AN EXAMINATION OF THRESHOLDS AND FOREST SUCCESSION IN THE ACADIAN FOREST OF NEW BRUNSWICK UNDER A CHANGING CLIMATE

by

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ABSTRACT

Climate change has warmed the atmosphere over scales relevant to modern society, causing widespread and rapid changes to the pedosphere, cryosphere, biosphere, and oceanic systems. Through our actions or inactions, we may be fundamentally altering the very nature of our environmental systems by forcing them beyond critical environmental thresholds. These environmental systems are complex and have many interconnected and interacting parts, so when a disturbance occurs the whole ecosystem can be impacted in ways that may not be readily apparent. To deal with this complexity, I have developed a conceptual framework to examine the historical simplifying assumptions foresters have used, from the simplest logistic curves to representations of forest dynamics as seen in hybrid process-based models, such as the Forest Landscape Model. The conceptual framework is separated into two parts, namely (i) ecological, and (ii) socio-economic constraints, each with their own results. Using this framework, this thesis seeks to unpack how the structure, composition, and function of forests will shift under anticipated climate change. My results led me to conclude that our simplifying assumptions of human-ecosystem interactions may point to competition as a driver of system thresholds and tipping points. I was able to identify various scenarios focusing on interspecific competition between southern and northern species that will require due consideration in the future. Nevertheless, a flexible response to dynamic system shifts in human-forest ecosystem interactions suggests that a flexible option would provide resilience to a complex system. My results lead me to conclude that a scenario with increasing species diversity will allow us to create more robust solutions for the future and reduce uncertainty.

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CHAPTER 1

Introduction

The most recent series of IPCC reports (Working Group I, 2021; Working Group II, 2022) confirm that anthropogenic climate change is having a broad range of dramatic impacts on the world's natural and human systems. Climate change has warmed the atmosphere over scales of direct and immediate relevance to modern society, causing widespread and pervasive changes to the cryosphere, hydrosphere, biosphere, and oceanic systems (Masson-Delmotte, et al., 2021). Increases of greenhouse gas emissions (GHG's) in the atmosphere have already caused sea level rise due to thermal expansion and melting within the cryosphere (Stroeve and Notz, 2016: Masson-Delmotte, et al., 2021), ocean acidification and deoxygenation, and an increase in growing degree-days poleward, which has resulted in boreal forest dieback (Baltzer et al., 2021; Drijfhout et al., 2015; Masson-Delmotte, et al., 2021), and release of permafrost carbon.

At a national scale, Canada is acknowledged as a global hotspot. The 2019 report entitled, Canada in a Changing Climate: Advancing our Knowledge for Action, states that Canada's overall warming is on average double the magnitude of global warming. This will affect the rate and intensity of impacts on Canada's ecosystems and citizens (Natural Resources Canada, 2018). Within Canada, the impacts will be regionally specific. For the Atlantic northeast, data from multiple datasets provide evidence that this region has become warmer and wetter over the last 100 years, with significant changes occurring since 1970 (Rustad et al., 2012). This trend is expected to continue. Some possible impacts of this change on natural systems include changes to the hydrological systems (Huntington et al., 2009; Rustad et al., 2012), shifts in flora and fauna, including the encroachment of invasive plant species, pathogens, and insect pests (Dukes et al., 2009; Rodenhouse et al., 2009; Rustad et al., 2012), and impacts on biogeochemical cycling in Maritime forests (Campbell et al., 2009; Rustad et al., 2012). Other impacts include sea level rise (Natural Resources Canada, 2018), the potential for increased flooding, and drought; impacts on fisheries in both rivers and oceans, such as the loss of cold water refugia for Atlantic Salmon (*Salmo salar*) in rivers, e.g., the Miramichi (Kurylyk et al., 2015); and impacts on the forestry sector as tree species, such as balsam fir (*Abies balsamea*), may suffer dieback due to increased temperatures (Bourque, 2019; Taylor et al., 2017). Unfortunately, anticipating and preparing for such impacts, is fraught with difficulty given the high levels of uncertainty involved in projecting the future states of natural and human systems.

Shifts in forest species for instance, typically occur over centuries (Warren and Lulham, 2021) through natural processes, such as competition and excessive herbivory. But there is also the possibility for abrupt dramatic change, as historical pollen records have indicated for hemlock (*Tsuga* spp.; Foster et al., 2006; Shuman et al., 2009) during the mid-Holocene. Reasons for this decline have been hotly debated, but it is thought that an abrupt change in climate along with an increase susceptibility to fire, wind, and disease, and changes in other long-term patterns sparked the rapid decline of hemlock (Williams et al., 2002). Similarly, the current IPCC Assessment Report (AR6) suggests that ‘our actions or inactions’ may be fundamentally altering the very nature of environmental systems by forcing them beyond critical environmental thresholds (Masson-Delmotte, et al., 2021). The worry is that Earth subsystems can be switched under circumstances by small perturbations into a qualitatively different state (Lenton et al., 2008, pg. 1786). The event or moment a system passes into a qualitatively altered state, it is referred to as a 'tipping point'. Tipping points can also be defined as "a critical threshold beyond which a system reorganises, often abruptly and/or irreversibly" (Masson-Delmotte, et al., 2021, pg. 5-78). Going past such 'critical thresholds' may result in irreversible change (Masson-Delmotte, et al., 2021).

Such abrupt changes will have an impact on ecosystem goods and services, which will impact the sensitivity of the Canadian forest sector (LaFleur and MacLellan, 2020). The more immediate, short-term impacts of a rise in temperature will likely surpass any potential moderating effects that an increase in precipitation may have on wildfires (Zhang et al., 2019). There has been an increase in the frequency, severity, and size of fires over the last decade (Flannigan et al., 2009; Mori and Johnson, 2013) and it is expected that there will be an increased risk of wildland fire and drought in the decades to come (Boucher et al., 2018; Boulanger et al., 2017; Flannigan et al., 2009). Forest stand structure and composition may also be impacted through the increase in progressive disturbances, such as pest infestations brought on by changes in climate, impacting forests on both immediate and multiple-year time horizons (Burton, 2010; Price et al., 2013; Sturrock et al., 2011; Sulla-Menashe et al., 2018; van Lierop et al., 2015). The cumulative effects of these changes increase the risk of regeneration failure (Williams et al., 2002), and decrease productivity, health, and resilience of forests (LaFleur and MacLellan, 2020). Leading to an ever-increasing risk to the forestry sector as the timber supply is constrained by these stochastic and progressive disturbance events (Boucher et al., 2018;

Coulombe et al., 2010; Gauthier et al., 2014; McKenney et al., 2016; Price et al., 2013; Taylor et al., 2017; Williamson et al., 2009).

The complexity and interconnected nature of ecosystems increases the potential risk to the human socio-economic systems that rely on them (Kimmins, 1987). An abrupt change within the forest ecosystem could have unanticipated and wide-reaching impacts within both the ecosystem and the human socio-economic system (Folke et al., 2002; Kimmins, 1987). Therefore, it is imperative that we figure out ways to anticipate these tipping points or thresholds. However, this is also exceedingly hard due to their abrupt and often unique nature and the complexity in the system or subsystem components involved (Valdes, 2011).

In this thesis, I seek to develop an understanding of Maritime Forest systems under the forcing(s) of climatic change. By focusing on the conceptual notion of thresholds, I will not only examine the possibility of 'tipping points' events within the forest ecosystem, but I will seek to unpack the capacity for change within human socio-economic systems. While the concept of thresholds has been tied to natural processes, humans as well can initiate thresholds through their economic activities. More specifically, this thesis seeks to show that changes in the growth response of individual tree species to representative concentration pathways (RCP scenarios), may lead to dramatic system-wide impacts in terms of forest-species composition and/or structure. Such changes may be classified as 'noise-induced' (Masson-Delmotte, et al., 2021), pushing the Acadian Forest into a new state, where 'noise is defined by the gradual changes in temperature and precipitation implicit in the various 'RCP pathways'. The proposed mechanism behind such dramatic change is interspecies competition as based on species vital attributes. The Forest Landscape Model (Bourque, 2019) will be used to uncover the nature of such potential tipping points or more generically, system thresholds.

The next chapter will introduce key concepts relevant to this thesis, such as terrestrial ecosystem dynamics, climate change, forest succession, and environmental thresholds. These concepts will be synthesised into a conceptual framework of which the rest of the thesis is based on, as well as the general modelling approach, study area, and comparison studies. Lastly, this chapter will state the thesis objectives. Chapter 3 will give an overview of the Forest Landscape Model and how it will be used in this research. Chapter 4 gives the results of the study and their discussion. Chapter 5 provides concluding remarks.

CHAPTER 2

Ecosystem Dynamics

The term ecosystem was originally suggested by the English ecologist A.G. Tansley (1935). Tansley defined ecosystems as including "not only the organism-complex, but the whole complex of physical factors forming what we call the environment" (Tansley, 1935). Suggesting that an ecosystem is both the living, or biotic, and the abiotic, or physical factors, which impact the "organism-complex." While Tansley was the first to suggest the ecosystem concept several others have offered alternative definitions. Lindeman (1942) proposed that "an ecosystem is any system composed of physical, chemical, and biological processes active within any space-time unit" (Lindeman, 1942; Kimmins, 1987). Whittaker (1962) suggested that "an ecosystem is a functional system that includes an assemblage of interacting organisms (plants, animals, and saprobes) and their environment, which acts on them and on which they act" (Whittaker, 1962; Kimmins, 1987).

Kimmins (1987) suggests that based on the prior definitions that the term ecosystem is more of a concept, rather than a physical entity. He goes on to define ecosystem by six major attributes.

A. The structure, how the abiotic and biotic components are structured within the system.

B. The function represents the constant exchange of matter and energy between the physical environment and living community.

C. Complexity is derived from the high level of biological integration that is inherent in all ecosystems. All events and conditions in ecosystems are the result of multiple factors. They are, therefore, difficult to predict without a considerable knowledge of the structure and functional processes of the ecosystem.

D. Interaction and interdependency represent how the system is so complete in its interconnectedness of the various living and non-living components that a change in one will ultimately lead to a change in almost all other components of the system.

E. No inherent definition of spatial dimensions means that while defining the bounds of a population or community is possible, it is impossible to define the geographical bounds of an ecosystem because of its complexity.

F. Lastly, the attribute of temporal change, how the entire structure of an ecosystem undergoes change with time.

Complexity is derived from interactions and the interconnectedness of the system over time. This interconnectivity means that, depending upon the resilience of a system, a perturbation or disturbance that occurs to one component of the ecosystem could have potentially wide-ranging impacts on the entire ecosystem (Folke et al., 2002). Disturbances can create gaps in the canopy of a forest, freeing up resources for other species to integrate (Connell, 1978; Roberts and Zhu, 2002). It can also push a homogenous, mature stand towards an heterogenous, old-growth state (Roberts and Zhu, 2002), increasing environmental heterogeneity. A disturbance may be so great, e.g., large wildland fire or severe drought, the stand may experience successional regression (Kimmins, 1974). If the frequency or intensity of the disturbance is greater than the species resilience to that disturbance may eliminate the species altogether (Connell, 1978; Kimmins, 1974; Roberts and Zhu, 2002). A disturbance, such as climate change, will inevitably impact forest ecosystem dynamics and succession because of the highly interconnected nature of the system.

One way to model this complexity is through hybrid process-based models, such as the Forest Landscape Model. The FLM (Bourque, 2019) uses historical and future projections of climate along with historical and projected biotic information to predict future forest composition. The FLM simulates forest species competition, and succession while modelling the complex interactions between the biotic and abiotic features of a given landscape and/or sample plot.

Climate Change

Vegetation shifts have occurred in the past due to abrupt changes in climate. These shifts were studied using palaeoecological records, which exist in the form of a dense fossil pollen network. These pollen records have allowed researchers to interpret historical tree composition and climate of the areas, where these records were found (Foster et al., 2006). This pollen network was first identified by Deevey in 1939 in sediment cores (Foster et al., 2006), which contained a consistent series of fossilised pollen zones taken from lakes and bogs within the northeastern United States (Foster et al., 2006). Deevey interpreted these fossilised pollen zones as the ecological response to postglacial climate change. From these records, a dramatic historical decline in hemlock (*Tsuga* spp.) was observed (Foster et al., 2006; Shuman et al., 2009). Initially this decline was thought to be solely driven by pests and/or pathogens (Davis, 1981), but has since been attributed to excessive climatic variability in the eastern part of hemlock's natural range, along with autoregressive ecological and evolutionary processes (Foster et al., 2006). At the same time, the same abrupt events accelerated other long-term trends, such as regional increases in beech (*Fagus* spp.; Shuman et al., 2009). The observed response times in these examples have shown historical forest succession was rapid relative to species generation times and dispersion methods. Instead, this response was attributed to increasing mortality rates for mature trees brought on by increases in susceptibility to fire, wind, and disease caused by abrupt climate change (Williams et al., 2002).

Given historical precedence set by the pollen record, and knowledge that climate change is occurring on a global scale, models are needed to project future, possibly abrupt climate change. Currently, the IPCC uses GCM modelling to predict future changes in the Earth's climate. A GCM, or General Circulation Model (or Global Climate Model, for some) represents the physical processes within the Earth's atmosphere, ocean, cryosphere, and land surface, and are currently the most advanced tools available to simulate the response of the global climate system to increasing greenhouse gas concentrations (IPCC, accessed November 25, 2021).

RCM's (Regional Climate Models) are more detailed than GCM's and focus on regional processes and use high-resolution topographical data, land-sea contrast, surface characteristics, and other components of the Earth system. For this thesis, the RCM modelling was done out of the Université du Québec à Montréal and provides the projections of air temperature, precipitation, and wind speed and direction, from which annual growing degree-days and relative soil water content maps were derived.

To run a GCM, socio-economic models are used to create inputs of potential greenhouse gas emissions based on current socio-economic trends. Socio-economic models provide basic parametric assumptions for the GCM-RCM couplet to represent the most likely future scenarios (Moss et al., 2010). These assumptions provide the basis for different pathways that can be taken. Ranging from aggressive mitigation to a business-as-usual state. In the fifth IPCC Assessment Report (AR5; Topic 2, n.d.) there were four RCP identified, namely RCP 2.6, 4.5, 6.0, and 8.5. In the sixth IPCC Assessment Report (AR6; 2021), these pathways were supplanted by shared socio-economic pathways (SSP's; Masson-Delmotte et al., 2021), which by the naming convention emphasises the socio-economic linkage to global change. SSP's are meant to show the socio-economic steps required to adapt or mitigate climate change, and these pathways are most often used in climate change research to represent future states.

Unfortunately, modelling climate in this way is likely to miss abrupt changes. There is a possibility that the IPCC climate models may not be able to accurately reproduce critical thresholds or tipping points within the climate system. One such detractor is Valdes (2011), who argues that models of full complexity, like the ones the IPCC uses, cannot accurately reproduce past tipping point events (Valdes, 2011). To make his point, Valdes used four examples of past climate thresholds to test the ability of current IPCC models to accurately reproduce these tipping points. In all cases, the sensitivity of the models was noticeably off. For the Palaeocene-Eocene Thermal Maximum, the models were not particularly skilled at simulating the warm climate of the era before the abrupt change occurred. Valdes argues that if our current climate is like past conditions, this deficiency would impact our ability to predict abrupt change for the future. The desertification of northern Africa is another example, occurring between 5,500 and 9,000 years ago. The model was unable to simulate a vegetated state, which is important considering the earth is abundantly vegetated (Valdes, 2011). For the collapse of the Atlantic meridional overturning circulation, which occurred between 12,000 and 120,000 years ago, complex climate models failed to simulate such a shut-down with the magnitudes of meltwater production estimated for the past. The model was only able to simulate the oceanic circulation shut-down with a ten-fold increase in meltwater production from sources of ice worldwide (Valdes, 2011). Lastly, for the Dansgaard-Oeschger rapid warming events, which were incidences of rapid warming of up to 8^{o}C within a few decades, detected in Greenland ice cores, could not be simulated due to our imperfect understanding of pertinent processes (Valdes, 2011). In all cases, the models were flawed in some way that prevented critical thresholds from being determined.

Climate and forests are intrinsically linked; climate influences what tree species can grow on a site. Often ecosystems are defined by their climate and the flora and fauna that is best adapted to it. This is an old argument set out by Clements (1898), that 'natural vegetative formations or communities tended to develop or progress in a well-structured, predictable sequence, a product of the particular climatic patterns of a region' (MacLellan, 2006). Climate influences the type of vegetation on the site, i.e., individual species growth response and competition between species will respond directly to climate over time, which allows researchers to use analysis of past forests to infer what past climates might have been like. As stated before, our knowledge of past climates comes from our knowledge of the fossilised pollen record. There is inherent circularity within that system. By using RCP 8.5, an accepted example of predictable stationarity, this thesis asserts climate is noise so that forest-induced tipping points can be explored. One of the relevant processes associated with this is species succession.

Forest Succession

Succession as defined by Kimmins (1987) can be described in one of two ways. It can refer to the sequence in which the biotic components of a system successively occupy an area over time, or it can refer to the process of change by which biotic community members replace each other. Through disturbance and growth, the biotic and abiotic components of the stand change structurally over time. This change is driven by the colonisation of a site by "new" species, which change the composition of the site. Changes in the biota, in turn, have an impact on the physical characteristics of the site (Kimmins, 1987).

New Brunswick is expected to get warmer and wetter over the next 100 years due to anthropogenic climate change (Rustad et al., 2012). Table 1 gives the historical trends leading to this conclusion. This change in climate will fundamentally alter the abiotic factors influencing tree growth and competition within New Brunswick's forests on timescales within the lifespan of forest trees. This rapid change is expected to create lags in vegetational response, leading to complex patterns in overall stand response (Taylor et al., 2017). Adding a layer of complexity to this, past environmental conditions can play a significant and continuing role in the biotic and abiotic structure of most forest ecosystems (Christensen, 1989). Changes in past conditions, even small changes, can have an extensive and long-lasting impact on vegetation present on the site. When taking all this into consideration, every point in time from an ecological perspective, can be considered unique (Bergeron and Dansereau, 1993; Christensen, 1989). This means a species-specific growth curve can vary across time, it is not a static ideal for any location.

Table 1. Shows how the climate of the Northeastern USA and New Brunswick by extension is likely to change given different projections. These projections represent historical, low, and high emissions scenarios, with the more dramatic impacts occurring on the high emission scenarios, adapted from Hayhoe et al. (2007) and Rustad et al. (2012).

Climate Variable	Time Period	Total Historical Change	Historical Change 1970-2000	Projected Change to 2099, Low Emissions Scenario	Projected Change to 2099, High Emissions Scenario
	Temperature, °C				
Annual Temperature	1900-1999	+0.8	+0.75	+2.9	+5.3
Winter (DJF) Temperature °C	1900-1999	+1.20	+2.10	+1.7	+5.4
Summer (JJA) Temperature, °C	1900-1999	+0.70	+0.36	+2.4	+5.0
	Precipitation, mm				
Annual	1900-1999	+100	-24	+72	+144
Winter	1900-1999	-5	+9	+25	+63
Summer	1900-1999	+10	-0.9	+2.8	0
	Phenology, days				
First Leaf	1916-2003	-3.8	-6.6	-6.7	-15
First Bloom	1916-2003	-3.6	-2.8	-6.3	-16
Snow cover per month	1950-1999	-0.2	-1.6	-2.4	-3.8

Succession is a continuous, complex process. This complexity comes from how species interact with one another, as well as the interactions between biotic and abiotic forces, i.e., climate within an ecosystem. Given these moving elements, abrupt change may be difficult to detect. As demonstrated in Valdes (2011), exploiting palaeoecological and palaeoclimatological data one can identify when thresholds are surpassed, but modelling the complex processes involved with these thresholds is difficult to do (Valdes, 2011). Therefore, there is a need to take the complexity associated with these processes and simplify it. Climate as a driver and species growth curve as a response, it is possible to simplify the inherent complexity. One way of doing this is to unpack these complex relationships through the concept of thresholds.

Thresholds

The current IPCC Assessment Report (AR6) examines the possibility that 'our actions or inactions' may be fundamentally altering the very nature of environmental systems by forcing them beyond critical environmental thresholds (Masson-Delmotte et al., 2021). The concept of tipping elements can be traced back to an article by Lenton et al. (2008), wherein they describe the subject of a tipping point event as a "…subsystem(s) of the greater Earth system, which are at least subcontinental in scale, can be switched under particular circumstances by small perturbations into a qualitatively different state" (Lenton et al., 2008). Simplified, a tipping element is a system component that can experience a shift into a different state through forcing. It is important to note though, that the concept of 'thresholds'[1] has a much broader meaning and has been used extensively by scientists to track dynamic processes, whether natural or socio-economic.

Historically, the concept of critical thresholds, and the related term tipping points, have been related to dramatic environmental events and/or processes which are classified as a 'bifurcation' of the system (see Figure 1, after IPCC AR6). Generic bifurcation theory can distinguish between three possible kinds of bifurcations, namely safe, explosive, and

[1] The Oxford English Dictionary defines threshold in three different ways that are of interest to this thesis: i. "The beginning of a state or action; the starting point or early part of an undertaking, experience, etc.; the onset or outset of something." ii. "The border or outer limit of something (literal and figurative); the line or point crossed on entering something (esp. a region or place)." iii. "The magnitude or intensity that must be reached or exceeded for a certain reaction, phenomenon, etc., to occur. Also more generally: "a certain limit or level beyond which something comes into effect." These three definitions can be considered the standard. However, the concept of thresholds can be interpreted in several different ways that change as the complexity of the system increases.

dangerous. In each case, an attractor loses stability, and the system moves to an alternate attractor, or stable state (Ashwin et al., 2012). The moment when an attractor loses stability is the threshold, even though the impacts of crossing this threshold may be delayed (Ashwin et al., 2012).

