# Climate Change & Management Considerations for the Boreal Forest Zone

Gabrielle Habeeb
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# Abstract

The boreal forest zone is located in the cool, high latitudes of the earth and represents approximately one third of the world’s remaining forested area. Maintaining the functional capacity of boreal forests is of global importance as they will both affect and be affected by climate change. Boreal forests can help mitigate climate change by sequestering and storing carbon; however, this regulating service is only maintained so long as the system is functioning properly. This is why managing for climate adaptation is important not only from an ecological perspective, but from a climate standpoint as well. More mitigation in the near term may necessitate less adaptation in the long term. However, both management strategies require the preservation of basic forest system functions. This balancing act between mitigation and adaptation is made more challenging by the demands for timber made on this system. In order to maintain a functional boreal forest zone and the many services it provides, nations within the boreal zone must create plans to preserve intact forests, restore degraded forest stands, harvest timber sustainably, and manage the region holistically for climate resilience. These efforts will require policies to support and incentivize best practices, as well as consistent metrics for monitoring and assessing progress.

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# 1. Introduction

The boreal forest zone is primarily located in Russia, Canada, the United States, Sweden, Finland, and Norway (Bradshaw et al. 2009). The forests within this zone hold a variety of land use designations, ranging from stands highly managed for resource extraction, to unmanaged, old-growth, intact forests (Bradshaw et al. 2009). These forests hold global importance as they both impact and are impacted by climate change.  As the boreal forest zone is located in high latitudes - generally 50° or 60° N through 70° N, depending on location - it will likely see some of the largest shifts in temperature the world over (Perry 1994, Price et al. 2013). Significantly warmer temperatures will change the capacity of this system to provide a variety of ecosystem services, alter disturbance regimes, and lessen the long-term capacity of this globally vital carbon stock.

These systems are highly vulnerable to climate change impacts. Warming temperatures will thaw long-frozen soils, change system hydrology, and open the door for increased fire and pest damage. Misalignment between increases in temperature and precipitation can contribute to climate maladaptation of current vegetative populations, altering structural and biological diversity within these stands (Price et al. 2013). Reductions in diversity negatively impact the system’s ability to resist and recover from increasingly severe disturbances (Price et al. 2013). One change in forest functioning can have far reaching effects throughout the system. Sustainable management is critical as decisions made in this vital zone will influence global carbon fluxes and surface level warming.

# 2. Background

## 2.1 Location

The boreal forest zone represents approximately one third of the remaining global forested area (Bradshaw and Warkentin 2015). This zone is located primarily in the cold, high latitude regions of Canada, Russia, northern Europe, and the United States, i.e., Alaska (Trivino et al. 2017). This forest zone is characterized by short growing seasons and extreme winters (Gauthier et al. 2015). The boreal is also home to nearly half of the world's remaining intact forests (Bradshaw et al. 2009). They experience freezing temperatures lasting up to eight months of the year, and extensive snow cover, resulting in trees which are slow growing but well adapted to these conditions (Bradshaw et al. 2009). The trees generally dominant in this area are cold-tolerant conifers which can withstand frequent winter temperatures of -40℃ and below -- temperatures too cold for any tree not specifically adapted for such temperatures to survive (Perry 1994). One third of the boreal forest is underlain by permafrost, so soils are generally cold, wet, and acidic, with slow decomposition rates, slow carbon cycling, and low nutrient availability (Perry 1994). These poor-quality soils serve an important secondary function: carbon storage. Approximately one third of global terrestrial carbon stocks are contained within the boreal forest zone (Bradshaw and Warkentin 2015). Cold and freezing temperatures keep carbon stores slow moving and contained within the system (Gauthier et al. 2015).

## 2.2 Climate Change and Carbon

This high latitude zone is expected to see some of the most dramatic warming trends, globally. This is largely due to Arctic amplification, whereby the polar regions of the world warm faster than more middle latitudes (EO NASA 2013). This is due to melting ice and the resulting stark shifts in albedo, as well as global circulation patterns that move heat from the tropics to the Arctic (EO NASA 2013). Already, a mean annual temperature increase of 1.5°C has been documented (Gauthier et al. 2015). In fact, the annual mean temperature in the boreal forest zone could increase by as much as 5°C by the year 2100 (Price et al. 2013). As this region warms, high albedo ice and snow will melt, exposing the darker soils and water below; these darker substrates have a lower albedo and will only perpetuate this warming trend. With an estimated 95 percent of the boreal forest's carbon stores housed in cold or frozen peatland and permafrost soils, these soils are increasingly vulnerable to becoming a carbon source due to climate warming (Bradshaw and Warkentin 2015).

The global significance of the boreal zone's carbon storage is difficult to account for and has been consistently underestimated, as historical estimates of the carbon stocks were likely too conservative. One study estimated total boreal carbon storage to be between 367.3 and 1715.8 Pg (with a midpoint of 1095 Pg) of carbon (Bradshaw and Warkentin 2015). The midpoint of this range is more than three times higher than many previous estimates, likely due to other methodologies under-accounting for the full depth of peatland stores or determining carbon values for the zone by summing regional values (Bradshaw and Warkentin 2015).

The degradation of this carbon stock is not only made worse by climate change, but also exacerbates climate change, creating a positive feedback loop whereby warming soil and peatland releases long-stored carbon, increasing warming which further degrades frozen soils (Bradshaw and Warkentin 2015). Rapid warming threatens the stability of this interdependent system by altering the ways major systematic processes are carried out and the way species interact with each other. Such warming will undoubtedly affect this system's structural and functional capacity to provide the ecosystem services upon which humans and non-humans alike depend (Price et al. 2013).

