Chapter 6: Vegetation Modeling, Harvest Scenarios and Projected Impacts on the Landscape

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As a key outcome of this project, our team wanted to better understand the impacts of climate change (Chapter 5) on regional forest composition and important ecosystem processes. On the cutting-edge of modelling vegetation is the use of Dynamic Vegetation Models (DVM), that project the response of plant species and selected indicators to climate change. For example, DVMs can help project how long term trends in temperature precipitation changes can impact phenology (the timing of plant processes) and growth conditions for different species. For the forest sector, determining what species of trees will be best suited to different areas in the future can help to inform adaptation actions, such as assisted migration.

For this study, modelling experts Dr. Joe Melton and Dr. Jed Kaplan ran a number of different future scenarios for the vegetation of the Skeena region using a DVM called LPJ-GUESS. In order to do this, they first parameterized data for 19 major tree species and grass common to the Skeena region (shrubs were not included in this analysis). By inputting this information in combination with downscaled climate data from three different future scenarios described in the previous chapter (A2, A1-b, and B1) LPJ-GUESS simulates potential natural vegetation under each scenario without assuming any human interference. Next, they ran another suite of simulations to assess the impacts of each emissions scenario with historical and projected future harvest schedules for a sub-region that includes the Kalum TSA and TFL 1. Finally, three different harvest scenarios were devised by Brinkman Forest staff to represent alternative harvest options and better understand the significance of harvesting on the sub- region (the same study area as the SRWCP). The harvesting schedules were developed as hypothetical representations of the future that include a decrease in the AAC, an increase in the AAC, and no change in the AAC. Each of the three suites of model runs simulates changes to regional species composition and distribution, carbon pools and flows throughout the ecosystem, surface runoff, soil moisture, and annual fire probabilities, amongst other model outputs.

The climate and vegetation outputs from the LPJ-GUESS model are important for giving us a regional perspective and helping to strategically plan for the future. For example, we can talk about changes in runoff or carbon flux over a region. The results from these runs suggest that the impact of climate change will be far more significant on the entire study region than the impact of harvesting. However, we can’t use this model to tell us how runoff and carbon could change at the site level and we know that site level dynamics are important for integrated management of resources. For example, the impact of runoff of FSWs requires finer scale analysis than can be achieved through the LPJ-GUESS model. The cumulative effects analysis tool developed by Cortex Consultants as part of the Skeena River Watershed Conservation Project, complements the LPJ-GUESS approach by providing a way for resource managers to analyze the dynamics of climate change and land-use on a much smaller scale.

It is important to acknowledge that model outputs are only as good as the data available. For the Skeena region there is relatively poor data on soil (which is important for carbon outputs), and also for historical harvest patterns; this means that the model results are not perfect, but they can still be used to give us an idea of how things might look. Also, having completed the work of parameterizing 18 tree species and building a regional model means that in the future, we can continuously improve on the work that was done by investing in studies to create and format input data.

This chapter describes the vegetation modelling approach and the simulated impacts on tree species, carbon and runoff as result of both climate change and different harvesting scenarios. Technical information is included in the appendices at the end of the chapter. Scenario runs for the Skeena River Water Conservation Project are ongoing, but we have included some of the sample outputs in Chapter 9 and the project summary is included in Appendix 9.1 .The next step for both models would be to improve on the data available and to work more closely with resource managers to better achieve results and outputs useful for future planning.

6.1 Vegetation Modelling Approach

The vegetation of the Northwest Skeena region of British Columbia was modeled using a state-of-the-art dynamic vegetation model, LPJ-GUESS (Smith et al. 2001; Hickler et al., 2008). Model simulations were performed in three suites, all of which cover the time period from 1906 to 2080.

The first suite of model runs simulates potential natural vegetation, i.e. the model simulates the growth of trees and grass in the absence of any human interference, past or future, for the entire study region (Figure 6.1). This suite of simulations allows interpretation of the effects of changing climate and carbon dioxide concentrations ([CO_2]) in the absence of the confounding effects of tree harvesting or land-use changes.

The second suite of simulations investigates the impact of historical and projected future harvesting on a sub-region of the study area. Both the potential natural vegetation and harvesting suites were run for the historical period (1906 – 2006) and three future climate scenarios (2007 – 2080) (see Section 5.1 and Appendix 6.1).

A final suite of simulations investigates the effect of three different levels of future harvesting intensity. Each of the three suites of model runs simulates changes to the regional species composition and distribution, carbon pools and flows throughout the ecosystem, surface runoff, soil moisture, and annual fire probabilities, amongst other model outputs.

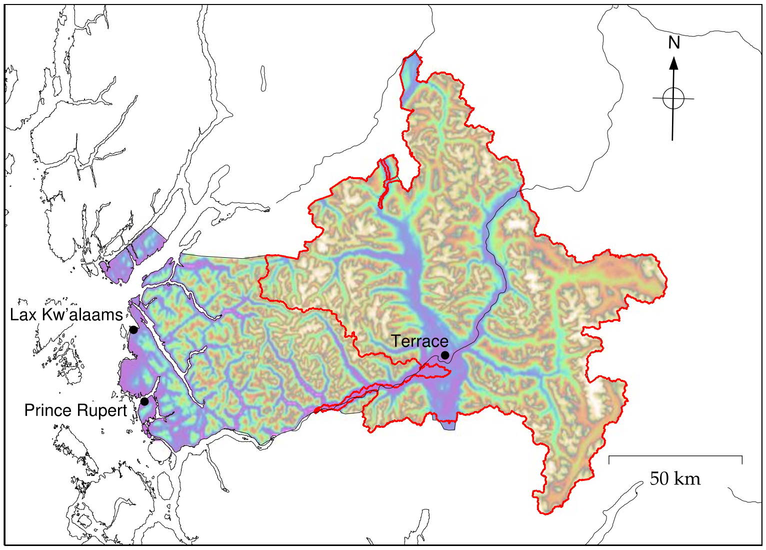
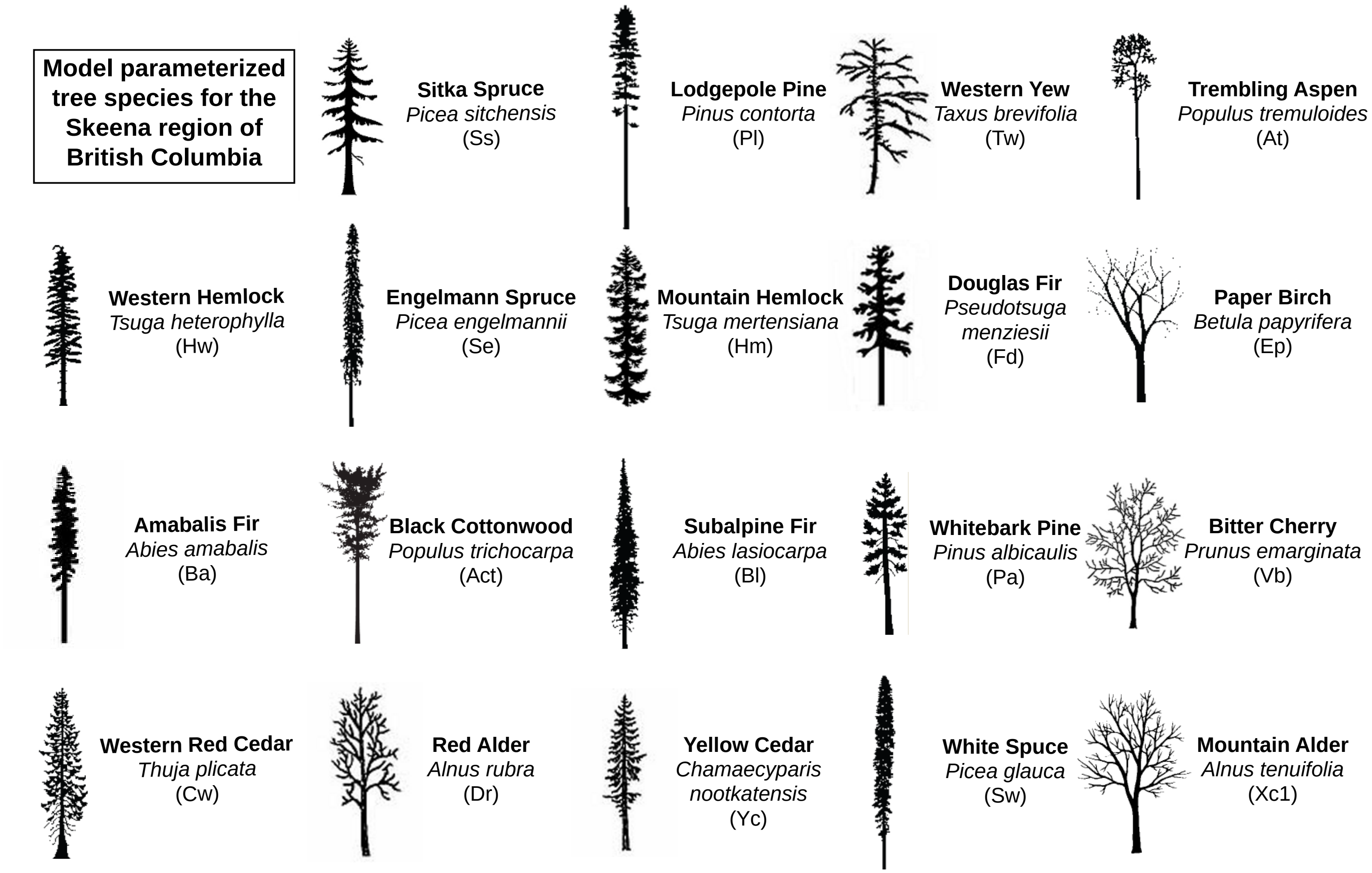


Figure 6.1: Topographic view of the CCAP project study region with SRWCP sub-region used for harvesting scenarios outlined in Red. Areas with blue to purple colours indicate lower elevation; red to white areas indicate higher elevations.

6.1.1 LPJ-GUESS Dynamic Vegetation Model

LPJ-GUESS is an ecosystem model that explicitly simulates growth and competition between individual plants. Each simulated plant is influenced by the conditions within its grid cell including climate, [CO_2], soil texture and other plants. Differences in the plant physical structure, such as height, crown depth, crown area and leaf mass, influence the plant's relative light interception and photosynthetic uptake. Within the model, each plant assimilates carbon through photosynthesis and allocates that carbon to its leaf, sapwood, and fine root tissues. The success of the plant in gaining carbon into its tissues, and its conversion of sapwood to heartwood, determines the plant height and stem diameter. Competition in the model occurs between plants for light with taller plants shading shorter plants, as well for soil water resources by plant root systems. Mortality to plants occurs through age-related processes, and through disturbances, such as fire, that intensify depending upon the conditions at the site. Each tree species is parameterized according to available scientific literature values to reproduce present day estimates of species ranges (see Appendix 6.1.3.). For this study, the nineteen major tree species from the Skeena region were parameterized for the model along with grass (Fig 6.2).

Historical climate was used as in input to the model for the years 1906 – 2006 (see Chapter 2). Future greenhouse gas (GHG) emissions scenarios and climate model outputs from the IPCC 4th Assessment (Meehl et al., 2007) were selected following the recommendations of Spittlehouse and Murdock (2010). The three selected emissions scenarios and climate model outputs are described in Chapter 5, along with temperature and precipitation projections for the study area.



[1]http://www.for.gov.bc.ca/hfp/silviculture/Compendium/ and http://www.pennine.demon.co.uk/Arboretum/Alte.htm (Oct 12 2010)

Figure 6. 2: Tree species of the Skeena region parameterized for the LPJ-GUESS dynamic vegetation model.

6.1.2 Harvesting scheme in LPJ-GUESS[1]

The LPJ-GUESS model simulates potential natural vegetation in its basic setup. In these simulations, no human influence on the plants is assumed and all plant mortality or disturbance comes from natural stresses. In other words, natural vegetation simulates hypothetical forest composition if there had not been any interference from humans, such as harvesting or replanting. For this study, we have developed a harvesting scheme to estimate the effects of past and future harvesting on the study region. Our harvesting scheme was applied to a sub-region of the entire CCAP study area. The sub-region for harvesting is the same as the area as the Skeena River Watershed Conservation Project (SRWCP) (Fig 6.1) and was chosen given the availability of quantified estimates of future harvesting and Coast Tsimshian Resources interest in understanding climate impacts on the company's tenure.