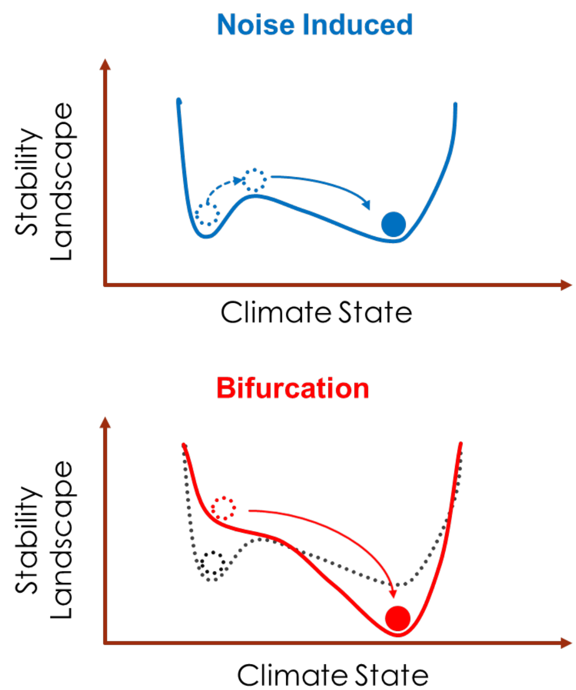


Figure 1. A climate state is implied by the depth of the valley. The current state of the system is represented by a ball. Both scenarios assume that the ball starts in the valley on the left-hand side (black dashed lines in the lower panel) and then through different mechanisms, dependent on the type of tipping point, transitions to the valley to the right (coloured lines). The diagram in the upper panel represents noise-induced tipping point events. These tipping points develop from fluctuations, known as “noise,” within the system, while the stability landscape remains stationary. The fluctuations can either represent a series of small perturbations or one large perturbation that pushes the system into a new stable state. Bifurcation tipping events occur when a critical level in the forcing is reached, which shifts the shape of the stability landscape (lower panel). Under gradual anthropogenic forcing the valley to the left begins to narrow through forcing and eventually vanishes at the tipping point, forcing the system to transition to the valley on the right-hand side (adapted from Masson-Delmotte et al., 2021).

More recently, repetitive weather events and disturbance, such as drought in the Amazon and fire in the boreal forest (Baltzer et al., 2021), have also been shown to result in dramatic ecosystem-wide changes. These chronic processes are categorised as “noise” and are intended to acknowledge that tipping points need not be initiated by dramatic climatic changes (i.e., bifurcations) alone, but can also be the result of gradual changes in the climate as expressed by the various RCP scenarios (Lenton et al., 2008). While the concept of thresholds has been tied to natural processes here, human activity may initiate thresholds as well. Either through indirect action, such as producing GHG’s and other air pollutants that contribute to climate change or through direct human action, such as forest harvesting.

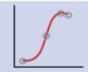
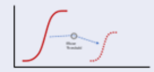
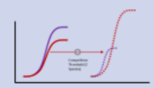
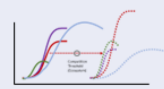
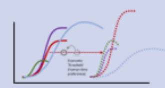
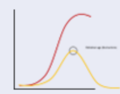
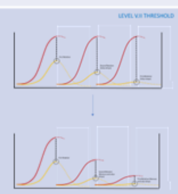
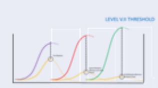
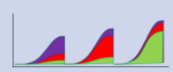
To examine noise-induced environmental thresholds, this thesis will be using tree species’ vital attributes, more specifically vital attributes to GDD and SWC (Appendix A1). Typically plant metabolic processes and growth increase with an increase in temperature (Nilsen et al., 1996). A plant’s range can be correlated reasonably well to the annual heat inputs and GDD (Hassan et al., 2007), resulting in lower, upper, and optimum limits. Tree species differ in their soil water requirements, which, in turn, have their own limits (Oliver et al., 1996). Using historical and future climate scenarios, as well as species limits, one can track potential species response to climate change. Passing either the lower or upper limit can represent an environmental threshold, where the tree species can no longer grow on a particular site, whereas hitting the optimum is also a threshold, where the tree species experiences potentially optimal growth. This is obviously a simplification of complex processes; however, it can be useful to track changes in tree species biomass over time, while comparing growth to the species’ vital attributes.

Within the maritime forest ecosystem of eastern Canada, there is a possibility that these forests may experience a tipping point or critical threshold over scales of direct relevance to socio-economic systems. Changes in the growth response of individual tree species based on RCP scenarios, may lead to dramatic system-wide impacts in terms of forest-species composition and/or forest structure. Such changes may be classified as 'noise-induced' (Masson-Delmotte et al., 2021), pushing the Acadian Forest into a new state, where noise is defined by the gradual changes in temperature and precipitation implicit in RCP scenarios. The proposed mechanism behind such dramatic change is interspecific competition as based on species vital attributes. The Forest Landscape Model (Bourque, 2019) will be used to unpack the nature of such potential tipping points. This model represents an end point in terms of our current technical ability to 'model,' and thereby project forest system complexity. My task here will be to approach this complexity incrementally by reviewing historical attempts to represent forest-climate dynamics through the conceptual lens of 'thresholds.'

Given complexity of the problem, and the notion of stationarity that I decided to start with the most simplistic models of environment human interaction, and using the concept of thresholds, I built up complexity to extract the essential elements of our modelling assumptions to bring us to the point where we can include climate change in management decisions.

In considering these assumptions, heuristics, and models, I was guided by Levins' notion of trade-offs. In modelling you can have a precise and realistic model (Type I), but it will not be general, or a general and precise model, but not realistic (Type II), or you can have a realistic and general model, but precision will be sacrificed (Type III). The conceptual framework (Table 2) has five separate levels with increasing complexity; going from a Levins' Type II model, where realism is sacrificed for generality and precision, to a Levins' Type I model, where generality is sacrificed for precision and realism (Levins, 1966). As the model becomes more complex it loses its ability to be general and becomes more specific.

Table 2. Presents a summary of forest landscape models within a modelling spectrum covering incremental system complexity from Levels I to V.IV. Models in Levels I–IV represent models based solely on ecological thresholds or constraints, whereas models in Levels V–V.IV represent models attending to both ecological and human-induced thresholds.

Level	Description	Associated Graph
I	Individual, logistic growth curve and associated transition points. The simplest forms of forest-related *thresholds*.	
II	Logistic growth curve *transition* (i.e., dynamic change in curve parameters across time – *linear\non-linear*). Increasing complexity in terms of forest-related *thresholds*.	
III	Competitive interactions between two species (i.e. between species\site specific growth curves).	
IV	Competitive interactions between multiple forest species as expressed in the output of the *Forest Landscape Model*.	
V	Human disturbance *thresholds* (i.e. harvesting) in terms of perceived value (i.e. forest rotation). This form of *threshold* is placed on top of the increasing layers of complexity described above.	
V.I	A single curve based upon a social discount rate of 3%, which identifies the maximized value of the logistics growth curve at a certain point in time; i.e., the rotation age. Simplest form of *human thresholds*	
V.II	Extends the planning horizon to contain multiple harvests for a single species. Implied infinite series.	
V.III	Considers climate's effects on multiple species over multiple harvests. Re-evaluation after every harvest to judge which single species to plant.	
V.IV	Plant Multiple Species on the same site after each harvest re-plant multiple species on the same site, which allows for competition. Maximizing for Total Site Volume of three species.	

Conceptual framework

Thresholds are typically understood as an event within a given system that moves that system to a new state. Naturally the idea of an *event* is subject to interpretation and so must be defined more explicitly, with reference to the system under consideration. Thus, thresholds need a defined scale; a climate event could take place over 5,000 years, or it could take place over several hours, e.g., due to an extreme weather event or storm. What needs to be established is the state before and after the threshold is reached, as well as its reversibility and impact on a human timescale. To do this, this thesis proposes a 5-level heuristic to explain these potential thresholds, from the individual tree to the ecosystem level, and finally to the human, socio-economic level.

The first level in the conceptual framework is represented by the logistic growth function. The logistic function was initially introduced by Pierre-Francois Verhulst in 1845. Verhulst proposed that a population in the early stages of growth would increase exponentially until such a time when crucial resources became limiting (Verhulst, 1845; Kingsland, 1982). Put another way, what the logistic growth function shows is the cumulative change in a population over time. The population begins with exponential growth as represented in the steep ascension of the curve. At some point, the population hits an inflection point where growth begins to become curtailed by environmental limiting factors, such as competition, or lack of available resources. Eventually a population's growth slows down nearly to zero as the population hits its carrying capacity. The result of this is an S-shaped (sigmoidal) curve known as a logistic curve. The equation for the simplest version of this curve is:

$$N = \frac{K}{1 + e^{a-rt}} \tag{1}$$

where N represents the number of individuals, t time, e the base of natural logarithms, K the carrying capacity or upper asymptote of growth, r the intrinsic growth rate or the maximum rate of increase in an unrestricted population, and a is a constant of integration. For this thesis, a modified curve was used, where P_0 or initial population size, was used to represent an existing site (Kingsland, 1982):

$$P(t) = \frac{K}{1 + \left(\frac{K - P_0}{P_0}\right) e^{a-rt}}. \tag{2}$$

The right-side of Figure 2 shows the modified logistic growth curve (Kingsland, 1982). This modified growth curve represents Level I in the conceptual framework. This curve shows the population of species x through time, from a population size near zero to its carrying capacity at the asymptote of population growth (i.e., K). The left-side of Figure 2 shows the associated *thresholds* with the logistic growth curve. Previously mentioned were the three stages of a logistic growth curve, exponential growth, inflection, and decelerating growth. These three *stages* are associated with four *thresholds* as illustrated in Figure 2.

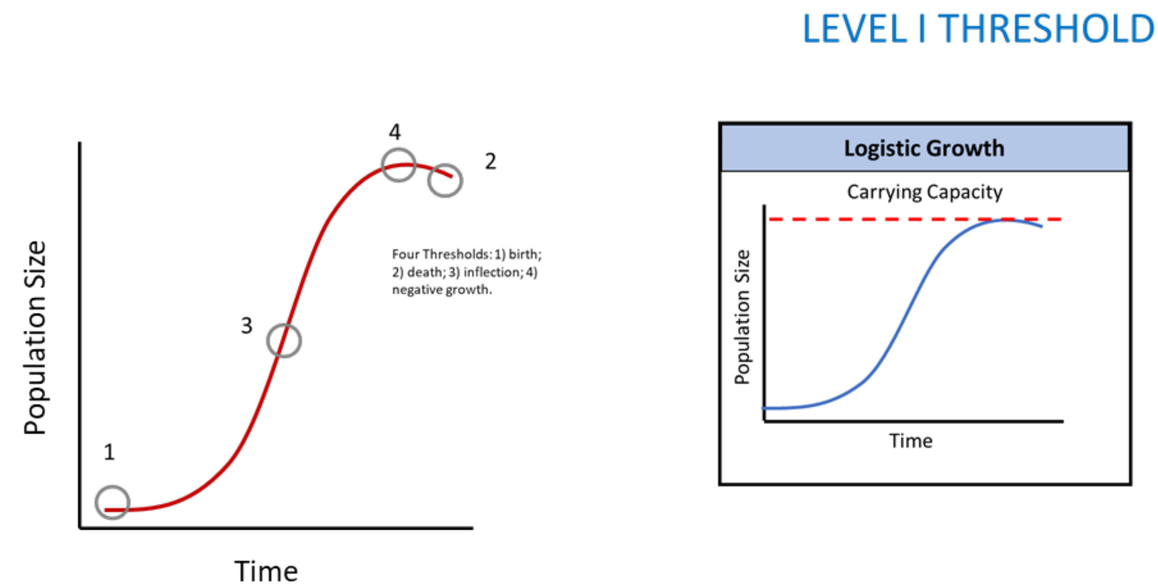


Figure 2. Individual, logistic growth curve and associated transition points. The simplest forms of ecological (forest)-related thresholds.

Birth initiates the curve. Without this initiation there is no growth, and the species cannot grow on the site. An example of a birth threshold is if seedlings from a tropical climate were planted in New Brunswick, because of the immense difference in climate, the seedlings may fail to germinate. This is an extreme example, but if a tree is unable to germinate on a site, then that tree is functionally dead to the site. If a site had a species on it but is no longer able to support that species (due to external changes) then that would in essence represent a threshold. Death is self-explanatory as it is fundamental to every living organism and is the ultimate *threshold*. Death occurs for a multitude of reasons, and can be associated with age, intense competition among members of a community, disease, environment-induced stress, and so on.

Inflection and decelerating growth are related and are characteristic of the fundamental drivers of the logistic growth curve (Figure 2). A species would see exponential or geometric growth on a site if not for constraining factors that produce negative feedback. This negative feedback is known as environmental resistance.

As a population starts to increase from a single breeding unit, the environmental resistance is low, and the population expands exponentially. With this increase in population, environmental resistance increases (the tangential slope, derivative of the curve decreases), which steadily reduces the rate of population growth until the resistance becomes so great that no further increase is possible (Kimmins, 1987). The point in which geometric growth stops is the inflection point, and the point where the environmental resistance becomes so great that further growth is impossible, reaching the point of negative growth (Kimmins, 1987).

Although not often considered, given the need for simplifying assumptions (i.e., reduction of complexity through assumptions of stationarity), growth curves may change over time, as seen in Figure 3. In the current 'climatic' context we can interpret this in one of two ways, linearly or punctuated. In the first situation, the *noise* of climate change (Figure 1) is expected to act on the growth rate and/or the carrying capacity of the site for a species in a linear fashion, with either or both the growth rate or carrying capacity increasing or decreasing consistently through time. The latter situation is indicative of a punctuation or *threshold* the species crosses, which changes by increasing or decreasing the growth on a site (Figure 3).

The way the Forest Landscape Model handles these changes is complex, but this thesis will place these changes within the context of the fundamental drivers of species growth (namely, SWC and GDD). Both SWC and GDD have limits inherent to them, an upper, a lower, and an optimum. The optimum limit is when the species growth and carrying capacity is at its peak. The further away the input is from this optimum, the lower the growth rate or carrying capacity will be. Crossing the lower and upper limits on the other hand represents periods of no growth, and the model then invokes mortality in affected individuals. In the first year of no growth a 25% chance of mortality is applied, for each subsequent year up until four years, this mortality factor is increased. After four years the tree is assumed dead. Therefore, a species on the lower or upper limit has an increased likelihood of mortality than a species near its optimum. If temperatures rise past a certain threshold, which may cause drought to occur in an area, or if precipitation is so heavy that an area undergoes permanent saturation, these would also be considered thresholds, as both can impact the growing characteristics of a site.

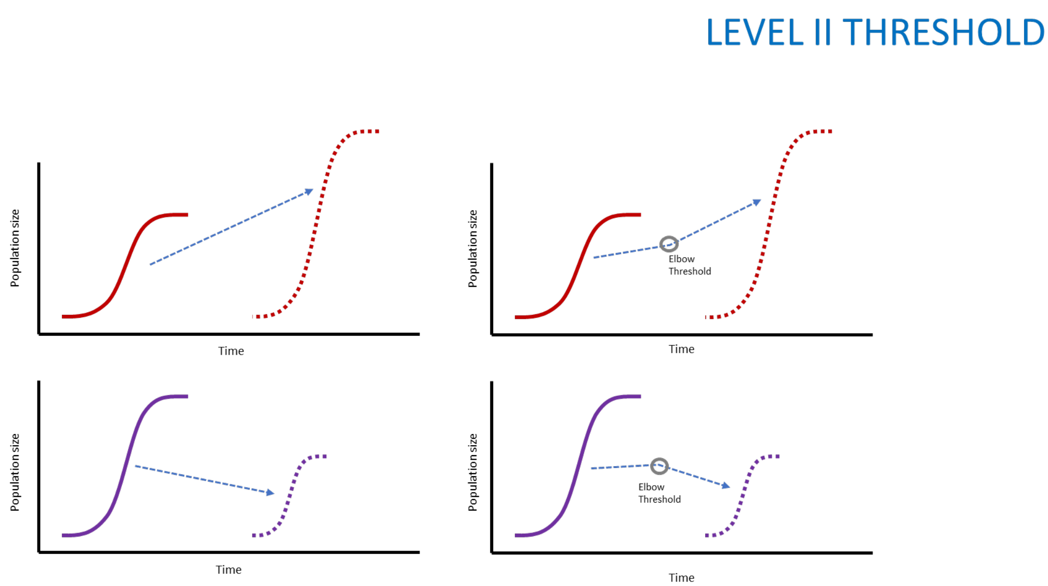


Figure 3. Logistic growth curve transition (i.e., dynamic change in curve parameters across time, linear or nonlinear), increasing complexity in terms of ecological (forest)-related thresholds.

This leads to Level III thresholds which account for *competition*, which is the central focus of this thesis. Levels I and II thresholds show the complexity of growth curves over time, with the implication that a specific potential growth curve, for a specific species over a specific time, is unique based on current environmental factors as illustrated in Figure 4. Any species may be forced into an optimum or a more downgraded growth rate and carrying capacity. A simple example of this is the *noise* of continuous climate change, which forces the growth curve to change with time, i.e., in an abrupt or gradual manner. Historically, climate has been held constant (i.e., stationary) to eliminate this level of complexity given the inability to account for it.

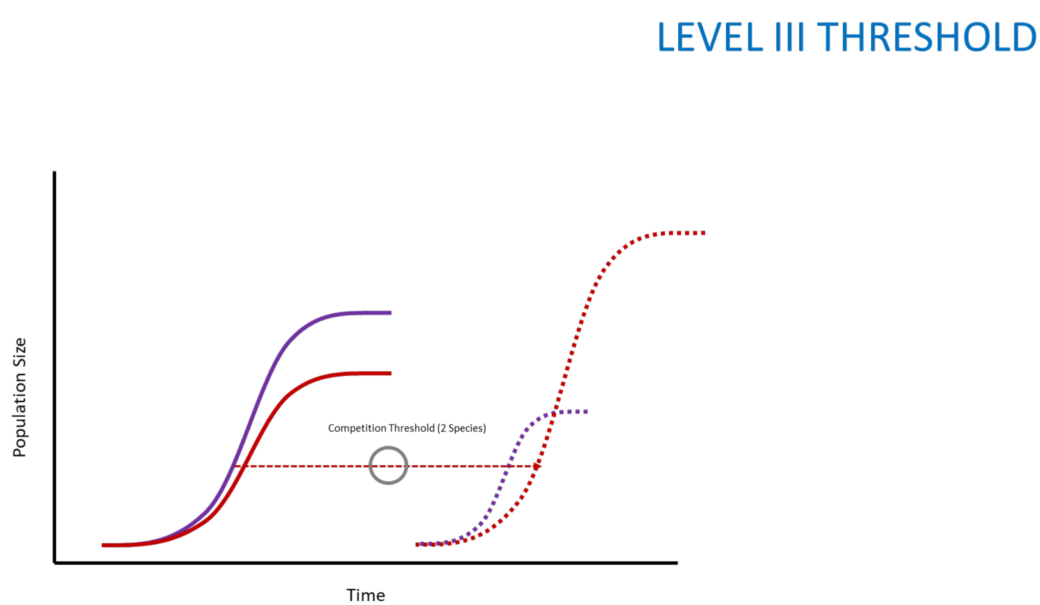


Figure 4. Competitive interactions between two species (i.e., between species- and site-specific growth curves), continuing increases in complexity in terms of ecological (forest)-related thresholds.

Level III thresholds show two growth curves in *competition*, though long understood in a theoretical context is nevertheless hard to account for in modelling natural ecosystems (although see JABOWA, 1969). When there is a minimum of two species on a site, each may benefit each other, as a source of food and/or shelter, or they may constitute a threat to one another in several different ways (Kimmins, 1987). Kimmins stated that interspecies relationships, which may not always be readily apparent, is a major contributing factor in controlling the performance and even the presence of a species in an ecosystem. Through antagonistic and beneficial relationships, the abundance and distribution of species populations and the diversity of species in an ecosystem is maintained. Antagonistic relationships include non-consumptive physical exploitation, consumptive physical exploitation, antibiosis, including allelopathy, and competition (Kimmins, 1987).

Both intraspecific and interspecific competition are important drivers within the FLM. Intraspecific competition is competition between individuals of the same species and interspecific competition is between individuals of different species. Competition occurs when two individuals attempt to utilise the same resource when that resource is in limited supply, or when the resource is not in short supply, but the two species interfere with each other's use of it (Kimmins, 1987, pg. 368). This is related to the concept of the competitive exclusion principle, which states that "two species competing for the same resource cannot coexist indefinitely. One of the two species will eventually dominate" (Kimmins, 1987, pg. 370). However, while this may work in a laboratory environment between two competing species, in nature species evolve to exist in different ecological niches, allowing them to survive on a site, despite being outcompeted by more competitive species (Kimmins, 1987). The main driver of competition between tree species is light. Different species have different shade tolerances that allow them to survive in different levels of light. So, a species with a low shade tolerance, such as pin cherry, cannot become established if the plot is dominated by balsam fir (see Table A1, for species-specific shade tolerances).

Growth curves represent a snapshot in time. Growth curves are not static, every moment, given varying environmental conditions, can change a growth curves' trajectory. Because of this, this thesis asserts that the shape of the growth curve, and the competitive ability of the species to survive on the site will change over time, as climate changes the environmental variables, as illustrated in Figure 4.

A possibility for New Brunswick is that boreal species (e.g., balsam fir) which currently dominate the landscape may see a shift in their ability to compete as temperatures rise within the next 100 years, while temperate species have the possibility to become more competitive as temperatures rise, leading to a threshold where temperate species take over the Acadian Forest (Taylor et al., 2017). And while the RCP-climate scenario is also nonlinear, this may hide competitive interactions as the dominant driver on multi-species sites.

Extending this understanding of causal determinants, Tansley stated that ecosystem level system behaviour is greater than the sum of its parts. The complexity within an ecosystem is a combination of "the total net action of the effective environmental factors and the combined actions of the individual organisms themselves"

(Tansley, 1935, pg. 291). What this means is that everything discussed in the previous three levels applies here and has an added layer of complexity through the interactions between multiple species by way of competition (Level IV). These interactions, along with the history of the site, will fundamentally influence competition and succession through time (Kimmins, 1987). For example, balsam fir and pin cherry, depending on the history of the site (i.e., initial species composition), the manner in which species compete on the site may change. A site starting from bare ground conditions will see early successional, and shade intolerant species take advantage of the lack of overstory canopy and undergo rapid growth. While sites with a well-developed overstory canopy, such as in mature balsam fir stands, shade intolerant species that make their way to the understory are promptly eliminated from the site. In contrast, shade tolerant species impacted by gaps in the overstory canopy will initiate rapid growth (release) due to improved lighting conditions in the understory. Given changing environmental conditions, species taking advantage of these gaps will vary (Botkin, 1993; Kimmins, 1987; Taylor et al., 2017).

