Sustainability of Energy Production from Yukon's Forests: Review of Morrison Hershfield Assessment

prepared by
Dave Daust (RPF) and Karen Price (PhD)
pricedau@telus.net

for
Don Reid & Hilary Cooke
Wildlife Conservation Society Canada

June 26, 2012

Table of Contents

Introduction

In a report to the Yukon Energy Corporation, Morrison Hershfield Ltd. presented a preliminary assessment of the feasibility of generating electricity from tree biomass[1]. They estimated that there is sufficient feedstock[2] available within 250 km of Whitehorse to support a 26 MW power generation facility.

This document reviews two aspects of the Morrison-Hershfield proposal: first it evaluates the assumptions and parameters applied to the biomass feedstock assessment; second, it examines the ecological sustainability of post-disturbance logging in Yukon forests, in general and in relation to the specific proposal.

Part 1. Review of biomass feedstock assessment

This section critiques the Morrison Hershfield estimates of feedstock supply and feedstock cost.

There are substantial uncertainties relating to feedstock. Morrison Hershfield identified security of feedstock, due to lack of appropriate tenure, to be a significant project risk. They noted the need to further investigate the socially acceptable rate of dead tree harvesting from burned stands and the status of the biomass inventory. Morrison Hershfield also indicated that feedstock costs are a substantial portion (about 2/3) of total system costs and that further analyses of these costs are needed.

1. Feedstock supply

Is there sufficient feedstock, in the form of dead tree biomass, available from existing burned and beetle-killed forests, within a reasonable distance, to support a power generation facility in Whitehorse? Morrison Hershfield responded with a tentative “yes”, identifying sufficient feedstock for a 26 MW power generation plant. Table 1 summarises Morrison Hershfield parameters and assumptions, and our comments.

The underlying assumption that a power plant with a generation capacity of > 20 MW is needed for cost-effective energy production may not be warranted. The proposal does not consider smaller projects that may be viable given a market for heat and emerging technology[3].

The assumptions and parameters used to calculate the volume of biomass needed to support a 26 MW facility seem reasonable. In most cases, parameters and assumptions are clear and consistent with the literature. The proposal seems to address moisture content, but is not clear on how energy calculations account for moisture (Table 5 in Morrison Hershfield).

The proposed rate of biomass extraction in the Haines Junction area exceeds long-term sustainable harvest rates. Sustained yield forestry spreads a harvesting cycle over a hundred years or more to allow trees to achieve near-maximum average growth rates and to provide a relatively steady flow of economic benefits. Harvesting in excess of sustained yield is unsustainable from social, ecological and timber perspectives.

Based on a rough estimate, the long-term sustained yield for the forested ecosystems in the Champagne and Aishihik Traditional Territory (CATT) forest management zone (Haines Junction area), assuming regeneration success, is 29,000 – 39,000 m^3/year (Table 2). This estimate is within the upper range of yield because it does not account for all conservation of non-timber values (e.g. higher retention in high wildlife value ecosystems), the current age class imbalance (i.e., mostly young forest remains), regeneration challenges, natural disturbance and climate change. Even this upper range is only about a third of the 100,000 m^3/year included in the Morrison Hershfield calculations. When disturbance events create a stock of dead trees that exceeds sustained yield, forest managers are often tempted to increase harvest levels in order to harvest stands before wood decays and becomes unmerchantable. Such policies bring short-term economic benefits (e.g., company revenue and jobs), but can negatively affect mid-term timber supply and social-ecological values[4].

With climate change, it is possible that these ecosystems may undergo a state shift from spruce forests to aspen and/or shrub parkland (see Ecological Sustainability section). In that scenario, there is no long-term sustained yield for these ecosystems, and any logging should be considered a one-time opportunity. The possibility of an ecosystem shift could be used to argue for either less harvest in order to maintain resilience, or to argue for more harvest because the ecosystem is already fully impacted.

The Morrison Hershfield estimate of available biomass from the Haines Junction beetle-disturbed ecosystems is double previous estimates of available harvest, even for a one-time salvage opportunity. Within the beetle-disturbed ecosystems around Haines Junction, about 1 million m^3 of biomass is available for harvest over a period of about a decade[5]. This biomass is a one-time salvage opportunity and does not represent a sustainable harvest level[6]. Morrison

Hershfield, however, extrapolate the 1 million m^3/decade to two decades and conclude that 2 million m^3 will be available over 20 years. They do not provide a rationale for this assumption.

The 1 million m^3 harvest level is based on a decision rationale[7] and timber supply analysis[8] that accounts for the Integrated Landscape Plan for CATT[9], and is reasonable and consistent with the plan. Although 380,000 ha have been disturbed by spruce beetles[10], much less area is available for harvest. About a quarter of the infestation lies in Kluane National Park[11]. Most of the rest falls in CATT, with about 10,000 ha to the north and southeast. When management objectives and timber quality are accounted for, only a very small proportion of the CATT is suitable for harvesting: 7,100 ha of relatively high volume stands and 15,000 ha of low volume stands (Table 3). The total volumes (mostly white spruce, some deciduous) associated with these areas are 729,000 m^3 and 741,000 m^3 respectively[12]. Only the high volume stands (> 75m^3/ha) are considered merchantable[13], but the timber supply rationale assumes that 50% of low volume stands may be harvestable[14]. Thus, excluding deciduous forest, about 1,000,000 m^3 is available for post-disturbance harvesting, although uncertainty about timber supply projections is quite high[15].

The provisional forest management “yellow” zone in CATT does contain an additional million m^3 of salvageable timber[16]. This area can be considered for harvesting following an evaluation of forestry success in the forest management “green” zone[17], but seems unlikely to be available in the short term.

The estimates of available biomass in the fire-disturbed ecosystems are also optimistic. Within the Fox Lake and Minto fire-disturbed ecosystems included in the Morrison Hershfield proposal, the estimate of harvestable biomass considers neither non-timber values nor the economics of low-volume stands. The proposal notes that volumes available from these areas may be reduced to meet other management objectives, but does not include estimates. For example, considering biodiversity values, within the CATT area, only 62% of the area within the forest harvest zone (only 22% of total forest area) is available for harvest after accounting for within-stand retention (Table 3). There is uncertainty about the level of retention required in the burns: the areas are smaller than the CATT area, possibly allowing for lower retention depending upon landscape condition; the Minto burn, however, lies within caribou habitat, calling for higher retention and fewer roads. To correct for low productivity, Morrison Hershfield only subtracts 10% of the volume estimated by the growth model, whereas the timber supply scenarios calculated for the CATT area subtract 32% from the modelled growth[18].

Morrison Hershfield note that other burns might be available to provide additional biomass. Other recent burns, however, are mostly inaccessible or a long distance from Whitehorse (e.g., burns between Carmacks and Faro are ~250 km from Whitehorse)[19].

There is uncertainty about the assumptions of the increased biomass available from whole-tree harvest for the Haines Junction harvest. For the Haines Junction logging, the Morrison Hershfield proposal assumes an increased harvest volume of 40% from whole-tree harvest relative to stem-only harvest. The actual volume that can be extracted is uncertain and depends upon the harvesting system, biomass characteristics and difficulty of access (e.g. whether tops, limbs and bark are used, loss during harvesting[20], and whether biomass can be hauled as chips or logs[21]).

Tree decay rates were not included in the Morrison Hershfield calculations. This assumption is likely valid for the 20-year period considered, because decay is very slow in the western Yukon[22]. It might be useful, however, to consider potential decay[23].

Table 1. Level of agreement (yes, no, uncertain) with Morrison Hershfield assumptions used to calculate feedstock.

Variable	Value	Morrison Hershfield assumptions		Comments
Generation Capacity based on feedstock	26 MW[24]	> 20 MW needed for economy of scale (cost estimates based on 25 MW over 20 year project lifespan).	?	Commercially viable plants usually range from 20-100 MW[25]. If heat is marketable, emerging technology may allow smaller plants[26].
Oven Dry Tonnes (ODT) feedstock needed for 26MW	145,400 ODT/yr	20.6 MJ/Kg (at 0% moisture). 25% energy captured as electricity. 90% plant utilization (i.e., generating). 15% moisture content.	✓ ✓ ✓ ?	Energy content (at 0% moisture), energy capture, and plant utilization are consistent with literature[27]. It is not clear how energy calculations accounted for moisture (Table 5 in Morrison Hershfield). At 20% MC, wood gives about 18.6 MJ/kg[28].
Biomass volume needed for ODT	319,880 m^3/yr	2.2 m^3/ODT.	✓	Literature supports 2.2 m^3/ODT[29].
Harvestable biomass from Haines Junction area	100,000 m^3/yr for 20 years	One million m^3 available for one decade can be extrapolated to two decades, 70% of which will be available for a new tenure.	X	Very likely too high: one million m^3 is a one-time salvage opportunity based on a decision rationale and timber supply analysis that accounted for the Integrated Landscape Plan for Champagne and Aishihik Traditional Territory[30] (Table 3). Long-term sustained yield is ~35,000m^3/yr (Table 2).
Whole-tree harvest	40% more than stem-only	Biomass harvesting increases harvest volume by 40% over AAC, which is based on volume of stem inside bark. 100,000 m^3 x 70% available x 140% biomass adjustment = ~100,000 m^3	?	Tops (< 10 cm diameter) increase volume by 13%[31]; tops and limbs increase volume by 25%[32]; tops, limbs and bark increase volume by 48%[33]. Actual biomass recovery depends in part on losses during harvesting[34]. Biomass may have to be hauled as logs (not chips) from some sites[35].
Harvestable biomass from burned areas	53,800 m^3/yr from Fox Lake 166,100 m^3/yr from Minto	Based on inventory data, VDYP growth model (assuming whole-stem harvest) and area harvestable. Minus 10% for volume lost to fire. Minus 10% volume adjustment for using VDYP in Yukon.	X ✓ ?	Likely too high because non-timber values and economics of low volume stands are not considered. For example, in CATT, only 62% (53,500 of 86,000 ha) of the area is available for harvesting after conservation measures are accounted for (Table 3). As above, biomass yield depends on harvesting losses and accessibility for chip trucks. Timber supply scenarios for CATT use a 32% volume adjustment[36].