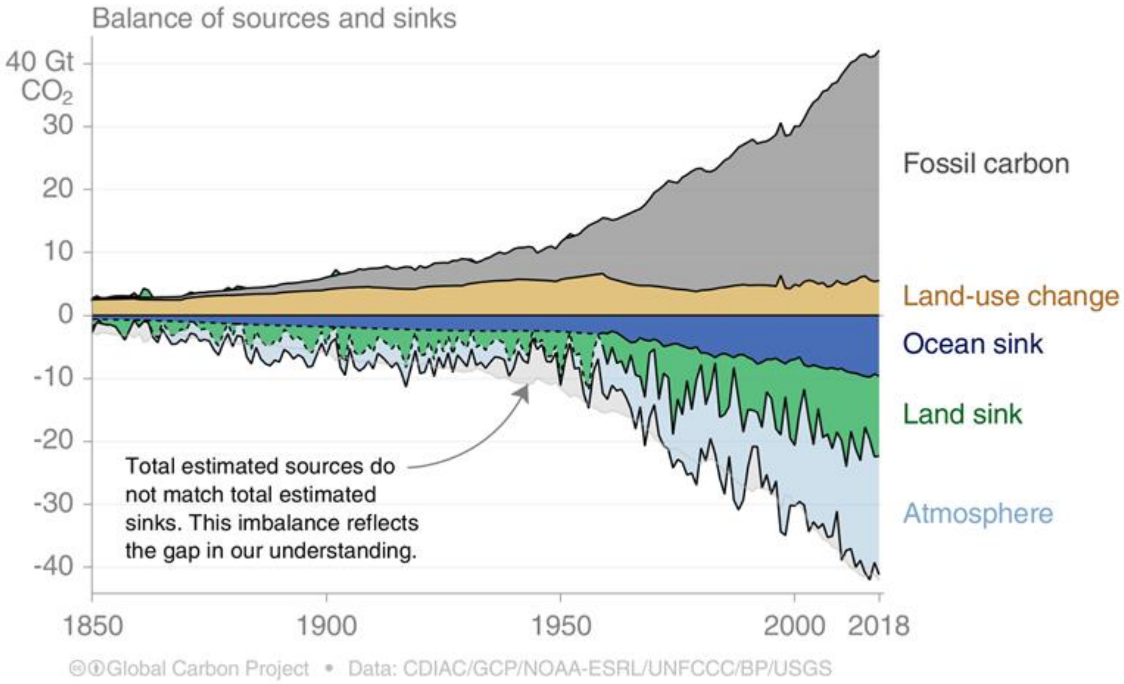
## 2.3 Ecosystem services

This biome provides numerous ecosystem services. Ecosystem services refer to the kinds of economic goods (or provisioning services) most often thought of when considering the value of an ecosystem; however, this concept expands upon traditional valuations by including "life support" services upon which human life depends (known as regulating services) as well as the cultural benefits provided by the system (Raudsepp-Hearnea et al. 2010). When it comes to provisioning services, the most *economically* notable product from this region is timber. Approximately 45 percent of the world's growing stock comes from boreal forests (Trivino et al. 2017), along with 33 percent of the world's lumber exports, and 25 percent of the world's paper (Gauthier et al. 2015). With such an economic driver, it comes as no surprise that two-thirds of the world's boreal forests under commercial management are managed with the primary goal of timber production (Gauthier et al. 2015).

Except for extraction, boreal forests experience few human impacts, as this cold and harsh biome is generally characterized by low human population densities (Gauthier et al. 2015). Those who do live in these regions are often Indigenous Peoples who benefit from a variety of other goods sourced through hunting, fishing, and gathering practices (Berkes and Davidson-Hunt 2006). Such nontimber forest products (NTFPs) are less globally significant to the market; nevertheless, they represent provisioning services of vital importance to the local and Indigenous People living in and around these forests, for both subsistence and sale (Sills et al. 2011). These products range from leaves and roots to fruits and mushrooms, with a myriad of end uses from medicine and food, to decor and gifts. In some places, NTFPs are marketed and sold, providing income and livelihood opportunities consistent with traditional and cultural practices (Sills et al. 2011). When marketed effectively, boreal forest products like wild berry jam can be sold at a premium to niche markets, providing substantial income to Indigenous artisans (Boxall et al. 2003). Additionally, NTFPs are often valued for cultural or intrinsic reasons (Sills et al. 2011). It is worth noting that cultural and recreational ecosystem services may be reaped by residents and visitors alike, as the aesthetic value of the forests draw attention in and of their own right.

In addition to the provisioning services provided by the boreal forests, this biome also provides various important regulatory ecosystem services. For one, the boreal forest contains the largest amount of surface freshwater of any biome (Gauthier et al. 2015). This area also plays a role in global temperature regulation and nutrient cycling, while forest transpiration impacts the hydrological cycle and patterns of precipitation globally (Gauthier et al. 2015). As mentioned previously, this system is uniquely suited to store carbon in soils and biomass. In fact, northern hemisphere soils and forests (so called “land sink” in Figure 1) along with oceans, are primarily responsible for the fact that while upwards of 40 billion tons of carbon dioxide is released through anthropogenic activities annually, only about half of those emissions remain in the atmosphere (GCP 2018).

Figure 1 (GCP 2018)



This uptake serves a regulatory function as carbon dioxide is the most significant greenhouse gas responsible for climate change (UNFCC 2015). Any alteration to the boreal forest system’s ecology can trigger far reaching impacts on carbon stocks and climate warming due to altered structural features, feedback mechanisms, and species interactions (Chapin III et al. 2010). The management goals of a forest stand will greatly impact the effectiveness of its regulating services. Though, managing forests to meet provisioning needs, to sequester carbon, and to maintain ecosystem function is a uniquely complicated challenge.

## 2.4 Biodiversity

The boreal forest zone is home to a relatively low level of tree species diversity (Gauthier et al. 2015). Present through this zone are about twenty species of tree, dominated by evergreen conifers like spruce (*Picea spp.*), fir (*Abies spp.*), and pine (*Pinus spp.*), as well as deciduous trees, including maple (*Acer spp.*), birch (*Betula spp.*), and poplar (*Populus spp.*)(Kayes and Mallik 2020). It is not uncommon for stands to consist of a single species, with six species present in a single stand considered on the high side of normal (Perry 1994). Due to the harshness of boreal winters and the shortness of their summers, the species within this forest zone must be specially adapted to these conditions. This means physical protections from the cold as well as adaptations to maximize the short summer period when conditions allow for photosynthesis (Kayes and Mallik 2020). Coniferous trees are particularly well suited for such conditions, with needles adapted for cold protection and water retention (Kayes and Mallik 2020).

Specialized boreal trees cover a wide range of functions with little redundancy, and work in a complementary fashion with one another to maintain system function and withstand disturbances (Wirth 2005, Paquette and Messier 2011). While more species diversity is beneficial to ecosystem function, the boreal trees have specialized their interactions to cope with the stressful and harsh boreal environment, making maintaining complementarity just as important as species diversity (Paquette and Messier 2011). For example, trembling aspen (*Populus tremuloides*) is a pioneer species that paves the way for later successional spruce (*Picea spp.)* (Paquette and Messier 2011). This relationship is specialized and would not necessarily benefit from more species being present.

Similarly, regarding adaptations to fire disturbances, the few species present in the boreal possess a variety of survival strategies, creating functional diversity with little redundancy (Wirth 2005). Through regular disturbance regimes, this diversity is selected upon, giving rise to structural diversity, which supports a myriad of habitat niches (Gauthier et al. 2015). The animals in this system are no less specialized and vary depending on the habitat conditions present. These relatively few trees are able to support a great amount of biodiversity among the other plants and animals in the system. Some of the first species to colonize these unique niches are cryptogams (spore producing plants like moss and lichen), meaning their abundance and diversity plays a foundational role in preparing sites for later succession while also forming the base of many food chain interactions (Newsmaster and Bell 2002). These species are specialized for individual microhabitats, fostering immense diversity directly related to the disturbance regimes - both natural and anthropogenic - present at the stand level (Newsmaster and Bell 2002).

Regular, natural disturbance regimes support biodiversity and are part of any system's evolutionary history. However, climate change is poised to dramatically alter these regimes and their impact, most especially by way of warming and changes in precipitation (Price et al. 2013).

# 3. Potential ecological impacts of climate change

## 3.1 Disturbance and Resilience

The boreal forest structure and its vegetational makeup have been extremely stable for about 5,000 years; flexible enough to take major climatic stressors in relative stride (Kayes and Mallik 2020). This system was largely unchanged through both the Medieval Warm Period and the Little Ice Age, suggesting a high capacity for climate resilience (Chapin III et al. 2010). Now, due to anthropogenic climate change and widespread extractive management, this resilience is being pushed past its limit. As a result, we are beginning to see the first signs of threshold crossing in which the system no longer retains the capacity to provide its fundamental functions and ecosystem services. Vulnerability refers to the likelihood of change due to exposure to a stressor and depends on the system's adaptive capacity (Chapin III et al. 2010). Resilience is the system's capacity to return to its prior stable state and/or maintain its key functions after a perturbation (Perry 1994, Chapin III et al. 2010). As the climate changes, forests are becoming more vulnerable and less resilient, making it harder for the boreal system to resist and recover from disturbances.