What Level IV does is represent multiple growth curves against one another to demonstrate competition through time, as displayed in Figure 5. Implied forest dynamics is consistent with the Forest Landscape Model, which causes multiple species, on a site or at the landscape level, to compete amongst each other over time relative to their vital attributes. This level features much more complexity than the previous levels, and this complexity has the potential of making interpretation much more difficult. In Figure 5, there are four different growth curves, red, purple, blue, and green, and changes in environmental factors affect the ability of the species on the site to compete.

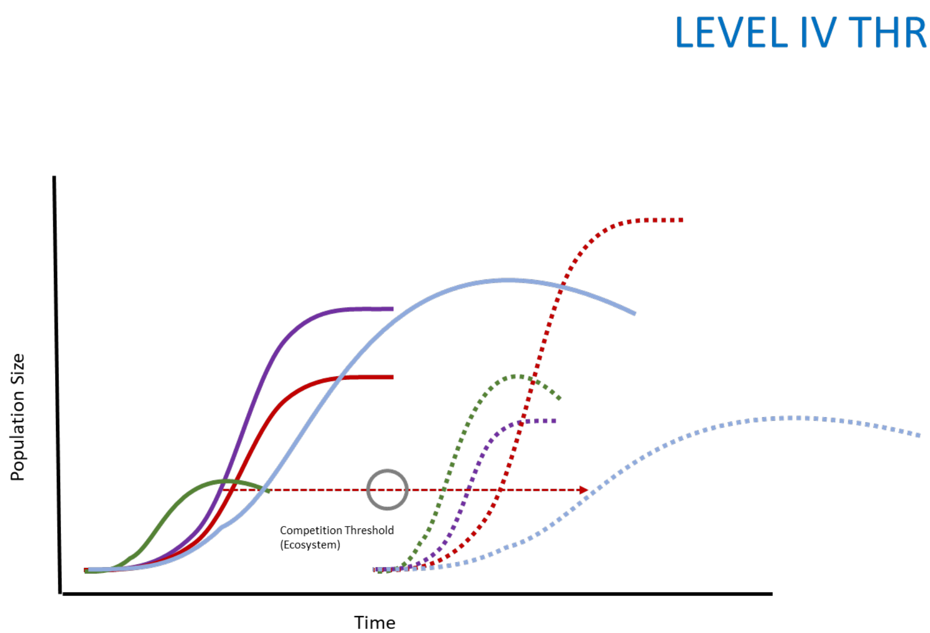


Figure 5. Competitive interactions between multiple forest species, continuing increases in complexity in terms of multiple species competition, as expressed in the output of the Forest Landscape Model.

It is important to note that competition thresholds for ecosystems are critical thresholds as understood in the current literature and reviewed extensively in the latest IPCC WG II, suggesting that a change in the dominant species on a site is representative of a threshold being surpassed. For the FLM, this could be represented through a particular species, or a type of tree (i.e., temperate deciduous or boreal coniferous) that takes over the site. As such, FLM is capable of accounting for these levels of complexity, but it is in the interpretation of model results where difficulty lies for a given site or region. In other words, FLM can represent these fundamental dynamics, but it is important to understand the multiple drivers that are responsible for creating these new patterns.

Finally, it is important to account for humans, themselves, as a major driver of landscape change (Lewis and Maslin, 2015; Steffen et al., 2007). Humans have increasingly become the primary determinant of environmental thresholds. Either through direct or indirect action, humans can force the system towards new states. This thesis has already spoken about the indirect actions that humans do to change the climate on a global scale, which impacts forests and by extension forestry practices at the local scale. While direct action in terms of forestry would be harvesting and planting of stands, stand rotation is typically understood in terms of economics, which requires a different level of interpretation.

In his 1974 paper, Kimmins (1974) views rotation and succession through a human lens. He asserts that the concept of resource renewability is not a biological concept, but a socio-economic one. For an ecological system to be considered non-renewable means that the time span involved in the recovery of the said system, to a point where it generates socio-economic benefits again, needs to be greater than the contemporary society's timescale (i.e., 30–40 years), even if it is obvious that the resource will eventually be reformed (Kimmins, 1974). Kimmins explained this using the concept of timber mining. Even though trees are a renewable resource, meaning that recovery is possible, the timescale that this recovery may be happening may be considered irreversible by human standards (Kimmins, 1974; Lenton et al., 2008; Masson-Delmotte, et al., 2021).

Human standards are based on a preferential timeline, which biases decisions on resource and wealth extraction. Ironically, when applying these concepts, assuming economics will add complexity, it *in fact simplifies* the system. By applying economic logic, which requires the maximisation of the productivity of a stock in the short term and the investment in increasing supply in the long term (MacLellan and Carleton, 2003), we, as managers, intercede in the system (Figure 6). Economic logic completely ignores the signals from climate and ecology and brings things down to provide simplistic representations of the forest to allow decisions to be made (MacLellan 2006).

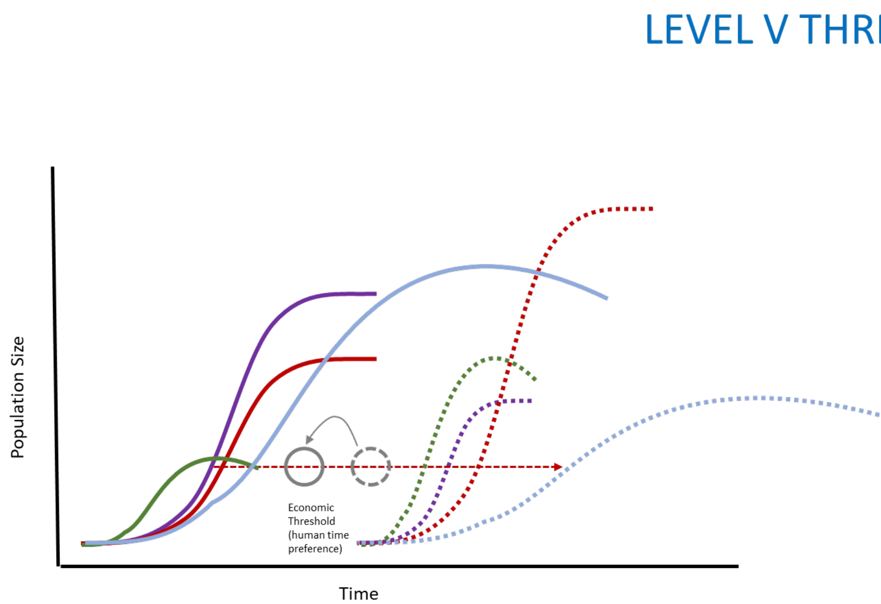


Figure 6. Human-induced thresholds (via harvesting) in terms of perceived value (i.e., forest rotation). This form of threshold is added on top of the increasing layers of complexity, as described earlier.

There are two ways, often used together, which allowed me to apply economic logic to forest ecosystems. The first way is by using net present value (NPV). NPV represents the present value of cash flow at the required rate of a project as compared to the initial investment. In other words, it is a method of calculating the return on an investment (Gallo, 2014). NPV is directly related to the potential growth of a product, and each time segment can be considered a unique point within the NPV curve. In this case, as biomass increases the NPV increases until such a point where the returns start to diminish. For forestry, the peak of this curve is usually when a rotation of a stand occurs. For this thesis, a discount rate of 3% (Julius, 1999) is applied.

NPV can be used in conjunction with the soil expectation value (SEV) or land expectation value. SEV assumes NPV of an infinite series of identical, even-aged forest rotations, starting from bare ground conditions. This assumes the site will continue along its current trajectory in perpetuity. Future rotation's NPV curves are expected to be lower than the initial rotation due to the human preferential timeline, with some variance due to changes in, for our purposes, biomass.

These concepts then can be applied to the ecologically-constrained levels within the conceptual framework (Table 2). In Level V.1, the NPV curve provides a way to identify the timing of rotation, which is a human construct. Level V.I, focuses on a single curve without a changing climate or competition; this was accomplished by maintaining climate at a historical point in time[2], and only running Species A for one rotation. An NPV curve can then be applied to the original curve (Figure 7). What is expected from this intervention is that Species A rotation age for each successive NPV-curve will repeat itself exactly every rotation.

[2] 'Climate' is defined statistically, as the average weather conditions over a 30-year interval; once determined, weather is assumed stationary for any given moment during that period.

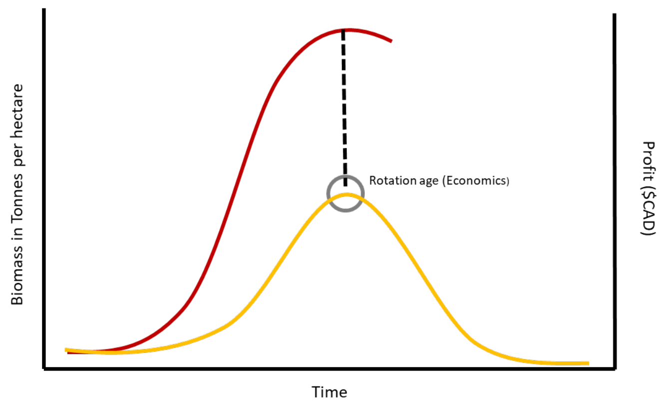


Figure 7. Relationship between biomass and NPV. A single curve based on a social discount rate of 3%, which identifies the maximised value of the logistics growth curve at a certain point in time, i.e., rotation age. Simplest form of human-imposed threshold. The red line represents changes in Species A's biomass, the yellow curve the net present value (NPV), and the dotted line is the rotation age. The horizontal axis represents time (in years), and the vertical axes on the left- and right-hand side of the graph represent biomass in tonnes per hectare and profit in $CAD, respectively.

The next step is to establish greater realism, using the ecological threshold of Levels V.II–V.IV. Establishing realism means including the impacts of climate change, multiple species stands, and re-evaluation of the site after every harvest.

Level V.II applies the infinitely repeating series for a single species (Species A) to bring a SEV into the model. For the first graph in Figure 8, what this does is maintain an infinite series of identical even-aged forest rotations, each presumed to have the same growth trajectory over time. The NPV diminishes at a constant rate between rotations due to the presumed uniformity of future growth curves. However, we know from Level II, the growth curve of a species changes over time as environmental conditions also change (Bergeron and Dansereau, 1993; Christensen, 1989), this is reflected in the second graph of Figure 8. In this case, Species A is declining over time[3], and the NPV-curve for each rotation is lower than it would have been in the first graph, due to the relationship between NPV and biomass.

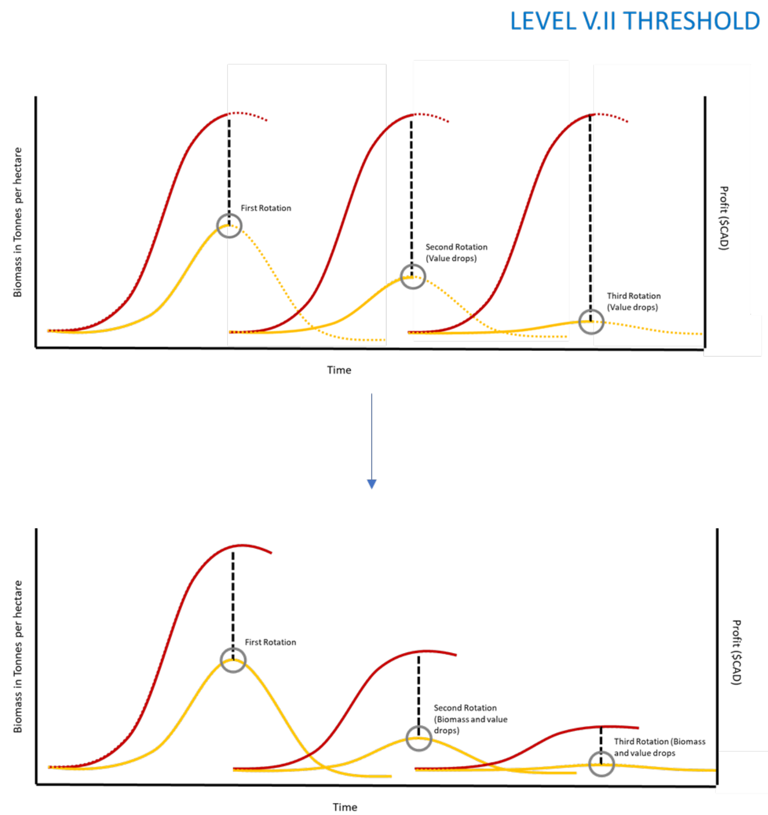


Figure 8. Extends the planning horizon to contain multiple harvests for a single species. This implies an infinite series that increases the complexity from the previous level in terms of human thresholds. The red curve represents a single species (Species A), the yellow curve the net present value (NPV), and dotted line rotation age. The horizontal axis represents time (in years), and the vertical axes on the left- and right-hand side of the graphs represent biomass in tonnes per hectare and profit in $CAD, respectively. The top graph represents the assumption that Species A's growth curve will remain constant between rotations, while the bottom graph assumes that it will change depending on the change in environmental variables.

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[3] Note that individual tree species can undergo decline or experience higher levels of growth due to climate change. This makes a point about changing growth curves over multiple rotations.

Level V.III assumes that the forest manager recognises the decrease in Species A with each rotation and decides to plant a pure stand of a different species each rotation to capture optimum growing conditions brought about by climate change. In the following example, as seen in Figure 9, Species A (in red) is the original species on the site. After the first rotation the manager consults his models and finds that Species B will do better on the site for that rotation period and plants Species B instead, and during the third rotation, they find that Species C is optimum and therefore plant Species C. In this example, timber prices, mills, disease/pests, and other costs are entirely ignored. The manager, in choosing which species to plant, creates an artificial threshold within the system, completely changing the stand to take advantage of optimum growing conditions to ultimately suit his needs.

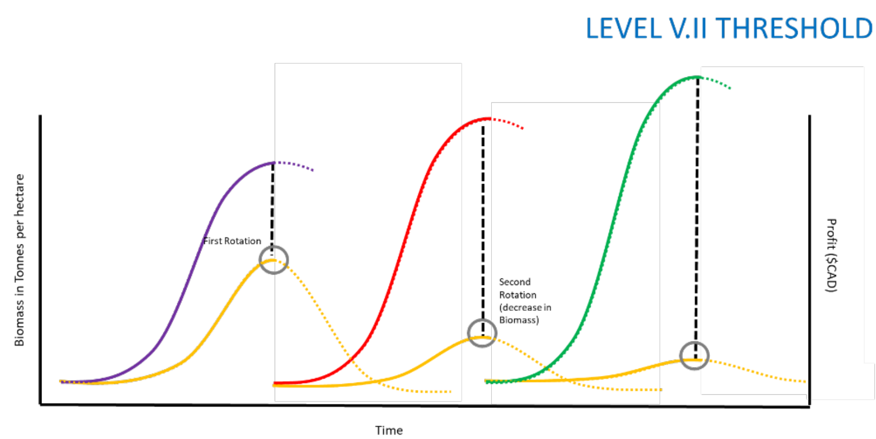

Figure 9. Considers climatic effects on multiple species, over multiple harvests. Re-evaluation after each harvest is done to determine which species to plant. The purple curve represents Species A, red curve Species B, green curve Species C, yellow curve net present value (NPV), and dotted line rotation age. The horizontal axis represents time (in years), the vertical axes on the left- and right-hand side of the graph represent biomass in tonnes per hectare and profit in $CAD, respectively.

Level V.IV is similar to Level V.III but instead of planting a single species per rotation, Level V.IV assumes the manager plants multiple species on the site instead of a single species (Noss, 2001; Whitehead, 2004). This mixture can be referred to as a "meta-species". Instead of having a pure stand of balsam fir, red maple, or beech, all three species are planted on the same site at every rotation, as illustrated in Figure 10. After each 1-year interval, the volume of the three species is summed and the NPV is applied to determine the next rotation. The idea is that competition will select the species best suited to the site, which should produce a dominant competitor suited to the environment, allowing the manager to maximise volume on the site. This is done because of the inherent uncertainty found within models due to the complexity involved within the systems they attempt to represent (Levins, 1966). By planning for uncertainty, managers can foster resilience in the system (Gitay et al., 2002; Nitschke and Innes, 2008).

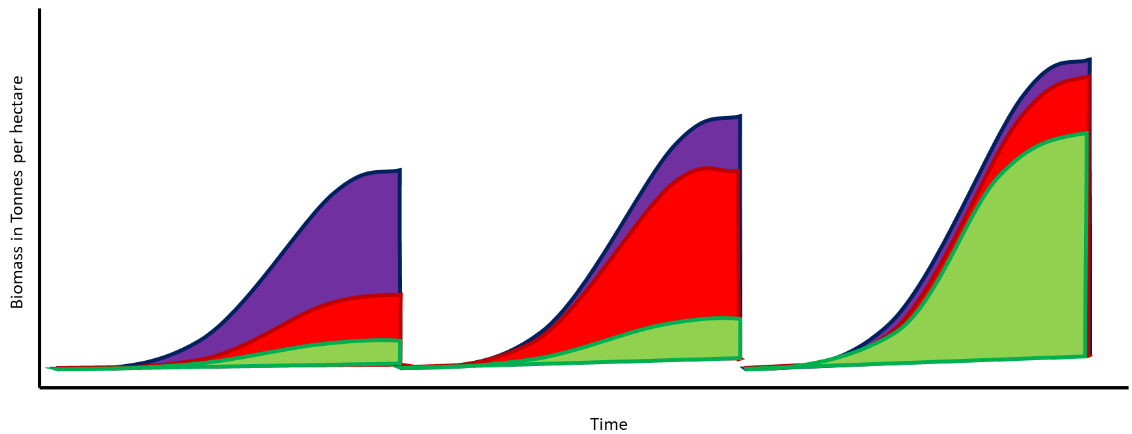

Figure 10. Multiple species are planted on the same site. After each harvest, multiple species are replanted on the same site, which allows for competition to occur. This maximises total site volume. Level V.IV represents a forest management adaptation strategy designed to increase forest resilience. The vertical axis represents biomass in tonnes per hectare, whereas the horizontal axis represents time. Each colour represents a different species. The top line in each rotation represents total biomass. The species are allowed to grow and are harvested at constant intervals.

This chapter has demonstrated the complexity within the systems inherent in forest succession and the need for a conceptual framework to properly define thresholds. While all models are imperfect, they are nevertheless required to further understand these systems and to allow us to make management decisions. This will be further explored in the following chapters.

CHAPTER 3

Modelling Approach

Modelling by its very definition is an imperfect representation of reality. To understand our relationship with reality and the environment requires isolation of 'systems and the examination of their parts and elements' (Tansley, 1935). Modelling is the representation of the interaction between these elements and is a selective dynamic abstraction of reality (Eppen et al., 1979).

The world and by extension the natural processes that govern it, form incredibly complex systems. Therefore, any attempts to create a perfect model of the world would require a complete understanding of its systems, massive amounts of computational power, and an understanding of the universe (epistemology; Levins, 1966; MacLellan, 2006; Oreskes et al., 1994). However, humans are imperfect beings, our understanding of reality is often flawed, and we lack the computational power to create a perfect model of the universe (Levins, 1966; MacLellan, 2006; Oreskes et al., 1994). Despite this imperfection, models are still massively important for they encourage human understanding of systems and influence our actions and decisions.

Through the use and integration of knowledge from multiple sources and disciplines we can have a reasonable idea of how forest succession may proceed. One way of doing this is through the decomposition of knowledge to its fundamentals so we, as managers, can identify thresholds and bolster our understanding of these systems. The conceptual framework that has been developed for this thesis is one such method. It deconstructs the concept of thresholds, through the results of the Forest Landscape Model, using simplifying assumptions to understand the complex interactions within the forest system.

The Forest Landscape Model (FLM; Bourque, 2019) is a spatiotemporal model of landscape-level forest growth (Figure 11). The FLM's purpose is to predict tree species trajectories to examine future forest-climate interactions, and forest species shift (Bourque, 2019). While the focus of this work is to project future species trajectories on the plot level, the FLM can project species trajectories up to the landscape level, using each cell in the landscape (digital elevation model, DEM, cell) as virtual forest plots.

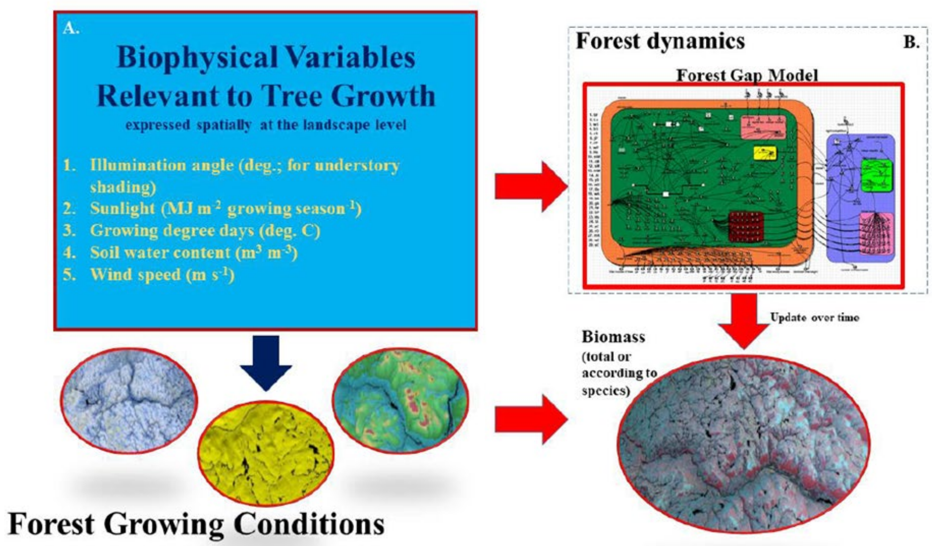

Figure 11. Schematic of the Forest Landscape Model. The FLM contains two principal components: the first component calculates the biophysical variables relevant to forest growth (A), and the second forest change over time (B) as forced by changes in environmental conditions, both from climate change and site biophysical interactions.

The analysis focuses on a detailed study of forest-state evolution under small-scale processes of interspecific and intraspecific interactions, regional potential tree species distribution, and historical climate surfaces of precipitation and temperature, as well as derived surfaces of incident solar radiation, GDD, SWC, and near-surface windspeeds from 1985–2014. Modelling forest change within individual plots requires modelling tree life-cycle processes, such as regeneration, growth, interspecific and intraspecific competition amongst individual trees, and their eventual death[4].