Table 2. Parameters used to roughly estimate maximum sustained yield in the Champagne and Aishihik Traditional Territory forest management (green) zone.

	Site Productivity Class				
Variable	**Good**	**Medium**	**Poor**	**Low**	**Total**
Net operable land base[37]	105 ha	5069 ha	53707 ha	8329 ha	67,210 ha
~Site index: tree height (m) at age 100[38]	23 (20-25)	18 (15-20)	13 (10-15)	5 (0-10)	
Mean annual increment at optimum rotation age[A]	2.05m^3/ha @ 130 yr	1.34 m^3/ha @ 150 yr	0.67 m^3/ha @ 160 yr	Too low to estimate	
Annual volume produced on landscape	215 m^3	6,792 m^3	35,984 m^3	0	42,991 m^3/yr
Adjusted yearly volume (10% to 32% decrease)[B]					29,000 to 39,000 m^3/yr

[A]Variable Density Yield Prediction[39] model estimate of whole stem volume (all trees > 4 cm DBH) of 100% white spruce stand in Black and White Boreal Spruce Subzone in BC.
[B] Past VDYP Projections were reduced by 10% (Morrison Hershfield) and 32% (Yukon Government Timber Supply analysis[40]) to account for Yukon context.

Table 3. Area of low and high volumes stands available for harvesting in Champagne and Aishihik Traditional Territory, based on Timber Supply Scenarios[41].

Zone	Description	Area (ha)[A]	% Area
Forested designation in CATT	Coarse resolution forest zone that includes other land uses.	246,900	
CATT forest available for management	Forested area minus town, agricultural and private land (8,000 ha)	238,900	100
Orange zone: conservation forest management	No commercial forestry	83,200	35
Yellow zone: provisional forest management	May be considered for forestry in future following evaluation of forestry in green zone	69,700	29
Green zone: available for forest management	Commercial forestry allowed (94,000 ha total zone includes town, etc.)	86,000	36
Green zone minus area needed for basic management (i.e., Timber Harvest Planning and Operating Guidebook, 1999, and Environmental Assessment assumptions)	Subtract 18,800 ha[B] of ▪ Riparian zones (100 -200m) ▪ Highway buffers (60m) ▪ In-block retention (10%)	67,200	28
Green zone minus basic management and minus area needed for high value wildlife guidelines[C]	25% retention over about 80% of net available landbase of 67,200 ha	53,500	22
Very low volume stand portion	Stands with < 25 m^3/ha	31,400	13
Low volume stand portion	Stands with 25 m^3/ha to 75m^3/ha	15,000	6
High volume stand portion	Stands with > 75m^3/ha	7,100	3

[A] Areas are approximate.
[B] Also includes "fires".
[C] This scenario is also likely to achieve other CATT landscape plan guidelines (< 50% harvest of each eco-region and eco-district; < 50% of each site class harvested; <20% harvest of a landscape unit prior to assessment)[42].

2. Feedstock cost

Feedstock costs are a substantial component of the total cost of biomass-based energy production[43] (e.g., 63 % in Morrison Hershfield). Cost estimates vary widely among studies and need further analysis[44]. Costs are difficult to extrapolate to different settings, because they vary with harvesting system[45] and type of equipment, terrain, timber characteristics and region. Yukon faces high workforce and energy costs relative to other regions[46]. Conversely, Yukon terrain is relatively gentle and includes abundant gravel, reducing road construction costs.

The Morrison Hershfield feedstock cost estimates are reasonable for relatively productive stands, but not for low volume stands. We estimate that costs could increase by 50% in the low volume stands that cover a substantial portion of the proposed harvest areas (e.g., about one third of the biomass supply in the CATT).

The Morrison Hershfield cost estimate ($53/m^3 for a 100km distance to plant) is consistent with other Yukon cost estimates and with the higher portion of the range of estimates for other jurisdictions (Table 4)[47]. Costs in Yukon are expected to be higher than in other jurisdictions (e.g., about 50% higher in southeast Yukon than in Alberta, before stumpage) due to several factors[48]:

- small average tree size and low stand volume (~150 m^3/ha or less versus an average of > 200m^3/ha across the prairie provinces)[49] increase harvesting costs,
- low stand volumes increase the amount of road required per unit volume harvested,
- the small annual harvest does not allow for "economy of scale" benefits in silviculture,
- the complexity related to a relatively "young" forest governance system increases overhead costs.

Biomass density surrounding a facility substantially influences total feedstock cost[50]. The cost estimates for Yukon are likely based on stand densities that have traditionally been targeted for harvest (e.g., 75 – 200 m^3/ha). We believe that costs will be higher in the low-volume stands (25 – 75 m^3/ha)[51] that comprise a substantial portion of proposed harvest areas (e.g., ~1/3 of volume near Haines Junction). Low volumes per hectare increase road development costs (2.5X), harvesting costs (1.7X) and silviculture costs (3X)[52]. Low stand volumes are typically associated with smaller tree sizes, and harvesting costs increase substantially as tree size drops below about 0.2 m^3/tree (e.g., a stand with 150 m^3/ha and 750 stems/ha)[53]. We estimate that low volume stands can increase harvesting costs by more than 50% over historic industry estimates (Table 4).

Long-distance hauling costs may decrease the viability of the project. Morrison Hershfield estimate transportation costs of $0.13/m^3 per km (one way). This estimate may be slightly high. Even with a more reasonable ($0.10/m^3 per km) transportation cost (Appendix), however, the long distances described in the proposal add substantially (e.g., $18/m^3 from Haines Junction) to total feedstock cost, particularly if fuel costs continue to rise[54]. For biomass energy applications, the economically feasible haul distance is quite short (e.g., about 70 km[55]; about 120 km in the US[56]). Even for more lucrative sawlog harvesting operations, round trip times of more than seven hours (about 250 km one way) are not considered to be economically feasible near Prince George, BC[57]. Ideally, energy plants should be centred amidst a dense feedstock supply[58].

Hence, despite the possible over-estimation of transportation costs, the proposed distances are not considered viable elsewhere. This raises the possibility that, if an energy-generating project in Whitehorse goes ahead, there may be increased pressure to log forest closer to the plant[59].

Table 4. Cost estimates for lumber and biomass harvesting from selected sources and with modifications. (Numbers have not been altered to account for inflation.)

Project →	Morrison Hershfield Biomass SW Yukon	Niquidet et al.[60] Biomass[A] Quesnel, BC	Price Waterhouse Cooper (PWC)[61] Lumber SE Yukon	PWC modified for this review for biomass[B]	PWC modified for this review for biomass and low volume stands[C]
Phase	**Cost ($/m³)**				
Road construction	5.39	3.22	4	3.20	8
Harvesting (i.e., felling, skidding)	15.90	11.56 to 24.08	25.50	16	27
Limbing/bucking and loading	4.00	0	included above	0	0
Chipping and loading	5.00	$3.60 at plant	0	8	8
Hauling (per 100 km to mill)	13.21	~10.00	10	10	10
Reforestation[D]	5.00	5.18 to 10.70	8	6.40	19
Administration	4.49	8.00	7	5.60	5.60
Delivered wood cost before stumpage	52.99	41.56 to 59.60	54.50	49.20	77.60

[A]Average density of harvestable trees over landscape ~ 150m³/ha (5.3 mil m³ per year over 25 years from 921, 527 ha).
[B]Excludes harvesting costs of $4.00/m³ for limbing and bucking[62] and $1.50 for loading[63]; all numbers except for transport and chipping multiplied by 0.8 to account for 25% more recoverable biomass; chipping costs increased to reflect chipping in the woods.
[C]Low volume means 50m³/ha (mid-point of 25 – 75 m3/ha volume class). Road construction costs increased by 2.5 X, harvesting costs by 1.7 X and silviculture by 3X[64]; effects of longer transportation distances not shown.
[D]Under current policy, the government pays for reforestation and collects a $5.00 fee as part of stumpage[65]. The intention is to base the fee on historic costs, so presumably stumpage fees will increase to reflect any increased reforestation costs. Reforestation includes natural regeneration and planting. If natural regeneration is successful, reforestation costs may not increase three fold.

Because of the large influence of transportation distances on feedstock cost, smaller plants could be considered. Transportation distances influence viable plant size. Optimum plant size can be determined by trading off the improved electricity generation efficiency and capital cost recovery of larger plants with increased feedstock requirements and hence transportation costs[66]. Where there is a market for heat, the efficiency of electricity production becomes less important and smaller combined heat and power plants can be considered, especially with emerging technology. Smaller plants can be located closer to feedstock to reduce transport costs. A BC study suggests that small 2 MW plants may be feasible with harvest costs of $40/m³ and transport distances of 50 to 100 km[26]. The Yukon Energy Corporation reports support for such small-scale energy and heat generation plants in the Yukon[67].

More broadly, Yukon faces several challenges related to forestry development that could increase costs[68]:

- uncertain policy environment,
- uncertain forest landbase,
- ongoing losses from natural disturbance,
- potential loss of forests due to climate change impacts on regeneration,
- limitations of tree species and stand characteristics,
- distance to markets,
- shortage of skilled labour.

Part 2. Ecological Sustainability of Post-disturbance Biomass Logging[69] in Yukon Forests

Consideration of the ecological sustainability of removing wood biomass from naturally-disturbed ecosystems in Yukon forests requires assessment of the potential cumulative effects of climate change, natural disturbance and post-disturbance biomass harvest in boreal forests. Potential ecological impacts, and uncertainties, increase from traditional green-tree logging, through logging of naturally-disturbed stands, to logging of whole trees for biomass conversion. Essentially, cumulative effects build as logging is added to natural disturbance, and as more biomass is removed from the ecosystem. To date, in Yukon forests, there is no experience with the latter two activities, and very limited experience with large-scale forestry operations[70]. Guidance thus arises from studies in boreal forests elsewhere, and from meta-analyses across a range of forested ecosystems. Additional uncertainty arises because dry forests of the southwest Yukon are at the edge of the extent of forested ecosystems, an ecotone that may shift with climate change.