Harvesting occurs in the model as the complete removal of all tree species within a grid cell ('clear cutting') during a harvest year. The year of harvest and spatial extent is prescribed based upon harvesting data available from the British Columbia Ministry of Forests, Lands, and Natural Resource Operations Vegetation Resource Inventory (2011) for lands outside of the present area of Tree Farm Licence 1 (TFL1). As past harvesting information for TFL1 was not available, we have estimated past harvest based upon historical annual allowable cut (AAC), TFL1 spatial extent, and yield tables derived for biogeoclimatic zones within TFL1 (see Appendix 6.5).

Harvesting amounts are prescribed on a basis of square kilometers per year harvested. The actual locations of harvest are distributed randomly within the study region, excluding present day areas of alpine tundra. The harvesting scheme does not allow subsequent reharvesting of a grid cell (second-growth cutting). After harvest, the harvested grid cells were replanted immediately following the replanting practices in the region for species planted, planting density, and site preparation (Engelbertink, 2011 Personal Communication)(see Appendix 6.5). Given that we did not have information about harvesting in the TFL1 region before CTR held the tenure and thus had to estimate past harvesting intensity, we feel our approach is an acceptable approximation for simulating the regional values of carbon fluxes and pools, surface runoff, and annual fire probabilities under the influence of harvesting. One possibility to improve and extend this research project would be to build on these results by inputting a more realistic harvest schedule including second growth along with more accurate historical forest history. Potential to fund such an extension of this research is being explored.

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[1] In February 2011, the Chief Forester decreased the annual allowable cut (AAC) for the TSA by 2.9 % to 424,000 m^3 and the AAC for TFL 1 was also reduced from 500 000 m^3 to 378 059 m^3 as of July 6, 2011. These reductions are not reflected in the harvesting scheme used for this project.

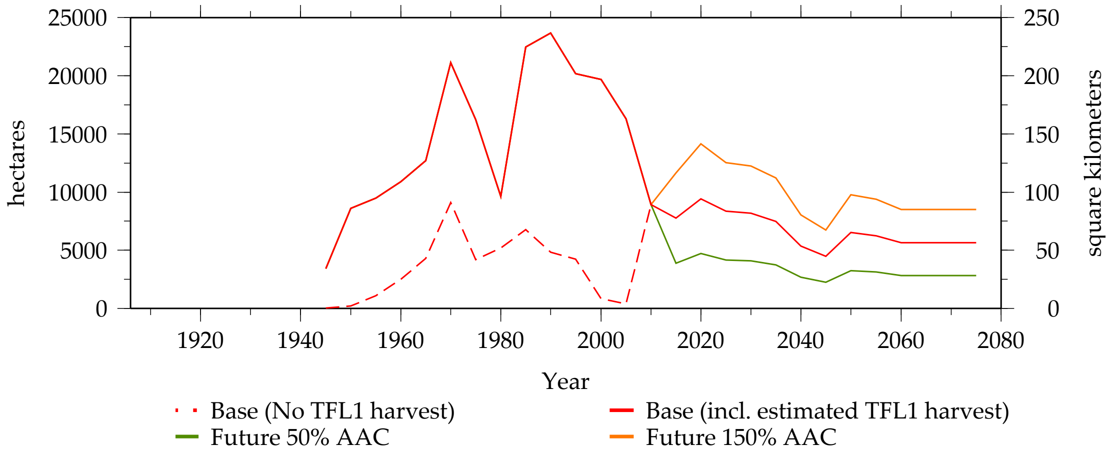

Figure 6.3: Spatial extent of past and future harvesting per five year period used in the suite of LPJ-GUESS harvesting simulations for the SRWCP study region. The baseline-harvesting scheme (solid red line) is used in the second suite of LPJ-GUESS simulations. The historical VRI-derived (Ministry of Forests, Lands, and Natural Resource Operations 2011) harvested area per five years outside of TFL1 is indicated by the dashed red line. The historical estimated TFL1 harvest is then the difference between the upper solid red line and lower dashed line. The estimated TFL1 harvest assumes a constant cutting rate at the annual allowable cut (AAC) as determined by the Chief Forester. This is especially visible in the decline of the non-TFL1 VRI-derived harvest from 1990 to 2005 (dashed line) and the lack of strong decline in the TFL1 estimates (solid red line). Future harvesting at the AAC level is according to the data provided by Cortex Consultants based on their calculations for the SRWCP study area and aligns with the level defined by the Chief Forester. The SRWCP simulations do not extend past 2060 thus the harvest intensity for 2060 – 2080 was left unchanged at the 2060 level. Two additional sensitivity tests to future harvesting were created for the third suite of LPJ-GUESS simulations. The first test has a reduction to 50% of the AAC future harvest intensity (green line), representing a 'conservation' scenario. The second test has an increase in harvesting to 150% of the AAC future harvest intensity (orange line), representing a scenario for harvesting of historical undercutting or for biofuel production.

6.2 Species distribution changes and forest health

Natural potential vegetation species distribution changes were simulated with LPJ-GUESS forced by the three climate scenarios (HADGEM-A1B, CGCM3-A2, and HADCM3-B1). The changes in species distribution are represented in Figure 6.4 as the change in percent of living carbon biomass (which includes then the leaf, sapwood, heartwood, and root mass for living trees and leaf and root mass for grass). All figures use the short name to denote each species, for reference please see Table 6.1 or Figure 6.2.

Across the study area as a whole, the largest changes are projected to occur to species that presently occupy the higher elevations of the study region. Mountain hemlock (Hm) declines across all scenarios likely due increased competition as, under a warming climate, more species encroach upon the higher elevations (Fig 6.5). The area with the largest declines of mountain hemlock appears on the western side of the Coast Mountains. The main species to increase at the expense of mountain hemlock is subalpine fir (Bl), with the primary increases on the coastal side of the Coast Mountains and in the higher elevation flanks of the interior valleys (Fig 6.6). Across all future climate scenarios, western hemlock (Hw) is relatively stable with possibly a slight increase into the future (~ +5%)(Fig 6.7) at the higher elevations of its present range. Western red cedar also shows a largely stable distribution through time (Fig 6.8) with some minor increases in higher elevation areas. Engelmann spruce (Se) also could increase its distribution into areas of the western Coast Mountains in the future, outside of its present-day simulated distribution (Fig 6.9).

For yellow cedar (Yc), our model shows no significant dieback in the historical period (Fig 6.10). A dieback has been observed in Alaska and parts of northern B.C. (Beier et al., 2008) that may also affect parts of the study area. The cause of the dieback is suggested to be due to winter warming trends reducing snow pack and making yellow cedar's shallow root systems exposed to more frequent severe freeze-thaw events (Hennon et al., 1992; Daniels et al., 2011). Since the regional climatology data available for input into LPJ-GUESS is monthly (see Appendix 1.2.2.), we are unable to properly simulate these rapid freeze-thaw events that damage yellow cedar. Future projections for yellow cedar are shown to be highly climate scenario dependent and could be inaccurate due to our simulations not capturing these damaging rapid sub-monthly climate changes. LPJ-GUESS can simulate freeze-thaw cycles but would require sub-monthly data to do so.

Deciduous species such as black cottonwood, trembling aspen, red alder, paper birch etc. (see Table 6.1 or Fig 6.2) remain minor species across the study range (< 5%). There is possibly some expansion of deciduous species from 2030 on, in scenarios HADGEM-A1B and HADCM3-B1 (Fig 6.4).

A large decline in grass area is visible in all scenarios, both into the future and across the historical period (Fig 6.4 and Fig 6.11). This decline is primarily in the alpine regions with some grass area loss in the valley bottoms due to expansion of forest regions. The warming observed across the historical period (described in Chapter 5) allows for the expansion of tree species into areas that were formerly alpine tundra. The actual speed of the colonization by tree species is difficult to assess. The LPJ-GUESS model does not explicitly simulate the speed of tree range expansion due to seed dispersal or transport via animals or wind. Recent reports suggest that tree species are not able to migrate as fast as was previously estimated (Zhu et al., 2011).

Douglas fir (Fd) sees some small expansion into the study region but we discount these results. As douglas fir has a large range across B.C. (Klinka et al., 2000), a large phenotypic plasticity, and presently no population within our study region, it is difficult to reliably parameterize douglas fir for our model study region, but given the high value of douglas fir, it may be of interest for forest managers to further investigate and monitor its growth potential.

Table 6.1: Tree species parameterized into the LPJ-GUESS model listed by short name (also see Fig 6.2.)

Short Name	**Common Name**	**Latin Name**
Act	Black Cottonwood	*Populus trichocarpa*
At	Trembling Aspen	*Populus tremuloides*
Ba	Amabilis (Pacific Silver) Fir	*Abies amabilis*
Bl	Subalpine Fir	*Abies lasiocarpa*
Cw	Western Red Cedar	*Thuja plicata*
Dr	Red Alder	*Alnus rubra*
Ep	Paper Birch	*Betula papyrifera*
Fd	Douglas Fir	*Pseudotsuga menziesii*
Hm	Mountain Hemlock	*Tsuga mertensiana*
Hw	Western Hemlock	*Tsuga heterophylla*
Pa	Whitebark Pine	*Pinus albicaulis*
Pl	Lodgepole Pine	*Pinus contorta*
Se	Engelmann Spruce	*Picea engelmannii*
Ss	Sitka Spruce	*Picea sitchensis*
Sw	White Spruce	*Picea glauca*
Tw	Western (Pacific) Yew	*Taxus brevifolia*
Vb	Bitter Cherry	*Prunus emarginata*
Xc1	Mountain Alder	*Alnus tenuifolia*
Yc	Yellow (Alaska) Cedar	*Chamaecyparis nootkatensis (Recently reclassified as Callitropsis nootkatensis)*

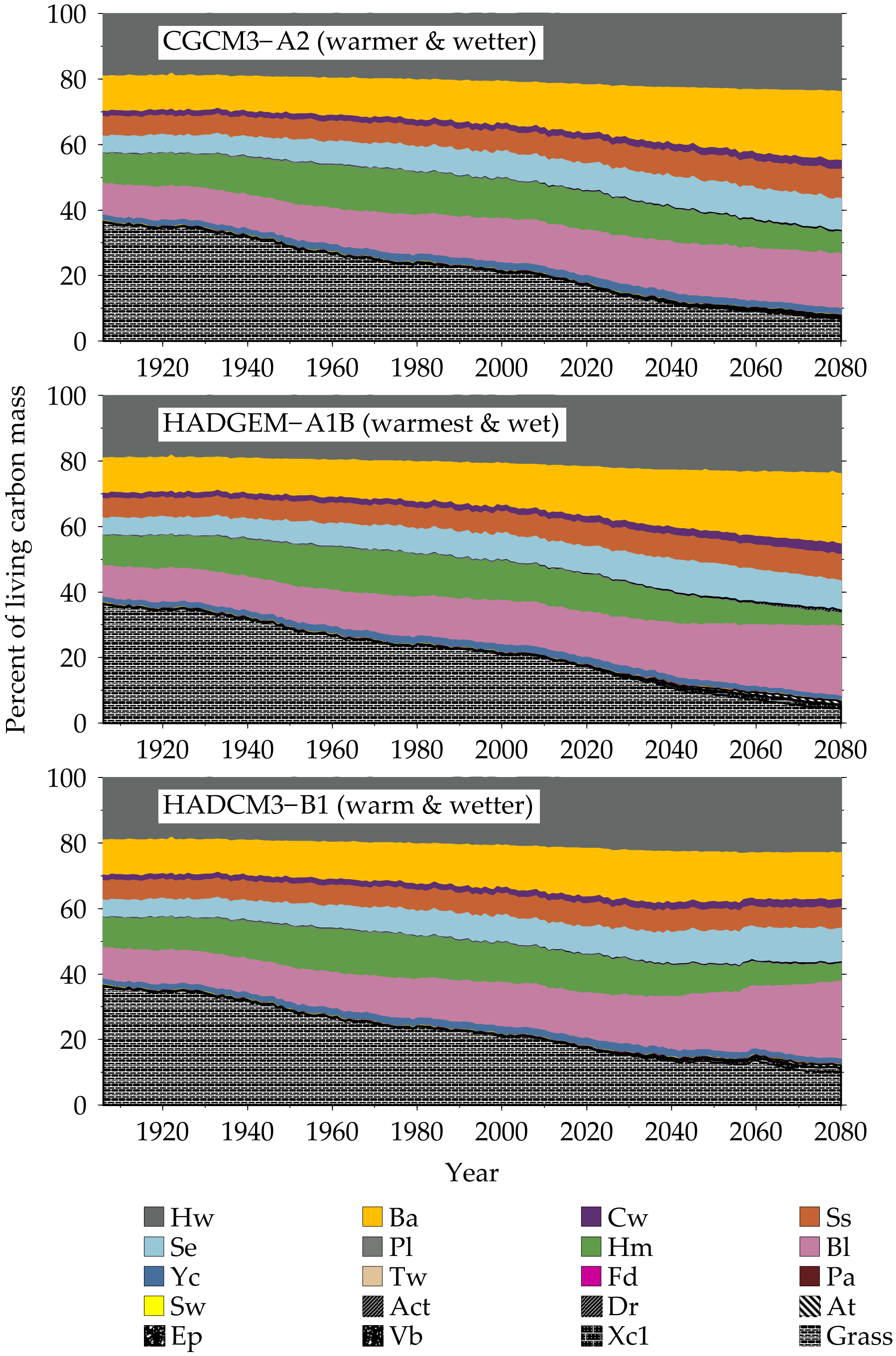

Figure 6.4: Changes in potential natural vegetation species distribution across the entire study region for all three future climate scenarios. Please refer to Table 6.1 or Fig 6.2 for species' common and Latin names.