Two aspects contribute to this problem: first, forests are more stressed and therefore less able to support the mechanisms which promote resistance; and second, the stressors perturbing the system are often stronger or more pervasive under these new climatic conditions. For instance, temperature is expected to increase more rapidly than the projected increase in precipitation, leading to heightened drought stress and many tree's vulnerability to mortality from otherwise minor disturbances (Price et al. 2013). This imbalance between water availability and temperature will also increase fire frequency and severity throughout the boreal zone, while warming is projected to expand pest range (Gauthier et al. 2015). Should a drought stressed forest stand be exposed to a pest infestation or a fire, the trees would be less resilient and less able to survive the stressor, as they are already coping with effects of the drought.

Disturbance regimes, water availability, and the species composition present in a given stand can lead to differing stability among sites. While the changes may be variable, we can expect an overall reduction in the stability of the system, and in some places, outright threshold crossing. Climate driven alterations in disturbance regimes, soil function, and hydrology, pick away at the highly selected assemblage that has kept the boreal system stable for so long.

## 3.2 Permafrost Degradation

The boreal forest zone must contend with a myriad of warming effects on the system. No part of the system exists in isolation and the warming of one component can threaten the stability of the system at large; especially should it perpetuate a local positive feedback mechanism which further drives warming. For example, permafrost is a soil type which remains at or below freezing for a minimum of two years, never fully thawing - making it particularly susceptible to warming effects (Jorgenson and Osterkamp 2005). As permafrost is achieved only in frigid temperatures, the soil is characterized by low productivity, slow decomposition, and low nutrient cycling rates (Kurz et al. 2013). While low productivity similarly indicates a low rate of carbon sequestration, the peatland and permafrost soils under these conditions serve as massive carbon pools, locking away the carbon it does sequester for centuries (Kurz et al. 2013).

The soil temperature of the permafrost is primarily influenced by seasonal variability and is stabilized from occasional heat waves by the more constant temperature of the groundwater below (Harris 2001). Changes in air temperature are less responsible for permafrost thaw than the timing and depth of snow cover, as later snowfall allows for greater ground cooling (Harris 2001). Changes in seasonality and precipitation due to climate change can therefore have significant impacts on the permafrost extent. Soil temperatures are of concern because warmer soils will have faster rates of decomposition and therefore nutrient cycling, reducing the stability of this pool and allowing the release of long frozen stores of both water and carbon (Price et al. 2013, Chapin III et al. 2010).

This warming can shift boreal soils from a carbon stock to a massive carbon source, while the loss of ice and snow reduces albedo, or reflectivity, and increases surface level warming (Gauthier et al. 2015). The increased warming speeds up permafrost thaw, and the cycle is perpetuated. Monitoring and measuring permafrost thaw will therefore be important when creating carbon budgets for the boreal zone (Turetsky et al. 2002).

In addition to being a positive feedback mechanism driving climate change, permafrost degradation has far reaching impacts on soil structure, subsurface hydrology, and nutrient cycling (Jorgenson and Osterkamp 2005). Depending on the hydrology, soil characteristics, and drainage, thawing permafrost can dramatically alter the ecosystem and its functioning (Jorgenson and Osterkamp 2005). Where lands are poorly drained, forests may become inundated with water and eventually convert to a wetland or marshland ecosystem (Jorgenson and Osterkamp 2005, Chapin III et al. 2009). Many of the Indigenous communities present in this region are already contending with these climate impacts and some have been forced to relocate due to erosion and flooding from permafrost thaw (Moen et al. 2014).

Conversely, well drained regions, especially in the highlands, may see drought induced mortality increase and a release of carbon; both from the lost permafrost stores as well as the reduction of forest cover and live biomass carbon (Chapin III et al. 2009, Gauthier et al. 2015). These dry and dying patches of forest are the perfect fuel for fires and effectively increase wildland fire extent. Further, along the southern portion of the boreal forest, where warm, well drained areas dry out and trees die back, the forest vegetation may be displaced by more drought tolerant shrubs and grasses, indicating a threshold crossing from the forest to a shrubland or grassland biome (Price et al. 2013, Gauthier et al. 2015).

## 3.3 Fire Severity and Forest Composition

The impact of melting permafrost on boreal forest health is second only to wildfire disturbances (Jorgenson and Osterkamp 2005). Fire regimes are a natural part of boreal community dynamics, as fire type and intensity directly influence forest succession. After a large, intense fire, the primary and secondary succession which follows may entail a different species composition than that of a more moderate fire (Chapin III et al. 2004). While no two fires are exactly alike, they act as a selection factor and influence habitat development, creating a complex and patchwork stand structure. This mosaic keeps climax successional species from dominating the forest stand and opens up gaps in the stand for the next generation (Chapin III et al. 2004).

This rich structural complexity is made possible by species who are specially adapted for this kind of disturbance regime. Several coniferous species, such as lodgepole pine (*Pinus contorta*), jack pine (*Pinus banksiana*), and black spruce (*Picea mariana*) have serotinous cones, which only open after being exposed to the heat of fire (Chapin III et al. 2004). Other early successional trees such as aspen (*Populus tremuloides*) and birch (*Betula neoalaskana*) resprout from surviving stem parts and roots after a fire, or after a disturbance exposes the seedbed (Mack et al. 2021). These trees are specialized to endure fire disturbances and have evolved mechanisms to naturally regenerate a comparable mix of species to that of the stand before the disturbance, indicating a high degree of functional resilience (Wirth 2005).

Fire regimes, to which the resilient system has, thus far, been well adapted, poses a new threat in this warming climate. Historically, fire has been extremely effective in maintaining forest diversity and function in the boreal zone (Kayes and Mallik 2020). However, over the last 200 years, effective fire suppression methods in managed stands have removed this revitalizing factor from the equation, leaving more detritus, an excess of ladder fuels, and forest stands dominated by later successional species (Zackrisson 1977, Kayes and Mallik 2020). Additionally, as the climate warms, the growing season will be lengthened, leading to greater productivity and increased fuel availability (Kauppi et al. 2014). With more available fuel and warmer, drier summers, an increase in the frequency and severity of wildfires is expected, while the fire season itself is projected to lengthen (Zackrisson 1977).

Seeds which depend on fires to trigger their release from a cone or germination may have an advantage over those who reproduce with other plant parts and unspecialized seeds, as fire intensity may overwhelm generalist reproductive strategies (Zackrisson 1977). This could change the stand’s species composition to favor trees with fire related adaptations. Conversely, if such fire adaptations are not sufficient to withstand the increased severity and frequency of the predicted fires and later successional states are never achieved, we may see a shift in stand dominance to that of early successional species (Zackrisson 1977). Earlier successional deciduous species, like aspen and birch, are often faster growing – and therefore better at sequestering carbon immediately after a fire – compared to their climax community counterparts (Mack et al. 2021). Increased burning may, therefore, reduce the historically dominant tree abundance, but provide near term carbon sequestration benefits (Chapin III et al. 2004). With the frequency of fire expected to increase due to climate change, the need for rapid carbon sequestration and storage between disturbance events is critical for offsetting fire related emissions and maintaining carbon stocks - making these increasingly common mixed forest stands more desirable from a climate mitigation perspective than later successional coniferous stands (Mack et al. 2021).

Large and intense fires will warm the ground locally and release stores of forest carbon into the atmosphere (Mann et al. 2012). The excessive burning of soil and biomass will shift this carbon sink to a carbon source, with the resulting greenhouse gas emissions perpetuating a feedback loop of global climate warming (Mann et al. 2012). In addition to releasing carbon from the trees being burnt, intense and severe fires will also degrade soil structure, warm frozen soils, and release soil carbon stores (Mann et al. 2012). This will have especially significant long-term carbon impacts.