This section begins with a brief overview of current and projected impacts of climate change, because these impacts form the background for any analysis of the impacts of forest harvesting. The following sections describe potential issues, risks and uncertainties associated with post-disturbance biomass logging in general, and with the Morrison Hershfield proposal in particular. The final section describes best practices for post-disturbance logging in boreal forests.

3. Climate Change Context

The boreal forest has persisted, relatively unchanged, for 6,000 years. The current rate of climate change, however, may be threatening this resilience[71]. Disturbances of all types (fire, insects, disease, permafrost thaw) are more extensive than at any time historically. In the past two decades in Alaskan boreal forests, more area has burned and late-season fires have burned more deeply into the soil[72]. In Kluane, spruce beetles have been kept at endemic levels by cold temperatures until a series of warm summers starting in the 1980s initiated the recent outbreak as beetles attacked drought-stressed trees[73]. An increase in the rate of larval maturation, due to warmer summers, exacerbated the rate of beetle increase. Although spruce beetle outbreaks have occurred reasonably regularly at about 50-year intervals in the warmer Kenai Peninsula ecosystems, there is only evidence of a single previous outbreak in the Kluane area over the past 250 years. With warmer summers, fires and beetle outbreaks are likely to increase.

Already, the increased disturbance frequency, as well as increased summer temperatures and decreased water availability have changed tree regeneration and succession trajectories[74].

Except on poorly-drained sites, severe fires have disrupted black spruce regeneration, and shifted successional trajectories from spruce-to-spruce replacement to trajectories dominated by deciduous seedlings, with very little spruce recruitment at all on dry sites[75]. White spruce growth rates have declined with warmer summers. Growth is now limited by drought rather than nutrients or temperature[76].

In dry ecosystems, such as the southwest Yukon, there are predictions that, with the change in disturbance regimes and with stabilising feedbacks weakened by warming, the boreal forest is potentially on the cusp of a non-linear conversion to shrub and/or aspen parkland[77]. Uncertainties remain about the rate of change and extent of compensation via redistribution of species.

4. Potential Issues of Post-Disturbance Logging

4.1. Nutrient Supply

Nutrient availability and limitation varies among ecosystems, and often defines forest structure. In general, boreal forests have low nutrient availability due to cold temperatures and slow decomposition rates. Some ecosystems (e.g. poorly-drained black spruce ecosystems) have particularly low productivity.

In Alaska, spruce growth was nutrient-limited until the past decade, when increased temperature and decreased moisture led to a shift from nutrient to moisture limitation during the growing season[78]. Currently, nutrients limit productivity only during early spring growth when the soil is cold, in cool moist sites, or in wet years. At other times and sites, moisture availability controls tree growth on warm sites, and temperature limits growth on cold sites. This change in an ecological process demonstrates how climate change can lead to non-linear state changes that are difficult to predict.

Studies over multiple rotations in Scandinavia suggest that green-tree logging (whether by clearcut or selective harvest) that does not leave structure on-site can reduce nutrients over time (e.g. dead wood volume reduced from 30 – 40% of total wood volume in unmanaged stands to 1% after several rotations[79]). In Canada, studies have not yet found long-term nutrient depletion, likely partly because most of the country, including the boreal forest, has not yet experienced multiple rotations of industrial biomass removal. In addition, regulations for leaving remnant structure are intended to mitigate the impacts of extraction of nutrients from a site. Further, with most stem-only logging, nutrient-rich foliage is left on site, and organic material on the forest floor remains in place.

Natural disturbances can alter nutrient balance. Fire can increase or decrease nutrients depending on burn severity. In black spruce and jack pine boreal forests in Quebec, light-moderate burns increased Ca, Mg and K concentrations in the forest floor and upper mineral layer, while severe burns reduced levels of N, Mg and K[80]. Nutrients rebuild through weathering and precipitation, but can take a century to recover. Harvest following severe fires may impact nutrients negatively. On severely burned sites, post-disturbance harvest has been projected to lead to reduced nutrient levels (of Ca, Mg and K, but not N) that would not return to pre-burn levels throughout an entire 110-year rotation[81].

Whole-tree harvest potentially has a larger impact on nutrient supply though effects vary by ecosystem and harvest methods. Most nutrients are contained within foliage and on the forest floor, and hence left on-site following stem-only harvest, particularly if limbing occurs in situ.

Whole-tree harvest of live trees, or recently dead trees with foliage still attached, removes this nutrient source from the ecosystem, reducing tree growth in some stands[82]. Removing downed wood and forest floor organic materials potentially has a larger impact[83]. Productivity effects vary among studies, with nutrient-poor sites likely at greater risk.

Importance of Issue to Proposal

The proposed harvest likely does not pose a high risk to nutrient supply on most sites. With climate change, moisture likely supersedes nutrient level as the limiting factor in the boreal forests of the southwest Yukon. Provided that forest harvest leaves sufficient structure to meet biodiversity objectives (as planned within the CATT ILP), and provided that biomass removal does not take foliage, downed wood or litter layers, there is no strong evidence that nutrient supply will be at high risk from a one-time harvest, except perhaps on the most nutrient-poor sites. The availability of nutrients may be moot if these ecosystems undergo the projected state change; although decreased nutrient levels might accelerate the shift.

4.2. Forest Regeneration and Successional Pathways

In boreal forest stands, black and white spruce trees typically replace themselves either directly, through understory to overstory replacement, or via a deciduous seral stage following a severe fire disturbance. Except where covered by deep ash layers, seedbeds are receptive after fire due to exposed mineral soil. Climate change, bringing increased fire frequency and intensity, and decreased moisture, reduces spruce regeneration. In dry boreal ecosystems, regeneration and succession have already been impacted by climate change[84].

Traditional green-tree harvesting considers regeneration a prerequisite for sustainable forestry and hence includes provisions to manage for successful regeneration (e.g. avoiding harvesting low-productivity sites, avoiding soil compaction, planting where appropriate, retaining seed trees). Green-tree logging, by definition, does not take place after a natural disturbance; hence impacts are not cumulative.

Conversely, post-fire logging may exacerbate regeneration difficulties through several mechanisms[85]: 1) loss of seed source through removal of branches with cones; 2) loss of seed source through removal and/or death of live spruces; 3) disturbance of seedbank on forest floor. If there are no retained live spruce, and if active seedbanks are destroyed, the only source of new spruce is from advanced regeneration or planting. On-site chipping of wood for biomass can further hinder regeneration in areas near roads by covering mineral soil with a blanket of chips[86].

White spruce is vulnerable at the site level. There is uncertainty about whether it can disperse to moister sites currently dominated by black spruce. If conditions are appropriate for dispersal, white spruce may be less vulnerable at the landscape level[87].

Currently there is no agreement on whether post-disturbance logging increases or decreases risk of subsequent fire[88].

Importance of Issue to Proposal

The proposed harvest likely increases the risk of an ecosystem shift. Following fire, harvest in dry boreal ecosystems will likely accelerate the projected shift from spruce-dominated to aspen parkland forests. The ability of these disturbed ecosystems to regenerate as spruce forests is uncertain under the current climate even without logging. Post-disturbance harvest, particularly if it disturbs advanced regeneration, has the potential to put regeneration at a higher risk and shift the successional trajectory to a new state. In the Minto fire site, white spruce is regenerating on lower and mid slopes, and pine is dominating the more-intensely disturbed southern aspects. In the Fox Lake burn, there is a shift from spruce to mixedwood or aspen forest post-fire.[89]

In the area of spruce beetle mortality proposed for biomass harvesting, there are few aspens. In these ecosystems, understory spruce will compete with shrubs (*Salix* sp., *Sheperdia canadensis* and *Betula glandulosa*). Given the paucity of surviving mature spruce trees, and hence lack of seed source, lack of good seedbeds (due to lack of soil disturbance), the successional trajectory will depend upon the abundance of healthy white spruce in the understory. If the spruce population is insufficient, the area may become dominated by the best-competing woody shrubs[90]. Maintaining advanced regeneration will be critical to increasing resilience.

4.3. Hydrology

Changes in water flow and sedimentation, as well as temperature and water chemistry, can impact hydroriparian ecological function. Forest harvesting can disturb soil surfaces and cause compaction, particularly on roads, landings and skid trails. Compaction influences water flow; increased erosion influences water quality. Traditional forestry aims to maintain site-level and watershed-level hydrology through limits to harvest amount per unit time (e.g. 1% of the forested area of a watershed per year[91]), limits to activities on sensitive terrain (e.g. steep, unstable slopes, floodplains, wetlands) and maintenance of riparian vegetation. Concern remains that current best management practices will not maintain the function of small streams because standards call for narrow, if any, buffers.

Intensive natural disturbances kill most of the trees in an area, changing hydrology within the stand and increasing variability in soil moisture levels. In general, the hydrological properties of unlogged stands of dead trees lie between those of undisturbed forests and clearcuts[92]. Post-fire logging can increase the risk of erosion of vulnerable soils[93].

Biomass removal has the potential to further affect hydrology. Increased areas of machinery use will increase compaction; conversely, if patterns of machinery use are similar to stem-only harvest, impacts will be similar. Removal of downed wood removes impediments to flow and potentially increases overland flow[94]. On-site chipping can leave a blanket of wood chips that further changes water flow and potentially leads to toxic leachate[95].

Importance of Issue to Proposal

Impacts to hydrology are likely similar to traditional logging for a given volume of biomass removed provided that organic matter on the forest floor is not removed and that woodchips are managed effectively. The low productivity (most stands < $75m^3$/ha) means that a high road density will be needed to access a given volume of biomass; hence following hydrological best management practices for roads will be important.