Species attributes determine the rate of growth of a particular species on a site. As environmental variables, such as GDD or SWC are impacted by climate change, species growth changes due to the relation between species attributes and environmental variables (Girardin et al., 2016). The closer a species is to its optimum limit for a particular variable, the higher the species potential growth becomes. Species that start at their optimum limits can only decrease, while species that start near a lower limit, such as red maple, or red spruce can only see an increase in growth up to the optimum. Forest dynamics is modelled through a forest-gap sub-component of the broader FLM (Figure 11) based on a re-writing of the GIZELA gap model (Smith, 1998) in Simile (Simulistics, UK).

Study Area

This study is focused on the Acadian Forest in the Province of New Brunswick (Figure 12), within the Atlantic Maritime Ecozone of eastern Canada. This region is characterised by a fragmented landscape of predominately forest and agriculture on variable elevation (elevations ranging from 0–834 m above mean sea level, AMSL; Bourque, 2019; Zelazny et al., 2007). About 85% of New Brunswick's land area is

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[4] Mortality due to its stochastic and nonlinear properties is difficult to model purely from field observation. Therefore, it is being handled through inversion techniques, including parameterisation guided by field data and automated data fitting algorithms (i.e., PEST); however, this is specific to individual permanent sample plots.

dominated by forests, with agriculture taking up about 6%. The Acadian Forest Region is an important region to study for climate change researchers because it is in a transition zone (ecotone) between the northern boreal forests and the temperate forests of the south.

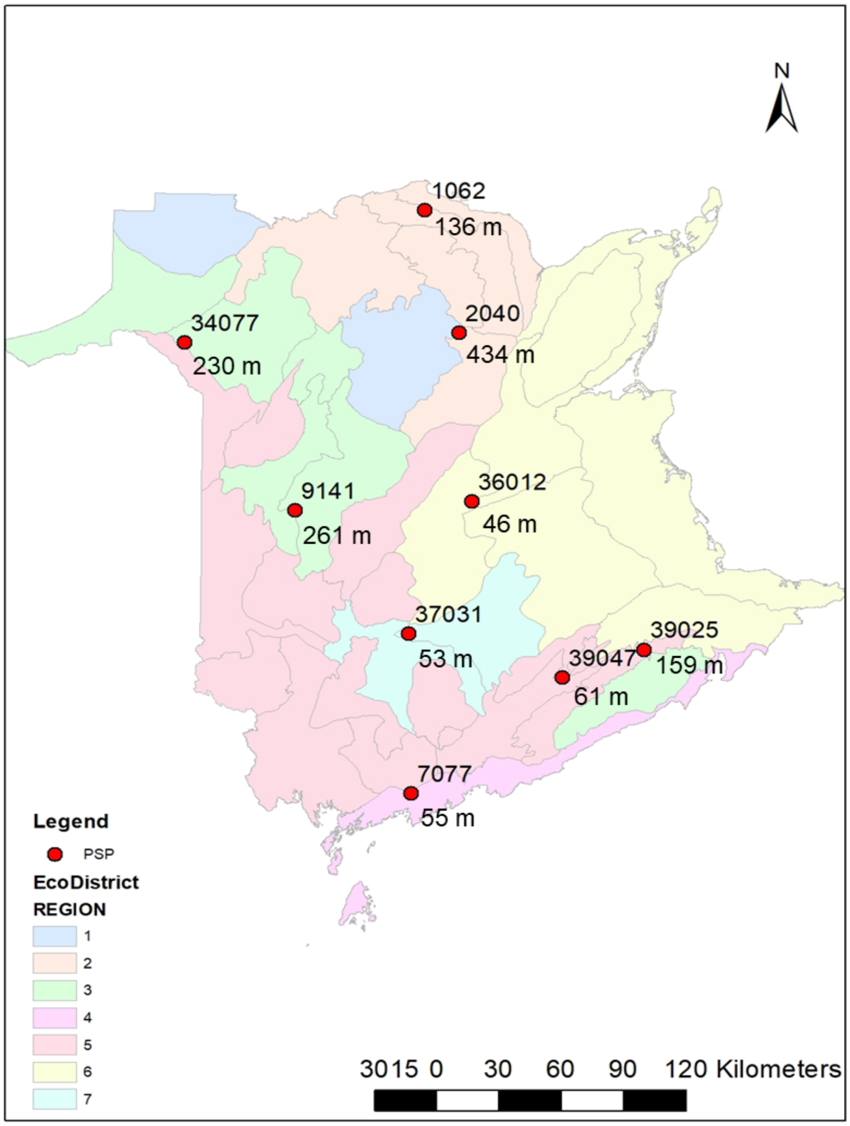

Figure 12. Map of New Brunswick (NB) with permanent sample plots, PSP's (red circles), with plot identification number and elevation (in m) identified. Initial non-bare ground conditions (NBG) for model simulation are based on the forest conditions at the time of plot establishment. Thin black lines on the map delineate the seven ecoregions of the province, i.e., Highlands (labelled 1), Northern Uplands (2), Central Uplands (3), Fundy Coast (4), Valley Lowlands (5), Eastern Lowlands (6), and Grand Lake (7).

The provincial climate is mostly influenced by the major bodies of water that surround it, the Bay of Fundy in the south, the Northumberland Strait in the east, and the Bay of Chaleur in the upper northeast corner of the province. On average, New Brunswick's winters are generally mild, spring is often late and cool, and summers are breezy with modest temperatures. The average annual mean temperature and total precipitation of the province is 5–6°C and 1,000–1,360 mm, respectively (ECCC, 2018).

New Brunswick is subdivided into ecoregions, ecodistricts, ecosections, and ecosites (Webb and Marshall, 1999), each characterised by different scaling attributes. Ranging from climate, elevation, and proximity to the coast at the ecoregion scale, to elevation, slope, drainage, and soil attributes at the ecosite scale. There are 7 ecoregions in total, namely (i) the Highlands, (ii) Northern Uplands, (iii) Central Uplands, (iv) Fundy Coast, (v) Valley Lowlands, (vi) Eastern Lowlands, and (vii) Grand Lake Lowlands (Zelazny et al., 2007).

The Highlands' climate is generally cool and wet, given to rough topography and high elevation (Zelazny et al., 2007). Compared to the rest of the province, the Highlands experience the lowest annual temperatures. The Northern Uplands' climate is defined by its lower elevations, northern slopes, and the rain shadow from the mountainous Gaspé region of Quebec. Generally, the Northern Uplands are cool and dry (Zelazny et al., 2007).

The Central Uplands consists of two different geographically separate regions that have similar climate and topography. The Central Uplands climate is cool, with ample precipitation. This region is influenced by its higher elevation, with the northern

Madawaska region benefitting from orographic lifting, and the Caledonia Uplands from the moderating effect of the Bay of Fundy (Zelazny et al., 2007).

Fundy Coast's climate is impacted by its proximity to the Bay of Fundy. Compared to the Northumberland Strait and the Bay of Chaleur, the Bay of Fundy is colder, and this moderates this ecoregion's climate throughout the year. This ecoregion sees the highest precipitation in the province, and it has a steep temperature gradient between the coastline and the inland areas (Zelazny et al., 2007).

The Valley Lowlands has a continental climate and are sheltered from the maritime influences of the Northumberland Strait and Bay of Fundy. This ecoregion generally has warmer summers and colder winters than those areas moderated by coastal waters. Because of the lower elevation compared to the other two ecoregions with continental climates, the Valley Lowlands see less precipitation (Zelazny et al., 2007).

The Eastern Lowlands fall between two rain shadows. Any moisture coming with the westerly winds is intercepted by the Highlands and the southwesterly winds are intercepted by the higher elevations of the Fundy Coast and Central Uplands ecoregions. The Eastern Lowlands are generally warmer than its surrounding ecoregions, but not as warm as the Grand Lake Lowlands ecoregion (Zelazny et al., 2007).

Lastly, the Grand Lake Lowlands have the longest growing season and warmest summer temperatures in New Brunswick. Grand Lake, of which this region is named after, is a large lake and acts as a heat sink for the entire area (Zelazny et al., 2007). It stores heat over the summer and slowly releases it during the fall and winter, moderating the nearby climate.

Permanent sample plots were created by the Canadian Forest Service and the New Brunswick Department of Natural Resources and Energy to be representative of New Brunswick's entire provincial forest (Porter et al., 2001). The purpose of these PSP's was so that the data collected could be used to define stand structure at specific points in time so that growth and yield models could be calibrated and validated (Porter et al., 2001). For this model the placement of permanent sample plots (PSP's) was based on their representativeness of forest conditions at the ecoregion scale, as well as their position within the landscape (slope, aspect, longitude, latitude; Zelazny et al., 2007).

The Forest Landscape Model is applied to forest conditions in twenty-three PSP's representative of ten different forest types: PSP's, include PSP No. 1057, 1062, 2028, 2037, 2040, 2061, 3055, 3087, 5023, 6124, 7077, 8043, 9020, 9077, 9141, 10325, 34077, 35056, 36012, 36016, 37031, 39025, and 39047. Nine PSP's were then chosen to serve as test cases. These nine plots involve a variety of terrain, elevation, and climate characteristics across the province. These PSP's include PSP No. 1062, 2040, 7077, 9141, 34077, 36012, 37031, 39025, and 39047 (Figure 11).

Tree Species and Biomass

FLM has the potential to track the temporal response of thirty different tree species native to New Brunswick (Table 3).

Table 3. Binomial nomenclature of the thirty tree species and their species codes. The tree species list includes 10 hardwood and 20 softwood species. The red lettering denotes those tree species used for demonstration purposes.

Softwood			Hardwood					
Species Name	Common name	Sp. Code	Species Name	Common Name	Sp. Code	Species Name	Common Name	Sp. Code
Abies balsamea	Balsam fir	bF	*Acer pennsylvanicum*	Striped maple	stM	*Fraxinus nigra*	Black Ash	bA
Larix larcina	Tamarack	La	*Acer rubrum*	Red maple	rM	*Fraxinus pennsylvanica*	Green ash	gA
Picea glauca	White Spruce	wS	*Acer saccharum*	Sugar maple	sM	*Ostrya virginiana*	Ironwood	Iw
Picea mariana	Black Spurce	bS	*Acer spicatum*	Mountain maple	mM	*Populus balsamifera*	Balsam poplar	bP
Picea rubens	Red spruce	rS	*Alnus rugosa*	Alder	Al	*Populus granidentata*	Large tooth aspen	ltA
Pinus banksiana	Jack pine	jP	*Betula alleghaniensis*	Yellow birch	yB	*Populus temuloides*	Trembling aspen	tA
Pinus resinosa	Red pine	rP	*Betula papyrifera*	White birch	wB	*Prunus pennsylvanicum*	Pin cherry	pC
Pinus strobus	White pine	wP	*Betula populifolia*	Grey birch	gB	*Quercus rubra*	Red oak	rO
Tsuga canadensis	Hemlock	He	*Fagus grandifolia*	Beech	Be	*Sorbus americana*	Mountain ash	mA
Thuja occidentalis	Eastern Cedar	ec	*Frazinus americana*	White Ash	wA	*Ulmus americana*	White Elm	wE

The nine reference PSP's had fewer then seven tree species at a time. The final runs had fewer than eight initial species per plot (Bourque, 2019). In total, between the 23 PSP's, 17 tree species were represented at the time of stand initiation. The complete species list (Table 3) becomes more important through time, as species shift due to climate change, and their associated trajectories are extended beyond the calibration period. With climate change, and the anticipated changes in forest succession patterns, its important to address a wide range of potential new tree species that may migrate to a site due to improved growing conditions.

The primary variable used in tracking forest change in the FLM is total species biomass (in tonnes ha^{-1}). To be able to compare model results with field estimates of species biomass, actual aboveground tree biomass (AGB) was estimated for all tree species present on a plot, with a diameter at breast height (DBH) > 9 cm. Originally, 17 tree species were used in the calibration of FLM because they represented at least 3% of the total AGB in the Acadian Forest of northeastern North America (Taylor et al., 2017).

Allometric equations were used to estimate PSP-level AGB because they avoid using destructive harvesting methods. However, due to variation in geographical location, equations can vary, chiefly in their coefficients (Chave et al., 2014). These equations can either be based on DBH alone, or DBH with tree height (Table A2). For this study, total tree biomass was calculated by summing individual calculations of AGB for foliage, branches, stem, and bark, using DBH as the sole independent variable (Table A2). DBH-based equations used in this thesis are those developed by Lambert et al., (2005), i.e.,

$$y_{wood} = \beta_{wood1} DBH^{\beta_{wood2}}$$

$$y_{bark} = \beta_{bark1} DBH^{\beta_{bark2}}$$

$$y_{foliage} = \beta_{foliage1} DBH^{\beta_{foliage}}$$

$$y_{branches} = \beta_{branches1} DBH^{\beta_{branches2}}$$

$$y_{AGB} = y_{wood} + y_{bark} + y_{foliage} + y_{branches} \qquad (3)$$

where y_i is the dry biomass of the aboveground components of the living trees (in kg), and $\beta_{jk}'s$ are coefficients (k=1) or exponents (k=2; Lambert et al., 2005) associated with the equation set (Table A2).

Application

For the first three levels of the conceptual framework, there will be an emphasis on balsam fir, red spruce, and red maple, with the fourth level allowing for beech (Table 3). These species were chosen based on their representation of cold-adapted, northerly softwoods, and warm-adapted, southerly species[5] for reasons of comparison (Burns and Honkala, 1990). The expectation is that under Levels I and II, these species will do better than they would under competition. For example, red maple and red spruce are expected to do better over time with atmospheric warming, due to their biases toward warmer climates.

PSP No. 1062 was then chosen to work as a sample plot to represent the dynamics associated with Levels I–III of the conceptual framework. PSP No. 1062 is located on a warmer northern site near the Bay of Chaleur. This site was chosen as it features characteristics of both northern and southern New Brunswick sites.

It is important to note that each species biomass curve starts when the stand turns 22. This was done to solve the issue of competition when running the model for a single species. As birth processes can only be on or off, and all 30 species are introduced with these processes. In this way, the problem is avoided. However, it means rotations occur 22 years later, and the planting of the tree species happens 22 years earlier.

For Level I, the selected species were run as pure stands, using a mixture of both historical and experimental data, which initially consisted of running one hundred individual saplings, but was eventually reduced to 10 trees each, of equal age, DBH, and height, to form a basic logistics growth curve for the species. These runs were done for both the historical (represented by H) and climate change scenarios (CC). For Level II,

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[5] Red spruce has a very specific temperature window and is known to grow favourably in cool and moist environments, compared to other tree species has a narrow tolerance range. New Brunswick is at the northern edge of the species' range. For purpose of this thesis, red spruce will be classified, along with red maple and beech, as warm-adapted southerly species.

these reduced runs were then repeated in ten-year intervals up to 2085 (100 years) to show how species growth curves changed with time in response to changing environmental conditions. Since the projections of climate change used in this model only go out to 2100, a repeat of the last 10 years was used to fill in any missing data. So, if I run a climate change, CC 20 run, meaning the run starts in 2005, the last 10 years of the projected RCP-scenario were repeated twice. The same method was used to project historical data, but with the first 25 years being repeated.

This same format was used to characterise Level III, with the only difference being that two species were put into competition with one another to explore the impact of competition on tree growth. The competitive exclusion principle states that two species in competition will reduce the other's growth until there is one species on the site (Kimmins, 1987). It is therefore expected that both species will do worse as compared to their pure stand counterparts found in Level II. This format was then applied to three species in competition to see how the addition of a third species would change the competitive dynamics within the stand. This was done twice, once for balsam fir, red maple, and beech, and once for balsam fir, red maple, and red spruce based on the same conditions in PSP No. 1062.

For Level IV, the highest level of complexity before human constraints are imposed on the system, we ran the model using each PSP in four different scenarios to demonstrate a range of possible stand conditions as result of climate change. The runs were separated into intersections of historical climate (H) and climate change (CC), and bare ground (BG) and non-bare ground conditions (NBG), which form (1) historical bare ground (HBG), (2) historical non-bare ground (HNBG), (3) climate change bare ground

(CCBG), and finally (4) climate change non-bare ground conditions (CCNBG). Historical runs were created to act as points of comparison for the climate change runs (labelled with CC). Historical stand conditions were based on PSP-data from 1985; (i) historical climate conditions were constructed by cycling climate from 1985 and 2010 to 2100; (ii) bare ground conditions were constructed by planting five of each of the 30 tree species, setting DBH (cm) and tree height of all trees (m) at 0.1; (iii) and climate change scenarios were based on RCP 8.5. Lastly, species AGB's were normalised to allow a comparison of the results.

PSP No. 1062 was used as a sample plot to show how species respond to competition from more than one other species through time, with the hope that later research will expand upon this concept. In this example, we assume PSP No. 1062 is a "managed" stand (see Level V), where each tree species on the site is present in equal amounts and assumed to have the same age, height, and DBH. While there is some variation in total biomass due to difference in species-specific biomass equations, this was largely done to create a more equal playing field for competition

Comparison Studies

"*Rapid 21st century climate change projected to shift composition and growth of Canada's Acadian Forest Region*" by Taylor et al (2017), is the first of two comparison studies chosen. This study focuses on the Acadian Forest Region sensitivity to change. This sensitivity is based on the transition zone status of this region, with many species being at either their northern or southern limits. Taylor predicts that some species, such as the northern conifers, will face extirpation from the province, while others will see a boost in productivity. This is in agreement with Searls' (2021) predictions that projected climate change will impact both different and the same species differently depending on their position within the landscape, with some gaining a boost and others seeing a reduction in productivity.

To test this theory, Taylor et al. used a forest ecosystem simulation model called PICUS. They explored the potential impacts of climate on the composition and growth of the Acadian Forest Region from 2011–2100 under two net radiative forcing scenarios, RCP 2.6 and 8.5. Taylor et al. split their results into 30-year time segments to examine the short-term (2011–2040) as well as long-term impacts (2071–2100) of climate change, as compared to baseline forest conditions from 1981–2010 (Taylor et al., 2017). Modelling for the short-term impacts yielded little to no changes in forest composition or growth for either the RCP 2.6 or 8.5 scenario. For the long-term impacts, PICUS projected that by mid-century and beyond, both scenarios departed from the baseline scenario. The greatest deviations occurred under RCP 8.5 during the late 21^{st}-century (2071–2100; Taylor et al., 2017). This study predicts that the Acadian Forest will lose its boreal character, as key tree species fail to regenerate and survive. With this rapid loss of boreal species, the increased growth and establishment of warm-adapted, temperate tree species may not be able to keep pace producing a "lag effect" that may result in a decrease in forest growth and wood supply (Taylor et al., 2017).

The second case study is "*Occurrence, pattern of change, and factors associated with American beech-dominance in stands of the northeastern USA forest*" by Bose et al. (2017). This study details the increase of beech (*Fagus grandifolia*) within the Northeastern United States of America (USA) and gives possibilities as to why this may be the case (Bose et al., 2017). Bose et al. showed that amongst four different stand types (i.e., beech-dominated, commercial hardwood-dominated, other hardwood-dominated, and softwood-dominated), the beech-dominated stands at the time of study, accounted for 27.4% of the total northeastern USA forest area. Beech has had a ~5% increase over the past 16 years, with an even greater increase in the forests of New Hampshire, New York, and Vermont (Bose et al., 2017). It should be noted that this increase in beech included stands infected with beech bark disease – a fungal infection of the bark caused by a combination of feeding on beech sap by the beech-scale insect (*Cryptococcus fagisuga*) endemic to Europe, coupled with a nectria fungus native to North America (Horticulture Week, 2008; *Beech Bark Disease: Ontario's Invading Species Awareness Program*, n.d.), which often results in severe dieback in mature beech trees.

Bose et al.'s results showed increasing mean annual precipitation and greater overstory basal area were positively correlated with the occurrence of beech-dominated stands, but negatively correlated with the occurrence of other stand types (Bose et al., 2017). Beech-dominated stands were generally associated with higher elevations, greater mean annual precipitation, warmer temperatures, and larger overstory basal area. Beech dominance in the understory was associated with overstories dominated by beech, as well as overstories dominated by commercial hardwood species. Therefore, overstory harvesting in stands with beech being dominant in the understory (irrespective of overstory composition) will tend to promote beech in the overstory. Bose et al.'s results emphasise the need for greater attention to improving regeneration composition in stands where beech is dominant to increase the long-term productivity and commercial value of northeastern forests of the USA.

The possibilities given in the article include: (1) greater ability of beech to grow under the deep shade of a mature stand; (2) absence of stand-replacing events, and increased use of partial harvesting that favours beech; (3) mortality of overstory beech from beech bark disease also creates small openings, favouring beech saplings to grow; (4) ability of beech to reproduce through root suckering, which are more vigorous than seed-sourcing stems; (5) logging-induced root damage promotes suckering of beech; (6) herbivore preference of sugar maple and yellow birch over beech; (7) beech has shown to be more efficient relative to sugar maple in assimilating carbon under elevated CO_2 conditions; and (8) elevated temperatures during the growing season, and greater annual precipitation, favour beech over other species in northeastern forests.

Points 7 and 8 are particularly interesting to this thesis. Under anthropogenic climate change there has been an increase in CO_2 in the atmosphere, which benefits beech over other tree species such as sugar maple. Along with this increase there has also been an increase in temperature and precipitation within Northeastern North America, which, as Point 8 states, will favour beech over other tree species. It shows a negative relationship between the occurrence of softwoods and temperature, while there is a positive correlation when involving beech. Research suggested increased precipitation was the most important factor for the increase of beech, while it had negative effects on other hardwoods (Bose et al., 2017).

Along with the conceptual framework, these two studies provide a basis for the discussion of the results. The conceptual framework applies a formal structure of analysis, whereas these studies fill in the details and give possible reasoning for why certain results may have occurred.