## 3.4 Growing Seasons Change

Not all warming impacts have an immediately apparent negative effect on boreal forests. Due to the long winters and short growing seasons characteristic of the boreal forest zone, these immense forests tend to have low net primary production, despite their important role in global carbon storage (Perry 1994). Temperature increases associated with climate change are altering growing seasons and have been associated with increased primary productivity in the wetter parts of Fennoscandia, North America, and Russia (Gauthier et al. 2015). While coniferous trees can photosynthesize year-round in theory (as they do not lose their leaves), their capacity for primary production is temperature limited (Perry 1994). Typically, trees adapted for boreal conditions can continue to photosynthesize until about -5℃ (Perry 1994). Boreal winters historically remain well below that temperature threshold for the majority of the year, while summers only last about three months (Perry 1994). Year over year, this region is experiencing more growing-degree-days (GDD), or days in which the temperature is warm enough to facilitate growth (Kauppi et al. 2014). Forest inventories and meteorological data can be used in tandem to determine the result of such a shift in growth opportunity, and one such study found that more than half of the forest's growth improvement was due to an increase in GDD as a result of climate change (Kauppi et al. 2014). As climate warming lessens the harsh winter cold and increases the growing season, trees will be able to photosynthesize for more of the year, increasing primary production.

Carbon fertilization is a secondary factor influencing primary production, as it is only relevant if the temperature is warm enough for trees to photosynthesize in the first place. Greater amounts of carbon dioxide ($CO_2$) in the atmosphere can increase photosynthetic rates as well as water use efficiency (Pendall et al. 2004). This is because stomata do not need to be open for as long to take in the necessary $CO_2$ for photosynthesis, giving water within the leaves less of a chance to escape via evapotranspiration (Pendall et al. 2004). Different species regulate stomata differently due to their own ability to regulate their water supply (Perry 1994). As more $CO_2$ is taken up for photosynthesis, a portion of that will be transformed into the plant's biomass, sequestering the carbon (Perry 1994). The rest will be respired through the normal growth and survival functions of the tree.

A study by Lapenis et al. (2005) found that forests in Russia were sequestering more carbon than inventories or assessments had projected. This is due to an acclimation in carbon allocation, effectively increasing carbon storage capacity within the tree's biomass. Acclimation is a non-genetic, phenotypic change to improve an individual's survival in new environmental conditions (Lapenis et al. 2005). In places where temperature and precipitation increased, the proportion of green leaves and needles on trees also increased (Lapenis et al. 2005). Where temperatures increased but precipitation decreased, green parts also decreased, while the proportion of roots and woody parts increased (Lapenis et al. 2005). The carbon rich atmosphere and warmer temperatures provoked an acclimation response at the individual tree level - shifting resources and making the best use of the conditions as they are. As the region warms, there will eventually be a nexus where the amount of sequestered carbon levels off and the tree's respiration increases due to the additional climate stress (Perry 1994).

While increased productivity is, at first blush, beneficial to climate change mitigation, it is important to remember how complex and interconnected forest systems are. Higher leaf area and longer growing seasons, while better for primary production, also leads to more detritus, feeding the decomposition on the forest floor (Kauppi et al. 2014). More growth will be more demanding on the water supply, even with the increased water use efficiency afforded by carbon fertilization (Pendall et al. 2004). Increased productivity also increases the available fuel supply. With more fuel, drier conditions, and longer, warmer summers, the boreal region can expect an increase in fire disturbances (Zackrisson 1997). This makes the benefits of increased productivity highly water dependent.

## 3.5 Defoliation and Browsing

As the climate warms, pest species are able to broaden their range and speed up lifecycles, while increased growing seasons keep them well fed (Regniere et al. 2010). This win-win for defoliating insect species makes pest invasion a more *immediate* threat to boreal forest health than even fire disturbances (Price et al. 2013). Further, these insects are not only spreading in range and reproducing more rapidly than before, but are for these same reasons, better suited to adapt to changing climate conditions than the trees which play host (Price et al. 2013, Kurz et al. 2013). It can be expected that insects able to adapt to changing climatic conditions quickly will put any climatically maladapted and pest prone tree species at a greater competitive disadvantage (Price et al. 2013, Kurz et al. 2013).

While defoliator outbreaks are not usually enough to kill a tree by itself, the stress can make these stands more vulnerable to mortality when compounded with disease, drought, or heavy browsing (Price et al. 2013). Unfortunately for the trees in question, climate change is expected to exacerbate such compounding phenomena. As such, species which currently dominate these forests may face significant dieback, thereby changing the forests' composition and function.

For example, in Canadian stands dominated by balsam fir (*Abies balsamea*), spruce budworm (*Choristoneura fumiferana*) outbreaks, compounded by increased browsing pressure from moose (*Alces spp*), are of significant concern (Piene et al. 2003). The spruce budworm is virtually always present in the boreal forests of Canada. Outbreaks can last decades, and defoliated trees experience negative impacts from reduced growth to death, seriously impacting ecosystem function and production of timber (Piene et al. 2003). There are many predators that eat the spruce budworm, from small mammals during outbreaks, to birds and other insects (Morris et al. 1958). At low densities, spruce budworms are consumed by a wide variety of birds (Crawford and Jennings 1989). At higher densities of budworm, there are just too many individuals and predation becomes an ineffective biological control for the disturbance (Crawford and Jennings 1989). This is essentially the worst-case scenario for a forest manager and significant dieback of the host species should be expected.

After a disturbance, such as a pest outbreak or a harvest, browsing can significantly alter succession and forest composition. Moose are selective browsers, preferring deciduous trees over conifers. This may impair natural succession, where deciduous trees typically set the stage for later, shade tolerant conifers. The trees themselves are also differently hardy to browsing stress, further shaping stand composition (Speed et al. 2012). When the next generation of balsam fir begins to sprout, the saplings will be more attractive than other conifers, as the young plants are more tender than their mature counterparts (Speed et al. 2012). Unchecked by top predators, moose will over browse both the balsam fir and deciduous tree species, reducing tree diversity, and shift forests to favor other species (Speed et al. 2012). Changes in stand composition due to herbivory have complex and far-reaching impacts that go beyond immediate habitat and food chain considerations. As stands in this zone have little redundancy among the species present, shifts in composition can threaten the stand's stability and resilience.

## 3.6 Climate Maladaptation

Dramatic climate warming has left trees in some regions maladapted to new and changing climatic conditions, increasing stress and lowering their natural resilience (Perry 1994). In a stable climate, vegetation is distributed along spatial gradients. When the environment becomes less than ideal, species populations can adapt, migrate, or perish. As a result of climate change, we are seeing migration and changes in assemblage among species in the boreal zone (Chapin III et al. 2004). Changes in vegetation can be gradual, as seen in the northernmost reaches of the boreal forest zone. Several species of shrubs and trees are encroaching on the tundra and are largely limited in seed dispersal by their distribution rate; however, long, warm growing seasons are beginning to relieve climatic barriers to northward migration (Chapin III et al. 2004). Climate simulations show that as vegetation encroaches on northernmost latitudes and obscure high-albedo snow, there is a warming effect on the climate which may not be entirely offset by the carbon sequestration of the new growth (Bonan et al. 2002).