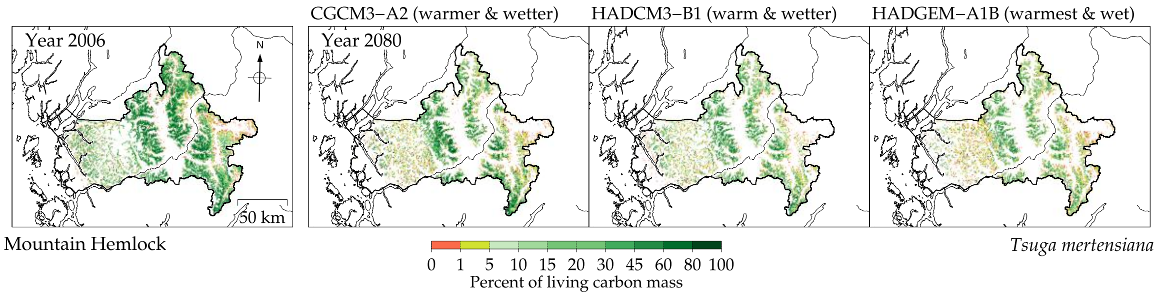

Figure 2.5: Potential natural mountain hemlock distribution for present day (2006) and year 2080 for all three potential future climate scenarios.

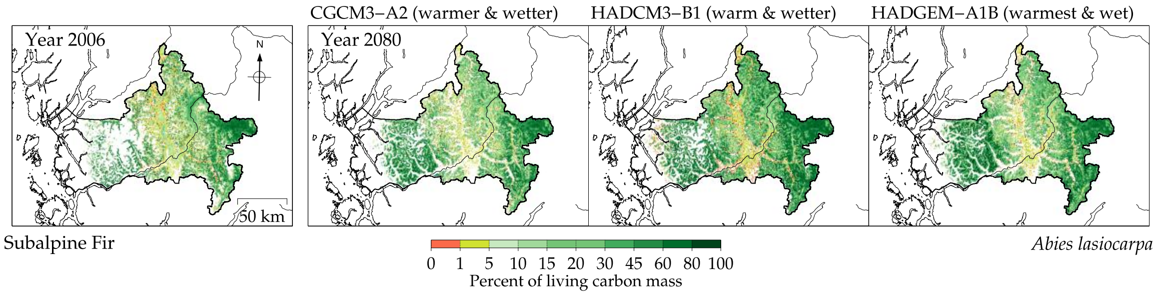

Figure 6.6: Potential natural subalpine fir distribution for present day (2006) and year 2080 for all three potential future climate scenarios. Large gains occur in the regions that were formerly dominantly mountain hemlock.

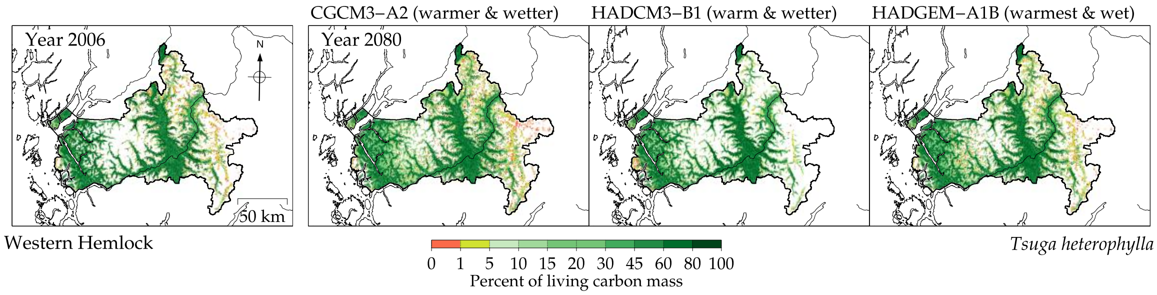

Figure 6.7: Potential natural western hemlock distribution for present day (2006) and year 2080 for all three potential future climate scenarios. Mountain hemlock maintains its position as a dominant species into the future for all three climate scenarios.

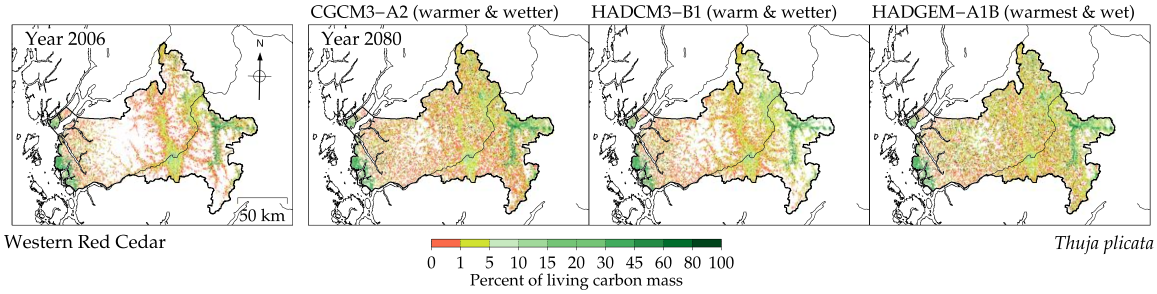

Figure 6.8: Potential natural western red cedar distribution for present day (2006) and year 2080 for all three potential future climate scenarios. Western red cedar could experience some very slight increases into the higher elevation regions.

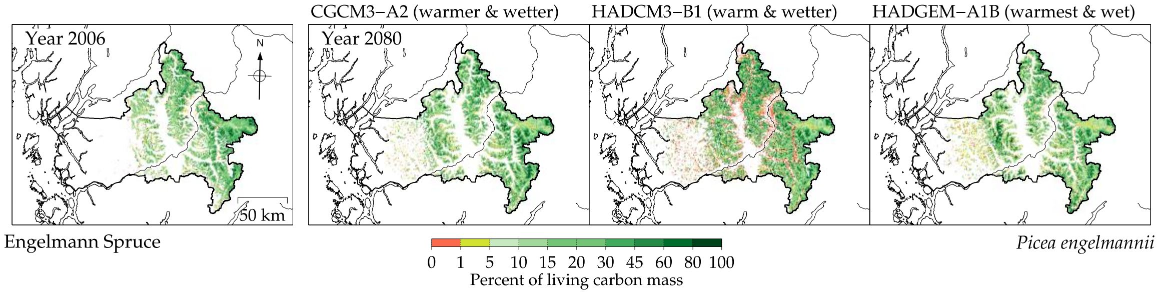

Figure 6.9: Potential natural engelmann spruce distribution for present day (2006) and year 2080 for all three potential future climate scenarios.

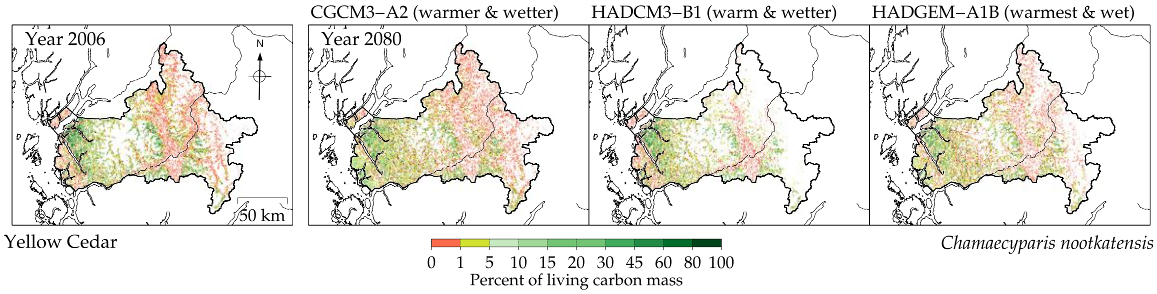

Figure 6.10: Potential natural yellow cedar distribution for present day (2006) and year 2080 for all three potential future climate scenarios.

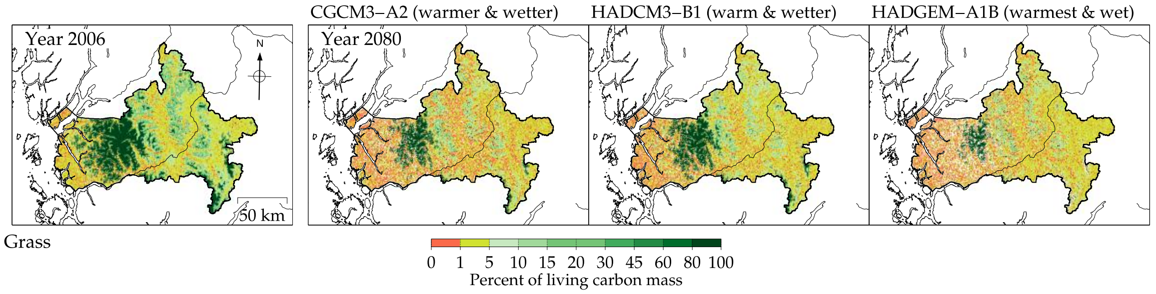

Figure 6.11: Potential natural grass distribution for present day (2006) and year 2080 for all three potential future climate scenarios. The actual speed of the tree encroachment on the alpine tundra regions is difficult to estimate; however the rate of encroachment is likely slower than modelled here.

6.2.1 Species Composition Changes at Community Level

Species composition changes at the local level (10 km^2) surrounding each community (Lax Kw'alaams, Prince Rupert, and Terrace) have been plotted for the CGCM3-A2 scenario (warmer & wetter).

The present day Lax Kw'alaams area potential natural vegetation is simulated to be dominated by sitka spruce (Ss) and western hemlock (Hw) with lesser amounts of western red cedar (Cw) and amabilis fir (Ba) (Fig 6.12). Potential natural vegetation of course includes no human land use changes or tree harvesting. The future simulations suggest a small increase in sitka spruce at the expense of western hemlock. The effect of the ocean moderating the future climate change prevents large changes in the local species composition at this coastal community.

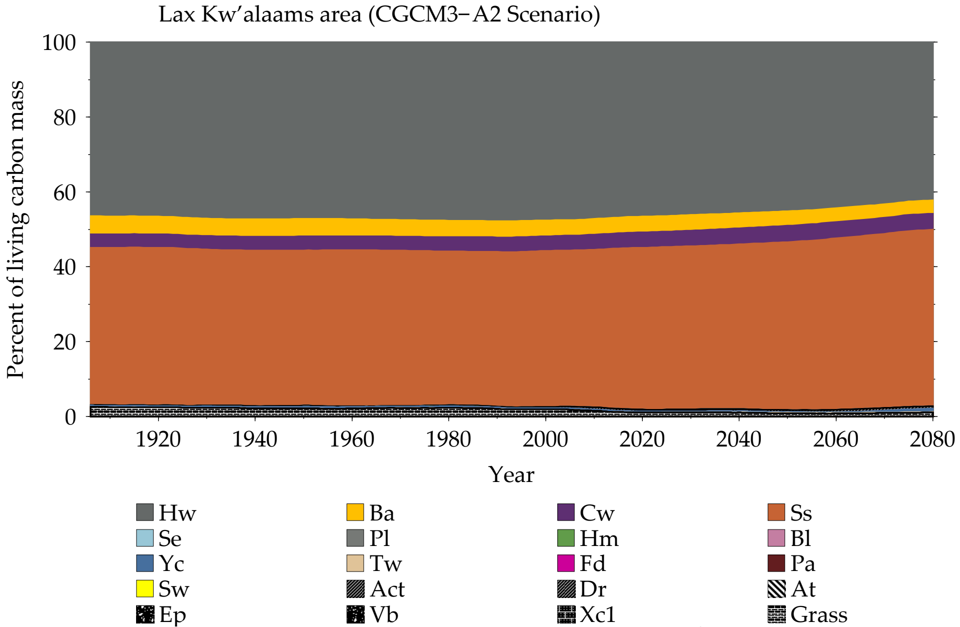

Figure 6.12: Simulated potential natural vegetation for a 10 km^2 area surrounding Lax Kw'alaams under the CGCM3-A2 scenario. Please refer to Table 6. 1 or Fig 6.2 for species' common and Latin names.