CHAPTER 4

Results and Discussion

We know that over time climate change will lengthen the growing season. With this, there is an assumption that with this longer growing season plant taxa will experience higher rates of productivity (Charney et al., 2016; D'Orangeville et al., 2016; Vose et al., 2012; Taylor et al., 2017). For PSP No. 1062 this is the case for temperate species, such as red maple (Figures 13, 14), red spruce (Figures 15, 16), and beech; the data is then normalised per species rather than per individual run. At each time interval these species see a boost in growth potential, more so in red spruce than in red maple, which in the latter half of the century sees a decline in AGB compared to red spruce. Its likely this decline in biomass comes from increases in precipitation (Figures 14 and 16), which red spruce favours, as compared to both species being subjected to similar GDD's. It is important to note that due to the nature of how future intervals are constructed, projections past 116 years, or 2100 are likely influenced by a more stable climate rather than an increasing climate (which is what is expected) which might throw off the projections for red maple and red spruce. Future work will seek to correct this deficiency by incorporating projections that go out 300 years rather than 100. However, not all species benefit from an increase in temperature. Depending on location and local climate, the same species may experience different impacts from an increased growing season, as it is observed with balsam fir (Searls et al., 2021).

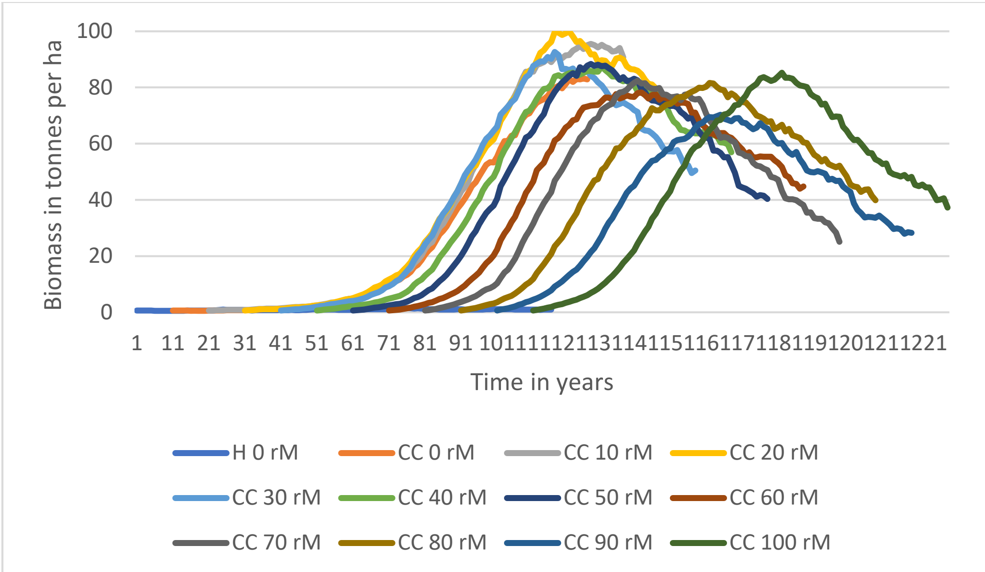

Figure 13. Red maple growth trajectory for every 10-year period for PSP No. 1062 given climate change. The x-axis represents time (in years) and the y-axis normalised biomass in %. This graph assumes all scenarios start from their assigned time; CC 10 starts at 10 years, and so on. This graph assumes a pure forest stand of red maple. With this visualisation, patterns emerge, such as the dropping off at around each runs respective year 109, which is consistent for all runs. H the historical scenario, and CC the climate change scenario, respectively.

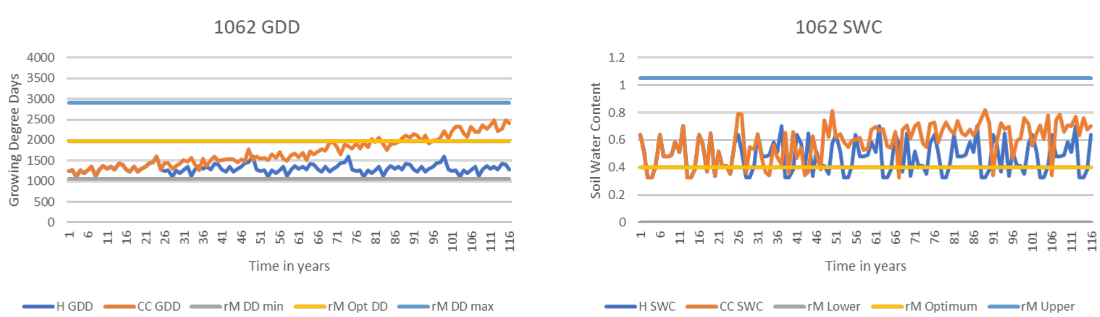

Figure 14. Red maple (*Acer rubrum*) growing degree-days (GDD) and soil water content (SWC) limits. The curves represent climate, orange for climate change (CC) and blue for historical (H), whereas the horizontal lines represent the species' limits (thresholds), blue for upper, gray for lower limits, and yellow for optimum.

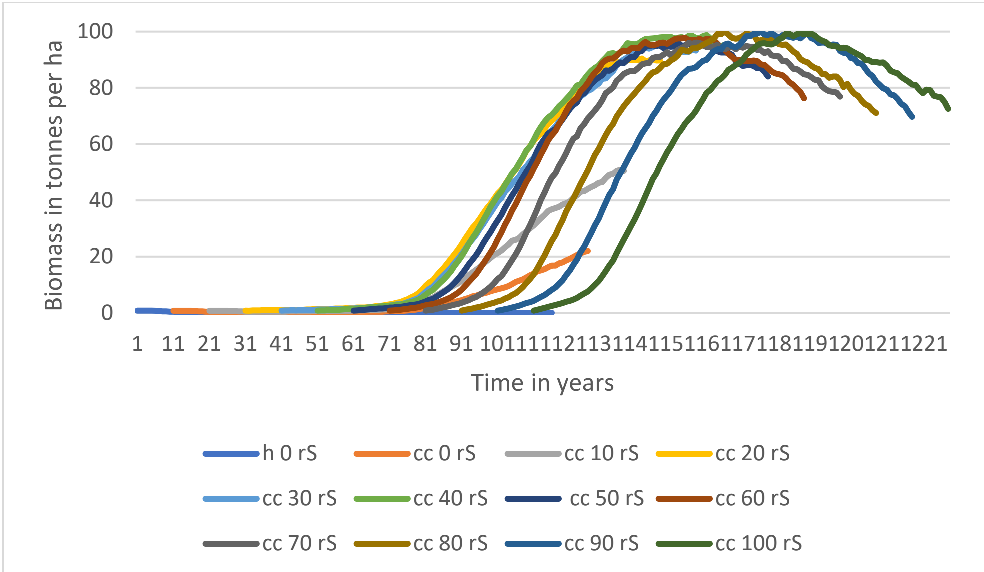

Figure 15. Red spruce growth trajectory for every 10-year period for PSP No. 1062 given climate change. The x-axis represents time (in years) and the y-axis normalised biomass in %. This graph assumes all scenarios start from their assigned time; CC 10 starts at 10 years, and so on. This graph assumes a pure forest stand of red spuce. With this visualisation, patterns emerge, such as the approach towards red spruces carrying capacity after the CC 20 interval. H the historical scenario, and CC the climate change scenario, respectively.

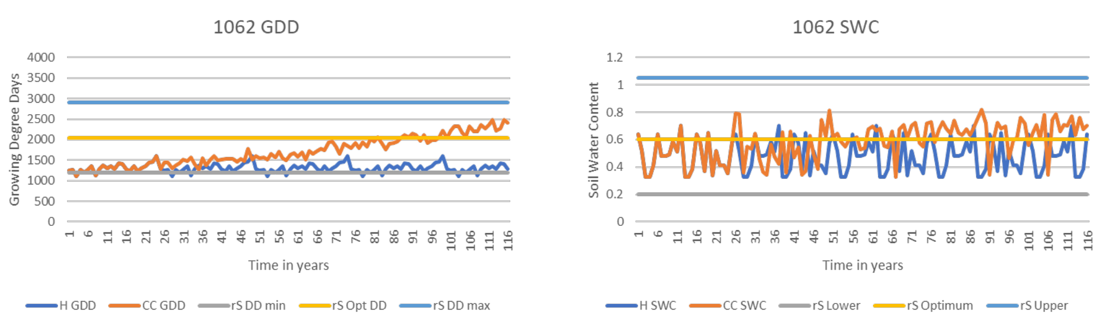

Figure 16. Red spruce (*Picea rubens*) growing degree-days (GDD) and soil water content (SWC) limits. The curves represent climate, orange for climate change (CC) and blue for historical (H), whereas the horizontal lines represent the species' limits, blue for upper, gray for lower limits, and yellow for optimum.

For balsam fir (Figure 17), the historical scenario has greater AGB than the climate change (CC) scenario. After each 10-year time segment, balsam fir's potential growth curve, and maximum AGB (carrying capacity, K) decreases. Balsam fir begins its trajectory at its optimum GDD limit, and through time with an increase in temperature, it deviates from this limit, approaching its upper limit (Figure 18). Each subsequent 10-year time segment, balsam fir starts further away from its optimum limit, meaning its potential growth decreases. It is reasonable to expect that a growth trajectory close to crossing an upper or lower limit, the lower AGB will be, and the sooner it will succumb.

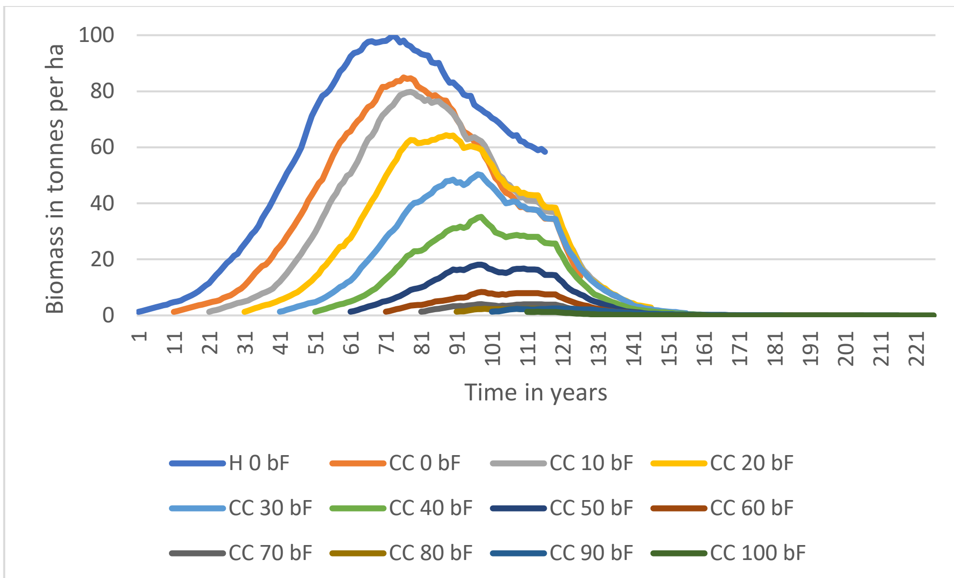

Figure 17. Balsam fir (*Abies balsamea*) growth trajectory for every 10-year period for PSP No. 1062 given climate change. The x-axis represents time (in years) and the y-axis normalised biomass in %. This graph assumes all scenarios start from their assigned time; CC 10 starts at 10 years, and so on. This graph assumes a pure stand of balsam fir. With this visualisation, patterns emerge, such as the dropping off at year 109, which is consistent for all runs. H the historical scenario, and CC the climate change scenario, respectively.

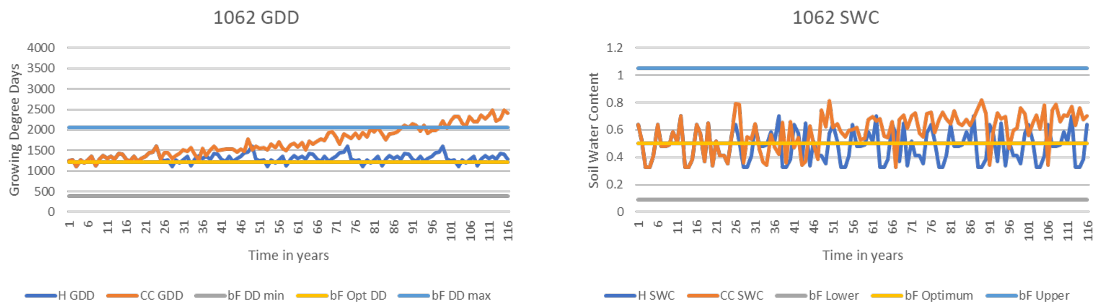

Figure 18. Balsam fir (*Abies balsamea*) growing degree-days (GDD) and soil water content (SWC) limits. The curves represent climate, orange for climate change (CC) and blue for historical (H), whereas the horizontal lines represent the species' limits, blue for upper, gray for lower limits, and yellow for optimum.

In all cases, there was a significant drop after year 116, or by 2100. This could have been caused by how climate after 2100 is represented, as a repetition of years 106–116. During these years, GDD for PSP No. 1062 surpassed balsam fir's upper limit (Figure 18). Any species that surpasses its upper or falls below its lower limits enters a simulated period of no growth. After four years of basically no growth, it is declared dead by the model. Balsam fir surpasses its upper limit before year 116 (Figure 18). It is reasonable to expect that with repeated climate, balsam fir suffers a death threshold, as well as a birth threshold, since it can no longer regenerate at that time. The issue of how intervals were constructed, as previously mentioned, do not affect balsam fir. With increasing temperature, the likelihood of balsam fir regenerating is next to zero, due to the GDD being past balsam fir's upper limit.

Level III Thresholds represents competition over time for two species based on current environmental factors (as of stand initiation; Figure 14, 16, and 18); where normalisation is done for each graph and all of its components together, rather than at an individual level. As discussed for Level II thresholds, stand initiation can be moved through time to demonstrate different instances of competition. By maintaining a consistent climate scenario and applying competition, I can explore competition-related species response. This is done for balsam fir, red maple[6], and red spruce[7].

The results of various competition scenarios between red maple and balsam fir are shown in Figure 19; normalisation is done per scenario, not per tree species. For scenario CC 0 balsam fir outcompetes red maple for the first half of the time sequence, but as temperatures increase past balsam fir's upper GDD limit (at year 2073) balsam fir sees a decrease in AGB, whereas red maple approaches its optimum GDD limit and sees an increase in biomass. This results in a point of intersection between balsam fir and red maple at around 2080, which results in red maple becoming the dominant species on the site. The timing of the point of intersection decreases from 2080 in the CC 0 scenario, to 2050 in CC 50 (which begins at 2035). The other point of intersection of interest is when red maple passes the maximum AGB of balsam fir during the historical scenario. This point of intersection first occurs in the CC 30 scenario (beginning at 2015). What this shows is that balsam fir's productivity has decreased leading to a decrease in its competitive ability, while red maple has increased. Lastly, the red curve represents a pure

[6]To simulate competition, 50 discrete forest-change simulations were completed for PSP 1062 for both historical and climate change scenarios. PSP and stand conditions were kept the same for 50 simulations due to the stochasticity built-in the model. Initial species age for both red maple and balsam fir was kept to 22 years old, using 5 identical trees based on historical data for each species. The following runs were based on a constant seed-rain. I define "threshold" as the point of intersection between species.
[7] Refer to Appendix B. Red maple and red spruce share similar growth characteristics associated with Level II, as a result, if red maple outcompetes balsam fir, then it can be expected that red spruce will also outcompete balsam fir.

stand of balsam fir given the same climate conditions, and number of trees that were used for competition. While this line is also decreasing, what it shows is that under competition balsam fir is accelerating towards its thresholds faster than if the site consisted uniquely of balsam fir.

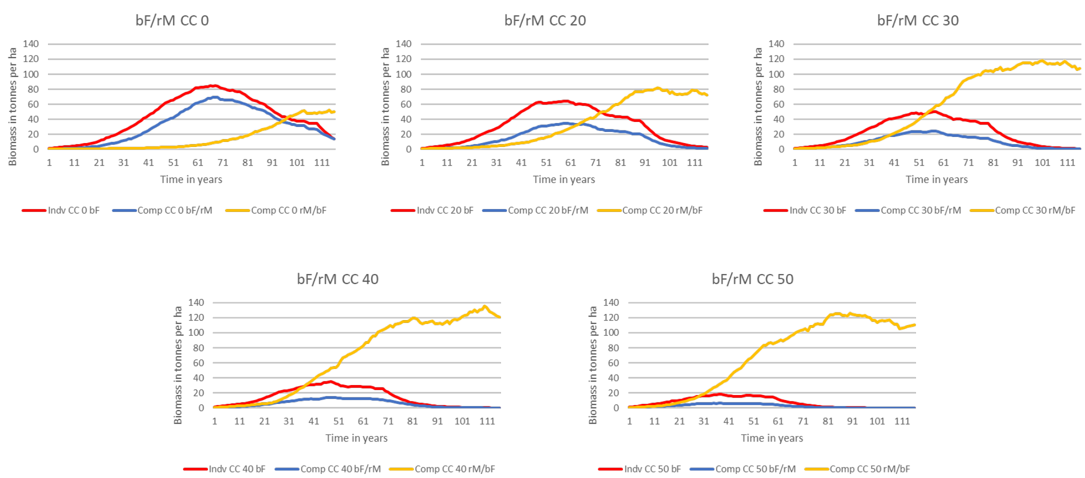

Figure 19. Competition between balsam fir (*Abies balsamea*) and red maple (*Acer rubrum*) starting form 1985, 2005, 2015, 2025, and 2035. The red curve represents balsam fir's total aboveground biomass given no competition, the blue curve balsam fir's total biomass given competition, and orange red maple’s total biomass given competition. The y-axis is a percentage based on the maximum total biomass given balsam fir’s individual historical scenario (H), with 100% representing the maximum total site biomass. The x-axis represents time (in years) since stand initiation; zero represents plot establishment year of 1985.

When red spruce competes against red maple, red spruce ends up becoming dominant in the CC 20 simulation scenario. This is likely due to red spruce’s SWC optimum being greater than that of red maple. If red spruce and balsam fir were in competition under climate change, the same outcome would be expected.

Taylor et al. (2017) stated that the Acadian Forest is losing its boreal characteristic as temperatures increase and balsam fir and other northern species, especially conifers, become less competitively viable (Figure 19). This implies that competition can quickly and abruptly change the composition of a site that is already under the influence of climate change.

This result is similar to Williams' (2002) theory regarding the cause of decline in hemlock in the historical record. This is not only associated with climate change, but competition, along with stochastic and progressive disturbance (Burns and Honkala, 1990)[8], that can quickly shift a region's species distribution. Level III, however, does not represent full system complexity. To represent the ecosystem better, trees need to compete against one another.

Level IV uses the Forest Landscape Model to compete multiple growth curves against one another, over time, using tree species and site base traits (Figures 14, 16, 18). Adding in multiple species adds complexity, which in turn makes it more difficult to point to a particular set of interactions and say that this result happened because of a specific event.

Continuing with the methodology shown in Level III, competition was enforced between balsam fir, red maple, and beech every 10 years across a 100-year time span given climate change (Figure 20). In the 1985 or CC 0 starting time, balsam fir dominates the site up until just before 2100. This contrasts with the balsam fir-red maple competition seen in Level III, where the point of intersection between red maple and balsam fir occurred ~20 years earlier, which shows how adding the extra species (beech) changes

[8] Stochastic events, such as fire and insects, which are not accounted for in this model, can kill off trees. If those trees cannot regenerate, the species becomes unavailable to the site. This is an example of a birth threshold.

how balsam fir and red maple interact on the site. In Figure 20, which occurs 20 years later, in 2005, the point of intersection between red maple and balsam fir is in 2068, which is two years earlier than under the two species scenario, whereby beech intersects balsam fir in 2098. With each successive 10-year interval, the relevance of balsam fir on the site diminishes, whereas red maple and beech benefit. With red maple taking over the site initially, and a second threshold occurring when beech intersects red maple in scenarios CC 30, 40, and 50, each instance the point of interception occurs sooner than in the previous 10 years.

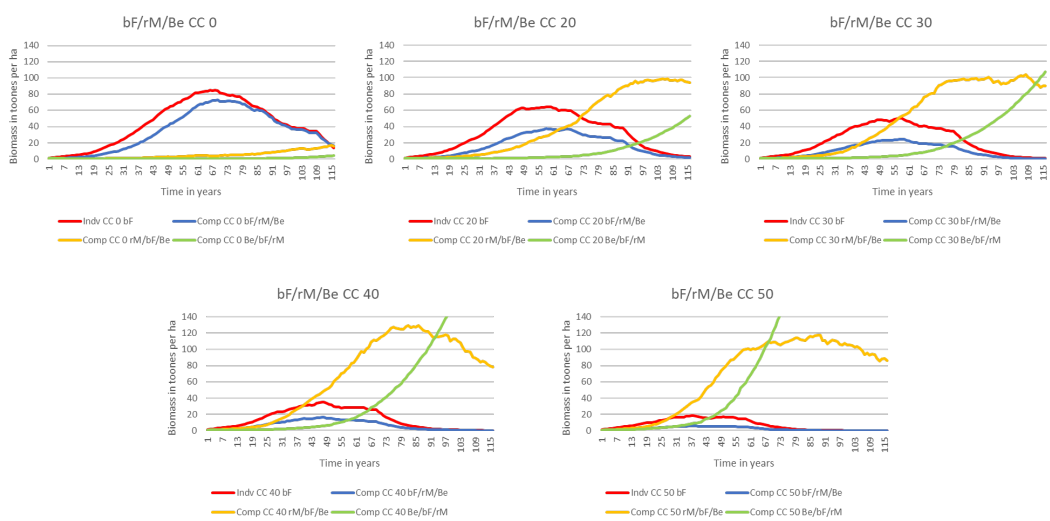

Figure 20. Competition between balsam fir (*Abies balsamea*), red maple (*Acer rubrum*), and beech (*Fagus grandifolia*) starting from 1985, 2005, 2015, 2025, and 2035. The red curve represents balsam fir's total biomass given no competition, the blue curve, balsam fir's total biomass given competition, the orange curve, red maple's total biomass given competition, and the green curve, beech's total mass given competition. The y-axis is a percentage based on the maximum total biomass given balsam fir's individual historical scenario, with 100% representing the maximum total site biomass. The x-axis represents time (in years) since stand initiation; zero represents plot establishment year of 1985.