4.4. Post-disturbance Biodiversity

Organisms are adapted to the natural disturbance regimes of their habitat[96]. Post-disturbance communities frequently differ from undisturbed communities within the same ecosystem type. In boreal ecosystems, fire and beetles create habitats that are neither emulated by harvesting nor prevalent in undisturbed mature forests.[97] These habitats will likely increase with climate change.

Natural disturbances are important ecosystem processes that can increase structural complexity and landscape heterogeneity, and maintain biodiversity and productivity. Remnant forest legacies (including green trees and patches, and trees killed by the disturbance) control recovery from disturbance[98]. Post-disturbance logging can undermine the benefits of disturbances. The loss of legacies from a disturbed area can impact many groups of organisms (e.g. cavity-nesters, beetles, mosses) and impair ecosystem recovery.

Studies of vegetation communities have found that ecosystems disturbed by fire have different communities than similar ecosystems that have been subsequently logged, particularly in the short-term[99]. Fire specialists are lacking from logged stands, and there are more weedy species. In general, the pre-burn community and fire severity dictate the post-fire vegetation community. In some cases in boreal forests in Siberia and Quebec, post-fire logging has shifted vegetation communities from forest to grassland[100].

Similarly, for birds, burned forests support distinct communities, with many species equally or more abundant than in undisturbed forests (some mature forest songbirds are in high abundance in burns; post-fire specialists, particularly woodpeckers, are either absent or at very low numbers in unburned forests)[101].Distinct bird assemblages are associated with dead trees (e.g. cavity nesters and beetle foragers), with residual patches of unburned, especially mature, forest, with the open parkland habitat created by open areas adjacent to residual patches, and with post-fire early successional habitat (e.g. shrub nesters). Burn severity is a critical determinant of bird abundance and community composition[102]. In various studies, post-disturbance logging led to fewer cavity-nesters, fewer post-fire specialists, fewer resident species, fewer canopy nesters and fewer insectivores[103]. Cavity-nesters are impacted by loss of nest sites and foraging opportunities: in some studies, even though the number of potential nest snags/hectare remained above recommended levels cavity nesters decreased, likely due to a reduction in food, particularly wood-boring beetles [104].

The processes of post-disturbance ecosystem recovery are not well understood, in part because it is hard to find naturally-disturbed sites that are not logged.[105] This uncertainty is particularly important given the potential shifts in disturbance regime and recovery from disturbance projected due to climate change.

4.4.1. Landscape-level Retention

At the landscape scale, retention of unmanaged areas is generally intended to provide habitat for a variety of species and space for ecological functions to continue without much management interference. Landscape-level retention primarily serves to maintain focal ecosystems (e.g. rare ecosystems and hydroriparian ecosystems) and to represent all ecosystems at a level that they can maintain ecological function. It also functions to provide habitat for focal species that are known to be associated with old forest structures or with structures remaining following natural disturbance.

Most theoretical and empirical studies agree that total amount of habitat is more important than habitat pattern[106]. If habitat amount over the landscape is too low, organisms are absent even from patches of suitable habitat. In boreal forests of Scandinavia, bird communities in small oldgrowth reserves, surrounded by managed forest, were more similar to those in young forest than to those in ecologically similar large reserves[107]. Retention in patches and corridors can be an effective supplement to patches of unmanaged forest in the landscape for maintaining biodiversity, but are not sufficient in isolation[108]. Even if old forest reserves retain old-forest species in the short term in managed forest landscapes, they will likely be insufficient over the long-term and at a regional scale. Several simulation studies for boreal Canada have suggested long-term declines in old forest birds under various old-forest retention strategies in managed forest landscapes given existing rotations, harvest rates, and retention levels[109].

A considerable body of literature has asked “how much habitat is enough” at the landscape scale to allow occupation of suitable habitat. Much of this literature has focussed on the search for thresholds, where populations suddenly decline, or ecosystem processes suddenly change. Few sensitive organisms cross detrimental thresholds when habitat amount exceeds 60%; nearly two-thirds of sensitive species studied cross thresholds before their habitat drops to 30%[110]. Natural disturbance patterns can be used to predict habitat amounts that pose low risk to biodiversity.

Importance of issue to proposal

The proposed harvest within the Haines Junction beetle outbreak area likely poses low risk to biodiversity. These ecosystems lie within the CATT. In this area, an ILP designates 34% of the area as conservation forest, closed to harvest; an additional 28% is reserved pending assessment of success in the forest zone. Hence, 62% of the landscape is currently unavailable for harvest. Additional constraints ensure that less than 50% of each site productivity class and ecoregion/ecodistrict is harvested, preventing harvest that targets the most productive ecosystems. In coastal BC, retaining more than 60% of a landscape unmanaged (equating to 70% of the area expected to be old under natural disturbance conditions) is considered precautionary; less than 30% is considered high risk.[111] In boreal forests, some companies are managing old forest retention within the natural range of variability, retaining 18% as old forest, although age-class distributions can be more difficult to estimate in these ecosystems than on the rarely-disturbed coast[112].

Without an existing plan, the effects of the proposed harvest on the burned areas are unknown. In the southwest Yukon, fire and beetle disturbances create unique ecosystems. Planning to retain a sufficient amount at multiple scales (i.e. within a fire and over larger regions) to maintain ecological integrity would be prudent. The current proposal evaluates two large burns, and there are potential impacts of post-fire logging to biodiversity within those burns depending upon retention. At the regional scale, new burns may be targeted once biomass production has begun, potentially impacting regional populations of post-fire species, depending upon the burn rate, harvest rate and retention level. As a general principle, disturbed sites should not be viewed as being more “harvestable” than undisturbed old forest.

4.4.2. Stand-level Structure

Forest structure provides the architecture of an ecosystem: large standing dead or live trees, large downed wood, horizontal and vertical heterogeneity. Natural disturbances provide pulses of death that increase structural heterogeneity. This structure, renewed by disturbance, supports an ecosystem’s processes and biodiversity.

At the stand scale, retaining structure within managed forests is generally accepted to serve three functions: 1) enriching re-established forest stands with structural legacies, so that as stands age they acquire complex structures and begin to function as older stands sooner than they otherwise would; 2) maintaining (‘lifeboating’) species and processes that would otherwise be absent from early seral stands, keeping them in the area until conditions become more favourable; 3) enhancing landscape connectivity[113].

As with landscape-level retention, evidence suggests that the amount retained is more important than the pattern. A review of studies in forests from North America and Europe found that retention below 20% has little value for structural enrichment or for lifeboating (insufficient studies exist to test connectivity)[114]. Above 20%, immediate post-harvest survival of some forest taxa increases, non-linearly, with the amount of retention. Small, young trees have limited value although they can provide important foraging opportunities[115]. Reviews of boreal studies have found that retaining structure increases the presence of old-forest birds and mammals, but have not found consistent patterns by amount retained[116]. More evidence supports aggregated retention, though response varies by organism. In cutblocks in boreal forests, retained patches > 5 ha may be necessary to retain old forest bird species[117]. Because most field studies are short-term, knowledge about long-term effectiveness is severely lacking[118].

Ecosystem-based forest management aims to maintain ecosystem processes and biodiversity through retaining structure at all scales. In Fennoscandian boreal forests, some species are threatened, and in some cases extirpated, because of centuries of intensive forest management resulting in depletions in old forest structures.[119]

Natural disturbances create structural heterogeneity. Standing snags are important features of both fire and beetle disturbance events. In the boreal forest, unburned forests typically have many deciduous, but few coniferous, snags: hence conifer snags require disturbance for maintenance[120]. Burn severity is heterogeneous over space. Even severe fires in boreal forests have patches of live residuals; larger fires have higher proportions of live residuals[121]. In the southwest Yukon, the slow decay rate means that dead trees remain as structure for many decades[122]. Post-disturbance logging can eliminate live residuals and snags unless retention is planned. Snags that are retained following post-disturbance logging are less likely to remain standing—a cumulative effect of double disturbance that limits the effectiveness of retention and potentially calls for higher retention levels.[123] In BC, the chief forester has provided guidance for increased levels of stand-retention in post-beetle harvest.[124]

Importance of issue to proposal

The proposed harvest within the Haines Junction beetle outbreak area likely poses low risk to biodiversity. In combination with high levels of landscape retention, the CATT ILP calls for in-stand retention of 25% in high-value wildlife areas that cover 80% of the forestry zone and 10% elsewhere. Increasing the diversity in retention levels could be beneficial to increase resilience.

Without an existing plan, the effects of the proposed harvest on the burned areas are unknown.

4.5. Access

Roads have a variety of impacts on ecosystems. They increase direct mortality by collisions and by providing access for predators, including humans[125]. Traffic along roads with low roadside cover can have far-reaching impacts (e.g. some ungulates are disturbed within 400 m of roads). Roads can either facilitate or hinder movement of large and small animals.[126] They are well documented avenues for the spread of invasive species[127]. Poorly located roads and/or poor culvert placement can alter hydrogeomorphic processes, stream ecosystems and fish survival.[128] Road building and skidding associated with post-disturbance logging can increase soil compaction and erosion[129].

Some biologists consider impacts of roads to be greater for some species than the impact of habitat alteration. Grizzly bears are particularly sensitive to roads because of their low reproductive rates, road-associated mortality, and displacement from areas near roads.[130] While adult males generally avoid road corridors, adult females with cubs tolerate high human presence along road corridors and can become habituated. These females are subject to increased mortality risk, potentially impacting population trends. The risk to grizzly bear mortality increases steeply with the first road into an area, then rises more gently until another threshold at 0.6 km/km^2. [131]

Importance of issue to proposal

A low volume of biomass per hectare leads to a high road density per volume harvested, increasing risk to biodiversity and potential increasing risk to hydrology. Large unroaded areas are considered an excellent indicator of large mammal populations, and open road density indicates potential risk. Effective deactivation of roads reduces impacts over time, but access control measures can be difficult to implement after people become accustomed to using resource roads. One of the burned sites is within the winter range of the Tatchun caribou herd[132]; hence access control might be an important consideration.

Providing a long-term biomass supply may increase road density. New roads may be built to access new burns to supply biomass over a longer time period. Planning will be important to address potential cumulative impacts over time.