Prince Rupert shares some similarity to Lax Kw'alaams with both sites being coastal and with a large proportion of the forest simulated to be sitka spruce (Fig 6.13). The simulated potential natural vegetation species mix for the Prince Rupert area shows a dominance of Sitka spruce with lesser amounts of western red cedar and amabilis fir. There is also an increasing amount of yellow cedar (Yc) into the future; however this result should be viewed with caution due to our model simulations' inability to capture the effect of possibly damaging rapid freeze-thaw cycles (see Section 2.2.).

The very different climate of Terrace compared to the two coastal communities is reflected in the potential natural vegetation for the area (Fig 6.14). The present day Terrace forests are simulated to be predominantly western hemlock (Hw) with lesser amounts of amabilis fir (Ba), western red cedar (Cw), sitka spruce (Ss) and subalpine fir (Bl). Across the historical period, LPJ-GUESS simulates a strong decline in trembling aspen (At) with a decline from almost 10% of the forest biomass at year 1906 to <1% at present day. LPJ-GUESS also simulates a relative decline in subalpine fir starting about 1980 into the future. This decline in subalpine fir is balanced by an increase in western hemlock and western red cedar. There is also a simulated decline of grass area likely due to the expansion of the forest area. The Terrace area also sees a shift in proportion of deciduous to conifer species with slightly less than 20% deciduous species at start of the historical period (1906) dropping to approximately 1% at the end of the simulation.

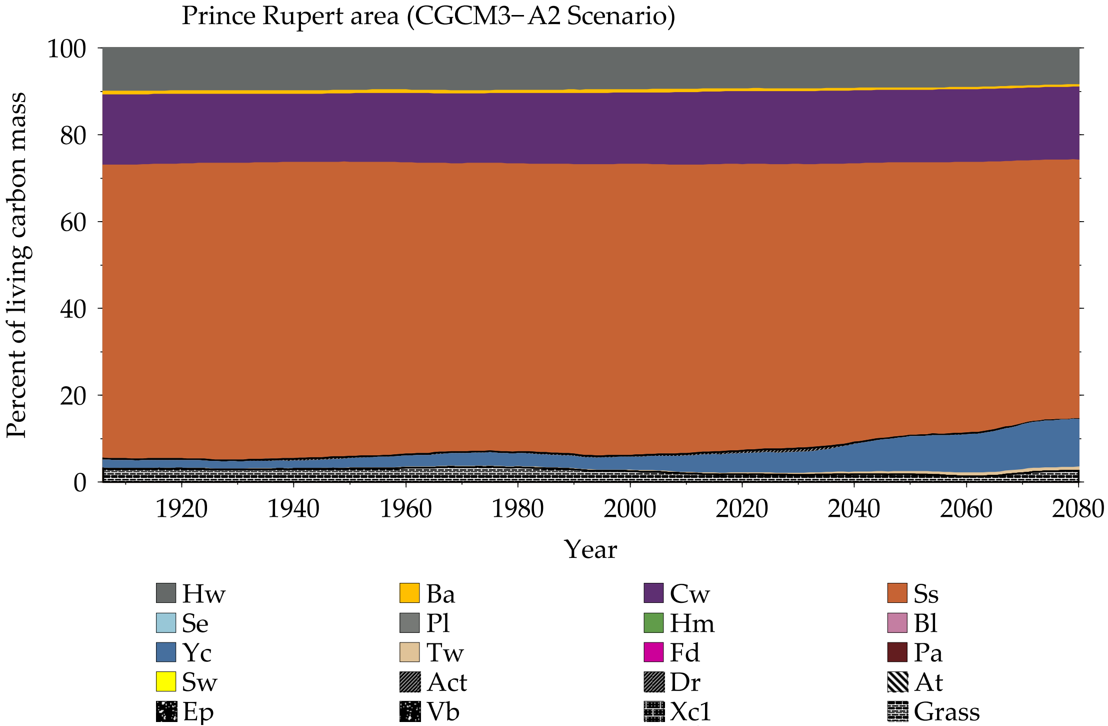

Figure 6.13: Simulated potential natural vegetation for a 10 km^2 area surrounding Prince Rupert under the CGCM3-A2 scenario. Please refer to Table 1 or Fig 2 for species' common and Latin names.

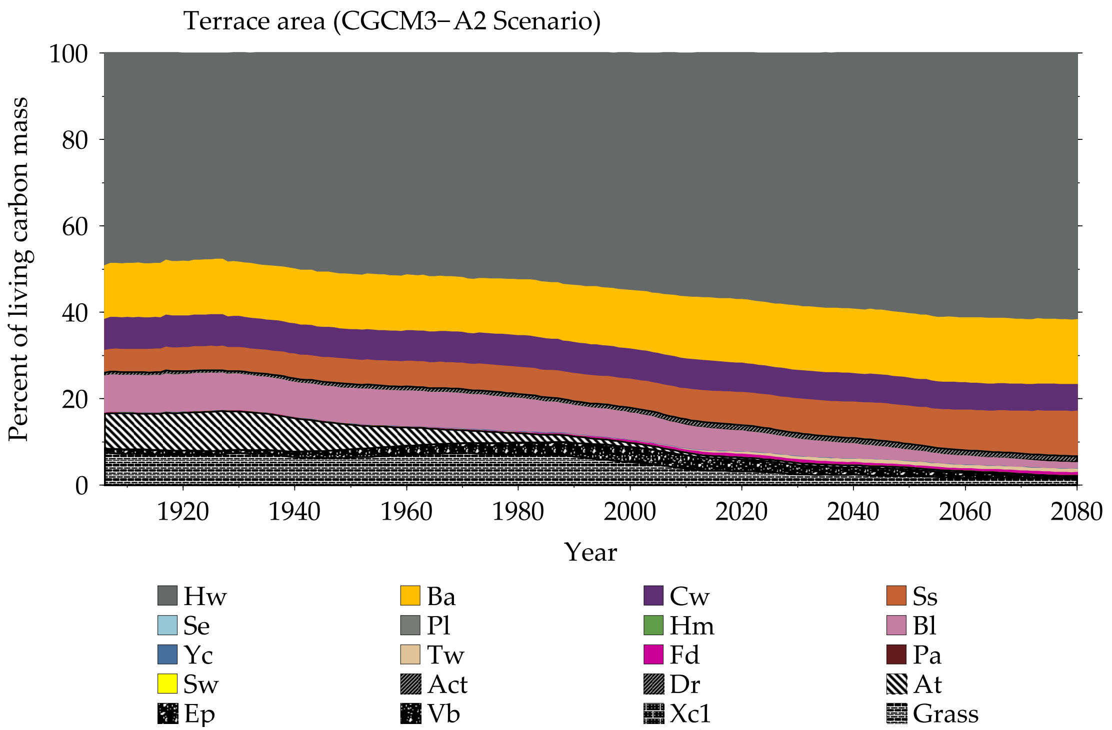

Figure 6.14: Simulated potential natural vegetation for a 10 km^2 area surrounding Terrace under the CGCM3-A2 scenario. Please refer to Table 6.1 or Fig 6.2 for species' common and latin names.

6.2.2 Forest Disease and Insect Infestations

Historically, the study region (predominantly in the North Coast and Kalum timber supply areas (TSAs) has a relatively low disturbance rate due to pest outbreaks (Taylor, 2010) (pests in the analysis include: 2-year cycle budworm, balsam bark beetle, black-headed budworm, douglas-fir beetle, douglas-fir tussock moth, forest tent caterpillar, mountain pine beetle, spruce beetle, spruce budworm, western hemlock looper, and western spruce budworm). The non-fire disturbance rate can be calculated as the annual percentage of hectares that have evident effects of the pest disturbance out of the total TSA. The North Coast and Kalum have relatively low pest disturbance rates of 0.044% and 0.085%, respectively, over the period 1960 – 2002. These pest disturbance rates are quite low and within the bottom 15% of the total 37 B.C. TSAs (Taylor, 2010). However, some small sections of the eastern part of the study area fall within the Bulkley and Kispiox TSAs, which have pest disturbance rates of 3.38% and 1.41%, respectively. These are the first and eleventh most pest disturbed TSAs in B.C. The primary pests to affect the region, in order of hectares affected, for the North Coast and Kalum TSAs include black-headed budworm, balsam bark beetle, western hemlock looper as well as a lesser amount due to spruce beetle and mountain pine beetle (only within the Kalum TSA). Presently, the Kalum TSA is part of the B.C. Ministry of Forests, Lands, and Natural Resource Operation's Mountain Pine Beetle Management Area aggressive emergency management units (Sutherland, 2010) but not part of the spruce beetle management area.

The LPJ-GUESS model does not simulate forest disease and insect infestations explicitly thus we are not able to give estimates of possible future changes based upon our modelling work. Future disturbances by forest pests depend upon an interaction between climate, forest conditions, and pest life histories, migration strategies, and interactions between pests and disease agents.

Forest disease agents could also increase their disturbance levels under future climate change. For example, dothistroma is particularly sensitive to the number of rain events per month (more so than the rain amount) (Woods et al., 2005; Boateng, 2011). However, we are not able project future changes in the number of rain events per month with the presently available downscaled climate data.

Given the complexity of interactions, future projections of pest and disease outbreaks are difficult; however there are suggestions that climate change will bring about conditions more favourable for increase pest outbreaks (Woods et al., 2010). Any increase in pest and disease outbreaks could greatly change the carbon budget and forest composition results as modelled here.

6.2.3 Species Distributions Summary and Future Projections

Common species in the study region such as western hemlock and amabilis fir will likely become more dominant as the proportion of lesser species decreases. As the climate warms into the future, the areas of alpine tundra will become afforested though the actual speed of colonization by trees is highly uncertain. In the lower elevation regions, the forest will likely experience in-filling as the forests benefit from warmer growing season temperatures and higher moisture. The possible impact of forest pests and diseases is highly uncertain but likely to increase into the future. Additionally, the impact of extreme events on the forests is not adequately modelled in LPJ-GUESS and could result in higher mortality and changes to forest composition than presented here.

Table 6.2: Future projections for species distribution and vigour with an estimated confidence level. For a calibration of the projection confidence level please see Appendix 6.4.

Parameter	Source of estimation	Likely Direction of Change	Projection Confidence Level* (see Appendix 6.4)	Comments
Species distribution of important commercial timber species (western hemlock, amabilis fir, western red cedar)	LPJ-GUESS Vegetation Model	Increase (become more dominant)	Moderate	All three species are simulated by LPJ-GUESS (under potential natural vegetation) to increase in proportion for all three climate scenarios.
Timber growing conditions	LPJ-GUESS vegetation model	Improvement	Moderate	Increase in growing season temperature and moisture. However, impact of summer drought events, pest and disease outbreaks, or extreme climate events not well captured by the LPJ-GUESS simulations.
Species diversity	LPJ-GUESS vegetation model	Decrease	Low	Simulations indicate increased dominance by fewer species. Increased disturbances could, however, create more niche conditions for pioneer species.
Pest and disease outbreaks	Scientific Literature	Increase	Very Low	Full analysis is outside the scope of this report. Please refer to overview article by Woods et al. (2010) which discusses changes in the short-term (15 to 20 years)
Changes to tree line	LPJ-GUESS vegetation model	Movement towards higher elevations	High (direction of change) / Very Low (rate of change)	See Section 6.2.1. and 6.2.3.