The results for PSP's 2040, 7077, 9141, 34077, 36012, 37031, 39025, and 39047 are shown in Appendix D, with their environmental variables in Appendix C. For historical conditions (H), species continued as expected, with softwoods dominating most sites, and the reverse for climate change conditions. Another major trend was the early occurrence of competition-based thresholds under climate change. Signifying the projected point of intersection between two species occurred earlier under climate change (CC) than under historical conditions (H). An example would be PSP No. 1062 (Figure 21), with a possible point of intersection between balsam fir and red maple occurring sometime after 2100 under the historical scenario, and in 2083 in the climate change scenario. This trend occurs both under bare and non-bare ground scenarios.

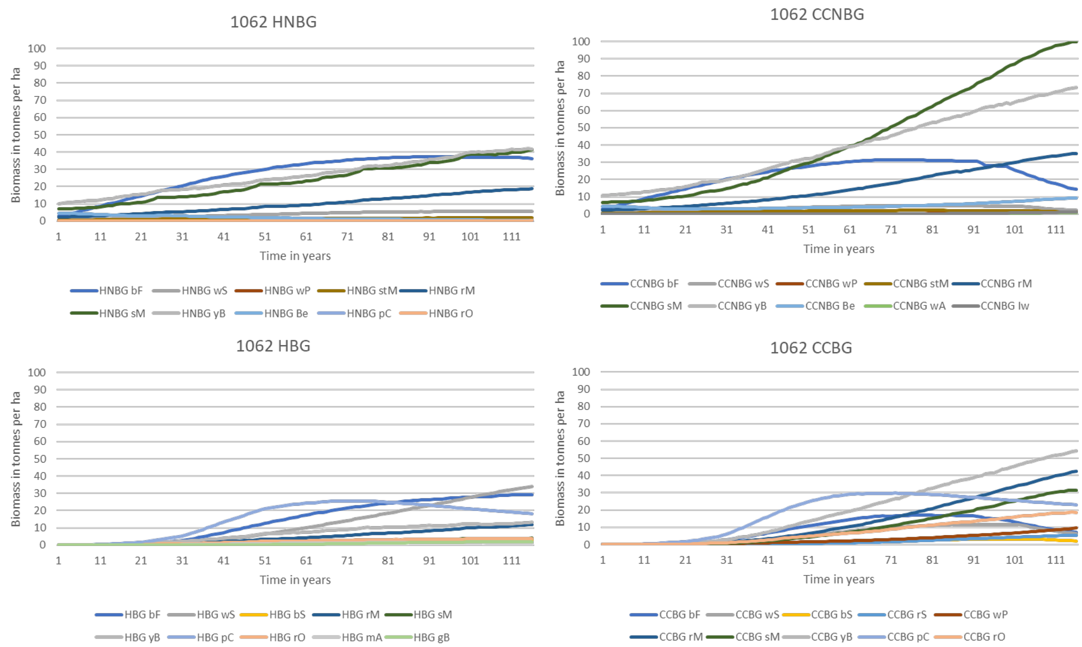

Figure 21. Comparison between different climate and initial ground conditions for PSP No. 1062. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years), and the y-axis represents biomass in tonnes per hectare. Data is normalised based on sugar maple in the CCNBG run, which has the highest biomass. Each graph is then reduced to the top 10 out of 30 species for each run.

The general trend, as seen in PSP No. 1062, was for tolerant hardwood species, with higher GDD limits to take over their respective PSP's over time as temperature increased, and boreal species began to disappear from New Brunswick's landscape.

This is consistent with projections offered by Taylor et al. (2017) and Bourque et al. (2000–2019). Balsam fir is set to decline in mid-century (2040–2060) in almost every cases, given uninterrupted growth since 1985. More severe decline is often seen after 2060. This correlates well to balsam fir's GDD limits, with balsam fir exceeding its upper GDD limit near the end of the century.

Under bare ground conditions, based on the nine PSP's, three assemblages were observed; these were (1) balsam fir-black spruce, (2) black spruce-balsam poplar, and (3) pin cherry-yellow birch sites. These assemblages were constructed using the top two species from each run. In the case of pin cherry-yellow birch association, pin cherry tended to dominate the site within the first forty years, until it succumbed to senescence, at which point yellow birch took over the site. This was likely due to site quality. Hardwood stands are more likely to have pin cherry than black spruce (Burns and Honkala, 1990). The sites with pin cherry are typically warmer. Landscape-areas where pin cherry-yellow birch associations predominated were located primarily in the southern part of the province, or in areas that exhibited unusually warm seasonal conditions, notably in the Northern Uplands, which sees a warm climate moderated by its proximity to the Bay of Chaleur. These assemblages did not always match up with real world data. This is likely due to how species compete in real life, and how dominance of a site often has to do with whichever species establish themself first.

This is further addressed in Appendix A, which details each of the 30 species, on each of the nine sample PSP's for each run type. This allowed me to make general statements about the state of each species on each PSP. However, it does not allow for an exhaustive interpretation of the results associated with competition between species on each PSP. When split into softwoods and hardwoods more detailed analysis can be forthcoming.

For the softwoods, four out of the ten species did better under transient conditions associated with climate change. These species were hemlock, jack pine, red spruce, and white pine. However, these species did not fare uniformly well on all sites. Generally, the further north, the higher was the likelihood that they would do better under climate change. Eastern hemlock is a staple of the maritime region, with its range going down into the USA, as far south as Georgia (Burns and Honkala, 1990). Jack pine has a more boreal range, and this is reflected in the fact that the only plot it did well on was the one farthest north. Red spruce has a long-scattered range that stretches down to Tennessee. Lastly, white pine has a range that stretches down to Georgia, with some variants that grow in Mexico and Guatemala (Burns and Honkala, 1990). White pine in New Brunswick, generally does better in warmer conditions and has a wider GDD-tolerance range than other softwood species.

The other six softwood species all did worse, since many are cold-adapted, or already at their optimum limit in the province. As climate gets warmer and wetter, these species are expected to see a shift away from their GDD optimum, impacting the species' ability to grow in the province and their ability to compete, until GDD eventually surpasses the species' upper limit, causing it to die-off due to lack of growth.

Out of the hardwoods considered, four out of twenty species are expected to undergo a similar decrease to the softwoods, as conditions further deteriorate. These species are white birch, balsam poplar, mountain ash, and grey birch. These species are more northern, cold-adapted species, with GDD upper limits like black spruce at about 2,200. The other 16 species have higher GDD upper limits, signifying as climate warms their ability to compete will improve.

A general shift was observed towards temperate species and away from boreal species as was shown in other simulations and models conducted within the Maritime

Region (Taylor et al, 2017, Bourque and Hassan, 2007). This process has been described as "de-borealization" (Taylor et al., 2017). "De-borealization" occurs as key cold-adapted boreal species fail to regenerate and die. This "de-borealization" of the Acadian Forest is projected to occur late into the 21st-century (Taylor et al., 2017). Relating this to the thesis' theme of thresholds, the Acadian Forest will transition across a threshold, with the loss of boreal species, to a new state – a forest defined by temperate species (Masson-Delmotte et al., 2021). This transition is brought on by a stable consistent change in climate, vis-à-vis RCP 8.5 scenario, and small perturbations, such as individual tree death that will change the nature of the forest. In a sense creating an irreversibility, as trees function on much longer timescales than humans.

The previous results were all examples of environmental-induced thresholds. Level V models look at human-induced thresholds and their eventual outcomes. These thresholds do not necessarily follow the same trajectory as the environmental ones and are based on human-economic interest. Economic logic ignores the signals from climate and biology and brings things down to provide simplistic representations of the forest to make decisions. Typically, these decisions hinge on maximising profits and minimising losses.

Given a 3% discount rate, the optimal rotation age for a pure stand of balsam fir, on PSP No. 1062 given climate change, starting from 1985, is at 49 years (year 2034). It is important to note the discount rate is notionally different than the peak of the curve; meaning, its more profitable to harvest the stand earlier.

This simple representation assumes one rotation and disregards the complexity inherent in Level IV (Figure 22). What is interesting is that the rotation age does not occur simultaneously with the peak of the growth curve, instead it occurs almost 20 years before.

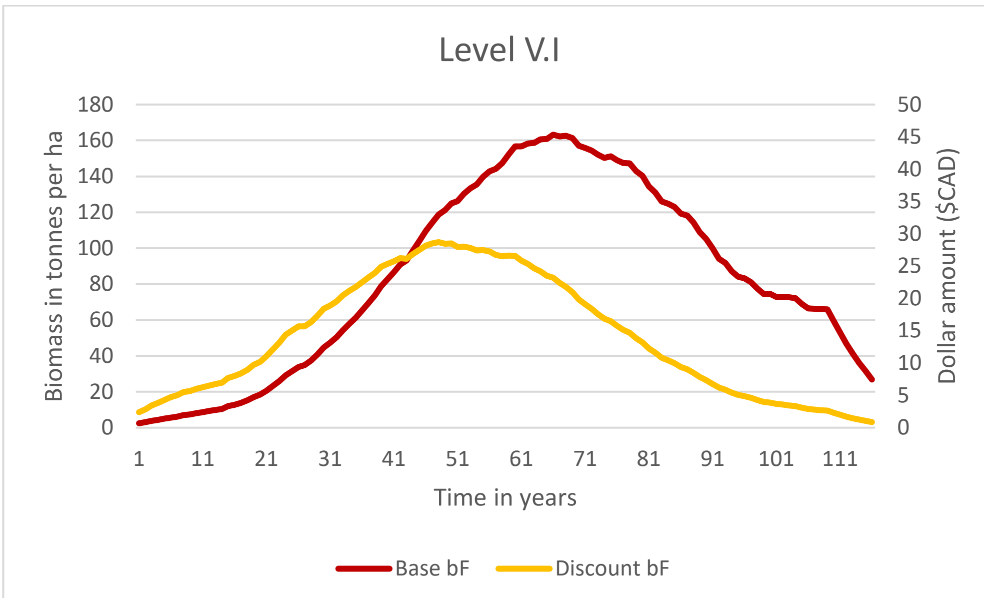

Figure 22. Balsam fir's (*Abies balsamea*) biomass versus its net present value (NPV) for a 116-year period. The red curve represents the overall biomass of balsam fir over the 116-year period, starting from 1985 using initial forest conditions of PSP No. 1062. The x-axis represents time (in years) and the primary y-axis represents biomass in tonnes per hectare. The secondary y-axis represents the dollar amount ($CAD) with the assumption that each tonne of biomass equal $1 CAD, and then is discounted by a rate of 3%.

Figure 23 brings in the soil expectation value, and assumes an infinite series of rotations, and assumes that the growth curve predicted in 1985 will be consistent between cycles. Extending the planning horizon over an implied infinite series.

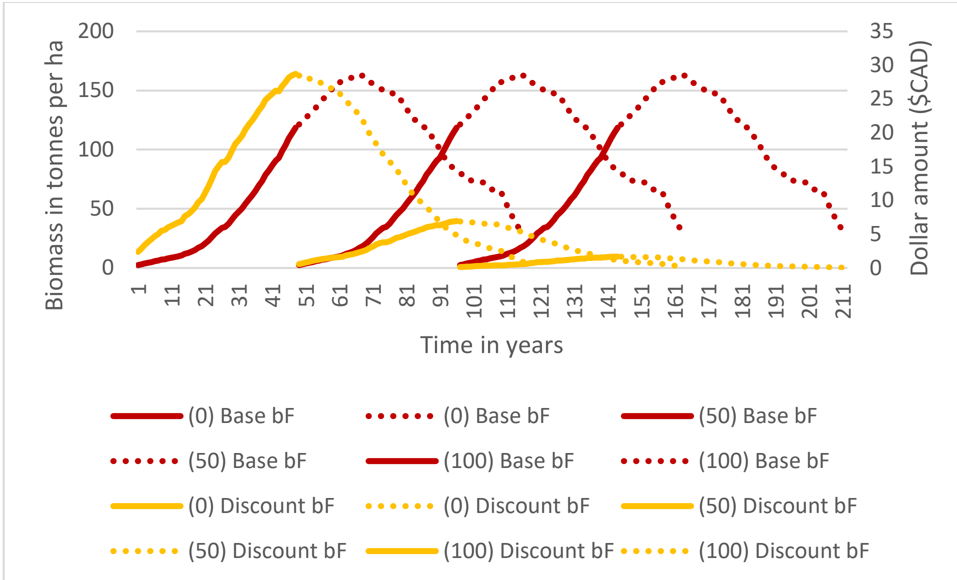

Figure 23. Balsam fir (*Abies balsamea*) biomass versus its net present value (NPV) over a series of rotations without climate change. The red curve represents the overall biomass of balsam fir over a 116-year period starting at 1985 taken from PSP No. 1062; at the point where the solid red line becomes dotted is the suggested rotation based upon the peak of the yellow curve representing NPV. The (0), (50) and (100) represent the timing of the beginning of each rotation. The x-axis represents time in years and the primary y-axis represents biomass in tonnes per hectare. The secondary y-axis represents the dollar amount (in $CAD discounted by a rate of 3% assuming 1 tonne of biomass is equal to $1). This level of complexity adds in the concept of multiple harvests based on an infinite series.

Figure 23 incorporates the environmental threshold Level II and shows the effects of climate change on balsam fir over the 214-year run time; balsam fir diminishes with each rotation, and by the third rotation it is practically gone from the site. The NPV curve responses to the decrease in balsam fir and diminishes at a greater rate than what was predicted in Figure 22, showing that the impact on balsam fir decreases due to climate change is not only environmental, but economic (Figure 24). If I was to continue with Level V.II thresholds, a good assumption would be to harvest sooner and capture as much profit as possible from the declining species. However, there are other options.

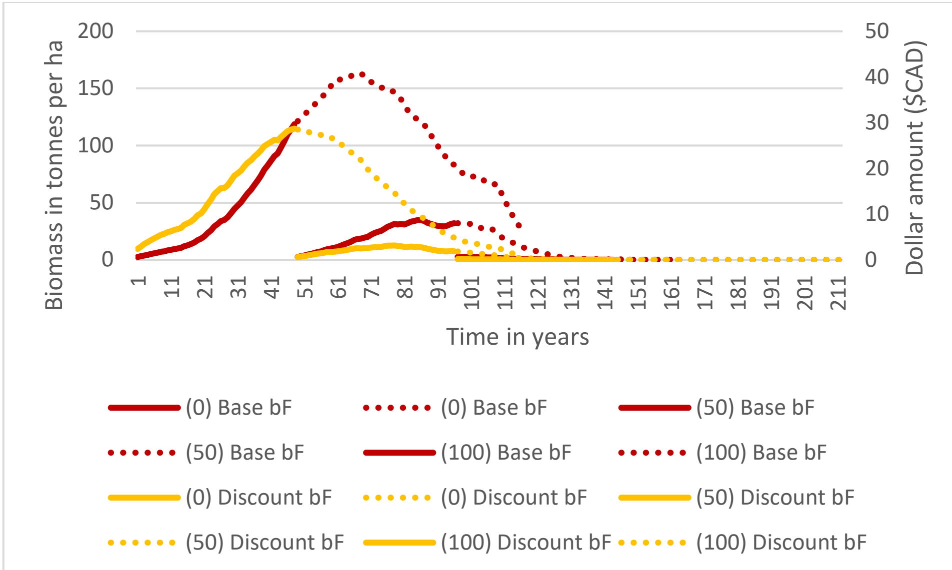

Figure 24. Balsam fir (*Abies balsamea*) biomass versus its net present value (NPV) over a series of rotations with climate change. The red curve represents a pure stand of balsam fir under climate change, with stand initiation in 1985; at the point where the solid red line becomes dotted is the suggested rotation based upon the peak of the yellow curve. The yellow curve represents the NPV, or discounted curve of the pure stand of balsam fir. The discount rate is set at 3%, and 1 tonne per hectare is assumed to be worth $1. The (0), (50) and (100) represent the timing of the beginning of each rotation The horizontal axis represents the time in years, with zero representing the plot establishment year of 1985. The vertical axis represents biomass in tonnes per hectare, the secondary axis represents the dollar amount ($CAD at a discounted rate of 3% assuming 1 tonne of biomass is equal to $1).

Figure 25 shows the results when the manager makes the decision to take advantage of windows of optimum growth, the NPV in future rotations increases.

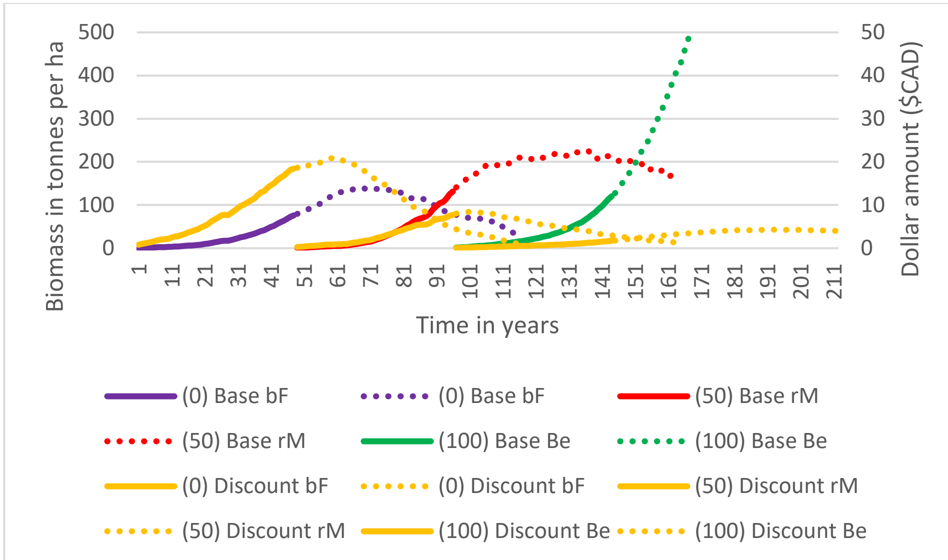

Figure 25. Climatic effects on multiple species over multiple harvests. Re-evaluation is done after every harvest to determine which single species to plant. Level V.III shows six curves, the purple curve represents a pure stand of balsam fir under climate change with stand initiation in 1985; the red curve represents red maple after the first rotation, and green represents beech. The yellow curve represents the NPV, or discounted curve of the pure stand of balsam fir. The discount rate is set at 3%, and 1 tonne per hectare is assumed to be worth $1 (CAD). The moment when the solid lines become dotted, is the suggested rotation age, in this case based off of balsam fir's discount rate at the year 49. The x-axis represents the time in years, with zero representing the plot establishment year of 1985. The y-axis represents biomass in tonnes per hectare.

The other option, as seen in Level V.IV is to plant a mixture of species on the site, as expressed in Figures 26-28. Instead of having a pure stand of balsam fir, red maple, or beech, all three species are planted on site at every 50-year rotation.

Fifty year rotations were to demonstrate the importance of shortening the rotation period. By using the knowledge gained in Level II, shortening rotations allows us to smooth the transition from what our forest is now, to what it might become. That through shortening rotation and letting competition select the species best suited to the site, we can maximise site volume while reducing the risk that comes from the inherent uncertainty within modelling and the stochasticity found in real life.

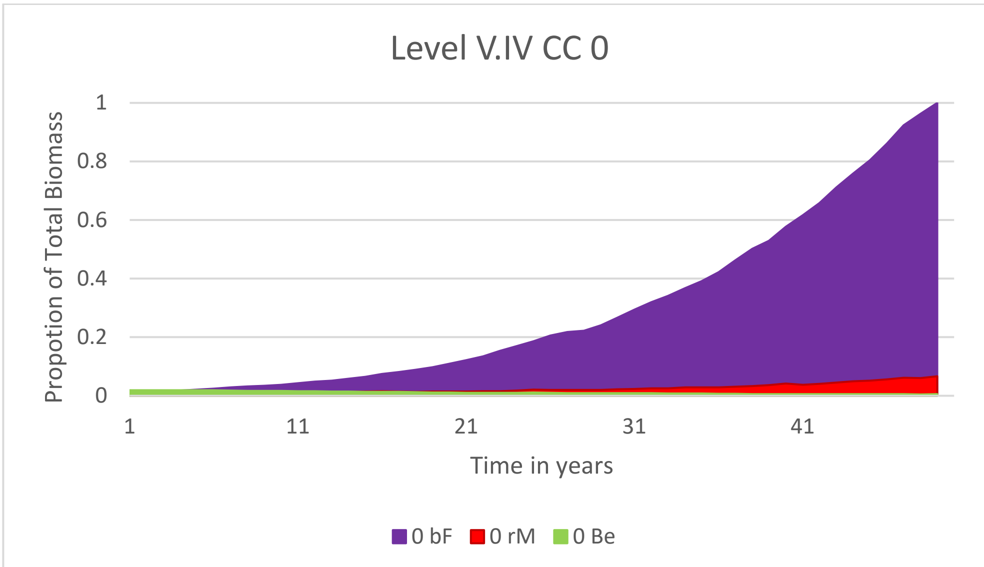

Figure 26. Overall potential biomass in PSP No. 1062 and the proportion of each species during the first rotation, maximising total site volume of the three species. The horizontal axis represents time (in years), and the vertical axis represents proportion of total biomass. The purple curve represents balsam fir, red curve red maple, and green curve beech. In this example, during the CC 0 scenario, balsam fir dominates the site up until the moment of harvest. For reasons of interpretation, biomass is normalised.

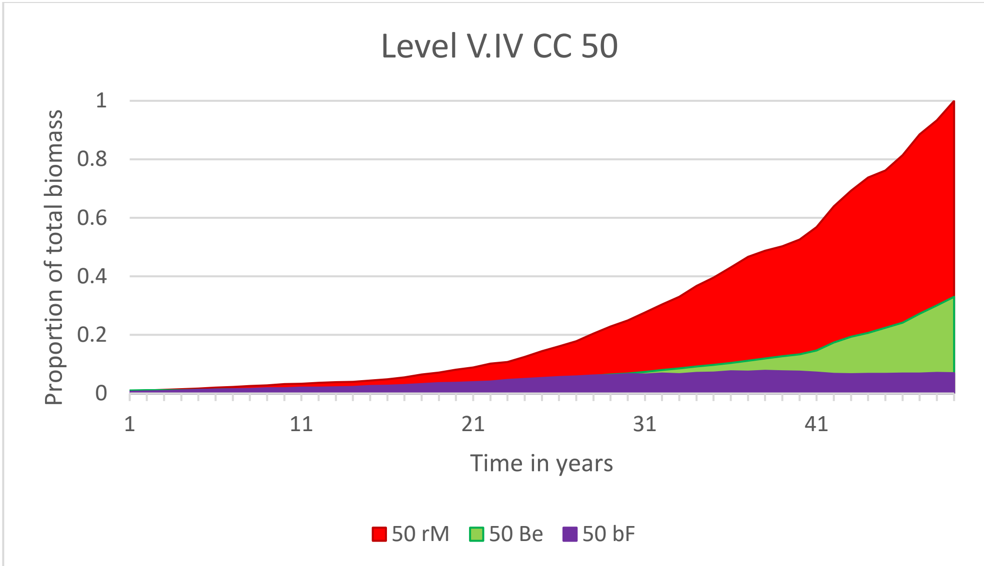

Figure 27. Overall potential biomass of PSP No. 1062 and the proportion of each species during the second rotation, maximising total site volume of the three species. The horizontal axis represents time (in years), and the vertical axis represents proportion of total biomass. The purple curve represents balsam fir, red curve red maple, and green curve beech. In this example, during the CC 50 scenario, red maple dominates the site up until the moment of harvest. For reasons of interpretation, biomass is normalised.

