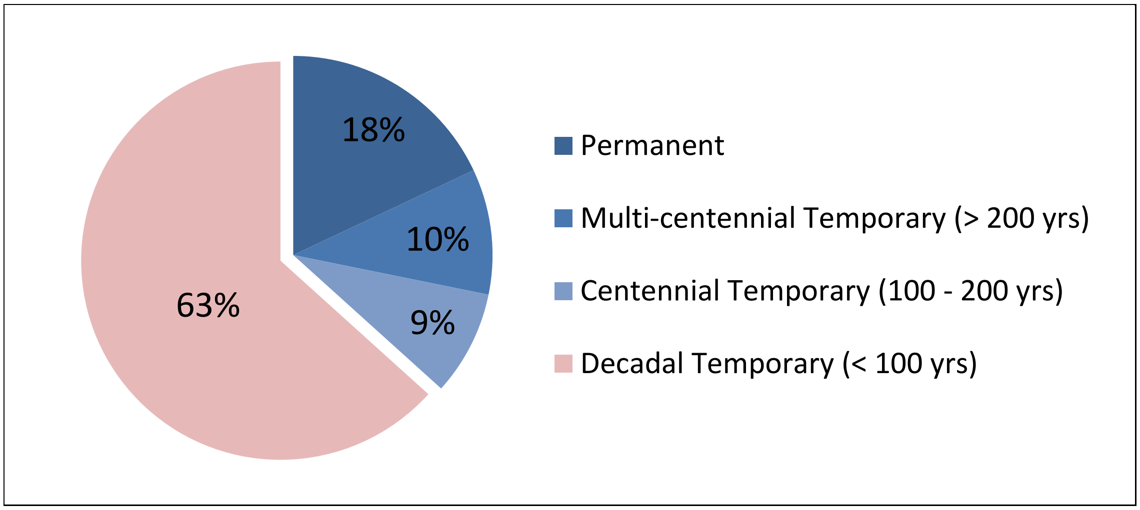

Figure 14. Cumulative net GHG impact in 2050 by duration of impact. This chart shows the proportional contribution of the permanent impact and the three “types” of temporary impacts to the cumulative GHG impact of burning debris piles in 2050. If the temporary impacts that will persist greater than 100 years after the management period are considered to be effectively permanent (the blue, grouped segments), then this would double the “permanent” GHG impacts of burning debris piles, compared to excluding temporary impacts entirely. Using a 100-year threshold is arbitrary, but illustrates the effect of considering temporary impacts of a particular minimum duration as equivalent to permanent impacts.

TABLES

Table 1. Disturbance matrix for used to represent clearcut harvesting with the burning of debris piles. Each row of the matrix describes the proportional transfer of the carbon from a particular source pool (listed in the first column) to one or more destination pools (listed in the first row). This matrix replicates the application of the default “clearcut (no salvage)” disturbance matrix followed immediately by the application of the default “clearcut with slash burn” disturbance matrix, as described in the text.

	AGVF	BGVF	AGF	BGF	M	AGS	BGS	BC	P	CO2	CH4	CO	prod
SWM					0.133					0.015	0.0002	0.0015	0.85
SWF	0.779									0.199	0.0022	0.0199	
SWO			0.779							0.199	0.0022	0.0199	
SWSM			0.779							0.199	0.0022	0.0199	
SWCR			0.39	0.5						0.099	0.0011	0.0099	
SWFR	0.3895	0.5								0.099	0.0011	0.0099	
HM					0.133					0.015	0.0002	0.0015	0.85
HF	0.779									0.199	0.0022	0.0199	
HO			0.779							0.199	0.0022	0.0199	
HSM			0.779							0.199	0.0022	0.0199	
HCR			0.39	0.5						0.099	0.0011	0.0099	
HFR	0.3895	0.5								0.099	0.0011	0.0099	
AGVF	0.779									0.199	0.0022	0.0199	
BGVF		1											
AGF			0.779							0.199	0.0022	0.0199	
BGF				1									
M					0.889					0.1	0.0011	0.0100	
AGS						1							
BGS							1						
SWSS					0.889					0.1	0.0011	0.0100	
SWBS			0.779							0.199	0.0022	0.0199	
HWSS					0.889					0.1	0.0011	0.0100	
HWBS			0.779							0.199	0.0022	0.0199	
BC								1					
P									1				

SW	softwood	AGVF	above ground very fast soil C	SS	stem snag
HM	hardwood	BGVF	below ground very fast soil C	BS	branch snag
M	merchantable	AGF	above ground fast soil C	BC	Black C
F	foliage	BGF	below ground fast soil C	P	Peat
O	others	M	medium soil C	prod	Forest products
SM	sub-merchantable	AGS	above ground slow soil C		
CR	coarse roots	BGS	below ground slow soil C		
FR	fine roots				

Table 2. The percentage of the total harvested area subject to “clearcut with slash pile burning” for each burning scenario, stratified by old-/second-growth. The remaining harvested area within each scenario is harvested by clearcut as well, but with no subsequent application of any burning.

Stratum	Baseline simulation	Burning scenarios			
	Zero burning	Low burning	Moderate burning	High burning	Very high burning
Second-growth	0%	6%	9%	12%	18%
Old-growth	0%	3%	4.5%	6%	9%

Table 3. Global warming potential values (GWP) for a 100-year time horizon, as used by the IPCC (Solomon et al., 2007).

Greenhouse Gas	100-year GWP value
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_2O)	298

Table 4. The cumulative GHG impact in 2050 of slash burning since 2008, relative to the zero burning baseline, with the contribution of the permanent and temporary components to the total net impact.

Scenario	Cumulative GHG Impact in 2050 (tons CO_2-e)		
	Total Impact	Permanent Component	Temporary Component
Low burning	248,211	44,676	203,536
Moderate burning	372,327	67,018	305,309
High burning	496,421	89,351	407,070
Very high burning	744,629	134,027	610,602

Table 5. The cumulative GHG impacts in 2050 that will persist at least 100 years (permanent, multi-centennial temporary and centennial temporary components) of two burning scenarios in terms of equivalent regional GHG impacts.

	Impact equivalent to cumulative GHG impact in 2050				
Burning Scenario	Forestry Operations in Strathcona TSA	Small Passenger Cars	Large Passenger Cars	Light Trucks, Vans, SUVs	Residential Energy Use
	(% of total GHG impact)	(# vehicles on road for 2008-2050)			(% of total GHG impact)
Low	12.0%	636	396	301	1.9%
High	24.0%	1271	793	602	3.8%