5. Best practices for post-disturbance logging in boreal forest

In any ecosystem, post-disturbance logging shares—at a minimum—many best practices with green-tree logging. Many authors have summarised forest management practices aimed to maintain ecological integrity[133]; these practices apply equally to post-disturbance management, and generally include such recommendations as reserving sufficiently large areas of all ecosystems to maintain function, retaining heterogeneity across scales, retaining structure within stands. Natural disturbance is well-accepted as a guide to resilient management, though climate change brings uncertainty to the approach[134]. Resilience in the face of climate change calls for a diversity of approaches including potentially higher levels of retention.

Because of special conditions following stand-replacing natural disturbances, post-disturbance logging may have greater impact, and the best practices for green-tree logging may not be sufficient[135]. Post-disturbance logging impacts an ecosystem that has already been disturbed and may hence be more vulnerable.

For post-disturbance logging, the following best practices have been described[136]:

Planning

1. **Honour pre-disturbance objectives. I**f ecological integrity was a priority for management pre-disturbance, natural disturbance should not alter that priority; yet disturbances have been used to change objectives from ecological to economic by allowing salvage where green-tree logging would not have been allowed at the same intensity[137]
2. **Consider potential cumulative effects of multiple disturbances over time and space including other anthropogenic disturbances**. The need for this step will likely increase with climate change as the frequency and intensity of fire and insect outbreaks both increase. In planning for cumulative effects, it is important to be proactive and plan in advance rather than responding to proposals individually.
3. **Manage for heterogeneity** (e.g. structure and species composition) within and among stands to increase resilience to climate change[138]. Traditional forest management increase homogeneity, unlike natural processes, and can increase probability of unexpected catastrophic change.
4. **Plan to address site-level concerns** (e.g. vulnerable soils, advanced regeneration)

Landscape-level Reserves

5. **At the landscape level, exclude post-disturbance logging from sufficient disturbed area to maintain desired functions**. Within naturally disturbed areas, the following sites and ecosystems should be reserved; i.e. excluded from post-disturbance logging:
    a. Large representative ecosystems that are designed to maintain ecological processes and biodiversity
    b. Smaller areas with high ecological value (biodiversity hotspots including hydroriparian ecosystems, where the structure provided by dead wood is particularly important, and legacy-rich habitats)
    c. Rare ecosystems

d. Where disturbed ecosystems are rare (e.g. following fire suppression), leave disturbed stands unlogged

e. Where recent human activity is limited, and hence the potential for natural recovery is strong

f. Sensitive sites (hydrologically, steep, erodable)

g. Unroaded areas

h. Old-growth areas

Stand-level Retention

6. **Retain undisturbed or partially disturbed patches within a disturbance**. These patches are refugia for surviving organisms. Preferentially retain larger patches.

7. **Retain sufficient legacies within the logged area to maintain desired functions.** Most jurisdictions have similar retention targets for post-disturbance harvest as from green harvest (e.g. retain average 7.5% in BC, although the Chief Forester has given recommendations for higher retention in beetle-outbreak areas). In general, higher retention levels are necessary than for green-tree logging to allow attrition and collapse. Levels below 20% provide few benefits. In particular, leave

    a. Large live trees

    b. Large dead snags

    c. Damaged trees

    d. Downed wood[139]

    e. Advanced regeneration

8. **Match the profile of the pre-harvested stand for structural elements**, or bias retention towards larger structures as longer-lasting legacies.

Management Operations

9. **Minimise ground disturbance after fires** because of increased soil vulnerability

10. **Schedule timing to minimise effects on natural recovery**

    a. Seasonally, harvest in winter to minimise impacts on regeneration

    b. Across years, delay to allow post-burn recovery and communities

11. **Avoid interfering with natural recovery**: replanting can impede recovery in some forest types by introducing invasive weeds, increasing homogeneity, and increasing risks associated with dense even-aged dense stands (fire, insect, pathogens)

12. **Decommission roads after post-disturbance logging**

6. Appendix: Notes on costs

Tree to truck

Biomass harvesting includes felling and skidding costs, but excludes limbing and bucking costs that make up about 20% ($4.00/m^3 out of $19.90)[140] to 33% ($2.23 out of $6.69) [141] of tree to truck costs.

Estimates of tree to truck costs (including bucking and delimbing) are very variable among studies and among regions. Kumar[142] present estimates from several studies that, range from $6.69 (assuming merchantable tree volume of 0.5m^3/tree) to $16.65. Estimates vary regionally: $13/m^3 in Alberta; $17/m^3 in BC; $19/m^3 in the prairies; $20/m^3 in Eastern Canada; $24/m^3 in Yukon[143]. Stennes and McBeath[144] also estimate $17/m^3 [145] for BC. JC Bartlett and associates Ltd.[146] estimate $20/m^3 to $25/m^3 for hand-felling in good stands in the Northwest Territories.

Chipping

Chipping costs are highly dependent on specific equipment and the scale of the operation. Roadside chipping uses small to medium chipping machines because of the limited availability of biomass at a given site[147]. High capacity chippers located at the energy plant reduce chipping costs. The cost of chipping roadside residuals (discarded limbs and sections of logs; ~25% of sawlog volume) depends on stand density and ranges from 6.49/m^3 to $9.80/m^3 for stands with > 250m^3/ha and < 150 m^3/ha respectively[148]. Similarly Kumar et al.[149] summarize a range of chipping costs from the literature, from $6/m^3 to $11/m^3 and estimate costs of $5/m^3 for a large scale operation (e.g., harvesting 2 or 3 million m^3/yr). Thakur[150] summarizes a range for piling and chipping cost (in the woods) from $5/m^3 to $12/m^3. Chipping at the energy facility could be relatively cheaper ($4/m^3)[151]. Thakur estimated chipping costs of $5.30/m^3 at the roadside and $4.49/m^3 at the energy plant, assuming full equipment utilization (i.e., an optimistic assumption).

In the woods, chips may flow directly into waiting chip trucks or be stored in piles for later loading[152].

Transport

A logging truck costs about $150/hr[153] or about ~$2/km given an average travel speed of about 75 to 80 Km an hour[154]. Loading and unloading takes about an hour (Transport Canada 2005), increasing costs to about $2.42/km on the 360 km round trip from Haines Junction cutblocks to Whitehorse[155]. Similarly, a B-train van (i.e., used as a chip truck) costs about $2.39/km (including typical loading/unloading time for an average 320 km round trip distance and 160,000 km/yr[156]. A rate of $2.40/km translates to about $8/m^3 for a 60 m^3 load going 100 km to a facility[157]. Winter hauling increases costs 5.9% (included in estimates) and hauling on gravel reduces speed by about 8 km/hr and increases repair and tire costs[158]. Loading/unloading time (about an hour) is typically included in transport costs[159], thus shorter hauls cost more per kilometre because loading/unloading costs comprise a higher proportion.

Given a fixed rate per kilometre, the amount of weight or volume (whichever is limiting) that a truck can haul determines the cost per unit of biomass. Super b-train chip trucks probably have similar capacities and costs as logging trucks[160]. Some chip trucks haul less solid biomass (e.g., 21.5 ODT)[161] than logging trucks (e.g., 30.4 ODT[162]) because chips are less dense than stacked logs and hence chip trucks are limited by volume[163].

Tampier et al.[164] estimate that loading/unloading costs $4/m^3 for logs. Thakur[165] uses an estimate about $2.25/m^3 for loading unloading bulk material.

7. Notes and References

[1] **Morrison Hershfield Ltd. 2011.** Preliminary Yukon Biomass Energy Evaluation. September 13, 2011. http://yukonenergy.ca/downloads/db/1081_Biomass%20Report%20Final%20Sept%2013_2011_DM.pdf

[2] "Feedstock" refers to wood biomass harvested from forests disturbed by beetles and fire. For energy generation, recently dead feedstock is preferred because it has lower moisture content than green wood and because it has not yet decayed. The dry climate near Whitehorse limits decay rates; hence rapid harvest is less critical than elsewhere.

[3] A BC study suggests that small 2 MW plants may be feasible with harvest costs of $40/m^3 and transport distances of 50 to 100 km (**Tampier, M., P.A. Beauchemin, D. Smith and E. Bibeau. 2006.** Identifying environmentally preferable uses of biomass resources—BC Bugwood: economics, technical feasibility and GHG implications of seven small to medium-scale technologies. Envirochem Services Inc., North Vancouver, BC. http://www.for.gov.bc.ca/hfd/library/documents/bib97175.pdf)

[4] **Burton, P.J. 2010.** Striving for sustainability and resilience in the face of unprecedented change: the case of the mountain pine beetle outbreak in British Columbia. Sustainability 2: 2403-2423. **Lindenmayer, D.B., P.J. Burton and J.F. Franklin. 2008.** Salvage logging and its ecological consequences. Island Press. Washington, DC, USA. p. 272.

[5] **Anon. 2006a.** Rationale for harvest level recommendation, March 14, 2006. Prepared by the Steering Group for the Forest Implementation Project for the Yukon Government and Champagne and Aishihik First Nations government.

[6] **Pers. comm. Kirk Price, 30-04-2012**, Forest Management Branch, Yukon Government

[7] **Anon. 2006a.**

[8] **Yukon Government. 2006.** Timber supply scenarios for the Champagne and Aishihik non-overlap traditional territory. Forest Management Branch, Energy, Mines and Resources, Yukon Government.

[9] **Anon. 2006b.** Integrated landscape plan for the Champagne and Aishihik traditional territory.

[10] **Yukon Government. No date.** Spruce bark beetle: Yukon forest health—forest insect and disease 19. Forest Management Branch, Energy Mines and Resources.

[11] **Anon. 2004.** Strategic forest management plan for the Champagne and Aishihik Traditional Territory.

