Modelling Historical Landscape Patterns on the Alberta-Pacific FMA

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A report prepared for Alberta-Pacific Forest Industries

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1.0 Introduction

The evolution of forest management in North America has been an ongoing process, but one that has inevitably been moving towards the goal of sustaining all forest values. Forest management is now expected to manage for a wide range of biological values including water and nutrient conservation, toxin filtration, carbon cycling, fish and wildlife habitat, food, pharmaceuticals, and timber (Davis 1993).

Under the auspices of this task, the concept of the using forest patterns created by natural processes as management guides is gaining favour in North America (Franklin 1993). The theory is attractive: by maintaining the type, frequency, and pattern of change on a given landscape, we are more likely to sustain historical levels of the various biological goods and services. So-called "coarse-filter" knowledge can also be applied directly and immediately to planning and management programs.

Natural pattern knowledge can be applied to a wide range of forest management planning issues, at virtually all levels of planning. Alberta-Pacific was one of the first forest management companies in western Canada to develop operator guidelines for residual material, and has for many years been using natural stand boundaries to guide block layout and supporting natural pattern research at the event scale (Andison 2012a). At more strategic scales, AlPac is also interested in understanding the natural, historical range of the levels of different seral-stages, and old forest in particular.

Developing this type of knowledge is particularly challenging because no reliable pre-industrial snapshots exist due to the combined impacts of fire control, cultural disturbance activities, and lack of historical records or data. What we do know about the disturbance history of these types of landscapes suggests that they are highly dynamic, and the age-class distribution from one time to another can vary widely (Romme 1982, Turner and Dale 1991, Payette 1993, Andison 1998a). This means that historical levels of old forest will be highly dynamic. For this reason, defining the historical range of landscapes is a fairly fundamental requirement of a natural pattern-based approach to forest management. More generally, it is one of the foundations of ecosystem-based approaches (Booth et al. 1993, Grumbine 1994, Long 2009).

In the absence of detailed and multiple historical data and/or photos, the only means left to capture explore the dynamics of forest ecosystem patterns at the landscape scale is via spatial simulation modelling. In its simplest form, spatial models allow one to explore how known (empirical-based) probabilities of key variables intersect in time and over space to create multiple possible landscape mosaics. It is much easier to acquire historical empirical data of modelling inputs than it is historical landscape snapshots.

As part of AlPac's 2006 long-term forest management plan, a spatial modelling exercise using LANDMINE (Andison 1996) was completed to help define a series of likely historical landscape "snapshots" generated from a simulation modelling exercise (Andison 2005a). The primary goal of this first modelling exercise was to create a defendable historical range of landscape conditions with which to use as an aide to defining long-term old forest level objectives.

This report summarizes the results from the second iteration of spatial modelling completed on the AlPac landscape. This second version of the AlPac spatial modelling captures:

1) The inclusion of old forest patch sizes as a modelling output metric,
2) An updated spatial dataset and current landscape condition,
3) A different set of key input assumptions, designed to match the forest management planning scenario modelling exercise to follow, and
4) New spatial output summary parameter requirements.

2.0 Study Area

The Alberta-Pacific Forest Management Area covers approximately 6.6 million hectares of land in northeastern Alberta, Canada, of which approximately 5.4 million hectares is forested (Figure 1). The study area includes most of the internal "donuts" that are not formally part of the FMA, but exclude the minerable oil sands area (MOSA), the Gypsy Gordon provincial park, and that part of the northeastern corner (in A15) that is physically isolated from the rest of the FMA (to avoid associated spatial bias).

Black spruce, and mixedood are the dominant forest types on the FMA, with smaller components of pine and deciduous and minor components of white spruce. Non-forested areas account for 19% of the landscape, most of which are vegetated wetlands (Table 1). Topography is flat to gently rolling. All but a small northern portion of the FMA is in the Boreal Plain Canadian eco-region (Wilkin 1986).

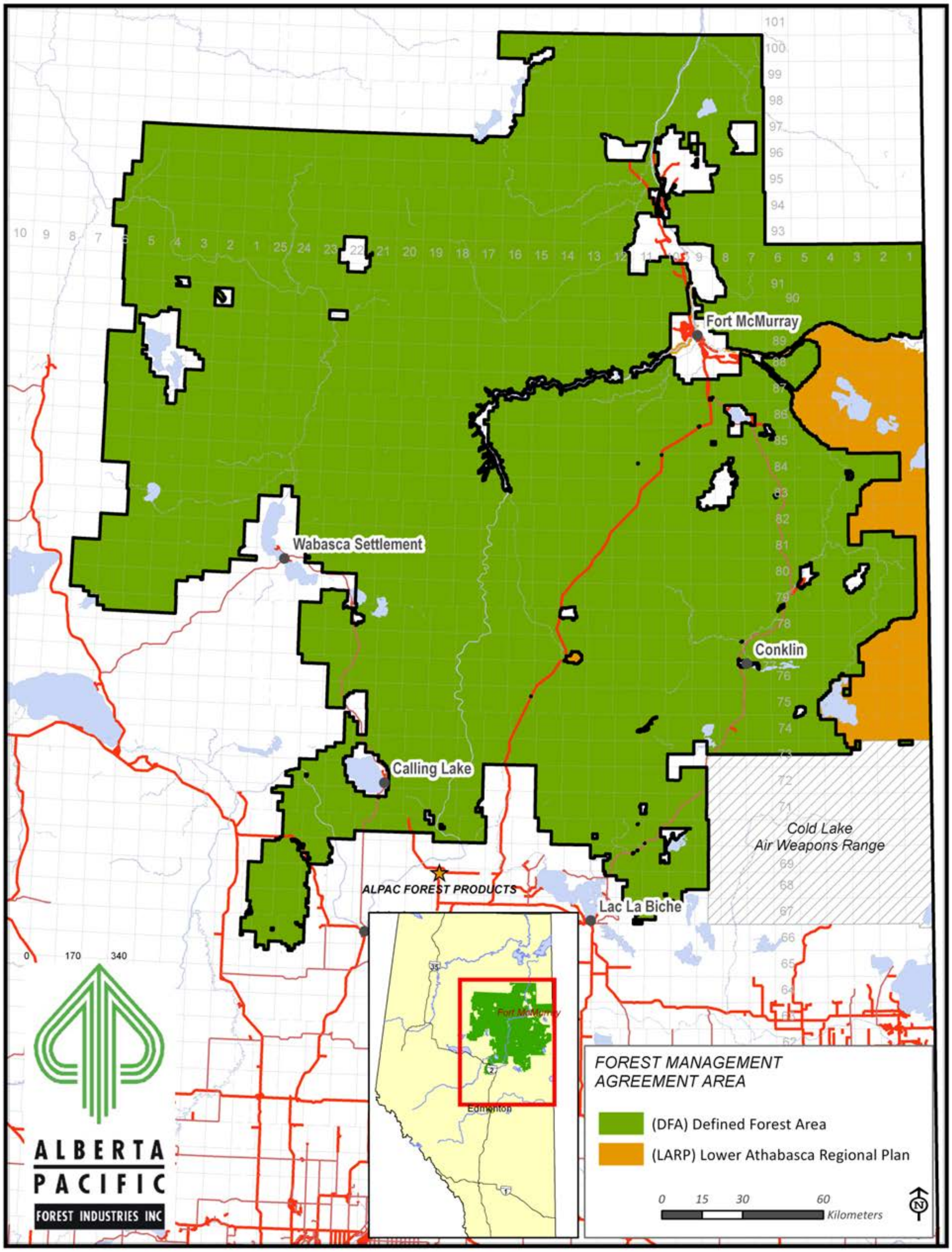


Figure 1. Map showing the location of the Alberta Pacific FMA.