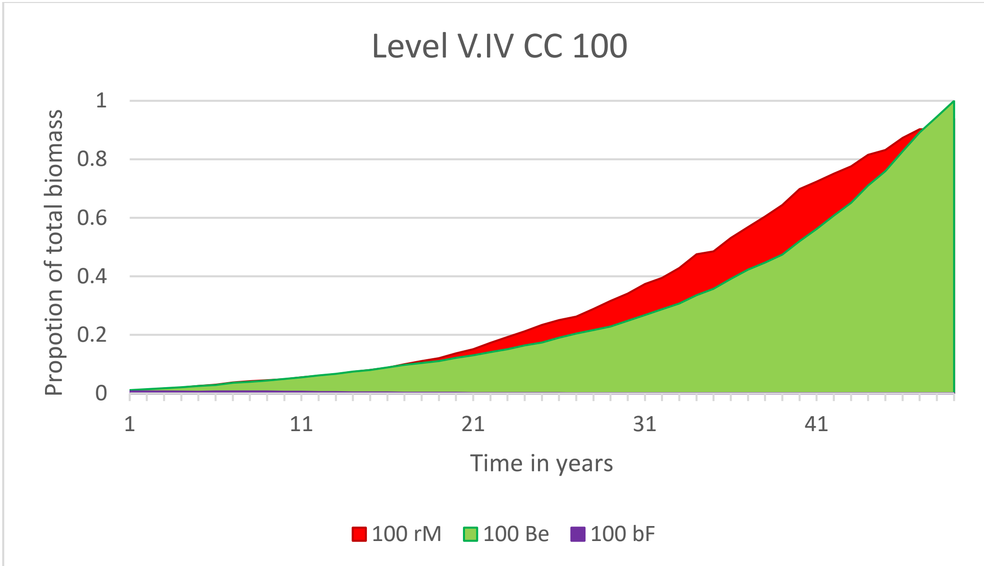

Figure 28. Overall potential biomass in PSP No. 1062 and proportion of each species during the third rotation, maximising total site volume of the three species. The horizontal axis represents time (in years), and the vertical axis represents proportion of total biomass. The purple curve represents balsam fir, red curve red maple, and green curve beech. In this example, during the CC 100 scenario, red maple then beech dominate the site up until the moment of harvest. For reasons of interpretation, biomass is normalised.

Each graph assumes a different rotation, with each rotation occurring in intervals of 50 years. Each graph shows the relative percentage of each species (balsam fir, red maple, or beech) as compared to the other species over time. In the first rotation, balsam fir dominates the site, with red maple and beech in far lower quantities. During the second rotation, red maple and beech become the dominant species. During the final rotation, beech, and red maple overtakes the stand. This allows the manager to select for the most profitable species, while promoting diversity and resilience of the site.

Kimmins (1974) talked about ecological rotation as the time it takes a plot to return to pre-harvest conditions. But with climate change, and the shifting of the dominant forest species, there is no returning to pre-harvest conditions. Instead, the forest will take on new characteristics, even between rotation periods. With increased species diversity, a site corresponding with Level V.IV should be able to adapt to a new climate regime and remain productive despite changing environmental conditions. Shortening rotation periods, while keeping competition and maintaining diversity in a stand is another way to smooth the transition between historical and future climatic conditions (Adler et al., 2012).

Level V.IV recommends that in order to reduce risk, as managers we must plant a diversity of species moving forward. But this raises a number of questions with respect to forest management, such as which species to plant, in which combinations, or on which sites? Unfortunately, the FLM does not explicitly model species succession at the microsite level. So, our ability to comment on actual prescriptions for species composition and spatial positioning is limited. Future work will need to address the inherent trade-offs between the approach as an exploratory vehicle for addressing climate change versus the needs of industry to maximise its operational efficiencies and profits.

CHAPTER 5

Conclusions

The latest IPCC report (AR6, WG2) predicts that anthropogenic climate change will have a broad range of environmental, social, and economic impacts. On the whole, New Brunswick is expected to become warmer and wetter over the next 100 years, which will fundamentally alter the abiotic factors influencing tree growth within the province's forests. This rapid shift is expected to lead to abrupt changes, tipping points, or thresholds within New Brunswick's ecosystems as trees fail to regenerate under a changing climate. Because of the complex and interconnected nature of forest ecosystems and the human socio-economic systems that rely on them, it was imperative that a model be generated to unpack and deconstruct this complexity so that these tipping points could be explored[9].

Thus, a conceptual framework (Chapter 1) was created that took the most complex representations of forest dynamics as seen in hybrid process-based models (e.g., FLM), and simplified it into more digestible, simplistic models of forest dynamics[10]. Only through deconstructing these complex systems, are we able to truly understand the broad range of thresholds at play.

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[9] Because of the many interconnected and interacting parts, a disturbance can impact the whole ecosystem ways that may not be readily apparent (Kimmins, 1987).
[10] In the words of Levins (1966), we need to reduce realism for generality, and once we understand generality, we can encourage realism.

My key results support the *de-borealisation* of New Brunswick over the next 100 years as temperatures and precipitation increase and key species fail to regenerate. This failure to regenerate is the result of not just the changing climate impacting the growth and survivability of boreal species, but also competition.

Level III has shown that competition quickens the impacts of climate change, as southerly, warm-adapted species gain a boost in productivity as they approach their optimum GDD limits, and northerly species see a decline in productivity and failure in regeneration and survival as they surpass their upper GDD limits. The temporal aspects of competition were also shown to be important. Under the 1985 scenario, balsam fir, while still impacted by the effects of climate change dominates the site when in competition with red maple or red spruce, but the later 10 intervals showed the competitiveness of balsam fir decreased with each rotation when in competition with another species. This competitiveness drops even faster when in competition with more than one species. Therefore competition, in combination with disturbance can abruptly change the composition of the Acadian Forest.

Humans' have, in some respects, become the ultimate tipping point. But the transition to becoming responsible managers of the environment is a more subtle question. Minimally, it requires we abandon simplistic representations of the environment (Level I), and we adopt a more nuanced perspective that accounts for the more complex interactions between climate and forest, at every stage through this transition. As managers, we need to address the uncertainty that comes with the potential of abrupt forest change.

To minimise this risk and maximise potential benefits, I recommend planting a diversity of species and allowing them to compete, especially with the potential for change, given accelerated competition dynamics, rather than maintain pure plantation stands (i.e., Level V.IV). Competition will select the species best suited to a site, which should produce a dominant competitor suited to the environment, allowing managers to maximise site volume[11]. By planning for uncertainty, whether it is due to the complex nature of forest ecosystem dynamics or the uncertainty inherent in models due to their imperfect nature, we can reduce risk and increase resilience in the system. Doing this will help us mitigate the potentially negative, and possibly abrupt changes that will come with climate change. Further work is needed regarding:

- Application of methodologies from Levels II and III on to Level IV to explore how 10-year intervals will change ecosystem dynamics;
- Socio-economic response to thresholds – what was covered here was a basic description of the processes at work; and
- Incorporate better definitions of birth and death thresholds.

[11] Via competitive exclusion principle.

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APPENDICES

Appendix A: Species Attributes and Trajectories

Table A1. Species attribute table. Lower, maximum, and upper are associated with soil water content (SWC); DD_{min}, DD_{max}, and Avg DD are associated with the range of growing degree-days (GDD). The Difference (column 8) is the change between DD_{min} and DD_{max}. The smaller the shade tolerance value, the less shade tolerant the species is.

Spp code	Lower	Maximum	Upper	DD_{min}	DD_{max}	Avg DD	Difference	Shade Tolerance
Al	0	0.8	1.05	700	3200	1950	2500	1
bP	0.5	0.8	1.05	800	2200	1500	1400	1
gB	0.085	0.395	1.05	400	2200	1300	1800	1
jP	0.2	0.6	1.05	750	2000	1375	1250	1
La	0.5	0.705	1.05	400	2500	1450	2100	1
ltA	0.06	0.51	1.05	1000	2500	1750	1500	1
pC	0.05	0.4	1.05	700	4400	2550	3700	1
rP	0	0.5	1.05	1400	2300	1850	900	1
tA	0.06	0.51	1.05	800	3000	1900	2200	1
wB	0.085	0.395	1.05	400	2200	1300	1800	1
wS	0.1	0.4	1.05	500	2100	1300	1600	1
bA	0.5	0.8	1.05	1275	5900	3587.5	4625	2
gA	0.165	0.455	1.05	1275	5900	3587.5	4625	2
rO	0	0.25	1.05	1175	3000	2087.5	1825	2
wA	0.3	0.65	1.05	1275	3000	2137.5	1725	2
wE	0.4	0.5	1.05	1300	3000	2150	1700	2
wP	0	0.533	0.8	1100	3400	2250	2300	2
bS	0.2	0.8	1.05	300	2200	1250	1900	3
eC	0.6	0.88	1.05	500	2500	1500	2000	3
mA	0.165	0.455	1.05	700	2200	1450	1500	3
rM	0	0.4	1.05	1050	2900	1975	1850	3

yB	0	0.3	1.05	1100	2900	2000	1800	3
bF	0.087	0.5	1.05	388	2056	1222	1668	4
Iw	0	0.25	1.05	1300	3000	2150	1700	4
mM	0	0.25	1.05	1000	2800	1900	1800	4
rS	0.2	0.6	1.05	1200	2900	2050	1700	4
Be	0	0.25	1.05	1300	3500	2400	2200	5
He	0	0.25	1.05	1300	2900	2100	1600	5
sM	0	0.25	1.05	1200	2900	2050	1700	5
stM	0	0.25	1.05	1150	2100	1625	950	5

Table A2. Equation coefficients and exponents in the calculation of aboveground biomass (AGB) for stemwood, bark, branches, and foliage for seventeen core tree species (Lambert et al., 2005).

Species	β_{wood1}	β_{wood2}	β_{bark1}	β_{bark2}	$\beta_{branches1}$	$\beta_{branches2}$	$\beta_{foliage1}$	$\beta_{foliage2}$
Balsam Fir	0.0534	2.403	0.0115	2.3484	0.007	2.5406	0.084	1.6695
Tamarack	0.0625	2.4475	0.0174	2.1109	0.0196	2.2652	0.0801	1.4875
White Spruce	0.0359	2.5775	0.0116	2.3022	0.0283	2.0823	0.1601	1.467
Black Spruce	0.0477	2.5147	0.0153	2.2429	0.0278	2.0839	0.1648	1.4143
Red Spruce	0.0989	2.2814	0.022	2.0908	0.0005	3.275	0.0066	2.4213
Jack Pine	0.0804	2.4041	0.0184	2.0703	0.0079	2.4155	0.0389	1.729
Red Pine	0.0564	2.4465	0.0188	2.0527	0.0033	2.7515	0.0212	2.069
White Pine	0.0997	2.2709	0.0192	2.2038	0.0056	2.6011	0.0284	1.9375
Hemlock	0.0619	2.3821	0.0139	2.3282	0.0217	2.2653	0.0776	1.6995
Striped Maple	0.0871	2.3702	0.0241	2.1969	0.0167	2.4807	0.039	1.6229
Red Maple	0.1014	2.3448	0.0291	2.0893	0.0175	2.4846	0.0515	1.5198
Sugar Maple	0.1315	2.3129	0.0631	1.9241	0.033	2.3741	0.0393	1.693
Mountain Maple	0.0871	2.3702	0.0241	2.1969	0.0167	2.4807	0.039	1.6229
Alder	0.0871	2.3702	0.0241	2.1969	0.0167	2.4807	0.039	1.6229
Yellow Birch	0.1932	2.1569	0.0192	2.2475	0.0305	2.4044	0.1119	1.3973
White Birch	0.0593	2.5026	0.0135	2.4053	0.0135	2.5532	0.0546	1.6351
Beech	0.1478	2.2986	0.012	2.2388	0.037	2.368	0.0376	1.6164
White Ash	0.1861	2.1665	0.0406	1.9946	0.0461	2.2291	0.1106	1.2277
Black Ash	0.0941	2.3491	0.0323	2.0761	0.0448	1.9771	0.0538	1.3584
Green Ash	0.0941	2.3491	0.0323	2.0761	0.0448	1.9771	0.0538	1.3584
Ironwood	0.0871	2.3702	0.0241	2.1969	0.0167	2.4807	0.039	1.6229
Balsam Popular	0.051	2.4529	0.0297	2.1131	0.012	2.4165	0.0276	1.6215
Large-Tooth Aspen	0.0959	2.343	0.0308	2.224	0.0047	2.653	0.008	2.0149
Trembling Aspen	0.0605	2.475	0.0168	2.3949	0.008	2.5214	0.0261	1.6304
Pin cherry	0.3743	1.9406	0.0679	1.8377	0.0796	2.0103	0.084	1.2319
Red Oak	0.1754	2.1616	0.0381	2.0991	0.0085	2.779	0.0373	1.674
American Mountain Ash	0.0941	2.3491	0.0323	2.0761	0.0448	1.9771	0.0538	1.3584
White Elm	0.0402	2.5804	0.0073	2.4859	0.0401	2.1826	0.075	1.3436
Eastern White Cedar	0.0654	2.2121	0.0114	2.1432	0.0335	1.9367	0.0499	1.7278
Grey Birch	0.072	2.3885	0.0168	2.2569	0.0088	2.5689	0.0099	1.8985

Appendix B: Red Spruce Competition Results

Table B1. Red spruce *vs.* red maple for PSP No. 1062. The data has been normalised and reduced to 40-year increments; rS is the species code for red spruce; rM for red maple; rS.rM is short-hand for the two species in competition. The historical and climate change scenarios are identified by H and CC, respectively; the values 0, 40, and 80 represent years after stand initiation.

	rS.rm							
Year	**rS H 0**	**rM H 0**	**rS CC 0**	**rM CC 0**	**rS CC 40**	**rM CC 40**	**rS CC 80**	**rM CC 80**
1985	0.041373	0.056721	0.041373	0.056721	0.041373	0.056721	0.041373	0.056721
1986	0.041373	0.052717	0.041373	0.054576	0.045138	0.067827	0.054242	0.0745
1987	0.04142	0.050429	0.041373	0.053527	0.047855	0.081745	0.066349	0.090705
1988	0.04142	0.050715	0.041373	0.053813	0.049857	0.097474	0.081316	0.110391
1989	0.04142	0.05062	0.04142	0.052622	0.052288	0.113775	0.09409	0.135319
1990	0.036082	0.046235	0.038227	0.047998	0.053194	0.123308	0.111153	0.158389
1991	0.032269	0.044328	0.034271	0.045949	0.056864	0.138227	0.129457	0.184032
1992	0.02817	0.046616	0.030648	0.044995	0.059724	0.156244	0.150477	0.211106
1993	0.02469	0.046949	0.027836	0.045329	0.06816	0.177026	0.166683	0.230744
1994	0.023022	0.047807	0.0245	0.0449	0.070829	0.187846	0.182984	0.250763
1995	0.021211	0.049857	0.022021	0.047664	0.077169	0.20286	0.203384	0.284795
1996	0.019066	0.052193	0.019542	0.048713	0.081125	0.222164	0.228742	0.337846
1997	0.017398	0.053432	0.01654	0.050906	0.084318	0.236559	0.257579	0.383603
1998	0.015634	0.053432	0.0153	0.053194	0.089466	0.239657	0.286511	0.429266
1999	0.015205	0.058723	0.014871	0.058866	0.094757	0.264061	0.320257	0.485176
2000	0.01449	0.062679	0.013966	0.061821	0.10143	0.281792	0.373213	0.541468
2001	0.012202	0.059581	0.012059	0.058627	0.111153	0.300143	0.428551	0.616444

2002	0.01101	0.05653	0.010486	0.058341	0.114252	0.317445	0.501573	0.699857
2003	0.010105	0.057007	0.009056	0.061868	0.117445	0.34795	0.579695	0.765205
2004	0.009581	0.054147	0.007674	0.059104	0.120305	0.380172	0.655624	0.84204
2005	0.008913	0.055624	0.006101	0.061439	0.127645	0.398808	0.753051	0.955195
2006	0.007388	0.05734	0.005624	0.064442	0.13489	0.433413	0.862774	1.110296
2007	0.007531	0.062154	0.005148	0.070972	0.141849	0.479028	0.983508	1.232459
2008	0.007531	0.068208	0.005338	0.079266	0.14714	0.499952	1.093947	1.386463
2009	0.008103	0.08041	0.00572	0.089085	0.16163	0.560248	1.22307	1.521115
2010	0.008103	0.079552	0.005767	0.091563	0.172164	0.639228	1.343613	1.659056
2011	0.008103	0.072641	0.005577	0.092993	0.185748	0.733651	1.442278	1.857674
2012	0.008103	0.072545	0.005291	0.096187	0.201382	0.859485	1.583031	1.967064
2013	0.007912	0.072784	0.005291	0.09266	0.229457	0.960248	1.721544	2.062965
2014	0.006578	0.069399	0.005338	0.095138	0.26592	1.078932	1.894805	2.196282
2015	0.00591	0.067302	0.005338	0.102574	0.319542	1.260915	2.045615	2.318446
2016	0.00591	0.063346	0.005815	0.110724	0.359962	1.367302	2.240181	2.444328
2017	0.005481	0.060629	0.006244	0.119542	0.393756	1.47898	2.380601	2.498999
2018	0.004194	0.060963	0.006482	0.13041	0.455958	1.701525	2.577312	2.617207
2019	0.003527	0.059152	0.00653	0.133556	0.525405	1.865682	2.72183	2.705767
2020	0.003527	0.063108	0.006625	0.128742	0.585796	1.957531	2.905481	2.800143
2021	0.003289	0.061487	0.007245	0.13327	0.663775	2.109533	3.063489	2.860724
2022	0.002431	0.062726	0.00734	0.135701	0.736988	2.202622	3.235796	2.888847
2023	0.002193	0.058961	0.00796	0.150334	0.824786	2.392993	3.368589	2.968446
2024	0.00224	0.058198	0.008723	0.165205	0.911535	2.52979	3.552479	3.07612
2025	0.002097	0.063298	0.009295	0.16816	1.022784	2.710915	3.736177	3.085415

2026	0.001859	0.058818	0.009962	0.177121	1.132888	2.889133	3.840133	3.132793
2027	0.001621	0.059724	0.010772	0.198665	1.249142	3.053527	3.989704	3.236082
2028	0.001621	0.059438	0.011344	0.22469	1.371687	3.263155	4.144423	3.342517
2029	0.001621	0.06001	0.012107	0.248951	1.47326	3.402479	4.241325	3.380553
2030	0.001382	0.062965	0.012059	0.274261	1.592803	3.57021	4.41878	3.428646
2031	0.001144	0.063298	0.012297	0.303003	1.721306	3.690467	4.537369	3.490896
2032	0.001192	0.068398	0.012297	0.32674	1.827121	3.738608	4.64919	3.477073
2033	0.001287	0.078551	0.013823	0.372307	1.945901	3.826787	4.712107	3.545234
2034	0.00143	0.092898	0.013918	0.403289	2.057912	3.908294	4.863632	3.573928
2035	0.00143	0.088704	0.015014	0.416111	2.166397	4.058866	4.931554	3.638656
2036	0.00143	0.082078	0.016158	0.459342	2.271068	4.390181	5.09347	3.751954
2037	0.00143	0.076168	0.01735	0.498236	2.422021	4.62183	5.186892	3.678217
2038	0.00143	0.076501	0.018541	0.546378	2.525071	4.714633	5.315729	3.825453
2039	0.000572	0.074261	0.020496	0.611153	2.654385	4.763727	5.397331	3.85081
2040	0.000572	0.066778	0.022307	0.675262	2.743518	4.814776	5.486845	3.847331
2041	0.000286	0.057722	0.025119	0.74347	2.871544	4.979218	5.558246	3.797474
2042	0.000286	0.057245	0.025262	0.803575	2.991039	5.008103	5.643708	3.849094
2043	0.000286	0.057579	0.026835	0.867159	3.14714	5.14938	5.632698	3.903908
2044	0.000286	0.059438	0.029886	0.937274	3.241039	5.301954	5.738084	3.978122
2045	0.000286	0.06001	0.033556	1.014109	3.333603	5.409724	5.869256	4.059581
2046	0.000286	0.055291	0.036845	1.070782	3.42531	5.726644	5.901668	4.136892
2047	0.000286	0.053956	0.041277	1.140038	3.531792	5.789037	5.93327	4.099619
2048	0.000286	0.055338	0.043708	1.189228	3.645663	5.841182	6.03041	3.984557
2049	0.000286	0.058532	0.047426	1.270591	3.747807	6.079171	6.075071	4.062869