6.3 Carbon fluxes and pools

6.3.1 Model Suite # 1: Potential Natural Vegetation

The LPJ-GUESS model simulates the movement of carbon as carbon dioxide is removed from the atmosphere by plant photosynthesis and incorporated into plant tissues. The plant tissues eventually die and are transferred to the soil or litter where they are eventually released (respired) back to the atmosphere. Organic matter decomposition (respiration) is sensitive to temperature and moisture conditions resulting in a climate-dependent speeding up, or slowing down, of the decomposition of dead plant tissues. The flow of carbon, termed fluxes, between model 'pools'; such as vegetation, soil, etc.; allow for estimations of how the region will respond to climate change either drawing more carbon from the atmosphere or releasing more of the carbon already bound.

For the future simulations, all scenarios show an increase in the vegetation uptake of carbon relative to 1906 to 2006 mean (increase in removal of carbon from the atmosphere (sink) in scenario order: HADGEM-A1B, HADCM3-B1, CGCM3-A2)(Fig 6.15).
This is reflected in an increase in the vegetation carbon pools for all scenarios as the increased fluxes of carbon result in an increase in the vegetation pool sizes (Fig 6.16). The potential natural vegetation in these simulations is responding to the combination of increased atmospheric [CO_2] through CO_2 fertilization and enhanced growing conditions due to warmer temperatures and increased moisture (however likely not with the HADGEM-A1B scenario as it has little moisture increase).

All scenarios show increased carbon fluxes out of soils (HADCM3-B1 shows generally the least increase) relative to the 1906 - 2006 mean (Fig 6.15). Increased temperatures increase soil organic matter decomposition, which release CO_2 from dead plant material; as well the increase in vegetation carbon pools provides more material for organic matter decomposition from the soils as some of the vegetation carbon is released into soils via the death of plant roots and exudates (substances that are released by the plants into the surrounding soils).

Litter carbon is simulated to decrease into the future with scenarios HADGEM-A1B and CGCM3-A2 (Fig 17) due to faster organic matter decomposition enhanced by the warmer temperatures. The increase in litter for scenario HADCM3-B1 is probably due to this emissions scenario's small temperature increase (thus a smaller enhancement of organic matter decomposition) with a relatively large increase in precipitation (Figure 5.2) and plant productivity of litter material (Fig 6.15).

For all carbon pools combined, LPJ-GUESS projects an increase in the total pool size into the near future, thus the region continues to act as a carbon sink (more carbon is taken in by the vegetation that is emitted by the organic matter decomposition). The region's future as a carbon sink, past year 2045, is scenario dependent. Scenario HADGEM-A1B switches from a carbon sink to become a carbon source after year 2045, thus emitting more carbon from organic matter decomposition than is taken in by the live vegetation. The main sources of the switch to a carbon emitting region appears to be an increase in emissions from the litter and soils with the vegetation also showing a decline in the strength of its sink. This demonstrates the dominant influence of the climate on the carbon cycling of the study region. These simulations are dependent upon the assumption of no major changes in the occurrence of pest or disease disturbances (see Section 6.2.2.), which can have a very large impact upon the carbon and species dynamics of regions (Kurz et al., 2008)

6.3.2 Model Suite # 2: Harvesting

On a region the size of the SRWCP study area, past and projected future harvesting as simulated by LPJ-GUESS is less important than climate for carbon pools and fluxes. Historical harvesting has relatively little impact upon carbon fluxes (Fig 6.17). The only significant changes are with fire (smaller fluxes with harvesting) and plant establishment (more establishment occurs with harvesting because there is prescribed replanting as each cell harvested).

Historical harvesting decreases the vegetation carbon pool as the trees harvested are removed from the grid cell (with the exception of the fine roots, which go to the soil carbon pool; and the leaves and 30% of the sapwood and heartwood which go to the litter carbon pool)(Fig 6.18). Historical harvesting very slightly increases the litter carbon pool, compared to potential natural vegetation, due to the transfer of leaves and wood during harvest. Into the future, the balance of litter inputs versus losses to organic matter decomposition will tip towards loss due to decomposition causing a shrinking of the litter pools for most scenarios. LPJ-GUESS simulates no significant change in the (large) soil carbon pool due to harvesting.

The strong influence of climate is evident from the plot of total carbon pools (Fig 6.18 bottom panel). While, the actual size of all carbon pools at the end of the historical period is highly influenced by the harvesting history, the range in the future total carbon pool is dominated by projected future climate changes, and not the previous harvesting history. Indeed, the entire historical period variability is less than the projected spread between the three different climate scenarios.

The simulated historical harvest acts to increase the carbon sink for the study region as compared to the simulation of potential natural vegetation. Into the future, across all scenarios, the presence of harvesting again increases the carbon sink for the region. This enhancement of the carbon sink is mostly related to smaller soil carbon fluxes with some smaller contributions from lower fire carbon fluxes and higher establishment due to replanting. Soil carbon fluxes likely decrease (less flow of carbon out of the soil due to organic matter decomposition) with harvesting due to the smaller carbon inputs on the replanted sites (smaller, younger trees) than in the uncut mature forests.

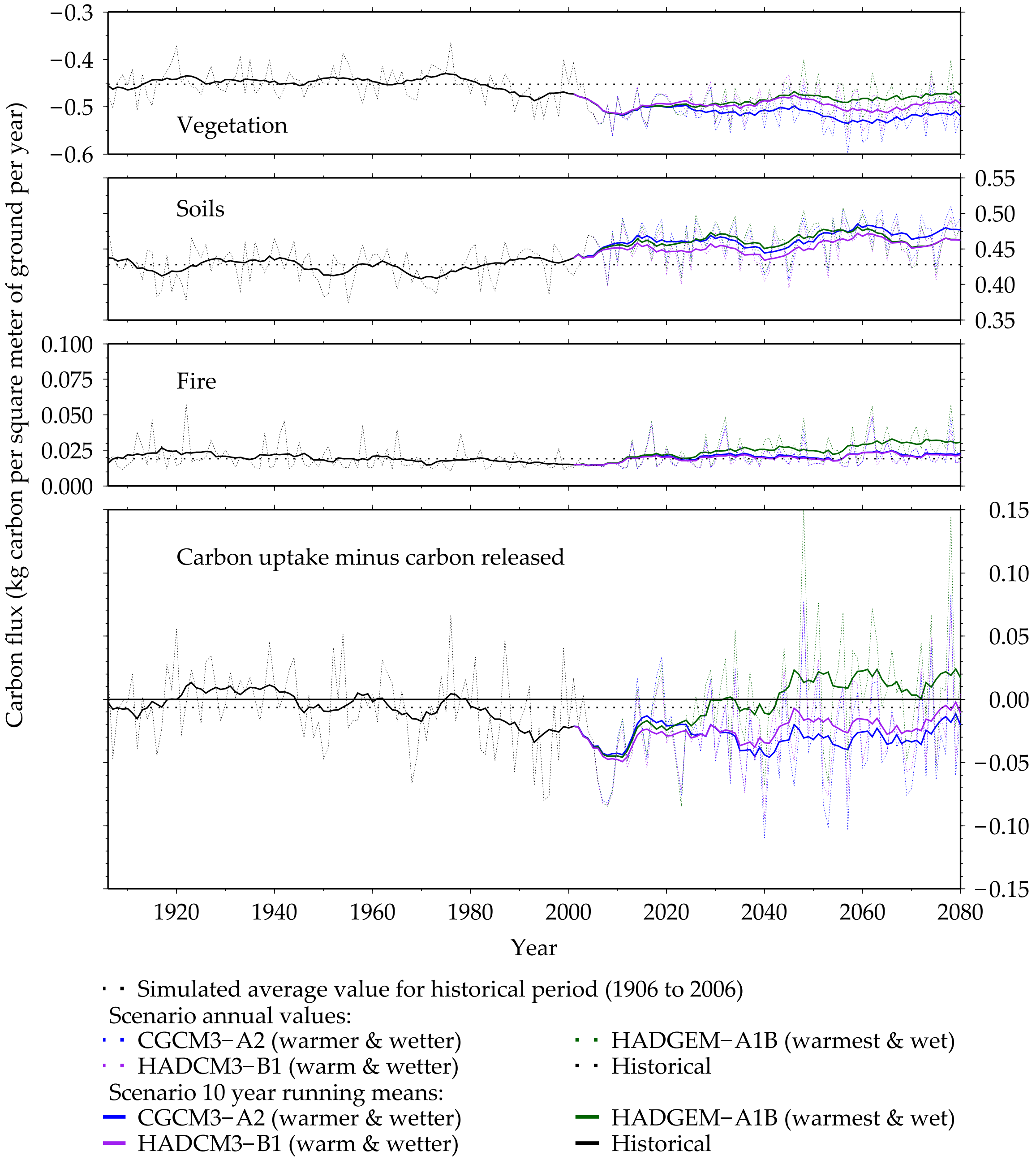

Figure 6.15: Carbon fluxes for the study region. Negative values indicate a flow of carbon into the carbon pool from the atmosphere (a carbon sink), positive values indicate a flow of carbon out of a carbon pool to the atmosphere (a carbon source). The net values (bottom panel) show a general sink behavior historically (with exception of the period between 1920 and 1940), with a possible switch to being a source of carbon for scenario HADGEM-A1B past year 2045.

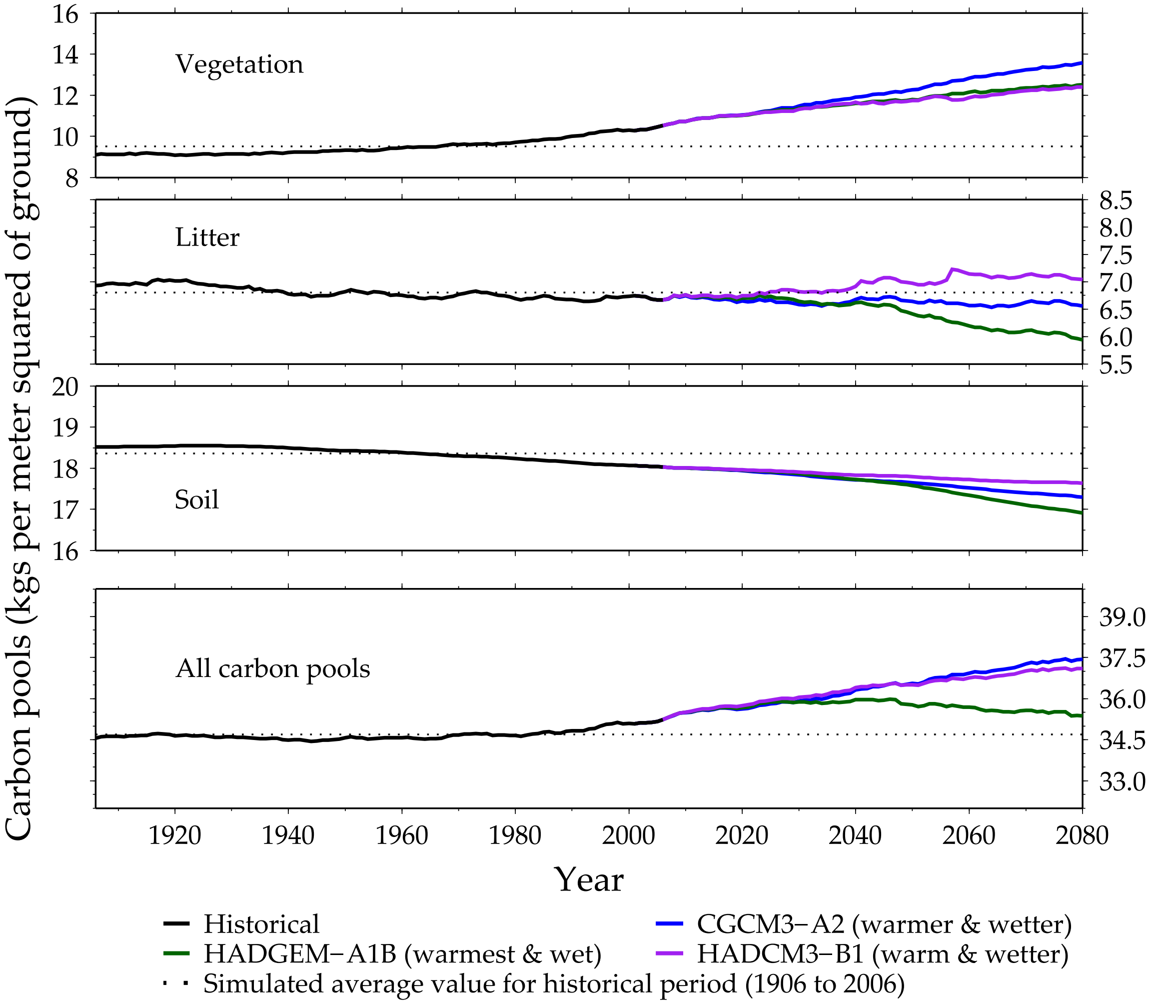

Figure 6.16: Carbon pools for the study region. The pools represent the result of the net fluxes of carbon through time.