The coarse-scale pattern of age-class across the study area is largely a function of the historical disturbance regime. The most common disturbance event on this landscape is stand-replacing forest fires (Johnson 1992), but incidents of insect and disease outbreaks, flooding and wind events also occur.

Table 1. Summary of the Al-Pac landscape as of 2012.

Land Type	Sub-Type	Area (ha)	Sub-total (ha)
Forest	Pine leading	586,987	
	Black spruce leading	2,911,362	
	Deciduous leading	271,739	
	Mixedwood	1,586,718	
			5,356,806
Non-Forest	Water	236,445	
	Non-Forested	998,095	
			1,234,540
Anthropogenic	Vegetated	29,013	
	Unknown	26,075	
			55,088
Grand Total			**6,646,434**

3.0 Methods

Several steps are involved in estimating the natural range of landscape conditions on the AlPac FMA.

3.1 The model

LANDMINE is a spatially explicit, Monte-Carlo landscape simulation model that was developed for landscapes dominated by stand-replacing disturbance events. LANDMINE uses a dispersal algorithm to spread fires from one pixel to another in such a way that fire movement responds probabilistically to various input layers such as fuel-type, topography, and wind. Fire movement thus favours uphill movement, older forest, higher percentages of conifer, or prevailing winds, and so on. Controlling layers can be added or removed depending on available data. The nature of the fire movement can also be calibrated to create different fire shapes and residual numbers, sizes, and locations to match empirical data as available. Fire size is controlled by an equation that represents the actual fire size distribution for each landscape. Ignition location probabilities can also be calibrated – usually using historical lightning probabilities. Finally, the total amount of forest burnt in any single time step (10 years in this case) is established through another equation describing the historical areas burnt. Each of these steps is stochastic, meaning that LANDMINE never burns the same way twice. However, over the long term it is consistent with internally defined probabilities. Clarke et al. (1994) also demonstrated that this method of growing disturbances created fractal images, meaning that the model could use spatial data at any scale of resolution. Finally, a succession module is available that includes a set of self-defined rules that governs successional pathways either probabilistically or deterministically depending on stand composition and age.

LANDMINE is thus a powerful landscape *disturbance model* (*i.e.*, it is good for exploring long-term disturbance regime trends over space and time), although not necessarily a good disturbance behaviour model (*i.e.*, it is not meant to predict the patterns of individual fire events). LANDMINE was developed in 1996 (Andison 1996), and has since been used eight times across western boreal Canada including the Hintion Wood Products FMA (Andison 1998), the Prince George TSA in BC (Andison and Marshall 1999). the Sunpine FMA (Andison 2004), the Alpac FMA (Andison 2005a), the RSDS north-eastern Alberta landscape (2005b), the Mistik Management FMA in Saskatchewan (Andison 2007a), the Tolko-Footner FMA (Andison 2007b), and the Alberta Newsprint FMA (Andison 2012b)

3.2 Model Assumptions

By definition, a model is a representation of reality – as opposed to reality itself. Not surprisingly, simpler models tend to represent reality better, and tend to be more believable, than more complex ones. Thus, the rule of thumb for any modelling exercise is, *as complex as necessary, but no more*. In other words, each modelling exercise should focus on achieving the desired objectives with the least possible number of explanations, equations, and assumptions. In this case the modelling objectives were very general in nature;

1) Define the natural range of variation (NRV) for the (non-spatial) areas of seral-stages X major vegetation types:
    a. For the FMA as a whole,
    b. By the three major management units,
    c. By the four existing woodland caribou herd boundaries, and
    d. By four woodland caribou habitat preferences.

2) Define the NRV for the (spatial) sizes of old forest for:
    a. All old forest combined, and
    b. “Old” forest as defined by each of the four main forest types.

Since the interest is in very broad patterns over hundreds of years, LANDMINE was run with minimal rules and assumptions. No topographic data was included; ignition probability was spatially random, and broad seral-stage and cover-type classes were adopted. Furthermore, succession rules were turned off in favour of creating a single “mixed” forest type that combines the mixedwood forest type with white spruce leading forest type. This decision was made based on the fact that no young white spruce leading stands exist, likely because of differences in life history characteristics (Lieffers et al. 1996). Furthermore, given enough time in the absence of disturbance, mixedwood stands tend towards white spruce leading stands (Kabzems and Garcia 2004, Brassard et al. 2008). In other words, the separation of these two stand types is artificial.

Although we believe that boreal mixedwood stands do not necessarily “break up” beyond a certain time since the last fire, for this exercise pixels not disturbed for at least 400 years were reset to zero, based on the assumption that over such a long period of time, such areas would be subject to other disturbance agents such as pathogens, disease, wind, snow, or ice.

Another simplifying assumption made for the model was that the AlPac FMA represents a single major fire regime. Since the FMA is dominated by a single ecological zone, and there is little empirical evidence to suggest that historical fire behaviour differs significantly from east to west or north to south, this seems a safe assumption. Certainly there will be some variation in ignition probability or climate conditions, but likely not significant enough to affect overall patterns of burning. Similarly, while it is possible to argue with most of these assumptions in the details, for the purposes of a coarse-level simulation exercise, they are not relevant.

3.3 Spatial Data

Since these runs are meant to represent “natural” conditions, it was necessary to create natural forest conditions. This was done by assigning any culturally modified polygons the age and cover-type attributes of the adjacent polygon with the greatest length shared boundary. In some cases, the attributes of the previous features were available and used directly. Thus, all roads, cutblocks, mines, and other developments were replaced by attributes of the last known, or the most likely last existing, polygon. This “natural” inventory polygon layer was then converted to raster format using 4 ha pixels. The inventory data was then used to define one of four forest cover-classes as follows:

- Black spruce (Sb) = at least 80% Sb.

- Jack pine (Pj) = at least 80% Pj.
- Hardwood (Hdwd) = at least 80% hardwood.
- Mixedwood (Mix) = everything else, including Sw leading.

Note that if a polygon had a leading tree species, it could be modelled regardless of whether or not it was productive forest. Non-forested land was included in the actual spatial modelling, but not tracked and summarized for the output.

Inventory age data was used to define four broad "seral" stages of stand development (consistent with the rules used by AlPac for other analysis) for each of the four forest cover-classes above as follows:

- Young = <20 yrs. for Pj and Sb, and <10 yrs for Mix and Hdwd.
- Immature = 21-60 yrs for Pj, 21-70 yrs for Sb, and 11-60 yrs for Mix and Hdwd.
- Mature = 61-80 yrs for Pj, and Hdwd, 71-120 yrs for Sb, and 61-100 for Mix.
- Overmature = >80 yrs for Pj, and Hdwd, >120 yrs for Sb, and >100 yrs for Mix.

It is important to keep in mind that the age breaks are meant to represent stages of stand development, and reflect the major tree species attributes such as tolerance to competition and light, growth rates, and senescence rates and causes. For example, spruce grows more slowly, is less light tolerant, less prone to disease, and lives much longer than aspen, and thus takes longer to reach the "overmature" stage of stand development where individual tree deaths are causing gaps, large woody debris, and a complex vertical structure.

Non-spatial summaries of area each of the 20 vegetation X seral stage classes will be compiled for the entire FMA, and by three different sub-divisions;

1) Forest Management Unit Zones (see Figure 2a):
    a. East = L11, L3, A14, A15, excluding MOSA and part of A15.
    b. West = S14, S18, S22, and S11.
    c. South = L1, L2, L8 and S7.