2050	0.000286	0.059533	0.050524	1.338084	3.806149	6.072545	6.192993	4.110391
2051	0.000286	0.059771	0.057912	1.453289	3.862154	6.209867	6.304576	4.163966
2052	0.000286	0.059867	0.064919	1.580219	4.000286	6.358437	6.387607	4.15591
2053	0.000286	0.059056	0.074929	1.691516	4.030172	6.419018	6.458866	4.148665
2054	0	0.058198	0.088751	1.788561	4.169447	6.288608	6.527598	4.030839
2055	0	0.060724	0.10429	2.008294	4.263012	6.103051	6.51306	3.938465
2056	0	0.064728	0.118065	2.157007	4.294137	6.088894	6.544137	3.749142
2057	0	0.072259	0.126072	2.301382	4.362631	6.013823	6.534223	3.714013
2058	0	0.083889	0.142517	2.507436	4.402288	6.251811	6.523451	3.668637
2059	4.77E-05	0.091754	0.154004	2.687703	4.388513	6.318637	6.496806	3.543947
2060	4.77E-05	0.090896	0.171258	2.925596	4.459199	6.362965	6.562536	3.583699
2061	4.77E-05	0.089847	0.185462	3.121211	4.519352	6.511344	6.657388	3.558198
2062	4.77E-05	0.089037	0.202002	3.37979	4.566587	6.610153	6.763203	3.578074
2063	4.77E-05	0.089371	0.222736	3.63694	4.53999	6.418255	6.815634	3.599571
2064	4.77E-05	0.08184	0.240896	3.770496	4.594519	6.447617	6.843947	3.399809
2065	0	0.06897	0.262393	4.074357	4.641659	6.552336	6.885081	3.421354
2066	0	0.068112	0.281173	4.392326	4.640276	6.535653	6.832412	3.364204
2067	0	0.066015	0.28489	4.555815	4.675357	6.5847	6.830029	3.389371
2068	0	0.066397	0.309152	4.902812	4.74123	6.684223	6.765729	3.492088
2069	0	0.059295	0.324166	5.087417	4.708675	6.695567	6.826978	3.539704
2070	0	0.061582	0.349619	5.308818	4.741468	6.689561	6.747331	3.553622
2071	0	0.053908	0.372116	5.528932	4.78632	6.662345	6.651668	3.538084
2072	0	0.054814	0.394376	5.820496	4.76368	6.663537	6.650858	3.43899
2073	0	0.05572	0.419924	5.959628	4.727312	6.645043	6.614013	3.329028

2074	0	0.061725	0.437321	6.031459	4.756673	6.450858	6.463727	3.242564
2075	0	0.066111	0.448141	6.377788	4.781792	6.428408	6.424023	3.31082
2076	0	0.063203	0.465729	6.858913	4.749285	6.3051	6.411106	3.257245
2077	0	0.062631	0.496806	7.204433	4.729647	6.335701	6.40858	3.205815
2078	0	0.065253	0.503194	7.357197	4.774833	6.392707	6.210582	3.254623
2079	0	0.06368	0.526168	7.641516	4.82817	6.300286	6.177073	3.012869
2080	0	0.065205	0.535462	7.782936	4.88327	6.175834	6.166063	3.018923
2081	0	0.069113	0.564871	8.160057	4.877216	6.208484	6.116683	2.915348
2082	0	0.073403	0.585796	8.382316	4.877359	6.120591	6.032126	2.791516
2083	0	0.082698	0.58489	8.727741	4.904004	5.876883	5.955386	2.827121
2084	0	0.092135	0.619971	8.906435	4.881983	5.759009	5.819733	2.846759
2085	0	0.091754	0.655767	8.959104	4.877884	5.879743	5.817302	2.894995
2086	0	0.087655	0.672688	9.353908	4.752622	5.948808	5.758627	2.904671
2087	0	0.081983	0.678265	9.522355	4.783317	5.933174	5.716587	2.865968
2088	0	0.082078	0.71511	9.739943	4.805338	5.657054	5.772212	2.761916
2089	0	0.076501	0.726311	9.913632	4.672307	5.691516	5.749094	2.670686
2090	0	0.070925	0.752955	9.937321	4.508866	5.570305	5.770067	2.50572
2091	0	0.062679	0.752431	10.09466	4.565157	5.60081	5.685272	2.4602
2092	0	0.062965	0.78694	10.1377	4.611344	5.512059	5.734461	2.378217
2093	0	0.061344	0.817016	10.3092	4.646092	5.298189	5.696711	2.256292
2094	0	0.060629	0.836559	10.53341	4.646425	5.21654	5.702812	2.168589
2095	0	0.06449	0.838942	10.61749	4.606101	5.392707	5.547617	2.175596
2096	0	0.063394	0.865682	10.78713	4.471973	5.273213	5.473451	2.168112
2097	0	0.065253	0.860057	10.88827	4.357722	5.086892	5.410582	2.114681

2098	0	0.062393	0.878408	10.76983	4.265729	4.766826	5.401335	1.851335
2099	0	0.063584	0.882507	10.65663	4.291563	4.707769	5.190086	1.888847
2100	0	0.066587	0.892755	10.67255	4.235272	4.566349	4.99633	1.927407

Appendix C: Climate Change Projections for specific PSP

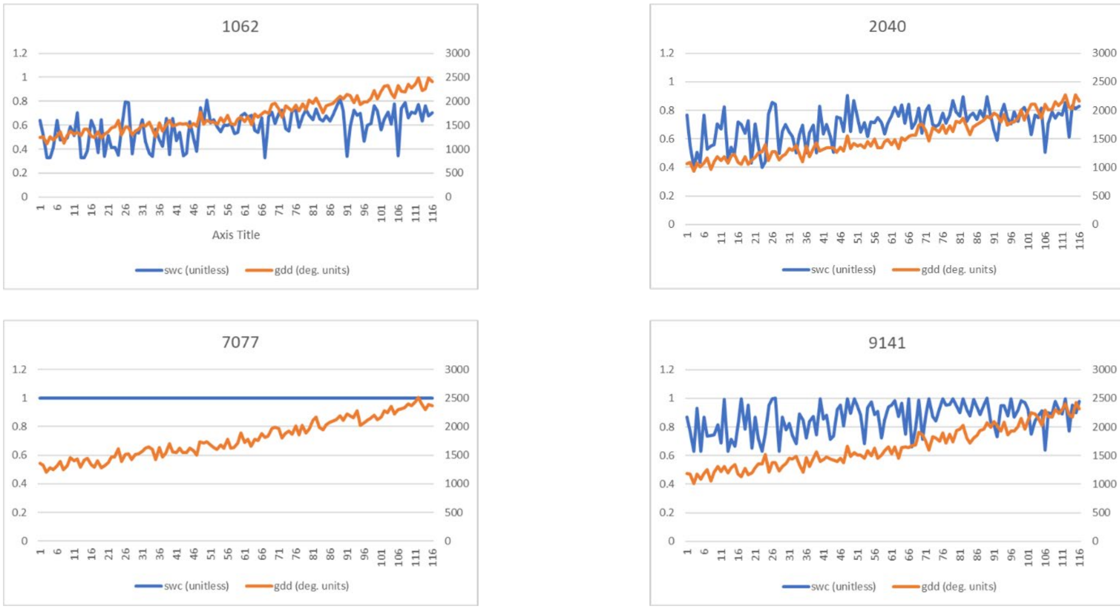

Figure C1. Climate change site data at individual plot locations over the projection period from 1985–2100. The start of each graph is at the plot establishment year of 1985. The upper graphs are for growing degree-days (GDD; orange lines) and relative extractable soil water content (SWC; blue lines). The column of graphs corresponds to PSP No. 1062, 2040, 7077, and 9141, respectively.

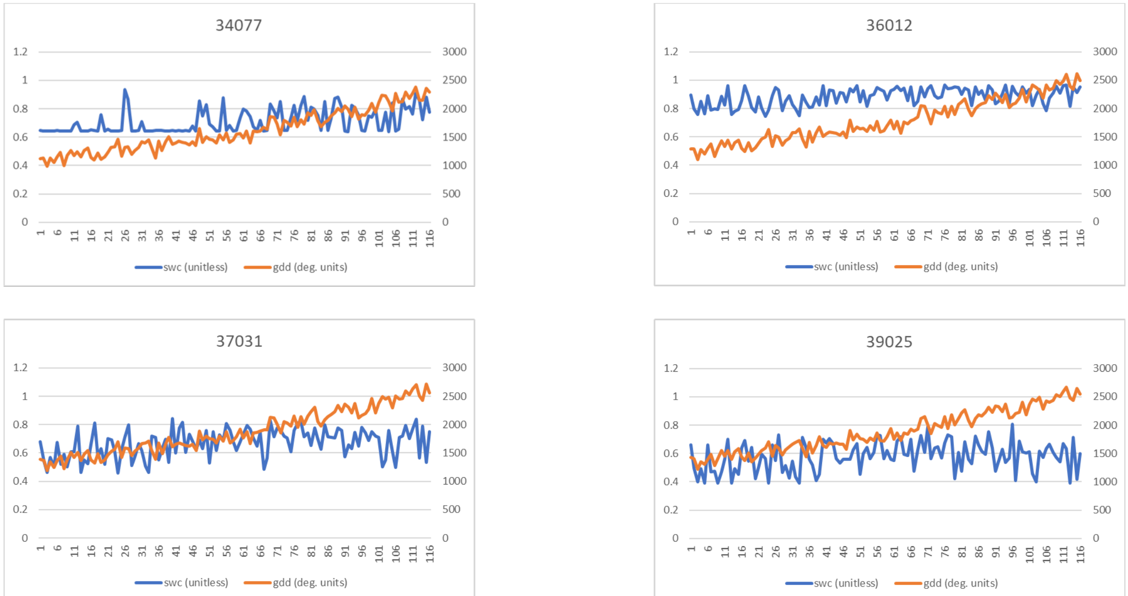

Figure C2. Climate Change site data at individual plot locations over the projection period from 1985–2100. The start of each graph is at the plot establishment year of 1985. The upper graphs are for growing degree-days (GDD; orange lines) and relative extractable soil water content (SWC; blue lines). The column of graphs corresponds to PSP No. 34077, 36012, 37031, and 39025, respectively.

Appendix D: Ecosystem-level Species Trajectories

Figure D1. Comparison between the different climate and ground conditions for PSP No. 1062. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

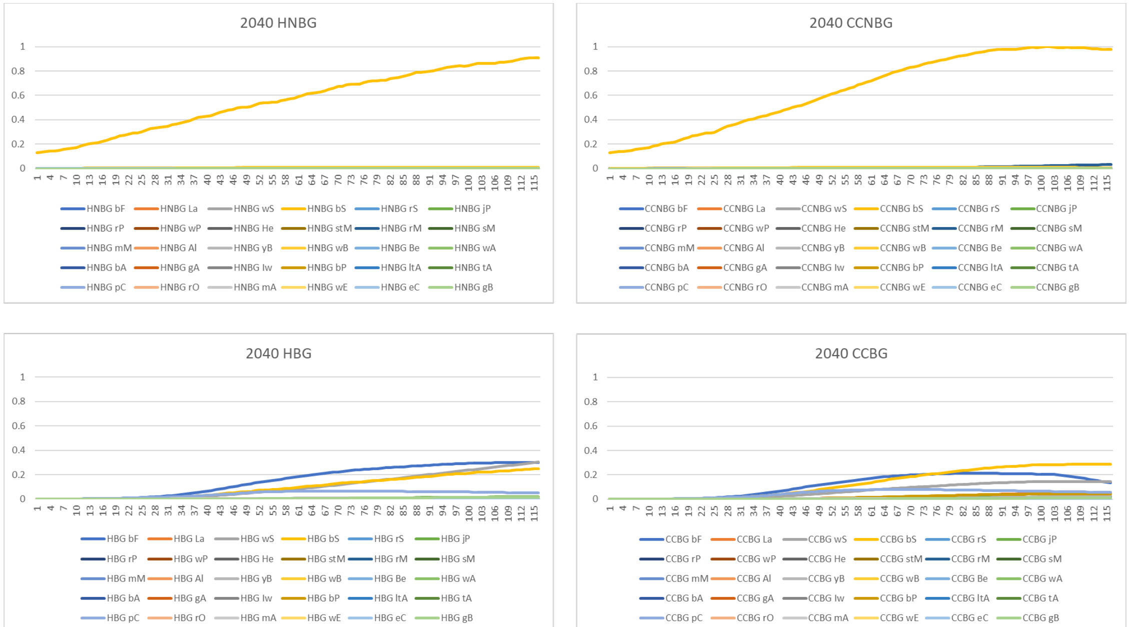

Figure D2. Comparison between the different climate and ground conditions for PSP No. 2040. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

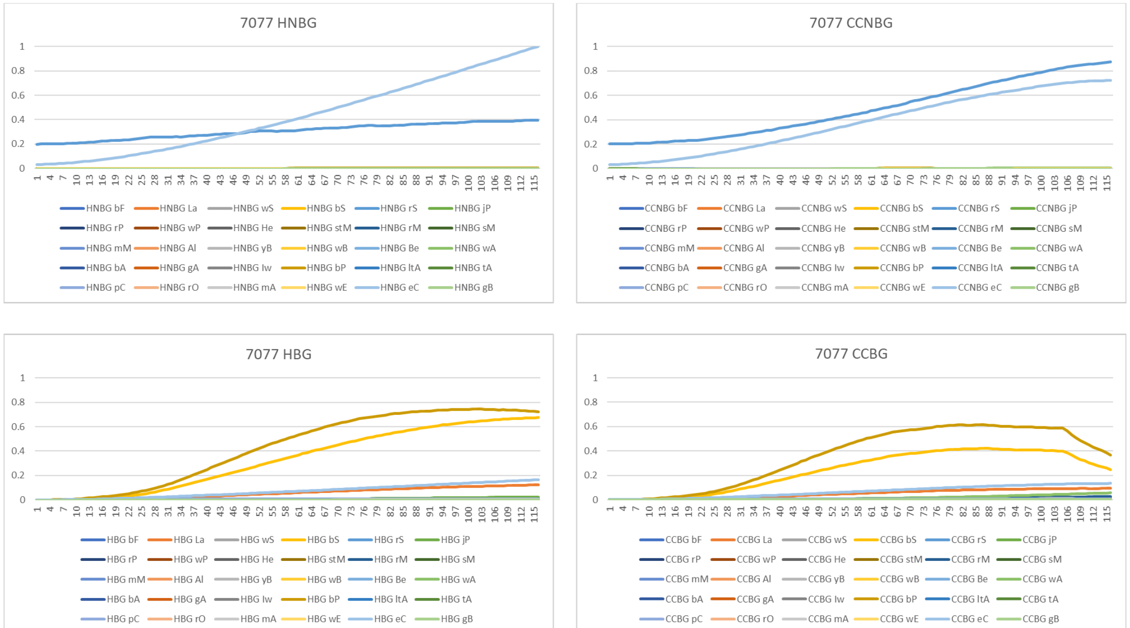

Figure D3. Comparison between the different climate and ground conditions for PSP No. 7077. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

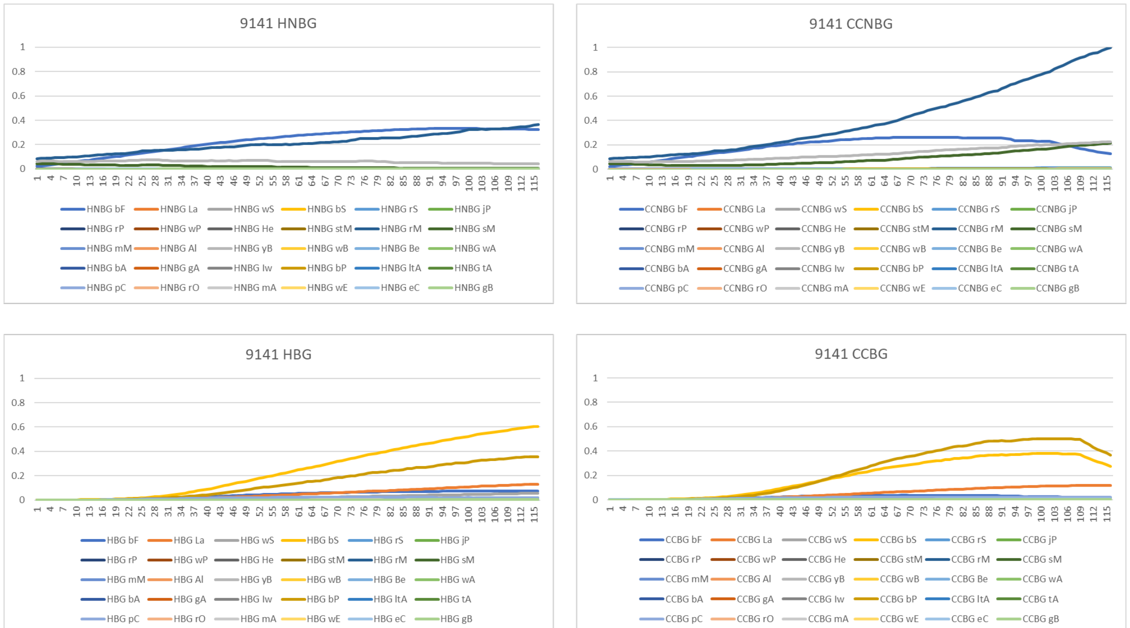

Figure D4. Comparison between the different climate and ground conditions for PSP No. 9141. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

Figure D5. Comparison between the different climate and ground conditions for PSP No. 34077. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

Figure D6. Comparison between the different climate and ground conditions for PSP No. 36012. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

Figure D7. Comparison between the different climate and ground conditions for PSP No. 37031. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

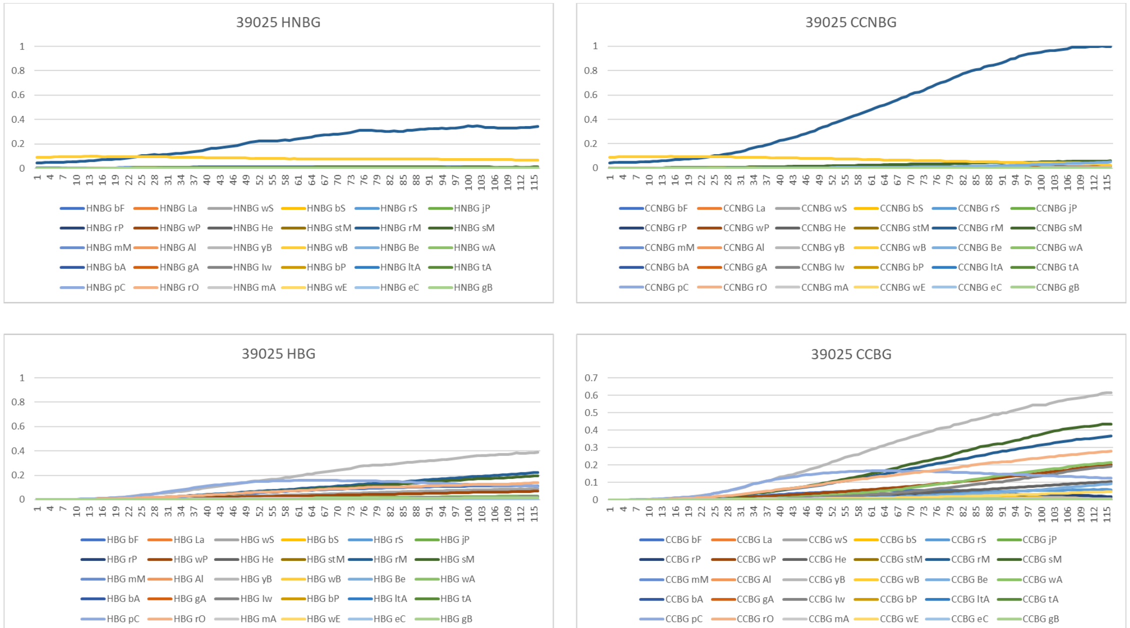

Figure D8. Comparison between the different climate and ground conditions for PSP No. 39025. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

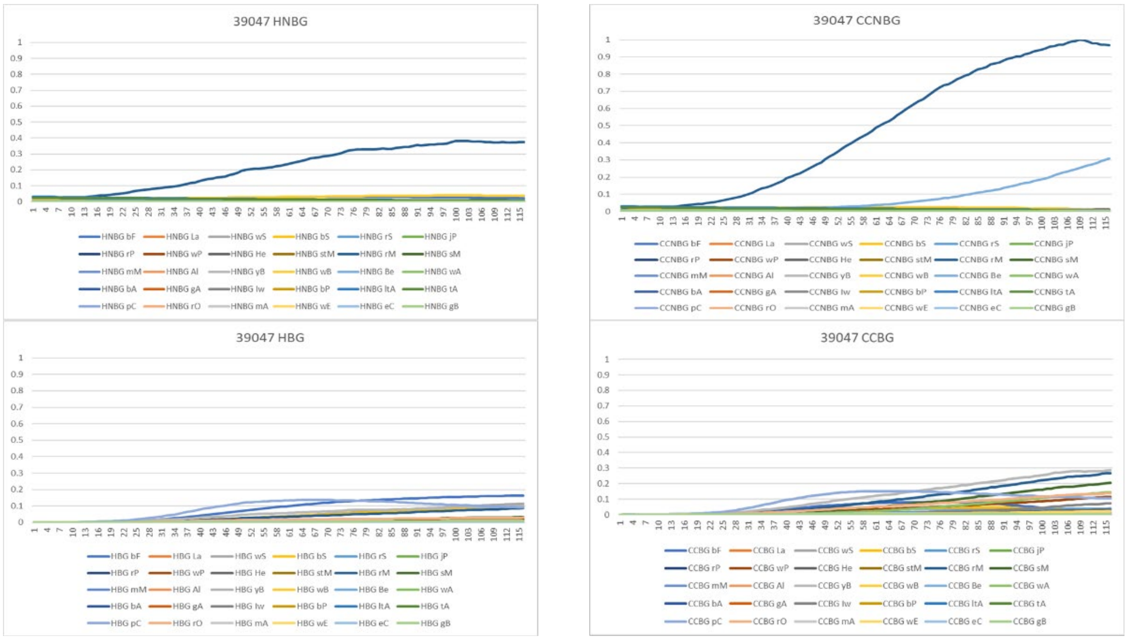

Figure D9. Comparison between the different climate and ground conditions for PSP No. 39047. Reading left to right from the top left, historical non-bare ground (HNBG), climate change non-bare ground (CCNBG), historical bare ground (HBG), and climate change bare ground (CCBG). The x-axis represents time (in years) and y-axis biomass in tonnes per hectare.

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Publications:

Bourque, C. P.-A. Gachon, P. **Maclellan, B. R.**, and Maclellan, J.I. (2020). Projected wind impact on *Abies balsamea* (balsam fir)-dominated stands in New Brunswick (Canada) based on remote sensing and regional modelling of climate and tree species distribution. Remote Sensing, 12(7), 1177. https://doi.org/10.3390/rs12071177.