Conversely, species further south and in upper elevations will generally experience an increase in growth-limiting factors such as drought frequency, creating new selection pressures within habitats as climate warming continues (Chapin III et al. 2009). Black spruce (*Picea mariana*) are one example of a species whose distribution is expected to shrink in range, with an estimated 57 percent of their contemporary habitat lost by 2090 (Joyce and Rehfeldt 2017). As their potential habitat shifts northward, there may be an increase in emergent habitat, though not commensurate with the area lost, resulting in a net habitat reduction of about 30 percent (Joyce and Rehfeldt 2017). As the northernmost vegetation expands, the southernmost tree line may experience die-off, changing the range and distribution of typical boreal species.

While some changes in stand composition may be gradual, in other parts of the boreal forest zone, changes are rapid, causing the ecosystem type to switch entirely - also referred to as “threshold crossing” (Chapin III et al. 2004). This phenomenon can be caused by “pulse” changes in disturbance and hydrology, such as fire, flood, and thermokarst - where melted permafrost leaves a depression in the land itself, creating a lake or wetland (Chapin III et al. 2009). As vegetation composition shifts to navigate the changing landscape conditions, we can expect to see some sections of boreal forest shift to entirely different biome types.

In a warming climate, boreal species adapted for cool conditions are at a competitive disadvantage, while prior climate barriers are lifted for unspecialized and non-native species which were prevented from inhabiting the region due to its cold and inhospitable conditions. These changes can have cascading impacts on the forest range and composition, as the cool climate zone shifts northward faster than boreal trees can naturally migrate (Gauthier et al. 2015).

# 4. Management

The boreal forest zone will both affect and be affected by climate change. This means boreal forest stewards and managers have to account for both aspects of this challenge. Boreal forests can help mitigate climate change by sequestering and storing carbon; however, this regulating service is only maintained so long as the system is functioning properly. This is why managing for climate adaptation - preserving key ecosystem functions and characteristics that will be better suited for the new climatic conditions - is important not only from an ecological perspective, but from a climate standpoint as well. More mitigation in the near term may necessitate less adaptation in the long term. However, both management strategies require the preservation of basic forest system functions. This balancing act between mitigation and adaptation is made more challenging by the demands for timber made on this system.

## 4.1 Current Management

There are numerous obstacles to effective management of the boreal forest zone. One of which is the designation of land use within boreal countries. Less than 10 percent of the forestland in most boreal countries is protected from logging and harvest (Bradshaw et al. 2009). Sweden has protected the largest percentage (not area) of forested land, with approximately 20 percent designated as national parks, wilderness areas, nature preserves, and the like (Bradshaw et al. 2009). In the six major countries within the boreal zone (Russia, Canada, United States, Sweden, Finland, and Norway), only Russia has any notable tracts of undisturbed forest (Bradshaw et al. 2009). While Russia has an extensive area of undisturbed forest, the amount of that which is formally protected remains only around 12 percent (Bradshaw et al. 2009). In the other countries, less than one third of the boreal forest is undisturbed (Bradshaw et al. 2009). It is also worth noting that these tracts of land are owned by a variety of entities - ranging from federal governments, to private landowners, and non-governmental organizations - each with their own management and land-use goals.

Land use matters because harvest disturbances and habitat fragmentation have far reaching impacts on forest health and resilience. Fragmentation, due to human development, logging, dams, and mining, increases fire risk in these already vulnerable ecosystems and limits the migration capacity of climate stressed species (Bradshaw et al. 2009, Lazarus and McGill 2014). However, fragmentation is not the only threat posed to the boreal forest zone by harvest. The kind of harvest or silvicultural strategy employed plays a significant role in the way these forest systems recover from such disturbances. A long history of even aged stand management and clear-cutting harvest practices has been the norm in commercially managed forests (Moen et al. 2014). While good for timber production, ecologists of today largely agree that clear cut, even aged stands are not ecologically sound, as their overly simple structure is less resilient and provides fewer habitat niches than more complex stands, while foregoing the many ecosystem services and co-benefits offered by the system (Moen et al. 2014).

In addition to logging practices, tar sand oil extraction is a socially and ecologically detrimental practice with a direct climate impact. Within the boreal forest zone, this form of highly land-intensive fossil fuel extraction is most prevalent in Canada - namely, Alberta - whereby large tracts of land are clear cut and oil is extracted from the tar sands below (Westman and Joly 2019). The extraction process not only destroys the carbon stores of the forestland and produces a climate change driving fossil fuel, but also pollutes the air, water, and ecosystems with heavy metals and toxic compounds (Westman and Joly 2019). Such ecosystem degradation fragments the land, harms human health, and hinders the exercise of Indigenous rights to fishing, hunting, and gathering on their lands (Westman and Joly 2019). Additionally, the influx of industry and the urbanization that follows threatens traditional ways of life and can lead to the loss of Indigenous language and knowledge (Westman and Joly 2019).

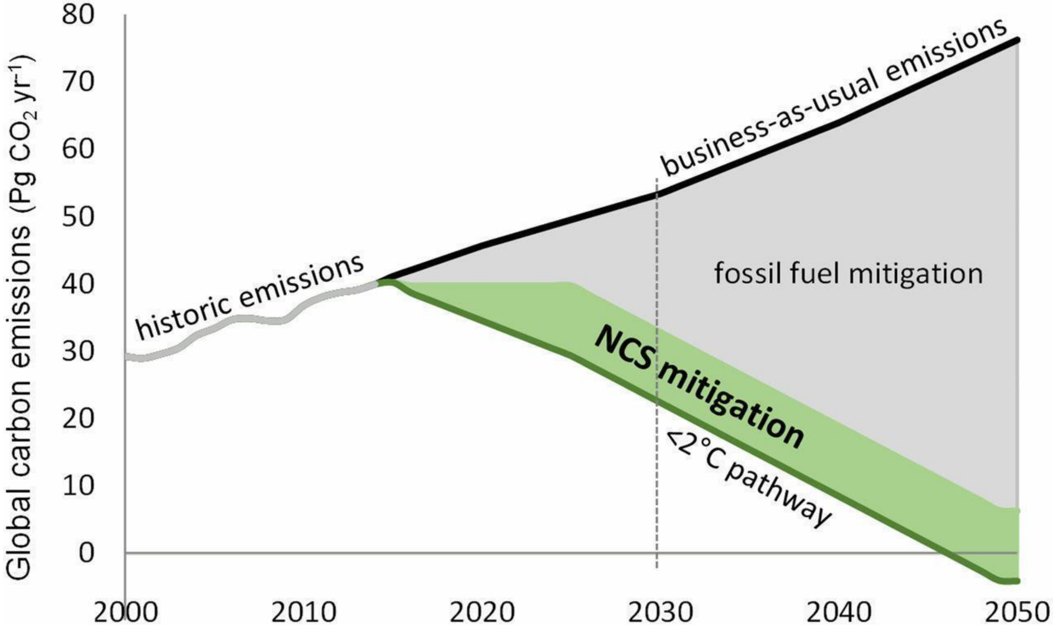
Indigenous communities have sustainably managed local tracts of boreal forest land for centuries and have pushed back against such unsustainable extractive management, making them vitally knowledgeable stakeholders and advocates. Many lessons can be learned from Indigenous land management which allows for resource provisioning while enhancing local biodiversity (Berkes and Davidson-Hunt 2006). Notably, working with a natural system - recreating natural disturbance regimes and succession; harvesting NTFPs seasonally; and managing at the habitat/landscape scale - will protect and perpetuate both local biodiversity and the ecosystem services garnered for human benefit (Berkes and Davidson-Hunt 2006).