2) Caribou Herd Areas (see Figure 2b):
    a. East Side Athabasca.River
    b. West Side Athabasca River
    c. Cold Lake Air Weapons Range
    d. Richardson

3) Major Caribou Habitat Types (Athabasca Landscape Team 2009)
    a. Forested wetlands (good habitat)
    b. Low shrub and grassland/forbs (good habitat)
    c. Upland tall shrub, black spruce and pine (poor habitat)
    d. All other mesic uplands (poor habitat)

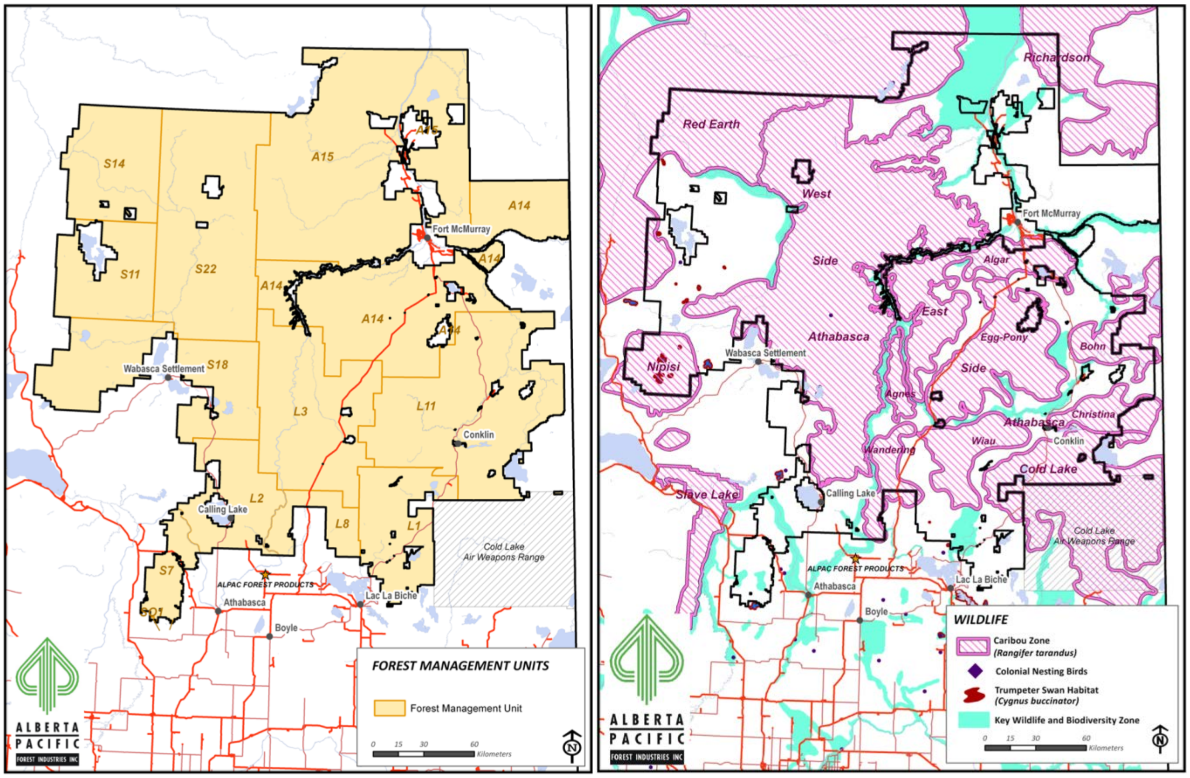


Figure 2. Map showing Forest Management Units (a) and caribou herd zones (b) on the Alberta Pacific FMA.

Spatial summaries were also included in the form of old forest patch sizes. Pixel membership in a "patch" of old forest was defined only by adjacency. Thus, any "old" pixel (as per the age rules defined above) is grouped with any other old pixel that is one of its eight neighbours. Old forest patch sizes were calculated two ways:

a) All old forest pixels combined, and
b) Old forest pixels from one of the four main forest types.

If an old forest patch crosses the FMA boundary, only that portion of old forest patches within the AlPac FMA boundaries is counted. This creates a negative bias on old forest patch sizes, but it allows the output to be compared directly to management planning scenarios. Old forest patches were only calculated for the entire FMA since calculating patch sizes on smaller areas creates even greater bias.

3.4 Model Calibration

The two most important pieces of model input are the sizes of fires, and the frequency of burning. The provincial historical fire database, and knowledge of fire sizes from an adjacent FMA in Saskatchewan were used to generate the following cumulative equation for fire size, in hectares:

$$FireSize = 10^{(1.85\times(-\log(1-RN))^{.65})} - 0.14$$

Where RN = a random number between 0 and 1. This equation allows for a very high probability of very small fires and very low chances of very large ones – consistent with the pattern of fire sizes observed virtually across the boreal forest in Canada (Ward and Tithecott, 1993, Taylor *et al.* 1994, Andison 1996, Andison 2003).

Disturbance rate (or the percent of the landscape disturbed per unit of time) is a more critical model parameter in this case. The model requires an area to disturb for each 10-year time step, and it is important that a natural range of disturbance levels is represented (and not just a single number representing an average). Estimates of decadal fire activity from historical records are short, and are reliable only for the period since fire control efforts were common. Alternatively, stand age data can be used to make rough estimates of decadal fire activity by “rolling back” age-class distributions (Andison 1996). Essentially, it peels back the most recent age-class, and assumes that the age of the forest underneath is proportional to the age-class distribution of the remainder of the landscape. It thus assumes that fire susceptibility is not related to stand age.

The method is more reliable for estimates of fire activity in more recent decades, and becomes progressively less reliable over time. For example, from Table 2, we can be fairly sure that the actual area disturbed during the 1960’s is close to 4.3%, but we are less confident of the 26.7% in the 1910’s. However, keep in mind that the objective of this exercise is not to reconstruct the exact fire history of the last several decades, but rather to estimate the variability of fire behaviour across millions of hectares and several decades. The fire cycle can be estimated and accounted for separately (see ahead). In any case, the patterns of fire behaviour are certainly consistent with other observations. For example, the high levels of fire activity during the first half of the last century is consistent with detailed fire evidence found on a 100,000 ha study area about 70km due east of the AlPac FMA in Saskatchewan. Stand origin mapping reveal at least 15 different fire years between 1880 and 1950 in this study area (Andison et al. 2005)

Disturbance levels after 1970 were not used for this analysis since fire control and harvesting have almost certainly biased the disturbance frequency levels. If available, the original ages were restored for all areas burnt or logged since 1970.

For those post-1970 polygons with no previous age, ages were assigned based on the dominant neighbour (if logged), or assumed to be aged proportionally to the remaining landscape (if burned).

Six estimates (Table 2) were used to represent the variation of disturbance levels, although the exact location of the resulting curve still required calibration in the model to match the target long term (LT) *fire cycle*. The LT fire cycle is the average number of years required to burn the number of hectares represented by the landscape. For a 100,000 ha landscape, that means the number of years for a total of 100,000 ha of fires to burn. Thus some areas burn several times during a fire cycle and others not at all.

Table 2. Estimated percent area burnt on the AlPac FMA by decade.

Decade	% Forest Today	Estimated original % disturbed.
1961-1970	4.0	4.3
1951-1960	9.4	10.5
1941-1950	22.9	28.6
1931-1940	14.6	25.7
1921-1930	12.8	30.2
1911-1920	7.8	26.7
Average		21.0 (48 yrs).