6.3.3 Model Suite # 3: Different Future Harvest Intensities

Three different future harvesting intensities were simulated with climate scenario CGCM3-A2 (warmer & wetter) for the SRWCP region (Fig 6.2): 1) a base-line level of harvesting at the allowed annual cut (AAC), 2) a 50% AAC harvesting scheme, and 3) a 150% AAC harvesting scheme (Fig 6.3). The different harvesting intensities take effect in the year 2010 with the same historical harvest occurring prior to that. For the carbon pools and fluxes, over a region of this size, the effect of different future harvesting intensities is small (Fig 6.19).

For the vegetation, the dominance of the CO_2 fertilization effect and increase in growing season temperature (with little drought across much of the study region) results in an increase in the vegetation carbon pools regardless of harvesting intensity. Naturally, the effect of harvesting intensity is visible, but the major influence is the increase in CO_2 concentration and changes to the climate. The litter carbon pool is strongly influenced by harvesting, compared to the potential natural vegetation simulation, however the effect of harvesting intensity is relatively small in comparison to the effect of climate. The simulations with 50% and 100% AAC harvesting intensity show little difference between themselves, with a greater distinction at the 150% AAC harvesting intensity.

Over all carbon pools, the effect of harvesting is to generally decrease the total carbon pools roughly corresponding to the intensity of harvesting, demonstrating the effect of removing wood from the landscape. The influence of CO_2 concentration and climate are dominant across the total carbon pools with all harvesting scenarios becoming closer to the potential natural vegetation simulation as we move towards 2080. However, how quickly the scenarios converge is dependent upon the harvesting scenario with less harvesting approaching the potential natural vegetation scenario more quickly and only a small convergence for the 150% AAC scenario.

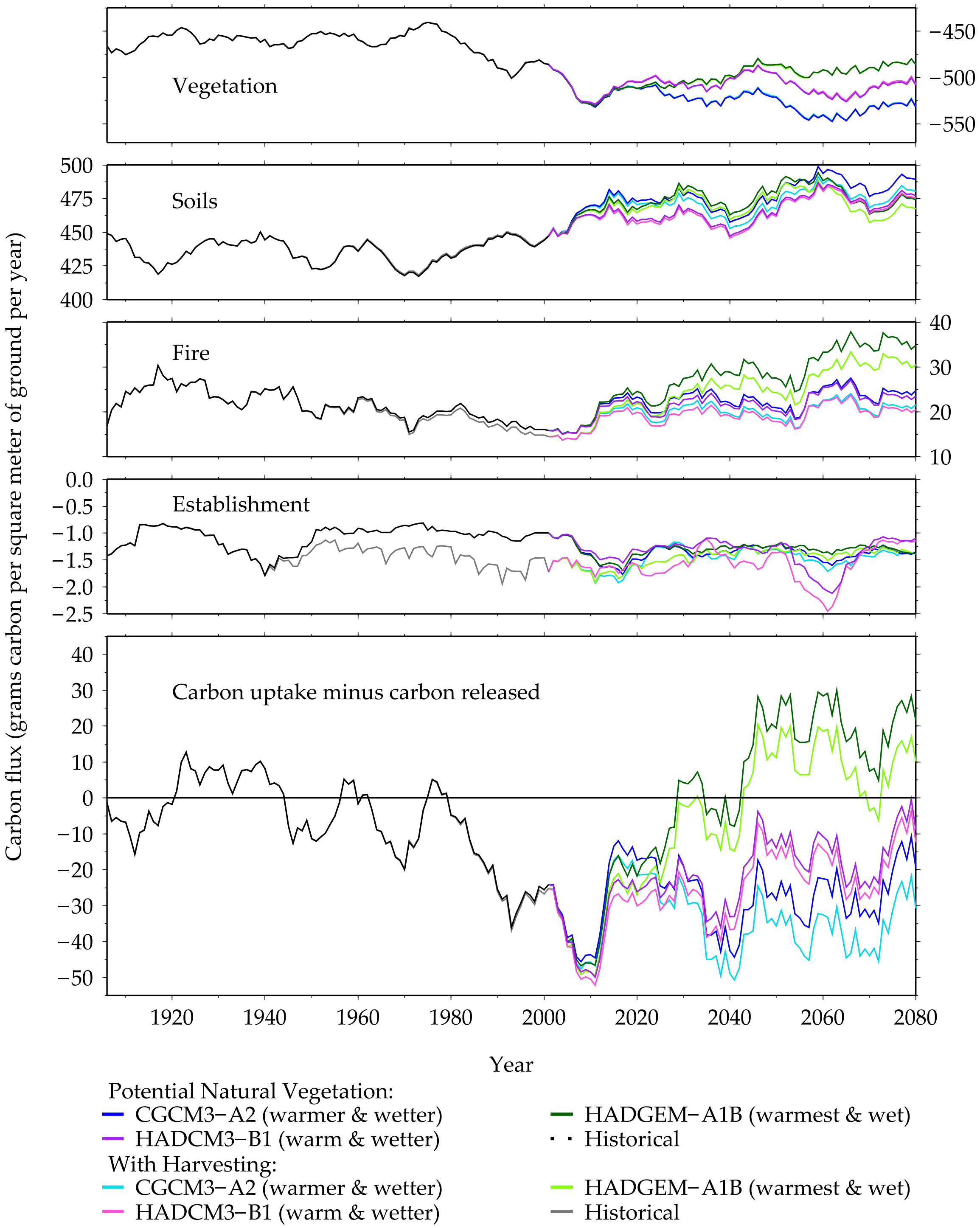

Figure 6.17: Carbon fluxes for the SRWCP study region (Fig 6.2) under potential natural vegetation and the base-line harvesting scheme (Fig 6.3). Historical harvesting includes the estimated harvesting in the TFL1 lands (see Appendix 6.5).

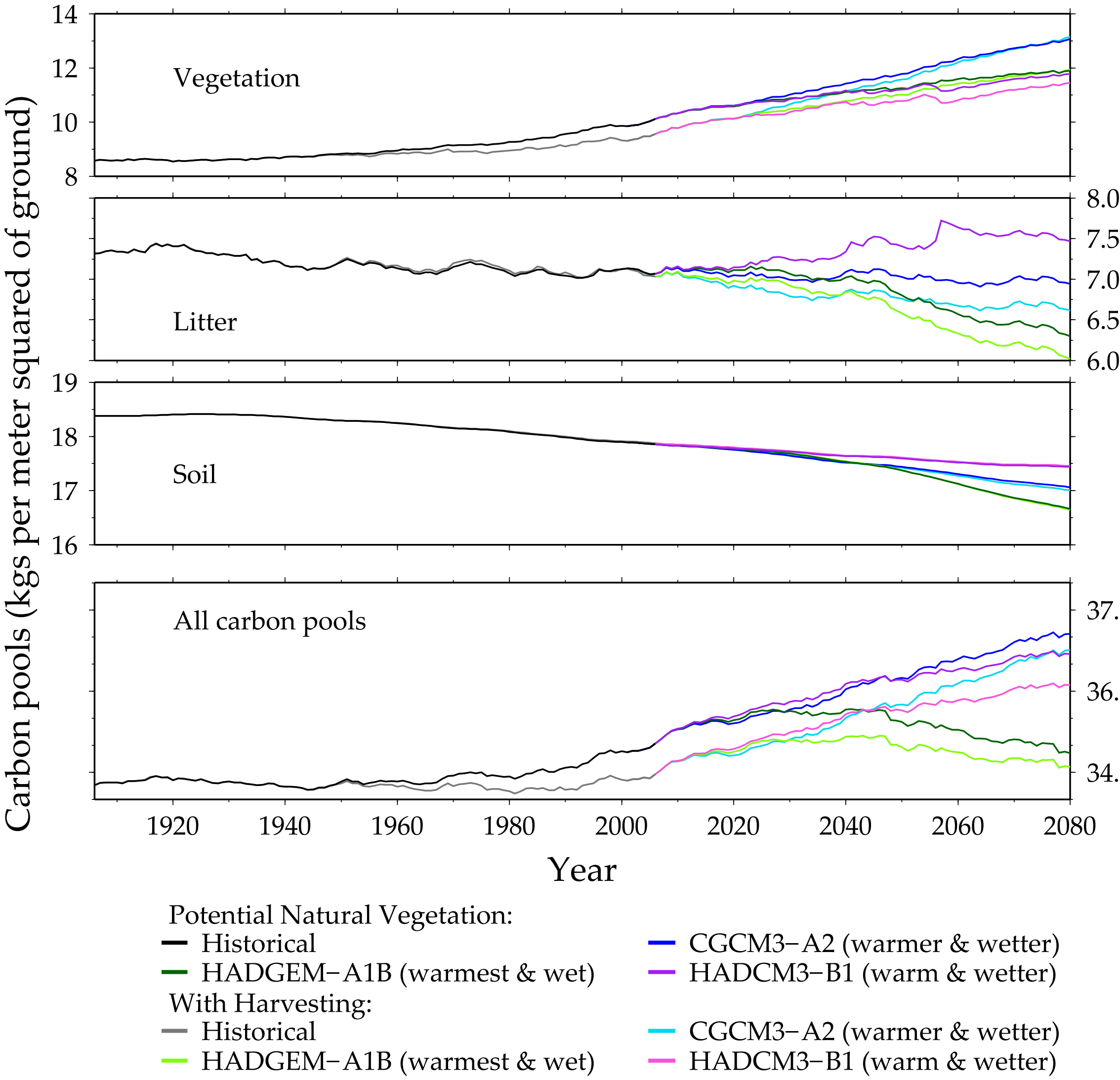

Figure 3: Carbon pools for the SRWCP study region (Fig 6.2) under potential natural vegetation and the base-line harvesting scheme (Fig 6.3). Historical harvesting includes the estimated harvesting in the TFL1 lands (see Appendix 6.5).

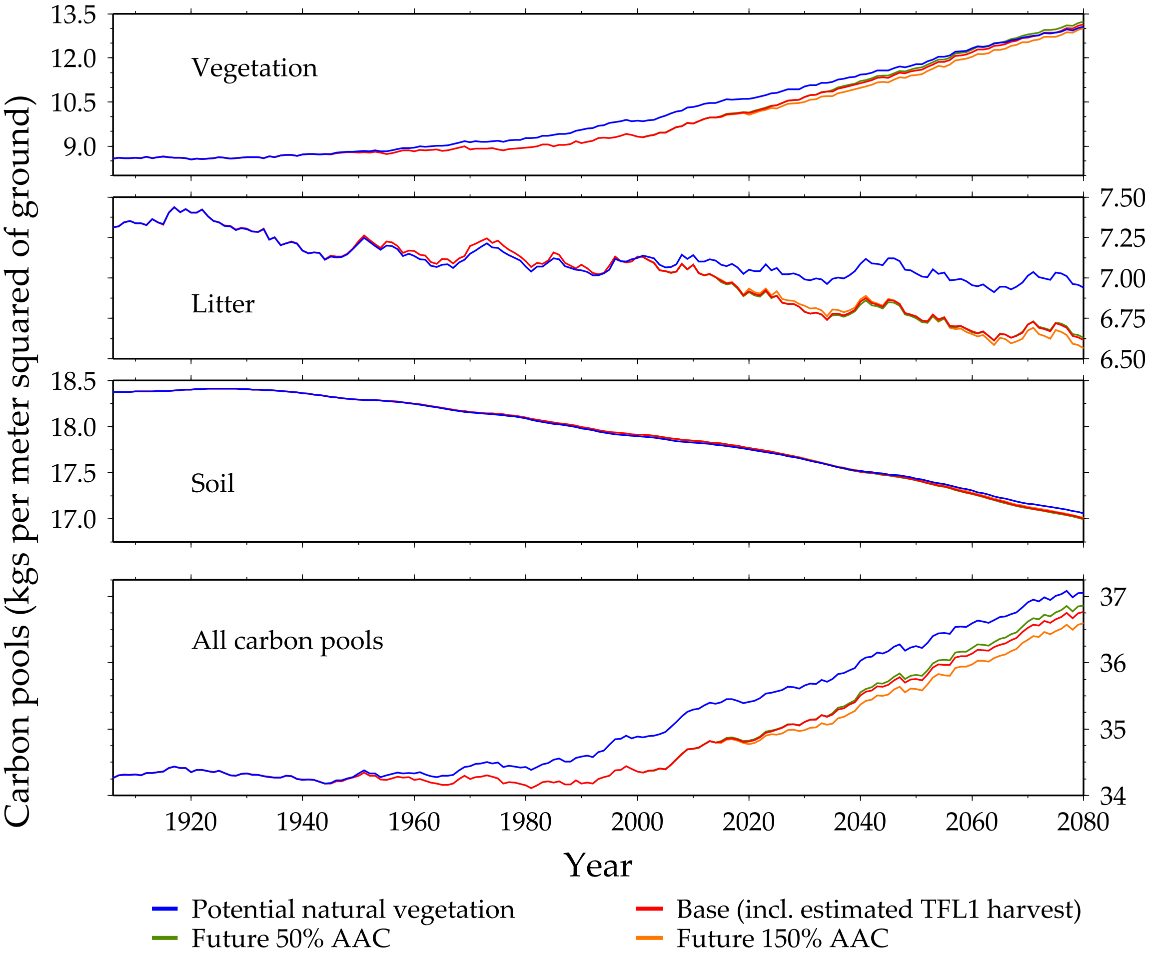

Figure 6.19: Carbon pools for the SRWCP study region (Fig 3) under a base-line harvesting intensity, a future 50% AAC and a future 150% harvesting intensity. The base-line harvesting scenario includes the estimated historical TFL1 harvest. All harvesting scenarios are for the emissions/climate scenario CGCM3-A2.