Should the preservation of the boreal forest zone be designated a priority, local management will have to work with Indigenous, regional, and international entities to set extraction regulations and create incentives for sustainable management. Ecosystem stability, carbon storage, and timber production are in many cases, going to be at odds with each other. Where harvest rotations are sustainably and holistically managed, these forests can support local and global economies without destabilizing the larger ecological system. However, such management will require oversight to guide harvest regimes and cease environmentally detrimental tar sand extraction. The demand for wood products and extracted resources is determined at regional and global scales. Such scales necessitate regional, national, and international regulations and policy to ensure management prioritizes climate and forest function in conjunction with production goals.

## 4.2 Mitigation Strategies

Mitigation depends on both carbon flux and carbon storage. Carbon flux refers to emissions and sequestration (also called sources and sinks), while storage refers to pools of carbon which reside in a given part of the system long-term (Keith et al. 2021). The capacity of the boreal forest to regulate carbon has been a recurring theme throughout this paper. This regulating service is dependent on living biomass to sequester carbon from the air through net primary production (primary production via photosynthesis - the plant's metabolic respiration = net primary production (NPP)), and on slow decomposition which facilitates long-term storage in cold, wet soils.  When management intervenes to bolster a system's capacity for carbon sequestration or avoided greenhouse gas emissions, the strategy is sometimes referred to as a natural climate solution (NCS) (Griscom et al. 2017). NCS can provide 37 percent of the carbon mitigation needed to achieve Paris Agreement mid-century climate goals cost-effectively, helping offset slow mitigation in other sectors and committed warming, see Figure 2 (Griscom et al. 2017). Of these solutions, reforestation and avoided deforestation are the two actions with the highest carbon mitigation and storage potential (Griscom et al. 2017). As the boreal forest zone consists of approximately one third of the globe's forested area and half of the world's intact forests, this region is especially rife with opportunities (Bradshaw et al. 2009).

Figure 2 (Griscom et al. 2017)



“Contribution of natural climate solutions (NCS) to stabilizing warming to below 2 °C. Historical anthropogenic CO2 emissions before 2016 (gray line) prelude either business-as-usual (representative concentration pathway, scenario 8.5, black line) or a net emissions trajectory needed for >66% likelihood of holding global warming to below 2 °C (green line). The green area shows cost-effective NCS (aggregate of 20 pathways), offering 37% of needed mitigation through 2030, 29% at year 2030, 20% through 2050, and 9% through 2100. This scenario assumes that NCS are ramped up linearly over the next decade to <2 °C levels ... and held at that level (=10.4 PgCO2 y−1, not including other greenhouse gases). It is assumed that fossil fuel emissions are held level over the next decade then decline linearly to reach 7% of current levels by 2050.” (Griscom et al. 2017).

Intact or old-growth forests are often under-appreciated for their contributions to climate mitigation, as they have a lower NPP and carbon sequestration rate than younger, fast-growing forests, due to the fact that more respiration is needed to maintain their biomass (D’Amato et al. 2011). This lack of appreciation is due in part to the metrics used in carbon accounting, which overemphasize sequestration and underemphasize storage (Keith et al. 2021). Another important component of the boreal system which is often overlooked is the carbon storage associated with the zone’s peatland and soil (Kurz et al. 2013). Younger forests lack in both respects, as their youth is a result of having recently endured a disturbance, such as a harvest or a fire. Both disturbance types remove aboveground biomass and disturb the soil below, resulting in a release of carbon from both pools (Keith et al. 2021). New growth from reforestation can quickly sequester large quantities of carbon; however, the soil remains degraded, and it takes a long time for the forest to achieve the levels of storage it once had (Keith et al. 2021). Preservation of existing forests provides immediate climate benefits and is sometimes called the “no regrets” forest management option as it is low cost, maintains the carbon stock, and protects invaluable biodiversity (Seymour 2020, Keith et al. 2021). Where the climatic conditions have changed to the extent that historical species composition can no longer be supported, management will need to prioritize adaptation in order to maintain the function and regulating services of the system.

One preservation target that is gaining popularity in mainstream environmental advocacy is known as “30x30”, which aims to preserve 30 percent of the world’s land and sea by the year 2030 with the twin goals of protecting biodiversity and ecosystem services, such as climate change mitigation (CFN 2020). To date, fifty countries have signed on to the formal High Ambition Coalition, including Canada, which is home to large tracts of boreal forest (Rosane 2021). Should other countries within the boreal forest zone make similar commitments, it would mark a significant increase in the amount of protected land designations for the region.

In preserving forests, managers are making a tradeoff between climate mitigation and the economic power of timber harvest. If preservation is to be seen as a viable management option, financial incentives must be made available to help offset this opportunity cost (Bradshaw et al. 2009). Common voluntary credit schemes, such as the popular REDD+, are not extended to most boreal forests (Duchelle et al. 2019). In fact, Mongolia is the only “non-tropical” country to participate in the program (UN-REDD 2018). Their participation is driven out of a desire to set and achieve climate targets, mitigate some of climate change’s worst effects, and create economic opportunities for sustainable management (UN-REDD 2018). While REDD+ is not a perfect program, it is a well-known example of the kinds of programs which could encourage the large-scale preservation of intact, old growth forests, and the carbon storage they provide.

In much of the boreal zone, preservation is not an option. Reforestation and restocking are, in harvested stands, the best options for carbon sequestration and storage, while also providing a full suite of co-benefits - from improving air and water quality to enhancing soil health and local biodiversity (Griscom et al. 2017). Reforested areas tend to have high stocking levels and tree density, thereby storing large amounts of carbon and enhancing mitigation (D'Amato et al. 2011). However, these benefits are only realized if the restoration is done in a strategic way. Natural succession in boreal forests often begins with deciduous species before shade tolerant conifers begin to populate the understory (Bright et al. 2014). If reforestation attempts to reestablish the later successional forest that was just harvested instead of recreating natural succession, they run the risk of losing the substantial near-term cooling effects that high albedo deciduous forest stands provide (Bright et al. 2014). Where this reforestation can be used to connect otherwise fragmented forest stands, the benefits to habitat connectivity are multiplied (Warkentin and Bradshaw 2012). Poor program design and a focus on carbon alone can overlook these significant climate benefits.

Programs with the sole aim of sequestering carbon (such as carbon offset schemes) can sometimes result in high-yield, low-diversity plantations to achieve afforestation targets, while negatively impacting ecosystems (Seddon et al. 2020). This a less desirable interpretation of the NCS concept and a poor use of these stands. Further, plantations are often comprised of fast-growing, non-native species which may become invasive and increase water scarcity (Seddon et al. 2020). This is why enabling the natural regeneration of a diversity of native trees, such as early successional deciduous birch (*Betula spp.*) and poplar trees (*Populus spp.*), should be prioritized, as they will be better suited to enhance system stability and provide co-benefits in addition to carbon sequestration and storage (Bright et al. 2014). Where carbon markets are established and used to financially support climate change mitigation, Indigenous stakeholders should be intentionally and meaningfully involved in the project development and implementation process (Dohan and Voora 2011). Their engagement in the development of carbon markets and policies will help ensure traditional livelihoods are protected, while program design benefits from the inclusion of traditional ecological knowledge (Dohan and Voora 2011).