The average LT fire cycle can be estimated from the average decadal disturbance level. For example, the average burning rate from Table 1 was 21% per decade, which is 2.1% annually, which is a 48 year fire cycle (48yrs x 2.1% = 100% of the landscape area. However, keep in mind that the primary reason for making decadal estimates of fire activity was to understand the variation in fire activity. The 48-year LT fire cycle estimate from these data is valuable information, but the choice of fire cycle average to be used in a disturbance modelling exercise involves more elements.

Long term fire cycles have been the focus of considerable research in the boreal forest. Unfortunately, fire cycles are notoriously difficult to estimate for many of the same reasons outlined above. These difficulties have resulted in a variety of creative empirical and modelling techniques. In a national overview, Ward and Tithecott (1993) found a range of fire cycles of between 20 and 500 years for the boreal forest, although in most cases, figures were between 50 and 150 years. This is more or less consistent with figures estimated for Alberta and Saskatchewan.

Unfortunately, no formal estimates of LT fire cycles have been made for the AlPac FMA. In my opinion, the historical long term (LT) fire cycle of the AlPac FMA is between 40-60 years, based on the following reasoning / evidence:

- The decadal fire rate based on AVI ages using the rollback technique (sensu Andison 1996) shows a 48-year average. However, inventory ages have already proven to be both inaccurate and biased (Andison 1999a, Andison 1999b). An intensive stand age validation program on the adjacent Mistik FMA in Saskatchewan showed the errors to be moderate, and that the age of young forest stands is under-estimated (which would actually decrease our fire cycle estimates) (Andison 1999a). The rollback method is rough, but consider that if we simply took the existing area in each of the six decades from Table 2 (the column on the left), the fire cycle would still be 98 years. However, that assumes that for the last 60 years, no wildfires burned over another one, which is an extremely unlikely scenario. Andison et al (2005) showed a high proportion of boreal stands in Saskatchewan with evidence of multiple burn years.
- Estimates of historical fire cycles in adjacent landscapes in Saskatchewan range from 42-55 years (Andison 1998b), which is consistent with the 48 years found using the decadal rollback estimates. The two landscapes have very similar topography, climate, and vegetation composition. An extensive age validation field program subsequent to this calculation showed that while inventory ages are inaccurate and show some age bias, they are more than adequate for making reliable estimates of fire cycles (Andison 1999a).
- No evidence of stands older than about 250 years exist on the FMA, and very few older than 200. This paralleled the findings from the Mistik FMA in Saskatchewan based on 550 field plots, many very close to the AlPac FMA (Andison 1999a). A general rule of thumb is that 1/3 of a landscape should be older than the fire cycle. It is true that many trees (such as aspen) would not be expected to live this long, but at the very least, we should be finding a substantial amount of (unburned) woody debris on the ground on a substantial part of the FMA if fire cycles were more than 100 years. This is also not observed.

- Dominance of aspen, and the paucity of abies species (.ie., balsam fir) suggest that disturbance frequency is very short. Aspen is a short-lived "pioneer" species, encouraged by fire. Balsam fir only invades many years after a stand is established. Abies dominates the extreme eastern Canadian landscapes where fire cycles are in excess of 200 years.
- We know (from both historical and recent empirical evidence) that this landscape is susceptible to very large fires. Extended fire cycles would therefore mean that these events are extremely rare, and dominate the disturbance regime. However, a detailed stand origin map completed in 2003 of 100,000 ha area in Saskatchewan (approximately 70km east of Cold Lake) reveals highly complex fire patterns, with a large number of key fire years very close together in time. This suggests that fire is more or less consistently active across the landscape.

The LT fire cycle decision is important because it affects the amounts of old forest that survives. Longer fire cycles will generate more older forest. The importance of this model parameter was such that the model was run using two LT fire cycle targets: one for 60 years, and one for 80 years. For a more complete exploration of fire cycles on the AlPac landscape, see Andison (2005a).

The following equations were derived to describe the 10-year disturbance levels used for the model:

$PctAreaDisturbed = -12.97 + \sqrt[3]{29.44}$ Representing an 80 year fire cycle

$PctAreaDisturbed = -16.35 + \sqrt[3]{41.89}$ Representing a 60 year fire cycle

For each of the two scenarios, the model was run forward a minimum of 100 time steps to eliminate any bias associated with initial landscapes. Then, another 100 runs were completed and the output at the end of each 10-year period was captured both digital snapshots, and the spatial and non-spatial summaries as defined above.

3.5 Analyses

The nature of this study is largely exploratory in nature; quantifying and understanding natural patterns at landscape scales. It is also important to keep in mind that the output will be either used as either input for, or in comparison to, forest management planning models and systems. The analyses are thus limited to simple summaries in graphical and tabular form.

4.0 RESULTS

4.1 Landscape Snapshots

LANDMINE produced approximately 1,000 runs for each fire cycle scenario, the first 100 of which were designed to delete any unusual or biased patterns associated with the starting landscape position. The next 800 runs were calibration runs. The last 100 were chosen to represent the 60-year and 80-year fire cycle scenarios as shown in Table 3. The 60-year fire cycle scenario in the end averaged 61 years, and the 80-year fire cycle runs averaged almost 83 years (Table 3).

Also shown are the average area disturbed for each of the ten centuries for the millennium used as the total modelling timeframe. Although there are no available empirical data with which to compare these data, the fact that there is a moderate amount of variation at the scale of centuries is consistent with what we know about the intimate relationship between climate and fire activity on a more general level, and in part explains why fire cycle estimates are so challenging. For example, the average fire cycle based on any single century of the 83-year scenario from Table 3 varies from 66 to 126 years, and for the 61-year scenario fire cycles within any single century vary from 41 to 85 years.

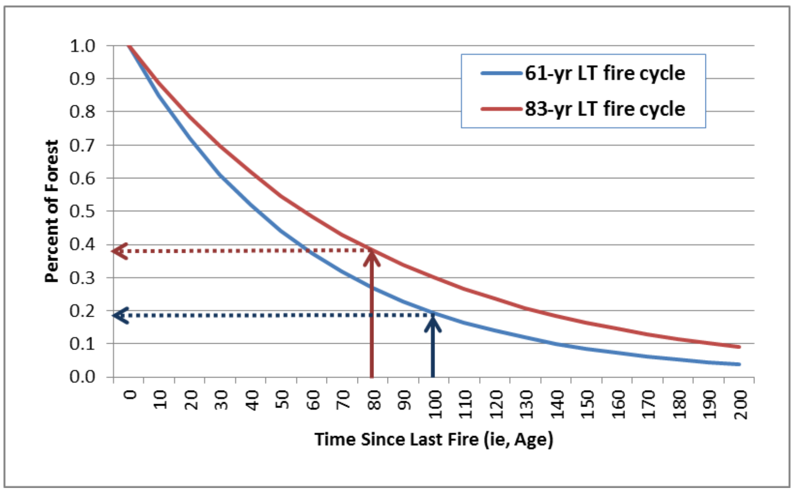
Table 3. Summary of LANDMINE Modelling Runs on the Alpac FMA.