[12] **Yukon Government. 2006.**

[13] **Yukon Government. 2006.**

[14] **Anon. 2006a.**

[15] **Yukon Government. 2006.**

[16] **Yukon Government. 2006.**

[17] **Anon. 2004.; Anon. 2006b.**

[18] **Yukon Government. 2006.**

[19] **Canadian Wildfire Information System.** Website accessed May 25, 2012. http://maps.nofc.cfs.nrcan.gc.ca/cwfisapps/interactivemap/index.phtml

[20] **Preto, F. 2011.** Biomass energy backgrounder paper (Yukon Energy Planning Charrette). CanmetENERGY, Natural Resource Canada. http://www.yukonenergy.ca/downloads/charrette/docs/papers/BIOMASS_YEC_Background_Paper.pdf

[21] **Tampier, M., P.A. Beauchemin, D. Smith and E. Bibeau. 2006.** Identifying environmentally preferable uses of biomass resources—BC Bugwood: economics, technical feasibility and GHG implications of seven small to medium-scale technologies. Envirochem Services Inc., North Vancouver, BC. http://www.for.gov.bc.ca/hfd/library/documents/bib97175.pdf

[22] **Garbutt, R. B. Hawkes and E. Allen. 2006.** Spruce beetles and forests of the Southwest Yukon. Information Report BC-X-406. Natural Resources Canada, Pacific Forestry Centre.

[23] Pine (*Pinus contorta*) snags lose about 30% of their merchantable volume over 25 years in dry cold ecosystems in BC (**Niquidet, K., B. Stennes and G.C. van Kooten. 2008**. Bioenergy from mountain pine beetle timber and forest residuals. Working Paper 2008-11. Resource Economics and Policy Analysis

Research Group, University of Victoria.; **Eng, M. 2004.** Provincial level projection of the current mountain pine beetle outbreak—appendix 4: details of the shelf life model. Research Branch, BC Forest Service, Victoria, BC.); black spruce (*Picea mariana*) snags lose 0.5% of their density per year in northwestern Quebec (**Angers, V-A, 2011.** Dynamique des arbres morts en foret boreale mixte et coniferienne. PhD Thesis. University of Quebec at Montreal); black spruce snags have a half life (remain standing) of about 20 yrs. Down wood (log residue) decay rates range from 1.7 to 4.9% per year for Norway spruce (*Picea abies*) in Norway (**Naesset, E.. 1999.** Decomposition rate constants of Picea abies logs in southeastern Norway. Canadian Journal of Forest Research. 29:372-381)

[24] Calculating electricity output from biomass:

145,400 ODT/yr x 20.6 GJ/ODT = 2,995,240 GJ/yr;
2,995,240 GJ/yr / 31,536,000 sec/yr = 0.095 GJ/sec = 0.095GW = 95 MW;
95 MW / 90% plant utilization x 25% efficiency = 26.3 MW;
26.3 MW x 8760 hours / year = 230.4 GW hours potential.

[25] **Preto 2011.**

[26] **Tampier et al. 2006.**

[27] **Ince, P. 1979.** How to estimate recoverable heat energy in wood or bark fuels. USDA Forest Service. General Technical Report FPL 29.

[28] **McKendry, P. 2002.** Energy production from biomass (part 1): overview of biomass. Bioresource Technology, 83: 37-46; **Ince 1979; Preto. 2011.**

[29] **Wilson, P.l., J.W. Funck and R.B. Avery. 1987.** Fuelwood characteristics of north american hardwoods and conifers. College of Forestry, Oregon State University, Corvallis, Oregon; **Preto 2011**

[30] **Pers. comm. Kirk Price, 30-04-2012; Anon 2006a; Yukon Government 2006; Anon 2006b.**

[31] **Yukon Government. 2006.**

[32] **Kumar, A. J.B. Cameron and P.C. Flynn. 2003.** Biomass power cost and optimum plant size in western Canada. Biomass and Energy, 24: 445-464; **Kumar, A. 2006.** A conceptual comparison of using bioenergy options for BC's mountain pine beetle infested wood. BIOCAP Research Integration Program Synthesis Paper. http://www.biocap.ca/reports.php

[33] (Bark (0.08) + Branches (0.22)) / Stem (0.58), excluding needles (0.12), = 0.52 based on **Apr, P.A., J. Ogilvie and M. Castonguay. No date.** Modelling and mapping nutrient supply—demand sensitivities to forest biomass harvesting, in New Brunswick. Unpublished report, University of New Brunswick. Available at http://watershed.for.unb.ca/files/NBbiomass.pdf; similar proportion in **Yarie J. and K. van Cleve. 1982.** Biomass and productivity of white spruce stands in interior Alaska. Can. J. For. Res. 13: 767-772.

[34] **Preto 2011.**

[35] **Tampier et al. 2006.**

[36] **Yukon Government. 2006.**

[37] **Yukon Government. 2006.**

[38] **Santry, M. 1995.** Forest cover mapping. Volume 1: Yukon forest classification/field sampling. http://emrlibrary.gov.yk.ca/forestry/Forest%20Cover%20Mapping%20Manual.pdf

[39] **Variable Density Yield Prediction Model (version 7).** Accessed May 2012 http://www.for.gov.bc.ca/hts/vdyp/

[40] **Yukon Government 2006.**

[41] **Yukon Government. 2006.**

[42] **Yukon Government. 2006.**

[43] **McKendry, P. 2002.** Energy production from biomass (part 1): overview of biomass. Bioresource Technology, 83: 37-46.

[44] **Tampier et al. 2006.**

[45] The biomass harvesting system and the type of equipment used affect costs. One approach follows the same steps as conventional logging: fell, skid, delimb, transport and then chip at the energy plant (**Tampier et al. 2006**). Another approach chips material at the roadside after felling and skidding and then transports chips (**Kumar, A., P.C. Flynn and S. Sokhansanj. 2005.** Feedstock availability and

power costs associated with using BC's beetle-infested pine. Report prepared for BIOCAP Canada Foundation, ON, and Province of BC. http://www.biocap.ca). Costs of these approaches are difficult to compare. Chipping in the forest captures limbs and tops and thus increases yield per hectare by about 25% **(Kumar et al. 2005)**. Road development, felling, skidding, silviculture and administration costs per unit volume are thus reduced. Also delimbing/bucking is not needed. Conversely, some costs increase. Chipping at the plant is generally cheaper than chipping in the woods (**Tampier et al. 2006**) because a large chipper can be used. Adding to uncertainty, forestry road conditions may necessitate the use of logging trucks rather than chip trucks (e.g., 70% of harvestable area may be inaccessible to chip trucks in parts of BC; **Tampier et al. 2006**). Harvesting systems can be combined: logs can be hauled to the mill for chipping; at accessible sites, residual biomass can be piled and chipped. Uncertainty about the steps in the feedstock harvesting process and about the equipment used increases uncertainty about costs.

[46] **Price Waterhouse Coopers. 2005.** Economic assessment of forest industry in Southeast Yukon. Report for Watson Lake Chamber of Commerce. http://www.energy.gov.yk.ca/pdf/se_yukon_economic_analysis_final_report.pdf

[47] An economic assessment of the potential for forestry development in Southeast Yukon[46] estimated delivered log costs of about $55/m^3$ (**Price Waterhouse Coopers. 2005.**). An assessment for an area near Quesnel, BC estimated a delivered biomass costs of about $50/m^3$ (**Tampier et al. 2006**)

[48] **Price Waterhouse Coopers. 2005.**

[49] Similarly, 99% of stands harvested around Prince George, BC, have greater than $182m^3$/ha cited in Province of BC. 2010. Prince George TSA Timber Supply Analysis Public Discussion Paper.

[50] **Niquidet, K., B. Stennes and G.C. van Kooten. 2008.** Bioenergy from mountain pine beetle timber and forest residuals. Working Paper 2008-11. Resource Economics and Policy Analysis Research Group, University of Victoria; **McKendry, P. 2002.**

[51] **Yukon Government. 2006.**

[52] Road development and harvesting increases based on formulae in **Kumar et al. 2003**; assuming a constant 750 stems/ha; similar increases in harvesting costs are reported by other authors (**Niquidet et al. 2008**.; **Karha K. 2006.** Whole tree harvesting in young stands in Finland. Forestry Studies. 45: 118-134). In BC, silviculture costs range from $800 to $1600/ha. If silviculture costs $1,200 /ha, stands with about 150 m^3/ha give a silviculture cost of $8/m^3$—same as the estimate for southeast Yukon (**Price Waterhouse Coopers. 2005.**)

[53] **Visser, R., R. Spinelli, J. Saathof and S. Fairbrother. 2009.** Finding the "sweet-spot" of mechanized felling machines. Council of Forest Industries Conference Proceedings: Environmentally Sound Operations. Lake Tahoe, June 15-18, 2009; **Niquidet et al. 2008**.

[54] Fuel accounts for about ¼ of the trucking cost and have increased substantially in recent years (**Logistics Solutions Builders Inc. 2005.** Operating costs of trucks in Canada 2005. Report prepared for Transport Canada)

[55] **Tampier et al. 2006.**

[56] **White, E. 2009.** Wood energy for biomass and biofuels in the United States—a briefing paper. College of Forestry, Oregon State University.

[57] **Province of BC. 2010.** Prince George TSA Timber Supply Analysis Public Discussion Paper.

[58] **McKendry 2002.**

[59] Green biomass, however, has a lower energy content than dry biomass and may offset cheaper transportation costs.

[60] **Niquidet et al. 2008.**

[61] **Price Waterhouse Coopers. 2005.**

[62] **PBrand Bioenergy Consulting. 2009.** An economic evaluation of a bioenergy opportunity in Yukon. http://www.energy.gov.yk.ca/pdf/yukon_bioenergy_final_report_2009.pdf

[63] **Price Waterhouse Coopers. 2005.**

[64] See note 52.