6.3.4 Natural Fire

Fire disturbance for provincial TSAs is available starting from 1960 (Taylor, 2010). While the local districts (predominantly the North Coast and Kalum with some smaller eastern areas in the Bulkley and Kispiox TSAs) include much more land than our study region, they are indicative of the general conditions in the area. Over the period 1960 – 2002, the North Coast TSA experienced a fire rate of 0.0006% and the Kalum TSA has a fire rate of 0.0089% (fire rate is calculated as the percentage of hectares burned per year of the total TSA). These fire rates are the second (after the Queen Charlotte TSA) and fifth lowest (after the Nass and Campbell River TSAs) for the province of B.C, respectively. Fire is thus a minor disturbance agent for the study region. However, some of the eastern areas of the study region are more influenced by fire. The Bulkley and Kispiox TSA’s have fire rates of 0.020% and 0.022%, respectively.

The LPJ-GUESS model simulated natural fire activity for potential natural vegetation is estimated to be low at present (2000 - 2009) with higher past fire activity (1906 – 1915) (Fig 6.20). Future natural fire under all climate/emissions scenarios is projected to be a return to fire conditions more similar to those of 1906 - 1915 with an increase in fire for some areas. This area is, however, small (ca. 700 km^2) compared to the total study area (ca. 32,000 km^2).

In the majority of the study area, the climate remains too wet for fire to be important. The scenario with the largest increase in fire is HADGEM-A1B, which has the highest temperature increase with the smallest precipitation increase (Table 5.3).

Harvesting reduces fire carbon fluxes due to a reduction in available fire materials because of smaller trees and smaller amounts of litter. Fire carbon fluxes are relatively similar between different harvesting intensity scenarios. More harvesting shows slightly less fire fluxes due to the less available fire material in the young replanted forests.

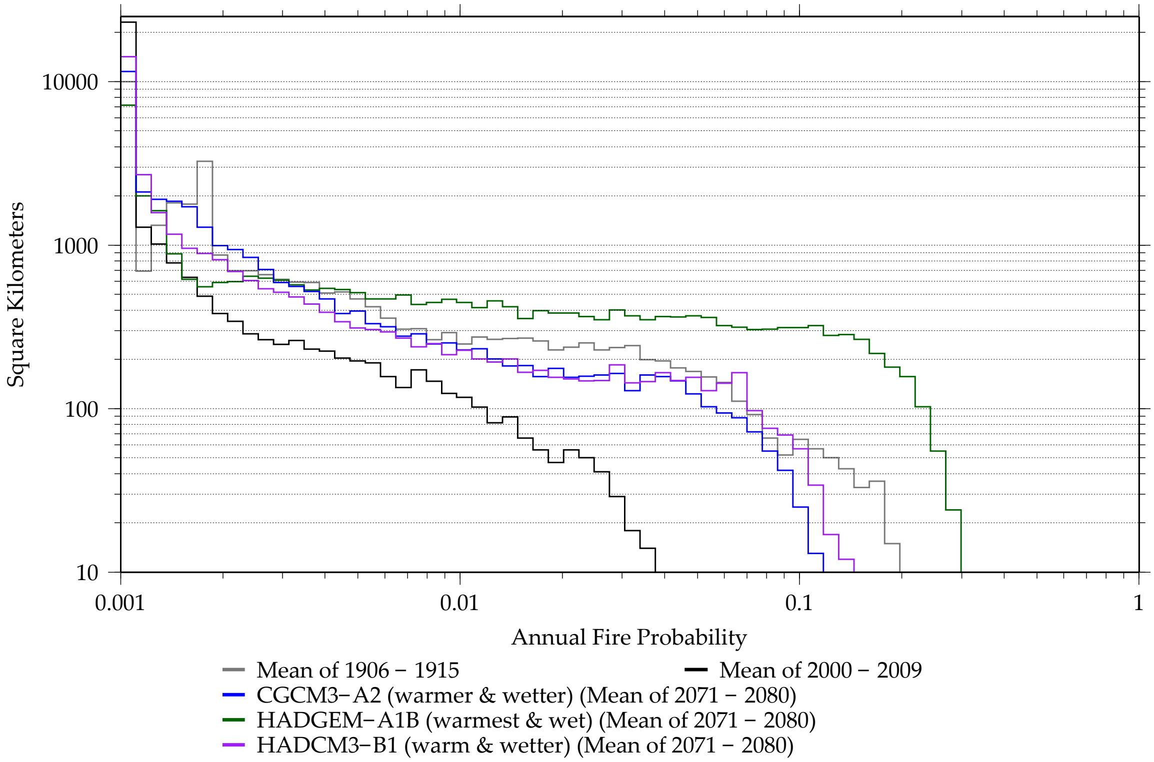

Figure 4: Histogram plot of annual natural fire probability for potential natural vegetation. A fire probability of 1 means a 100% chance of natural fire this year while a 0.001 fire probability means a 0.1% chance of fire this year. Note both axes are on a logarithmic scale (there is an increase by a factor of ten after each axis annotation, i.e the grid line ticks follow a pattern like 10, 20, …, 90, 100, 200, 300,…). The actual area that fire has an influence is on the order of ca. 700 km^2 in the eastern part of the study area, while the entire study area is ca. 32,000 km^2.

6.3.5 Summary of Carbon Dynamics and Future Projections

Vegetation in the study region will likely experience increased growth due to CO$_2$ fertilization and increased moisture and growing season temperatures. Within soil and litter carbon pools, the balance between carbon inputs from vegetation and outputs from organic matter decomposition will lead to a decline in soil carbon pools with a more climate scenario dependent future for litter pools. The influence of the spread in future climate scenarios is far greater than the influence of historical or estimated future harvesting for the regions carbon dynamics. The simulated variability in ecosystem carbon dynamics across the historical period is smaller than the spread of variability between the different climate scenarios. As well, the impact of extreme events and forest pest or disease outbreaks could greatly impact upon the region's carbon dynamics and are not adequately modelled here. Any attempts to manage the regions forests for carbon sequestration will become riskier into the future due to the large, and unpredictable, lever that climate and pests (Kurz, et al., 2008) can have on the forest ecosystems.

Table 6.4: Future projections for carbon dynamics with an estimated confidence level. For a calibration of the projection confidence level please see Appendix 6.4.

Parameter	Source of estimation	Likely Direction of Change	Projection Confidence Level* (see Appendix 6.4)	Comments
Total amount of carbon in the vegetation	LPJ-GUESS Vegetation Model	Increase	Moderate	Increase seen across all simulations. However, the influence of forest pest/disease outbreaks or extreme climate events could reverse the broader climate and CO_2-driven trend
Region's role as a carbon sink or source	LPJ-GUESS Vegetation Model	Continuation as carbon sink	Low	All climate scenarios show a continuation of the region as a carbon sink until 2045. After that point it is possible the region will become a carbon source.

6.4 Surface Runoff

6.4.1 Model Suite # 1: Potential Natural Vegetation

Surface runoff is influenced by precipitation, snow pack, snowmelt, and the vegetation surfaces themselves. For the future scenarios, LPJ-GUESS simulates winter runoff to be essentially unchanged from the historical mean (1906 – 2006) (Fig 6.21). Spring surface runoff is also pretty much unchanged into the future for all scenarios. Summer surface runoff however, declines for scenarios HADGEM-A1B and CGCM3-A2 noticeably. This decline in surface runoff could indicate increased drought stress for trees in interior regions and also lower river levels.

Autumn runoff levels, conversely, increase strongly following closely the predicted increase in autumn precipitation for all climate scenarios (Fig 6.21). The rise in annual total surface runoff is then strongly influenced by the large increases in autumn runoff (see Table 6.5).

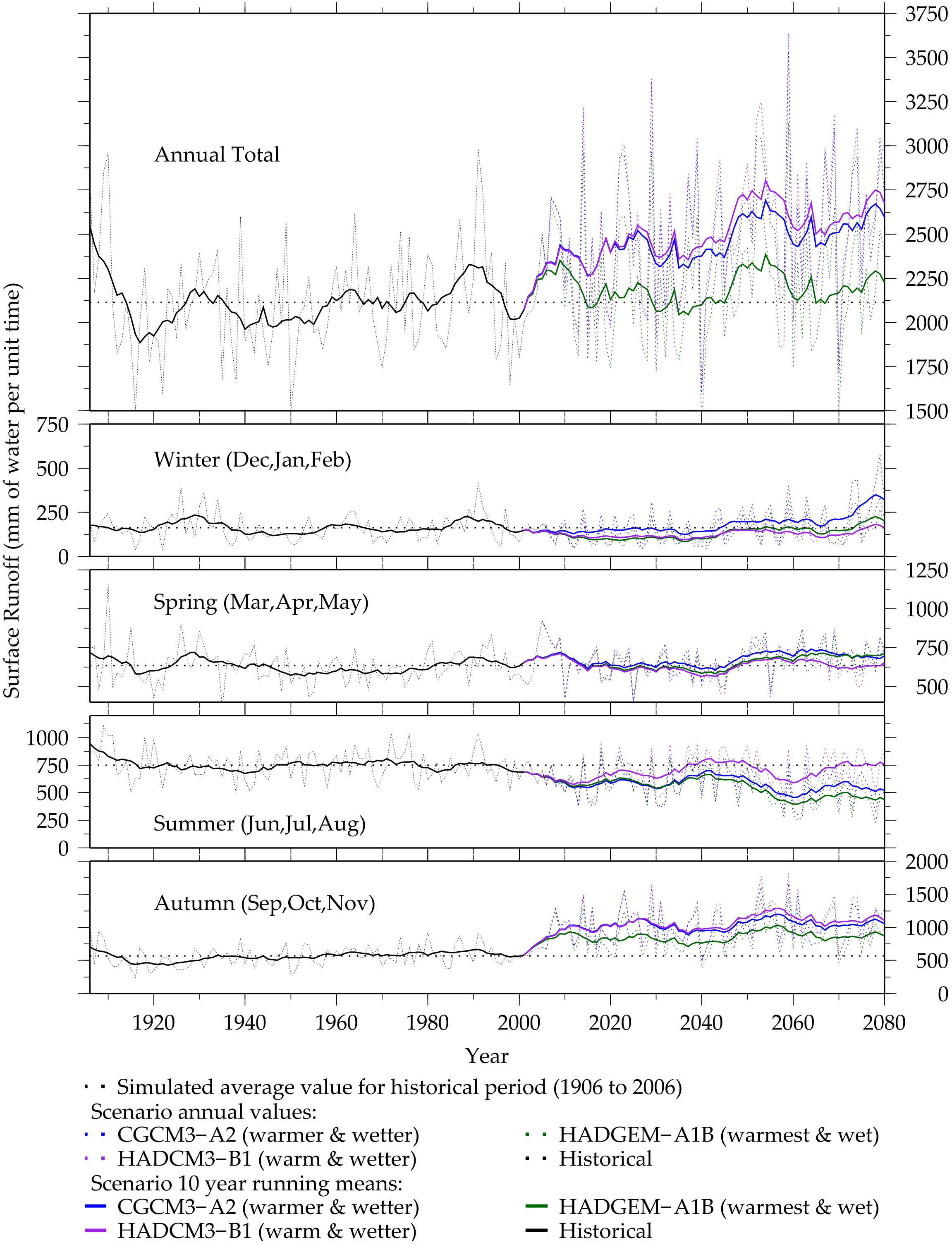

Figure 6.21: Annual and seasonal surface runoff simulated by LPJ-GUESS for the three climate scenarios under potential natural vegetation.