Decade Number	Average Area Burned Per Decade Per Modelling Scenario	
	61-Year Fire Cycle Scenario	83-Year Fire Cycle Scenario
1-10	850,128	698,310
11-20	736,216	494,761
21-30	1,248,813	447,162
31-40	662,372	410,172
41-50	704,276	616,139
51-60	711,258	778,567
61-70	604,668	746,981
71-80	1,006,947	710,385
81-90	921,186	655,803
91-100	1,050,825	677,232
Average Area Burned	**849,669**	**623,551**
Average Fire Cycle	**60.6 Years**	**82.6 Years**

4.2 Model Validation

Models that predict how a large number of inputs interact over time and space are difficult to validate. In many cases it is only possible through the validation of the various inputs. However, in this case, we are fortunate that landscape condition prediction models have been around for almost 40 years. The simplest of these is the negative exponential age model (Van Wagner 1978) which offered a simple method of calculating the probability of forest surviving a given number of years under different long term fire cycle assumptions. This same equation could be used to predict the average amount of forest expected to survive beyond different times. For example, in Figure 3, the negative exponential model predicts that under a 61 year LT fire cycle assumption, approximately 38% of the forest will survive beyond 80 years, and 19% of the forest older than 100 years will survive with an 83-year fire cycle assumption.

Figure 3. Cumulative age-class distribution using the negative exponential model.



The negative exponential model is fairly crude and includes some questionable assumptions. Most notably, it assumes that fire is *age invariant*, which means that fire is equally likely to burn forest of any age. This assumption was subsequently addressed by expanding the negative exponential equation into a Weibull function (Yarie 1981). Nor does the negative exponential model account for other critical details such as fuel-type differences, topographic complexity, or fuel-type discontinuities.

However, it is still a useful reality check for other, more sophistocated modelling exercises. To compare the LANDMINE results to the negative exponential model, I calculated the average amount of "old" forest generated in each of the four vegetation types for the three Natural Subregions (Table 4). This is essentially an "older than" age-class, which is comparable to the negative exponential model output. I then calculated the predicted amount of forest older than 80, 100, and 120 years from the negative exponential equation using the two LT fire cycles.

The results suggested that the LANDMINE model was creating older forest levels consistent with those from the simpler non-spatial model. The total average amount of old forest from the simulations was in each case close to the estimates from the negative exponential equations (Table 4). Furthermore, the differences could in part be explained by differences in fuel type. For example, LANDMINE generated 30% Old deciduous forest, compared to only 22% Old pine forest, despite the fact that both use 80 years to define Old. Given the lower flammability of deciduous forests, this is logical. The negative exponential model (which ignores age and fuel type) predicts 27% of the forest as old (Table 4). Similarly, the Landmine runs produced less Old black spruce than the negative exponential model, which makes sense given the relatively high flammability of black spruce.

Table 4. Comparison of the percent of forest area in the "older than" age-class between the Landmine output and that of the negative exponential model.

Vegetation Type	LT Fire Cycle	
	61 Years	83 Years
Hardwood (80 yrs)	30.1	40.1
Pine (80 yrs)	22.1	33.3
Neg. exp @ 80 yrs	26.9	38.1
Mixedwood (100 yrs)	18.0	30.3
Neg. exp @ 100 yrs	19.4	30.0
Black Spruce (120 yrs)	8.7	18.3
Neg. exp @ 120 yrs	14.0	23.6

In other words, in general terms, Landmine is responding as one would predict on this landscape.

4.3 Non-Spatial Results

The non-spatial modelling output is presented as frequency distributions for each of the 16 forest cover X forest age classes. The y-axis was standardized to represent the percent of model snapshots in each percentage class on the x-axis. The x-axis represents the amount of forest in that particular age-class as a percentage of the total area in each of the four cover-classes. There are several groups of results.

- Figures 4-7 - the entire FMA.
- Figures 8-11 - the West FMU.
- Figures 12-15 – the South FMU
- Figures 16-19 – the East FMU
- Figure 20-23 – the East Side Athabasca River caribou herd
- Figure 24-27 – the West Side Athabasca River caribou herd
- Figure 28-31 – the Forest Wetlands caribou habitat type

- Figures 32-35 – the Upland Tall Shrub, Black Spruce and Pine caribou habitat type
- Figure 36-39 – the Other Mesic Upland caribou habitat type.

For example, Figure 4 represents the percent of the pine forest type that is <10 years of age (as opposed to the percent of the entire landscape that is young pine).

4.3.1 Fire Cycle Assumptions

The impact of assuming a fire cycle difference of 22 years is most prominent in the youngest and oldest seral-stages. For example, the average amount of young pine jumps from 24% for the 83-year results to 32% for the 61-year results (Figure 4a). And since more area is being burned, the average percentage of old pine forest declines by 11% (from 33% to 22%) between the 83 and 61-year fire cycle results (Figure 1d). This trend is similar for all four forest types (Figure 1).

This is an example of a *sensitivity analysis*, where the impacts of major model assumptions are tested by choosing different levels of that input variable to see how they affect the model output. In this case, a shift of 9-12% on the average level of old forest (Figure 1a-d) has tremendous practical significance. The discussion will elaborate further on the impact of fire cycle assumptions.

4.3.2 Estimated Historical Ranges

The high volume of results is such that it will not be possible to discuss each graph in detail. In any case, the trends of each set of 36 graphs are similar. I will use the overall FMA data from Figures 1-4 to discuss the notable trends, and thereafter only point out where other results differ significantly.

The most important aspect of the model output is the high amount of variation demonstrated by *all* seral-stages – including old forest. For example, for the 62-year scenario, old pine historically ranges between 6-43% of the total area of pine on the landscape (Figure 4d), old black spruce ranges between 2-18% of the total area of black spruce (Figure 5d), old mixedwood 5-32% (Figure 6d) and old hardwood 8-56% (Figure 7d).

However, these ranges are more than just simple probabilities – they represent the most likely ***temporal*** patterns of old forest levels on the FMA, and the distributions themselves tell us something about those temporal patterns. So in the example above, not only do we know that the minimum amount of (61-year LTFC) pine forest that was historically "old" was about 5%, but we also know that it was a rare occurrence – old mixedwood accounted for less than 10% of the pine forest only 17% of the time. On the other hand, another 17% of the time pine forest was old

>25% of the pine forest was old, based on the 61-year results (Figure 6d).

This is typical of "natural range of variation" (NRV) forest patterns, and demonstrates the difficulty of representing dynamic patterns with averages or medians. No single number *at any single point in time* is any more or less "natural" than any other within the range. However, these temporal patterns are far from random. In summary, there is no single representative level of old (or young, immature, or mature) forest, but rather a wide range of not just possibilities, but also *probabilities*.

There are some significant differences in old forest levels between the four forest types Black spruce forest types have by far the lowest levels of old forest (averaging 9% and 18% respectively for the 61-year and 83-year results). This is likely due to both a) the highest age threshold for the "old" seral stage (at 120 years) and the relatively high flammability of black spruce. Not surprisingly, the highest level of old forest was found with hardwood forest, accounting for 30% and 40% of the forest for the 61-year and 83-year scenarios respectively. This is likely due to its relatively low flammability, and the low age threshold for the "old" seral stage (at 80 years). It is interesting to note that the amount of old for mixedwood and pine are similar. This suggests that the lower probability of burning for mixedwood is offset by the higher threshold for the old seral threshold (80 years vs. 100 years).

The differences in the amount of young seral forest in each of the four vegetation classes is, if anything, even greater than that of old forest, likely magnified by different age thresholds, and burn probability. The relatively high amount of young pine and black spruce can be explained by the combination of a 20-year upper limit on the "young" seral stage, and higher burn probabilities for conifer. The significantly lower levels of young mixedwood and aspen are a result of the use of a 10-year upper limit on the young seral stage, and much lower burn probabilities.