### 4.2.a Sustainable Harvest

Timber harvest will undoubtedly play a significant role in the future management of the boreal forest zone. While the maintenance of intact forests and reforestation of degraded forests hold the greatest potential for climate change mitigation, timber harvest can be done in such a way that its effects on forest health and carbon emissions are minimal. By prioritizing complexity through selective harvesting, managers can create multi-age and structurally complex stands (D’Amato et al. 2011). While boreal forest stands managed in this way are relatively uncommon, these stands would have a higher adaptive capacity than single age stands while maintaining the carbon stores of older trees (D’Amato et al. 2011). This may be most appropriate in the southern boreal regions that are at a higher risk of climatic maladaptation and are more productive than the still cool northern regions of this zone. As management is highly site specific, any one management strategy will not be appropriate in all places and different silvicultural methods will be required in different locations. Timing should also be a consideration when planning a harvest rotation, as such decisions can have near term impacts on albedo and soil structure. This includes harvest age/rotation period, timing of replanting, and harvest season (Bright et al. 2014). Regions of the boreal underlain by permafrost will be especially tricky to harvest without disrupting soil carbon stores. However, shifting harvest schedules to the winter months may minimize soil disturbance, as heavy machinery will degrade frozen soil less than summer-thawed, wet soil (Ogden and Innes 2007).

It is not only the harvest type that influences its climate impacts, but also the type of product that is being produced. Long-duration wood products (or products with a mean residence time of >25 years) can essentially serve as carbon storage over the life of the product (Profft et al. 2009). This does not offset the emissions associated with the harvest itself, the soil degradation, or timber processing, but it may serve as the lesser of evils when used as a substitute for high carbon alternatives. For example, steel and alloys are extremely carbon intensive building materials. Where they can be replaced with wood, there is a net carbon benefit while also reducing other harmful co-pollutants associated with heavy industry and commercial construction (Profft et al. 2009).

These long duration end uses are growing in popularity with commercial “mass timber” buildings going up in London, Atlanta, Minneapolis, Portland, and Chicago (Robbins 2019). While laminated mass timber is billed by some as an opportunity to turn a carbon source (traditional commercial construction) into a carbon sink (mass timber buildings), it is more accurate to frame these projects as an opportunity for avoided emissions (Robbins 2019). These construction projects are avoiding the worst emissions from traditional construction - however, it is not pulling new carbon out of the air, meaning it is technically a carbon storage solution at best. Further, these projects are creating new demand for logging, which some environmental organizations fear is a step in the wrong direction, when forest preservation is so critical to climate mitigation (Robbins 2019). Nevertheless, when a tree is cut down, these long-lived substitutions are a preferable end use over short-duration products, such as paper products or “energy wood” - also called biofuel or biomass energy - who share all of the same production emissions as their long-lived counterparts, while also releasing their stored carbon more immediately (Profft et al. 2009).

Timber production is a major economic force within the boreal forest zone. This is unlikely to change in the coming years, making the harvest and silvicultural methods employed of lasting importance. Should forestry management shift from clear cutting methods where possible, strategically plan harvest timing, and move away from short-duration wood products, harvest can continue while serving to enhance both climate mitigation and adaptation at the stand level.

## 4.3 Adaptation Strategies

As climate change alters environmental conditions within the boreal forest zone, managing for adaptation will become increasingly necessary in order to maintain forest function. Forest adaptation is happening on multiple scales. Naturally, trees are capable of long-distance gene flow, which allows for high genetic variation and adaptability (Kremer et al. 2012). This natural adaptability is hindered by the long-generation times of trees and difficulty in predicting the impacts of regional context on dispersal (Kremer et al. 2012). Long generation times means there is a marked lag between when conditions change and when the next generation has the chance to go through natural selection under those new conditions (Kuparinen et al. 2010). With low mortality, established trees remain the dominant population, regardless of current conditions.

Additionally, boreal forests establish slowly compared to coniferous forests in other biomes (Bonan et al. 2002). Climate models show these stands take as much as 200 years to progress to a community dominated by later successional conifers from a starting point of bare ground, compared to a mere 50 years in warmer climates (Bonan et al. 2002). Dispersal ability and maturation age also influence the rate of adaptation, as a species' ability to spread and reproduce determines its success in adapting to new conditions (Kuparinen et al. 2010). Regularly disturbed stands are freed from some of this reproductive stagnation and allow the existing genetic diversity to play out under new conditions more frequently (Kuparinen et al. 2010). Such regularly disturbed populations were found to be the quickest to adapt to the warming climate, due to the relatively frequent opportunities for natural selection to play out under present conditions (Kuparinen et al. 2010).

For these reasons, natural disturbances can be beneficial, as they drive boreal ecosystem dynamics. However, these regimes are expected to shift from beneficial to potentially detrimental under climate change conditions (Bradshaw et al. 2009). Managing for disturbances and anticipating their changes will be important for both climate adaptation and mitigation (Warkentin and Bradshaw 2012). One disturbance regime to monitor is that of wildfires. Prescribed burns are one management strategy which may promote stability within the boreal forest system by reducing the fuel load and simulating low levels of beneficial disturbance; however, this practice is extremely expensive and poses a variety of safety risks (Kayes and Mallik 2020). Another caution is that under climate change conditions, these prescribed burns can lead to hard to predict and potentially self-perpetuating interactions with other perturbing forces such as pests (Kayes and Mallik 2020). Managing forests in this zone to adapt to changes in disturbance regularity and severity is going to be an ongoing challenge for forest management.

Another hurdle for forest managers will be that of maintaining functional species compositions within stands as historical habitat ranges shift and natural migration lags. Where stands are managed for climate adaptation, the development of seed banks and active seed transfer practices should be employed. As mentioned previously, black spruce (*Picea mariana*) are going to experience a sizable decrease in habitat range over the next century (Joyce and Rehfeldt 2017). If the presence of this tree is to persist as a dominant species within Canadian boreal forests, extensive planting programs will be needed, with an emphasis on building up the seedbank within the most productive climate niches (Joyce and Rehfeldt 2017). Seed transfer is a method of seed selection and planting which typically uses geography to determine a suitable match between the individual seed and the planting site (Joyce and Rehfeldt 2017). Under climate change conditions, geography alone may not be sufficient to determine a suitable planting and may actually lead to the development of a maladapted stand as conditions continue to shift. Given the pace in which climatic conditions are changing, climate models are increasingly useful tools for determining what conditions might be like long-term, allowing for the planting of seeds with more climatically appropriate adaptations and a lower risk of future climate maladaptation (Joyce and Rehfeldt 2017).

This kind of assisted migration typically occurs across a randomly distributed grid within the targeted stand, at the end of the season after all existing trees have broadcast their seeds (Lazarus and McGill 2014). When planting under an assisted migration scheme, benefits can be maximized by focusing planting in stands where it can increase connectivity (Bradshaw et al. 2009). The boreal forest zone is fortunate in that it is far less fragmented than other forest systems, however, fragmentation is on the rise and protected lands are minimal, making it a consideration dangerous to overlook (Lazarus and McGill 2014).

## 4.4 Enforcement and Accountability

Prior to the adoption of the Paris Agreement in 2015, national and international regulations for sustainable forest management and carbon storage were weak and at times counterproductive (Moen et al. 2014). The Paris Agreement is the most recent and most ambitious climate accord to date, calling for nations to set targets to achieve net-zero carbon emissions by mid-century (UNFCC 2015). Article 5 of the Paris Agreement encourages Parties to the Agreement to implement “results-based payments" to positively incentivize emissions reductions, conservation, sustainable forest management, the “enhancement of forest carbon stocks," and the “non-carbon benefits associated with such approaches," (UNFCC 2015). The acknowledgement of non-carbon benefits may be understood as a nod to the ecosystem services provided by functional forest systems, including biodiversity. Boreal nations will need to implement such results-based payment programs if they are to incentivize practices to achieve their international goals and limit warming to 1.5 degrees Celsius (UNFCC 2021, Keith et al. 2021).