6.4.2 Model Suite # 2: Harvesting and Different Harvest Intensities

On a region the size of the SRWCP study area, simulations with harvesting show only a minimal influence of harvesting on the surface runoff. The level of harvesting intensity does not change the surface runoff significantly. This is likely due to the small annual harvest amounts (maximum estimated annual harvest is less than 1.0% of the SRWCP area) and, at least within the LPJ-GUESS model, small differences between mature and young forest runoff characteristics. Please note, however, this result cannot be downscaled to the site-level where the influence of harvesting on surface runoff can be significant and will likely be very different than the regional-scale response described here.

6.4.3 Flood events

Surface runoff for the autumn is projected to increase significantly for the study region. Additionally, the incidence of extreme precipitation events is projected to increase into the future. Higher background surface runoff coupled with greater likelihood of extreme precipitation events will likely lead to enhanced risk of flooding and higher river levels. The additional risk of 'rain on snow' events, such as that attributed to the recent December 2006 Terrace flooding (Septer, 2007), will likely increase due to higher temperatures, variability and precipitation amounts.

6.4.4 Summary of Surface Runoff and Future Projections

Total annual surface runoff changes follow the projected changes in precipitation from the climate scenarios. The major changes to surface runoff will be a possible decline in summer runoff and a significant increase in autumn runoff. The summer decline could result in lower river levels and be representative of higher moisture stress for vegetation in some parts of the study area. Higher autumn surface runoff likely indicates higher water levels in rivers and, combined with higher likelihood of extreme precipitation events, higher chance of flooding events. The simplicity of the LPJ-GUESS soil model, and our inability to model extreme precipitation, indicates these results could miss important rapid events and/or processes such as topsoil erosion. The influence of harvesting on surface runoff for the regional scale is found to be small but this result is unlikely to be applicable on a site-level.

Table 6.5: Future projections for surface runoff with an estimated confidence level. For a calibration of the projection confidence level please see Appendix 6.4.

Parameter	Source of estimation	Likely Direction of Change	Projection Confidence Level* (see Appendix 6.4)	Comments
Annual total surface runoff	LPJ-GUESS Vegetation Model	Increase	Moderate	Annual total surface runoff generally follows annual precipitation changes.
Mean winter surface runoff (Dec, Jan, Feb)	LPJ-GUESS Vegetation Model	No change	Moderate /Low	Scenario CGCM3-A2 shows an increase in winter runoff after 2060 above the mean value for the historical period. The other scenarios show no change.
Mean spring surface runoff (Mar, Apr, May)	LPJ-GUESS Vegetation Model	No change	Moderate	All climate scenarios do not show a significant departure from the historical mean value. All simulations show good agreement amongst themselves. However, changes in precipitation variability will be important and are not captured here.
Mean summer surface runoff (Jun, Jul, Aug)	LPJ-GUESS Vegetation Model	Decrease	Moderate / Low	Two out of three climate scenarios show a decrease in summer runoff. Scenario HADCM3-B1 does not depart significantly from the historical mean.
Mean autumn surface runoff (Sep, Oct, Nov)	LPJ-GUESS Vegetation Model	Increase	High	All simulations show an appreciable increase in autumn runoff. The size of increase is up to double the historical mean.
Risk of flood events	LPJ-GUESS Vegetation Model and scientific literature	Autumn - Increase Rest of year - No change	Moderate / Low	See Section 6.4.3

6.5 Limitations of Modelling Approach

There are several important limitations to the modelling approach adopted here. These limitations relate to the climate information, the LPJ-GUESS model and evaluation of its outputs, and to our ability to adequately forecast future events.

The climate information available for future simulations is presently only available as monthly values. We are then unable to simulate the impact of events occurring on rapid (hourly to sub-monthly) timescales. Additionally, we are not able to simulate the influence of these rapid events on the vegetation, which can be important, possibly even more important than the slow gradual changes we are simulating (Jentsch, et al., 2008). The vegetation, as simulated have then not been exposed to the more realistic conditions that would occur such as intense heavy snowfalls, short-heat waves, and storm rain events. Wind is also not included in the model and thus any damage to trees due to wind events is not considered.

Downscaled cloud cover was not available for either the historical or future climate scenarios thus the cloud cover used as a LPJ-GUESS model input is from a coarser-resolution historical climate dataset (see Appendix 6.2.2). Future cloud cover was assumed to be unchanged from the historical cloud cover, which is unlikely to be realistic given the projected increase in precipitation. These simplifications, while necessary, could also miss important dynamics of cloud cover between the valley bottoms and higher elevations. Cloud cover influences the amount of sunlight reaching the plant leaves, local humidity, reflection of long-wave radiation (acts to keep air temperatures warmer), etc.

The LPJ-GUESS model was parameterized for 19 tree species. Some species that are less common, or are not commercially important timber species, do not have field measurements of some model parameters, making appropriate parameter value selection difficult. The LPJ-GUESS model, while one of the state of the art models available, has a relatively simple soil model. The simplicity of the soil model may not adequately represent some soil processes such as freezing/thawing and excludes some processes such as groundwater flow. Evaluation of present-day modelled species distributions and other model outputs is hampered by the lack of high quality vegetation and observational datasets to compare to from the study region. Additionally, the LPJ-GUESS model is not able to simulate changing future disease and pest disturbance levels that could have a strong impact upon the landscape as was seen during the mountain pine beetle outbreak (Kurz, et al., 2008).

The largest limitation of the modelling approach is our ability to project future events. While, by choosing a very wide possible range for future climates, we have attempted to effectively cover the possible future the region will experience over the coming decades, we are not able to quantifiably estimate other potentially important factors. The future changes in extreme wind speeds, pest and disease outbreaks, extreme precipitation events, flood frequency, etc. can only, at present, be estimated in qualitative fashion. These variables can have a stronger impact upon the regions ecosystems than the variables we can adequately quantify thus caution should be exercised in planning for future changes to these ecosystems.

6.6 Suggestions for Future Work

Future attempts at quantifying changes in the study region due to climate change would benefit from improved local-scale observational datasets, improvements to the vegetation model, and better incorporation of historical harvesting information.

The Skeena region is relatively poorly studied. While historical climate information is available in the form of gridded reanalysis data (the information from weather stations is interpolated using climate models to create spatially continuous climate information), weather stations to evaluate the climate data are primarily located in valley bottoms. Weather stations located at altitude would aid efforts to verify the downscaled climatology. Additionally, if the downscaled climate had information such as rainy days per month, cloud cover, and daily temperature range a weather generator (program that uses monthly climatological information to generate pseudo-daily weather data) could be used to permit a more realistic climate forcing for the vegetation model. Other observational data that would be beneficial to future efforts would be soil and vegetation datasets. The presently available soil data likely misses some of the heterogeneity of the soils in the region. However, the most important dataset improvement would be a vegetation dataset that does complete vegetation surveys (assesses commercially and non-commercially important tree species) of variables such as presence/absence, biomass estimates, tree height, tree trunk diameter, etc. A dataset such as this would be valuable to evaluate the performance of the LPJ-GUESS model for regions of old growth and second-growth timber.

Future application of the LPJ-GUESS vegetation model could include several improvements. First, a more realistic soil model with better resolution of soil temperatures with depth and water flow will improve simulation of plant response to drought and the freezing/thawing of the soil. Second, a more realistic root distribution with depth for trees would improve simulation of inter-species responses to soil water deficits. The utility of this improvement is, however, highly dependent upon good information about each tree species rooting patterns. Third, shrubs should be simulated in the model. Shrubs are presently not simulated and represent a significant shortcoming of the simulations. Even with these suggested improvements to LPJ-GUESS, the major impediment to improved simulations is the ability to appropriately assess the model outputs with local observational datasets such as those described earlier.

Future improvements could also include a more sophisticated harvesting scheme. The prior harvesting history for TFL1, which was not accessible for this study, is necessary. Beyondthat, future harvesting schemes could be refined to allow different harvesting practices (other than just clear cutting), better spatial harvesting knowledge (thus the harvest will be simulated to occur at the true location of the harvest, and not just an equivalent amount of harvest for that year, see Appendix 6.5) and sub-grid cell harvesting amounts, and harvesting of second growth timber.

6.7 Conclusions

The climate of the Skeena region is anticipated to warm significantly and become wetter into the future. Precipitation changes could lead to drier spring months and much wetter autumn months. Extreme precipitation events are likely to increase, mostly in the cold season months, and extreme minimum and maximum temperatures are also suggested to increase into the future. Evidence from ecosystem studies suggests that this enhanced variability could have stronger impacts upon the ecosystems of the study region than any of the overall trends and shifts in annual values (Jentsch et al., 2008). Total annual surface runoff changes follow the projected changes in precipitation from the climate scenarios with a possible decline in summer runoff and a significant increase in autumn runoff. Summer declines in runoff could result in lower river levels and higher moisture stress for vegetation in more inland regions. Projected higher autumn surface runoff could lead to higher water levels in rivers and, combined with the higher likelihood of extreme precipitation events, a greater chance of flooding events. Interpretation of our results requires caution as the simplicity of the LPJ-GUESS soil model, and our inability to model extreme precipitation, indicates we could miss important rapid events and/or processes such as topsoil erosion and destabilization.

The region has mostly functioned as a carbon sink for the historical period with that pattern expected to continue into the future. LPJ-GUESS does, however simulate the region turning to a carbon source past the year 2040 if the climate/emissions scenario HADGEM-A1B (warmest & wet) is followed. The simulated variability in ecosystem carbon dynamics across the historical period is smaller than the spread of variability between the different climate scenarios. As well, the impact of extreme events and forest pest or disease outbreaks could greatly impact upon the region's carbon dynamics, and are not adequately modelled here. Any attempts to manage the regions forests for carbon sequestration will become riskier into the future due to the large, and unpredictable, lever that climate and pests (Kurz, et al., 2008) can have on the forest ecosystems.

Presently dominant species such as western hemlock and amabilis fir will likely become more dominant as the proportion of lesser species decreases and areas of alpine tundra become afforested. The actual speed of colonization by trees in the alpine regions is highly uncertain and thus may occur at a much different (slower) rate than modelled. Carbon dioxide fertilization, warmer temperatures and wetter conditions will enhance growing conditions. However, the possible impact of forest pests and diseases is highly uncertain but likely to increase into the future. Additionally, as mentioned previously, the impact of extreme events on the forests is not adequately modelled in LPJ-GUESS and could result in higher mortality and changes to forest composition than presented here. The net gains due to enhanced growing conditions could even be reversed by the cumulative impacts of extreme events and forest pest and disease agents.

The historical and future harvesting scenarios simulated by LPJ-GUESS show a relatively modest influence on the region's runoff and carbon dynamics. From the historical potential natural vegetation and historical harvesting simulations, the influence of the climate's interannual variability is much larger than the influence of the harvesting (at least on the regional-scale investigated here). The influence of the spread in future climate scenarios is far greater than the influence of historical or estimated future harvesting for the regions carbon dynamics. The influence of harvesting on surface runoff for the regional scale is also found to be small, but this result is unlikely to be applicable on a site-level. Note that these harvesting simulations do not evaluate harvesting impacts upon other parts of the ecosystem such as disruptions to wildlife, soil erosion, and changes in species diversity, wind speeds, or vegetation-atmosphere energy fluxes.

The LPJ-GUESS simulations presented demonstrate possible future changes to the forest ecosystems of the Skeena region. These simulations are idealized in their approach and do not account for many possibly important impacts of climate change that could be important for the study area. Regardless, over the three climate scenarios simulated by the LPJ-GUESS model, the highest future uncertainty is the climate. All harvesting and potential natural vegetation scenarios show that the influence of climate is dominant for this region. Given the very large spread between our three climate scenarios, this result is not surprising. Any adaptive actions for the coming climate changes should plan for a highly uncertain and variable future.

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