4.3.3 Current Conditions

A comparison of the current condition of the AlPac landscape to NRV suggests that disturbance rates are low (in some cases significantly so), and have been for some time. The 5% of young black spruce currently observed was occurred just 3% of the time for both the 61 and 83-year modelling scenarios (Figure 5a). The 7% (or less) of young pine only occurred 7% of the time in the 83-year scenario and 4% of the time for the 61-year scenario (Figure 4a). Current young mixedwood levels are well within NRV for both scenarios (Figure 4c). Young hardwood is above the historical median (although note that it only accounts for about 5% of the landscape).

Current levels of immature forest also tend to be low relative to NRV. Immature levels of pine forest are well within NRV, but the current levels of immature forest for the three other forest types are below the lower threshold of NRV. For example, the 12% immature mixedwood forest is only half as much as the lowest level observed for the 61-year scenario (Figure 6b). With the exception of pine, when young and immature forest stages are combined, the amount of forest less than 60-70 years of age on the AlPac FMA are on the very lower end of NRV. For example, the current amount of young + immature mixedwood is 19%. The lower bound of NRV for young+immature for mixedwood in the 83-year scenario is 20%, and 37% for the 61-year scenario. In other words, overall disturbance levels have been significantly depressed for at least 60 years in all but pine types, and most dramatically so in black spruce forest types.

Of the remaining two age-classes, the current condition of old forest is well within the middle two quartiles of NRV for all forest types, and in some cases close to the historical median. However, the level of mature forest in each case is beyond the upper end of NRV – regardless of the scenario. In the most extreme case, 66% of the black spruce forest is mature, which is 25% higher than the most observed from the 61-year scenario *and 50% higher than the average NRV* (Figure 5c). Even for the 83-year scenario, the current condition is 21% higher than the maximum observed historical condition.

The same patterns are evident to varying degrees when considering a) the three FMUs, b) the caribou herd zones, and c) caribou habitat (Figures 8-39). The slight increase in young forest in the south FMU is likely due to the 2003 House River fire. Note that there is less than 5,000 ha in both the mixedwood and hardwood forest types within the upland caribou habitat type, which is why Figures 34 and 35 are shaded.

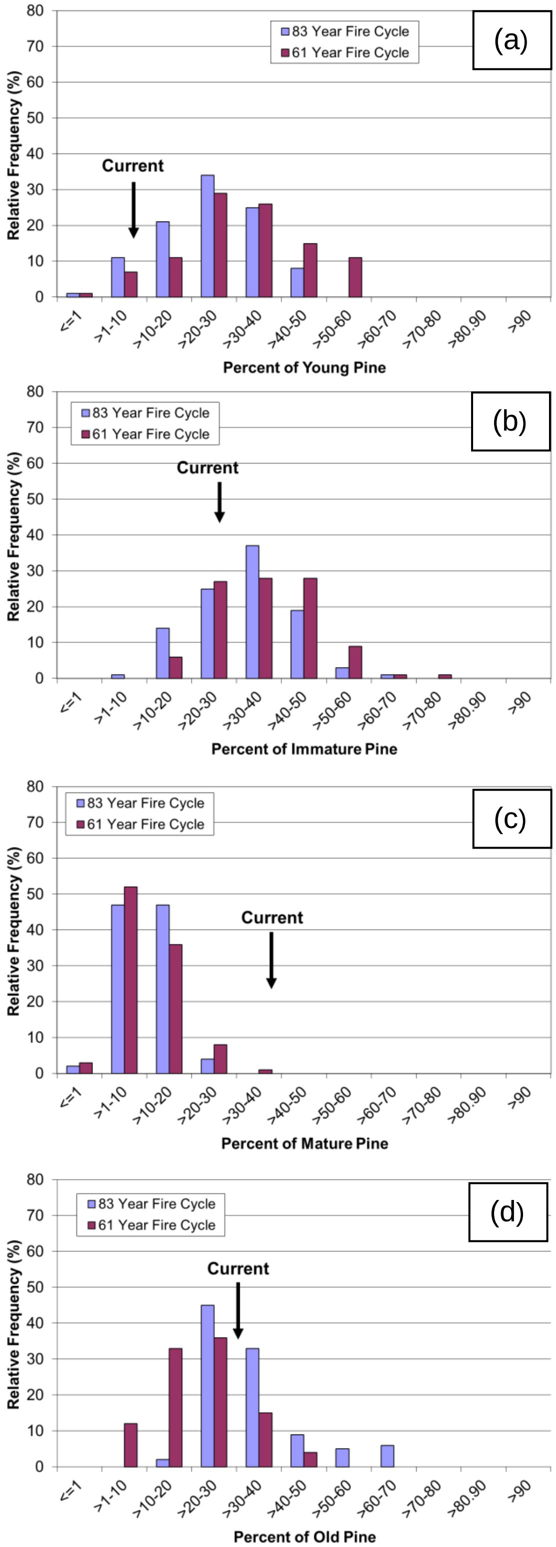


Figure 4. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands on the Alpac FMA.

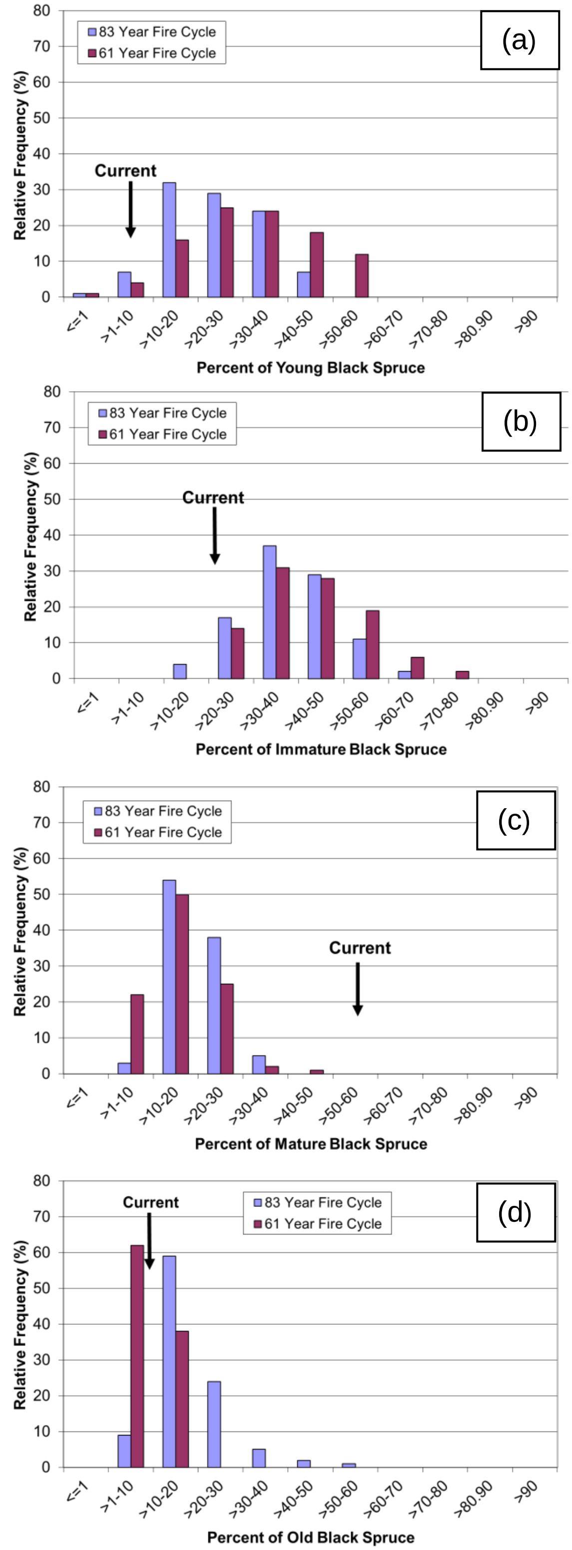


Figure 5. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands on the Alpac FMA.