[65] **Yukon Government. Accessed 2012**. Fact sheet: forest resource fees. http://www.emr.gov.yk.ca/forestry/forest_resource_fees.html#Development_Fee

[66] **Kumar et al. 2003.**

[67]Yukon Energy Corporation. 2011. Biomass energy workshop report. http://yukonenergy.ca/downloads/db/1081_Biomass%20Report%20Final%20Sept%2013_2011_DM.pdf

[68] **Price Waterhouse Coopers. 2005.**

[69] The term "*salvage*" infers that a value is saved. Although salvage logging uses wood that would otherwise be unavailable economically in the short-term, and hence can be considered to "save" money, it does not save ecological values. Indeed, there is general agreement that it has the opposite effect. We follow **Lindenmayer DB, Burton PJ and Franklin JF. 2008.** "Salvage logging and its ecological consequences. Island Press Washington" in using "*post-disturbance logging"* as a more neutral, appropriate term.

[70] Yukon softwood harvest has ranged from 18,000 – 42,000 m^3 annually between 2000 and 2010. **National Forestry Database.** http://nfdp.ccfm.org/index_e.php. Accessed May 22, 2012.

[71] **Chapin III FS and 15 others. 2010**. Resilience of Alaska's boreal forest to climatic change. Canadian Journal of Forest Research 40:1360-1370.

[72] **Kasischke ES and 10 others. 2010**. Alaska's changing fire regime—implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research 40:1313-1324.

[73] **Berg EE, Henry JD, Fastie, CL, DeVolder AD and Matsuoka SM. 2006**. Spruce beetle outbreaks on the Kenai Peninsula, Alaska, and Kluane National Park and Reserve, Yukon Territory: relationship to summer temperatures and regional differences in disturbance regimes. Forest Ecology and Management 227:219-232. **Garbutt R, Hawkes B and Allen E. 2006**. Spruce beetle and the forests of the southwest Yukon. Natural Resources Canada, Canadian Forest Service Information Report BC-X-406.

[74] **Chapin III et al. 2010. Johnstone JF, McIntire EJB, Pedersed EJ, King G and Pisaric MJF. 2010.** A sensitive slope: estimating landscape patterns of forest resilience in a changing climate. Ecosphere 1(6):article 14. doi:10.1890/ES10-00102.1

[75] **Kasischke et al. 2010.**

[76] **McGuire AD, Ruess RW, Lloyd A, Yarie J, Clein JS and Juday GP. 2010**. Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: dendrochronological, demographic, and experimental perspectives. Canadian Journal of Forest Research 40:1197-1209. The authors note that spruce growth rate is most affected in warm regions and in floodplains where rivers are dropping (on floodplains, there is a complex interaction involving moose browse, and increased invasive nitrogen fixers).

[77] **Chapin III et al. 2010.**

[78] **Chapin III et al. 2010**. **McGuire et al. 2010. Yarie J and Van Cleve K. 2010**. Long-term monitoring of climatic and nutritional effects on tree growth in interior Alaska. Canadian Journal of Forest Research 40:1325-1335.

[79] **Angelstam P. 1997**. Landscape analysis as a tool for the scientific management of biodiversity. Ecological Bulletin 46:140-170.

[80] **Brais S, Pare D and Ouimet R. 2000**. Impacts of wild fire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands. Forest Ecology and Management 137:231-243.

[81] **Brais et al. 2000**.

[82] **Thiffault E, Hannam KD, Pare D, Titus BD, Hazlett PW, Maynard DG and Brais S. 2011.** Effects of forest biomass harvesting on soil productivity in boreal and temperate forests – a review. Environmental Reviews 10:278-309. Some studies have detected impacts on productivity, but interactions and confounds, as well as a lack of long-term studies, lead to uncertainty (**Grigal DF. 2000.** Effects of extensive forest management on soil productivity. Forest Ecology and Management 138:167-185. **Janowiak MK and Webster CR. 2010**. Promoting ecological sustainability in woody biomass harvesting. Journal of Forestry Jan/Feb:16-23).

[83] **Janowiak and Webster 2010**.

[84] **Berg et al. 2006**. **Chapin III et al. 2010**. **Johnstone JF, Hollingsworth, Chapin III FS, Mack MC. 2010.** Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Global Change Biology 16:1281-1295. **Hogg EH and Wein RW. 2005**. Impacts of drought on forest growth and regeneration following fire in southwestern Yukon, Canada. Canadian Journal of Forest Research 35:2141-2150.

[85] **Greene DF, Gauthier S, Noel J, Rousseau M and Bergeron Y. 2006**. A field experiment to determine the effect of post-fire salvage on seedbeds and tree regeneration. Frontiers in Ecology and Environment 4:69-74. Spruce seeds remain viable for a single year (**Peters VS, MacDonald SE and Dale MRT. 2005**. The interaction between masting and fire is key to white spruce regeneration. Ecology 86:1744-1750); hence dispersal from surviving seed sources is critical for re-establishment following disturbance.

[86] **Kabzems R, Dube S, Curran M, Chapman B, Berch S, Hope G, Kranabetter M and Bulmer C. 2011**. Maintaining soil productivity in forest biomass chipping operations best management practices for soil conservation. BC Ministry of Forests and Range Forest Science Program Extension Note 98.

[87] **Chapin III et al. 2010**.

[88] **Lindenmayer et al. 2008**.

[89] **Johnstone et al. 2010.**

[90] **Garbutt et al. 2006.**

[91] **Church, M. and Eaton, B. 2001**. Hydrological effects of forest harvest in the Pacific Northwest. Technical Report #2 for the Hydroriparian Planning Guide.

[92] **Redding T, Winkler R, Pike R, Davis D and Schorder K (compilers). 2007**. Mountain pine beetle and watershed hydrology workshop: preliminary results of research from BC, Alberta and Colorado. FORREX Forestry Research Extension Partnership, Kamloops, BC. http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf

[93] **Lindenmayer et al. 2008.**

[94] **Naiman RJ and Bilby RE (editors) 1998**. River ecology and management: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag New York.

[95] **Kabzems et al. 2011**.

[96] **Bunnell F. 1995**. Forest-dwelling fauna and natural fire regimes in British Columbia: patterns and implications for conservation. Conservation Biology 9:636-644.

[97] **Schmiegelow FKA, Stepnisky DP, Stambaugh CA and Koivula M. 2006**. Reconciling salvage logging of boreal forests with a natural-disturbance management model. Conservation Biology 20:971-983.

[98] By providing habitat, restoring nutrient levels etc; **Lindenmayer DB, Foster DR, Franklin JF, Hunter ML, Noss RF, Schmiegelow FA and Perry D. 2004**. Salvage harvesting policies after natural disturbance. Science 303:1303.

[99] **Hart SA and Chen HYH. 2006**. Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381-397. **Kurulok S and Macdonald SE. 2006**. Impacts of postfire salvage logging on understory plant communities of the boreal mixedwood forest 2 and 34 years after disturbance. Canadian Journal of Forest Research 37:2637-2651. **MacDonald SE. 2007**. Effects of partial post-fire salvage harvesting on vegetation communities in the boreal mixedwood forest region of northeastern Alberta, Canada. Forest Ecology and Management 239:21-31.

[100] **Hart and Chen 2006**

[101] **Schieck J and Song SJ 2006**. Changes in bird communities throughout succession following fire and harvest in boreal forests of western North America: literature review and meta-analyses. Canadian Journal of Forest Research 36:1299-1318. **Morisette JL, Cobb TP, Brigham RM and James PC. 2002.** The response of boreal forest songbird communities to fire and post-fire harvesting. Canadian Journal of Forest Research 32:2169-2183.

[102] **Schieck and Song 2006. Schmiegelow FKA, Stepnisky DP, Stambaugh CA and Koivula M. 2006**. Reconciling salvage logging of boreal forests with a natural-disturbance management model. Conservation Biology 20:971-983.

[103] **Kotliar NB, Hejl SJ, Hutto RL, Saab VA, Melcher CP and McFadzen ME 2002**. Effects of fire and post fire salvage logging on avian communities in conifer-dominated forests of the western United States. Studies in Avian Biology 25:49-64. **Morisette et al. 2002**; **Hutto RL and Gallo SM. 2006**. The effects of postfire salvage logging on cavity-nesting birds. The Condor 108:817-831.

[104] **Schmiegelow et al. 2006**. **Hutto and Gallo 2006**. **Nappi A, Drapeau P, and Savard J-PL. 2004.** Salvage logging after wildfire in the boreal forest: is it becoming a hot issue for wildlife? Forestry Chronicle 8067-74. **Murphy EC and Lehnhausen WA 1998**. Density and foraging ecology of woodpeckers following a stand-replacement fire. Journal of Wildlife Management 62:1359-1372.

[105] **Lindenmayer et al. 2008**.

[106] **McGarigal K, and WC McComb. 1995**. Relationships between landscape structure and breeding birds in the Oregon Coast Range. Ecological Monographs 65:235-260. **Fahrig, L. 1997**. Relative effects of habitat loss and fragmentation on population extinction. Journal of Wildlife Management 61:603-610. **Schmiegelow FKA, and Mönkkönen M. 2002**. Habitat loss and fragmentation in dynamic landscapes: avian perspective from the boreal forest. Ecological Applications 12:375-389.

[107] **Väisänen RA, Järvinen O. and Rauhala P. 1986**. How are extensive, human-caused habitat alterations expressed on the scale of local bird populations in boreal forests? Ornis Scandinavica 17:282-292. **Virkkala R. 1991**. Population trends of forest birds in a Finnish Lapland landscape of large habitat blocks: consequences of stochastic environmental variation of regional habitat alteration? Biological Conservation 56:223-240.

[108] **Perault RD and MV Lomolino 2000**. Corridors and mammal community structure across a fragmented, old-growth forest landscape. Ecological Monographs 70:401-422.

[109] **Carlson M, Bayne E and Stelfox B. 2007**. Seeking a balance: assessing future impacts of conservation and development in the Mackenzie Watershed. Canadian Boreal Initiative. **Cumming SG, Burton PJ, Prahacs S and Garland MR. 1994**. Potential conflicts between timber supply and habitat protection in the boreal mixedwood of Alberta, Canada: a simulation study. Forest Ecology and Management 68:281-302.