To achieve this emissions goal and support complementary forest ecosystem services, climate policies and programs must be holistic in their approach (Moen et al. 2014). Land sector carbon storage is most effective when the ecosystem is functional, resilient, and adaptive (Keith et al. 2021). Such qualities are dependent on the functional diversity of the system, making the twin priorities of climate mitigation and ensuring the forests' adaptive capacity intrinsically linked (Keith et al. 2021). Policies should therefore include not only carbon targets, but also means of evaluating and incentivizing ecological function. This may come in the form of carbon credit schemes being paired with habitat payments and biodiversity banking to encourage management practices that optimize both priorities, for example (Moen et al. 2014).

A key stakeholder group that must be consulted throughout the planning process is that of Indigenous People living in the boreal forest zone. Climate change impacts on provisioning and regulating services within the boreal zone threatens the access of these communities to water, food, living spaces, and sacred lands, making climate driven migration a new and worsening issue (Creed and Serran 2018). This problem is compounded when forest management is undergone without their input. Too often when creating forest preserves and protected areas, Indigenous People are displaced and forced out of their native lands (Creed and Serran 2018). Involving Indigenous People in forest management and enabling their leadership on conservation and planning will not only ensure the safety of those living there, but also provide a forum to learn from keepers of traditional ecological knowledge, further informing site specific ecological management.

In addition to incentivizing targets and engaging stakeholders, there must also be some means of accountability. The Paris Agreement is largely non-binding in terms of enforceable actions, as the only major commitments nations are making are their nationally determined contributions (NDCs). Further, the Paris Agreement FAQ, responds to a question regarding enforcement by stating,

> "Countries have every reason to comply with the terms of the Agreement. It is in their interest to implement the agreement, not only in terms of achieving the benefits of taking climate action, but also to show global solidarity.
>
> There is no benefit to flouting the Agreement. Any short-term time gain will be short-lived. It will undoubtedly be overshadowed by negative reactions, by other countries, financial markets, and most important, by their citizens." (UN 2016).

As the United States demonstrated in 2020 with their temporary withdrawal from the Agreement, this collective accountability may not be sufficient to ensure nations are taking the necessary steps to achieve international climate targets (NPR 2020). This is offset somewhat by the enhanced transparency framework (ETF), under which countries will be required to report their progress starting in the year 2024, however, other than shaming under-performers, there is little to rely upon within the Agreement itself (UNFCC 2021). Ideally, nations home to boreal forests should review each other's ETF reports in order to learn what works well in similar environments and use that knowledge to inform revisions of their own NDCs.

Besides reporting progress toward NDCs, effective management will also need to monitor conditions over time and project future conditions in order to make the best use of limited time and resources. Geographic information systems (GIS) can be used to achieve both of these ends and has been an increasingly prevalent tool for management planning throughout the boreal forest zone in recent years. In terms of monitoring, ground surveys of vegetation, meteorological data, and remote sensing methodologies can be analyzed through the creation of maps using GIS, allowing for a clearer understanding of the ways in which different climatic conditions impact forest stands (Michaelian et al. 2011). For example, this process was used in the boreal forest stands of western Canada, where, after a drought, a massive amount of trembling aspen (*Populus tremuloides*) mortality was observed (Michaelian et al. 2011). Through this combination of monitoring and analysis, data revealed a moderately strong correlation between percent dead trembling aspen biomass and drought severity, highlighting an ongoing need for the monitoring of drought effects on these forests (Michaelian et al. 2011).

Similar studies have been conducted on fire extent and severity (Gaudreau et al. 2015, Barrett et al. 2010, Kafka et al. 2001, Amiro et al 2001); permafrost thaw and threshold crossing (Jorgenson et al. 2001, Rogan and Miller 2006); and forest extent (Wulder et al. 2008), to name a few. Such studies can be used to determine present carbon stocks and forest health, while integrating climate model data allows for the evaluation of site-specific climate threats. This is just one tool of many which may help nations track and manage their progress toward their climate goals.

# 5. Recommendations

In order to maintain a functional boreal forest zone and the many services it provides, boreal nations must create plans to preserve intact forests, restore degraded forest stands, harvest timber sustainably, and manage the region holistically for climate resilience. Monitoring programs for forest stand and permafrost conditions should be included in any climate management plan in this region. These efforts will require policies with real accountability measures to support and incentivize best practices, as well as consistent metrics for assessing progress and determining project success.

There are many considerations that must be taken into account when designing a sustainable forest management plan. Key among them are the metrics by which carbon mitigation is accounted for - including both sequestration *and* storage (Keith et al. 2021). While emitting sectors like power and transportation only need concern themselves with reducing carbon emissions, forest and land use sectors must account for mitigation more holistically due to their capacity to capture and store carbon. Equitable stakeholder engagement will be critically important in the development and implementation of these policies.

The first priority for maintaining boreal forest function in a changing climate should be the preservation or adaptation of intact forests to maintain carbon stores and prevent harvest-related carbon emissions (Keith et al. 2021). Such protection also provides the added benefit of preserving cold soil carbon stores, which lock away forest carbon long-term (Keith et al. 2021). This can come in the form of non-harvest land use designations such as nature preserves or parks, prioritizing areas with the greatest potential to increase habitat connectivity. Enhancing connectivity will help facilitate natural species migration, better allowing for species climate adaptation and forest resilience. These protections align with the Paris Agreement's mention of enhancing non-carbon benefits, including ecosystem services and biodiversity. The level of management and maintenance for these protected lands will depend on the site-specific needs and the financial capacity to do so. However, even just removing the possibility of harvest will produce a climatic and ecological benefit.

Sequestration must be enhanced through strategic reforestation and stand restocking to increase the carbon sink in a way that benefits the system overall (Keith et al. 2021). Such restoration projects should look to recreate natural succession to maximize near-term cooling effects, include Indigenous stakeholders and traditional knowledge, and increase habitat connectivity where possible. When planting new trees, it is vitally important to look at how those trees will affect the forest structure and function, including the quality of habitat, the impact on water availability, and the effects the species may have on the people who live in the area. No tree acts alone, therefore, reforestation efforts must take the entire stand and its stakeholders into consideration when creating a management plan.

Where harvest is undertaken, incentives should be developed to encourage low-impact harvest regimes, which while often more expensive, are less damaging to the system overall. The goods produced through this harvest should be long-duration wood products wherever possible. As each of these goals are important and require a slightly different set of management tactics, accurate carbon accounting will be needed to help governments assess potential policies and prioritize investments (Keith et al. 2021). By shifting to a more holistic carbon accounting approach which accurately values storage and pairing that approach with incentives for non-carbon benefits, nations can minimize their risk of incurring perverse social and ecological consequences when setting out to achieve climate goals.

# 6. Conclusion

The boreal forest zone is of global climate significance. Managing this vulnerable zone for climate resilience, adaptation, and overall function should be an international priority. This can be achieved by preserving intact forests; helping forests adapt to new and changing conditions; investing in holistic reforestation projects, increasing connectivity where possible; and with sustainable harvest regimes. These practices must be overseen by smart climate legislation which aims to reach these ends equitably, and with metrics which account for all of the interconnected components of the system as a whole. Diverse stakeholders, including scientists, economists, Indigenous People, and policymakers should work together to ensure such legislation is well developed and garners necessary buy-in.

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