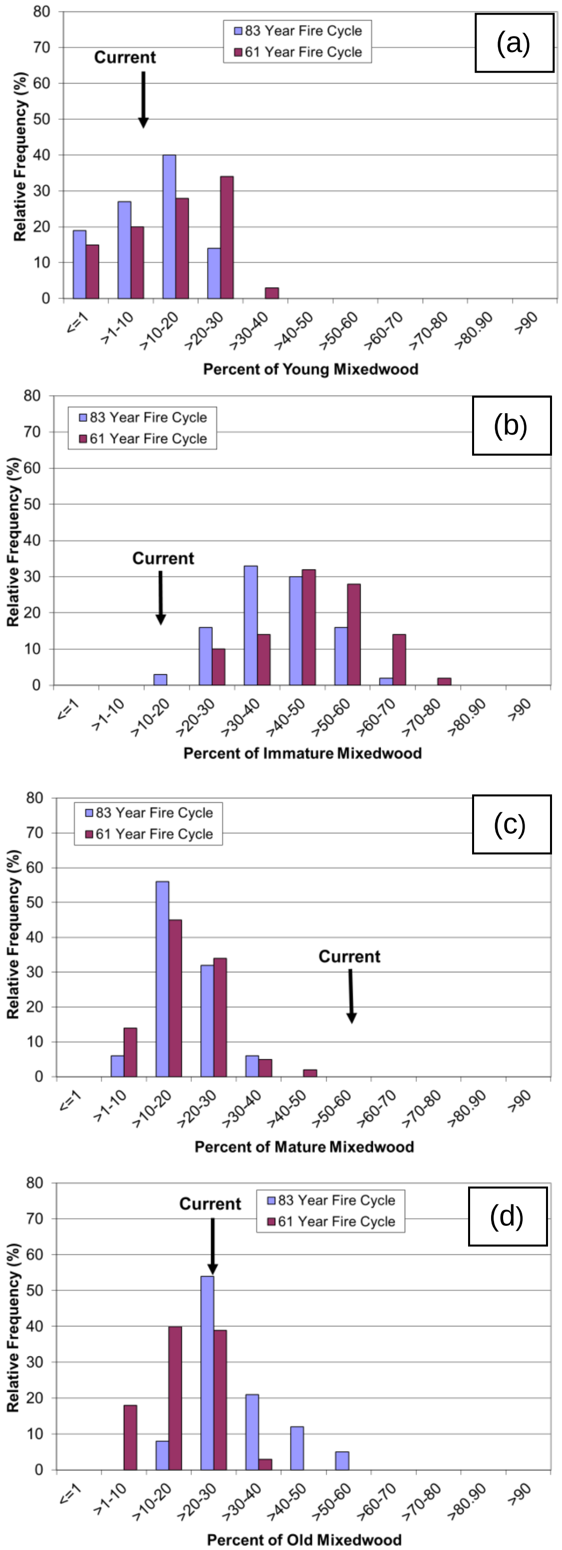


Figure 6. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands on the Alpac FMA.

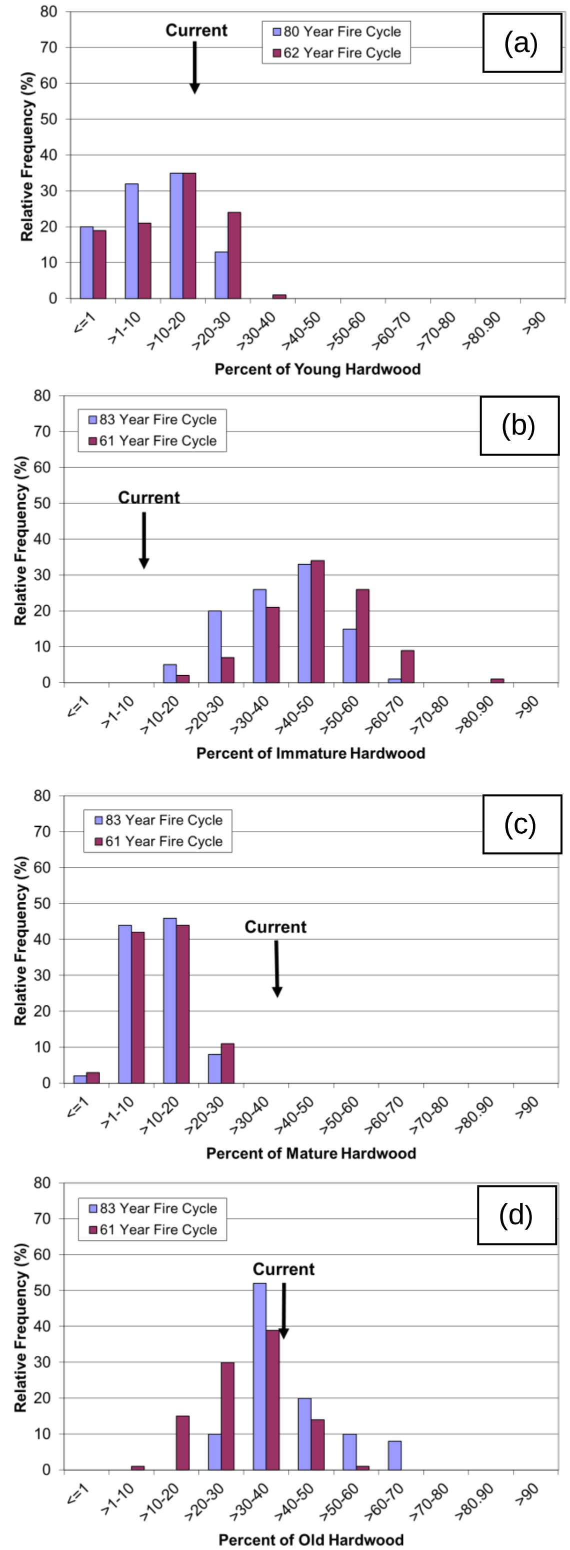


Figure 7. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands on the Alpac FMA.