[110] **Price K, Holt R, Kremsater L. 2007**. Representative Forest Targets: Informing Threshold Refinement with Science [online] URL: www.forrex.org/program/con_bio/forest_wrkshp.asp?AreaPkey=17., **Andren H. 1994.** Effects of habitat fragmentation on birds and mammals in with different proportions of suitable habitat: a review. Oikos 71, 355–366.

[111] **Price K, Roburn A and MacKinnon A. 2009**. Ecosystem-based management in the Great Bear Rainforest. Forest Ecology and Management 258:495-503.

[112] Alberta-Pacific Forest Industries operating in northwest Alberta manages for ~18% old-growth based on the current age class distribution across their Forest Management Area (**Dzus, E, Grover B, Dyer S, Cheyne D, Pope D, and Schieck J. 2009**. Setting, implementing, and monitoring targets as a basis for adaptive management: a Canadian forestry case study. Ch. 17 in M-A Villard and BG Johnsson (eds), Setting Conservation Targets for Management Forest Landscapes. Cambridge University Press.). **Cumming SG, Schmiegelow FKA and Burton PJ. 2000**. Gap dynamics in boreal aspen stands: is the forest older than we think? Ecological Applications 10:744–759.

[113] **Franklin JF, Berg DR, Thornburgh DA and Tappeiner JC. 1997**. Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. In: Kohm, KA. Franklin, JF (Eds.), Creating a Forestry for the 21st Century: The Science of Ecosystem Management. Island Press, Washington, D.C., pp. 111–139.

[114] Ectomycorrhizal fungi, epiphytic lichens and small ground-dwelling animals benefited most (**Rosenvald R and Löhmus A. 2008**. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. Forest Ecology and Management 255:1-15).

[115] **Lõhmus P. Rosenvald R and Lõhmus A. 2006**. Effectiveness of solitary retention trees for conserving epiphytes: differential short-term responses of bryophytes and lichens. Canadian Journal of Forest Research. 36:1319–1330. **Aitken KEH and Martin K. 2004**. Nest cavity availability and selection in aspen-conifer groves in a grassland landscape. Canadian Journal of Forest Research 34:2099-2109.

Cooke HA and Hannon SJ. 2012. Nest-site selection by old boreal forest cavity excavators as a basis for structural retention guidelines in spatially-aggregated harvests. Forest Ecology and Management 269:37-51. **Drapeau P, Nappi A, Imbeau L and Saint-Germain M. 2009**. Standing deadwood for keystone bird species in the eastern boreal forest: managing for snag dynamics. Forest Chronicle 85:227-234. **Mahon CL, Steventon JD and Martin K. 2008**. Cavity and bark nesting bird response to partial cutting in Northern conifer forests. Forest Ecology and Management 256:2145-2153.

[116] **Schieck and Song 2006. Fisher JT and Wilkinson L.** 2005. The response of mammals to forest fire and timber harvest in the North American boreal forest. Mammal Review 35:51-81.

[117] **Schieck J and Hobson KA 2000**. Bird communities associated with live residual tree patches within cut blocks and burned habitat in mixedwood boreal forests. Canadian Journal of Forest Research 30:1281-1295. **Cooke and Hannon 2012**.

[118] Schieck and Song 2006. Simulation studies suggest that

[119] **Angelstam P. 1997**. Landscape analysis as a tool for the scientific management of biodiversity. Ecological Bulletin 46:140-170. References in **Bunnell FL and Houde I. 2010**. Down wood and biodiversity—implications to forest practices. Environmental Reviews 18:397-421.

[120] **Schmiegelow et al. 2006**

[121] The proportion of live residuals is often underestimated due to low mapping resolution (**Schmiegelow et al. 2006)**

[122] **Garbutt et al. 2006.**

[123] **Lindenmayer et al. 2008**

[124] **Snetsinger J. 2005**. Guidance on landscape- and stand-level structural retention in large-scale mountain pine beetle salvage operations. BC's chief forester's guidance to forest professionals.

[125] **Bunnell FL, LL Kremsater and E Wind. 1999.** Managing to sustain vertebrate richness in forests of the Pacific Northwest: relationships within stands. Environmental Reviews 7:97-146.

[126] **Mader H-J. 1984**. Animal habitat isolation by roads and agricultural fields. Biological Conservation 29:81-96.; **Swihart, RK and NA Slade. 1984**. Road crossing in *Sigmodon hispidus* and *Microtus ochrogaster*. Journal of Mammalogy 65:357-360. **Merriam G, M Kozakiewicz, E Tsuchiya and K Hawley. 1988.** Barriers and boundaries for metapopulations and demes of *Peromyscus leucopus* in farm landscapes. Landscape Ecology 2:227-235.

[127] **Forman RTT. 2003**. Road ecology: science and solutions. Island Press. **Cameron EK and Bayne EM. 2009**. Road age and its importance in earthworm invasion of northern boreal forests. Journal of Applied Ecology 46:28-36.

[128] **Scrivener JC and MJ Brownlee. 1989.** Effects of forest harvesting on spawning gravel and incubation survival of chum (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46:681-696. **Church and Eaton 2001**.

[129] **McIver JD and Starr L 2001**. A literature review on the environmental effects of post-fire logging. Western Journal of Applied Forestry 16:159-168.

[130] **McLellan BN and DM Shackleton. 1988**. Grizzly bears and resource-extraction industries: effects of roads on behaviour, habitat use and demography. Journal of Applied Ecology 25:451-460.

[131] Information based on expert guidance; **Babine Watershed Monitoring Trust 2004**; www.babinetrust.ca

[132] **Yukon Government Forest Management Branch 2007**. Minto Burn Commercial Fuelwood Timber Harvest Project.

[133] **Lindenmayer DB, Franklin JF and Fischer J. 2006**. General management principles and a checklist of strategies to guide forest biodiversity conservation. Biological Conservation 131:433-445.

[134] **Drever CR, Peterson G, Messier C, Bergeron Y and Flannigan M. 2006**. Can forest management based on natural disturbances maintain ecological resilience? Canadian Journal of Forest Research 36:2285-2299.

[135] **Gayton D and Lara Almuedo P. 2012**. Post-disturbance management of biodiversity in BC forests. BC Journal of Ecosystems and Management 13:1-9. **Lindenmayer et al. 2008**

[136] **Gayton and Almuedo 2012**; **Lindenmayer et al. 2008**; **Lindenmayer DB and Noss R. 2006**. The impacts of salvage harvesting on biodiversity and ecosystem processes: a brief overview. Conservation Biology 20:949-958. **Schmiegelow et al. 2006**, **Beschta R and 8 others. 2004**. Postfire management on forested public lands of the Western United States Conservation Biology 18:957-967. **Nappi A, Drapeau P, and Savard J-PL. 2004.** Salvage logging after wildfire in the boreal forest: is it becoming a hot issue for wildlife? Forestry Chronicle 8067-74.

[137] **Lindenmayer et al. 2008.**

[138] **Drever et al. 2006**.

[139] **Bunnell and Houde 2010** recommend leaving 50% of natural amounts of downed wood.

[140] **PBrand Bioenergy Consulting. 2009.**

[141] **Kumar, A., P.C. Flynn and S. Sokhansanj. 2005.** Feedstock availability and power costs associated with using BC's beetle-infested pine. Report prepared for BIOCAP Canada Foundation, ON, and Province of BC. http://www.biocap.ca

[142] **Kumar et al. 2005**

[143] **Price Waterhouse Coopers. 2005.**

[144] **Stennes, B. and A. McBeath. 2006.** Bioenergy options for woody feedstock: are trees killed by Mountain Pine Beetle in British Columbia a viable bioenergy resource. BC-X-405. Natural Resources Canada. Pacific Forestry Centre, Victoria.

[145] Assumes 2.44 m3/ODT as cited in **Stennes and McBeath 2006**

[146] **JC Bartlett and associates Ltd. 2004**. Delivered log cost guide. Report to Deh Cho Land Use Planning Committee, NWT. Available at: http://www.dehcholands.org/docs/reports/Contractor%20Reports/Timber%20Potential%20Final%20Report%20%283%29/Timber%20production%20costs.pdf

[147] **Thakur, A. 2011.** Power generation from forest residues. MSc Engineering Management. University of Alberta, Edmonton.

[148] **Niquidet et al. 2008.**

[149] **Kumar et al. 2005.**

[150] **Thakur 2011.**

[151] **Stennes and McBeath 2006.**

[152] **Thakur 2011.**

[153] **Pbrand 2009; Niquidet et al. 2008.**

[154] Based on drivers wage section in **Logistics Solutions Builders Inc. 2005.**

[155] **Morrison Hershfield 2011.**

[156] **Logistics Solutions Builders Inc. 2005; Thakur 2011** estimated a lower cost of $1.62/km for a B-train in Alberta but did not include loading and unloading time.

[157] Other authors show transport costs ranging from about $8/m3 to $10/m3, depending on haul distance (**Tampier et al. 2006; Kumar et al. 2005**).

[158] **Logistics Solutions Builders Inc. 2005.**

[159] **Logistics Solutions Builders Inc. 2005.**

[160] **Transport Canada. 2005.** Demonstration of dual commodity log/chip trailer for reduced greenhouse gas emissions. Freight Transportation Case Studies 21.

[161] **Niquidet et al. 2008**

[162] **Tampier et al. 2006.**

[163] One ODT equals ~2.2 m3 of wood[25] and equals ~5.4m3 of chips (**McKendry 2002**); a bunk of logs uses about 1.4 x the volume of solid wood (**Jokai, R. 2006.** Maximizing logging truck payload when transporting dry beetle-killed short logs. Forest Engineering Institute of Canada, Vancouver, BC.); a chip van can hold about 113 m^3 of chips or about 19 (cited in **Thakur 2011**) to 21.5 ODT (**Niquidet et al. 2008**); van volume limits the weight hauled (ODT) when chips are relatively dry (< 40% moisture content; cited in **Thakur 2011**).

[164] **Tampier et al. 2006.**

[165] **Thakur 2011.**