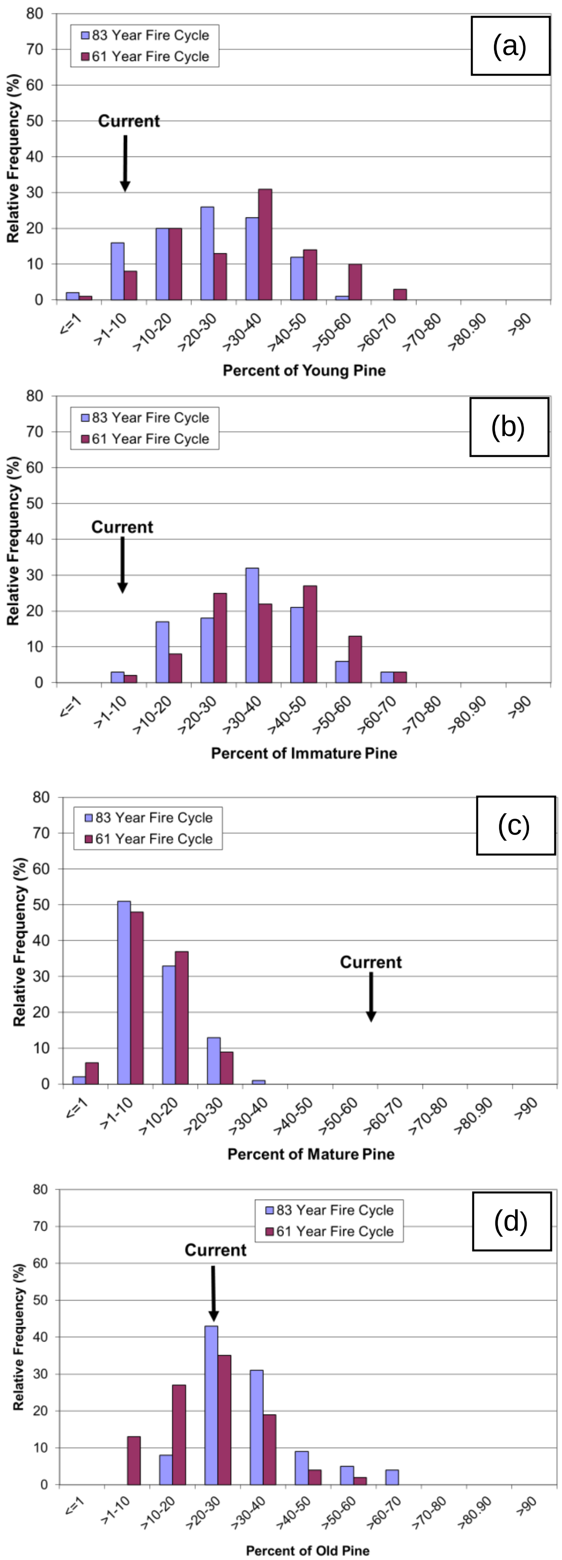


Figure 8. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands on Alpac's west FMU area.

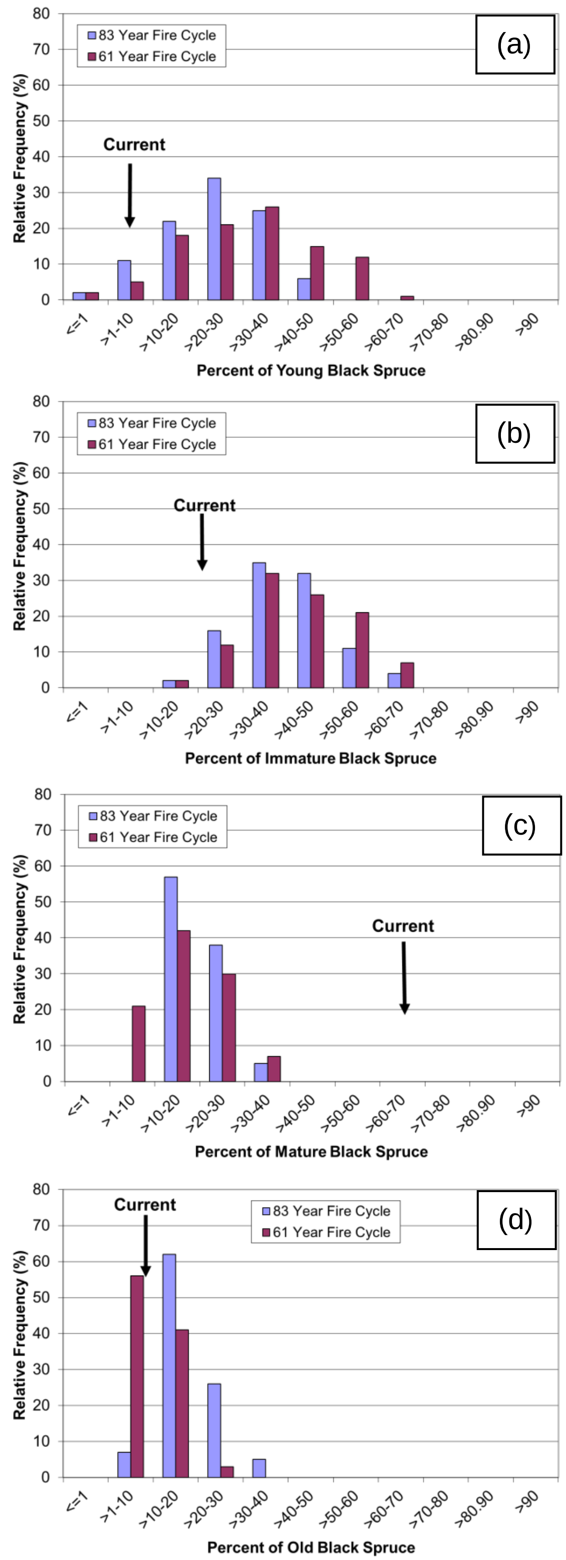


Figure 9. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands on the Alpac's west FMU area

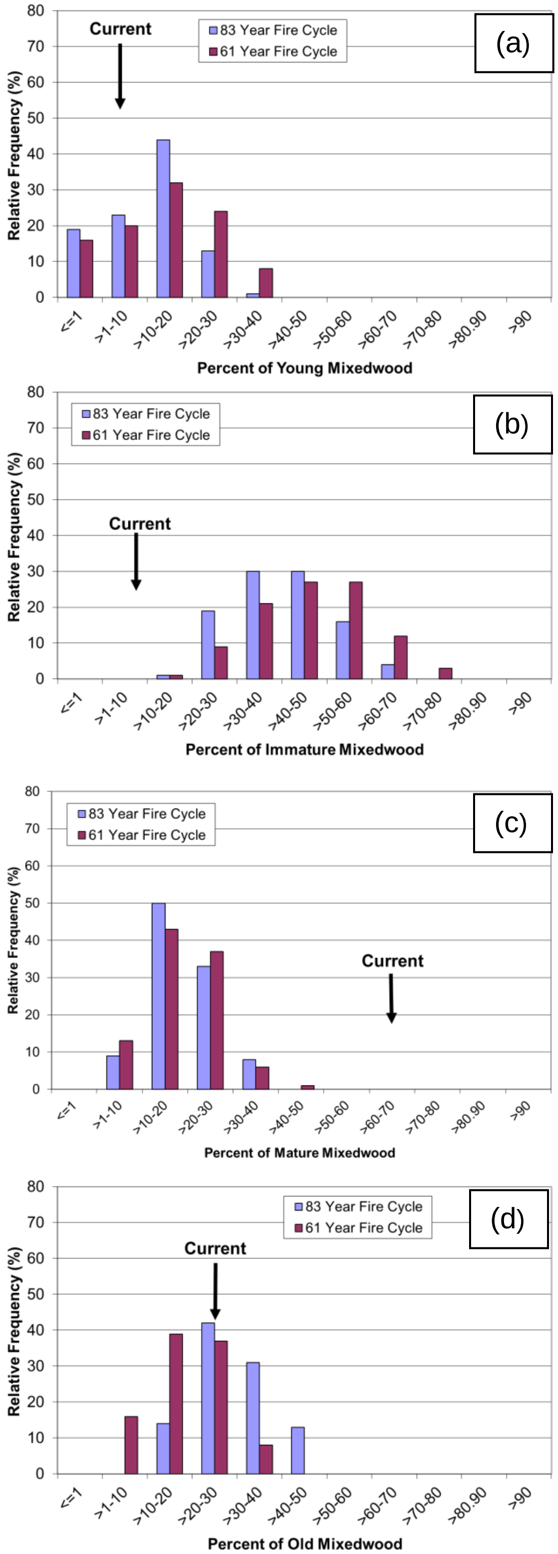


Figure 10. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixewdood stands on Alpac's west FMU area.

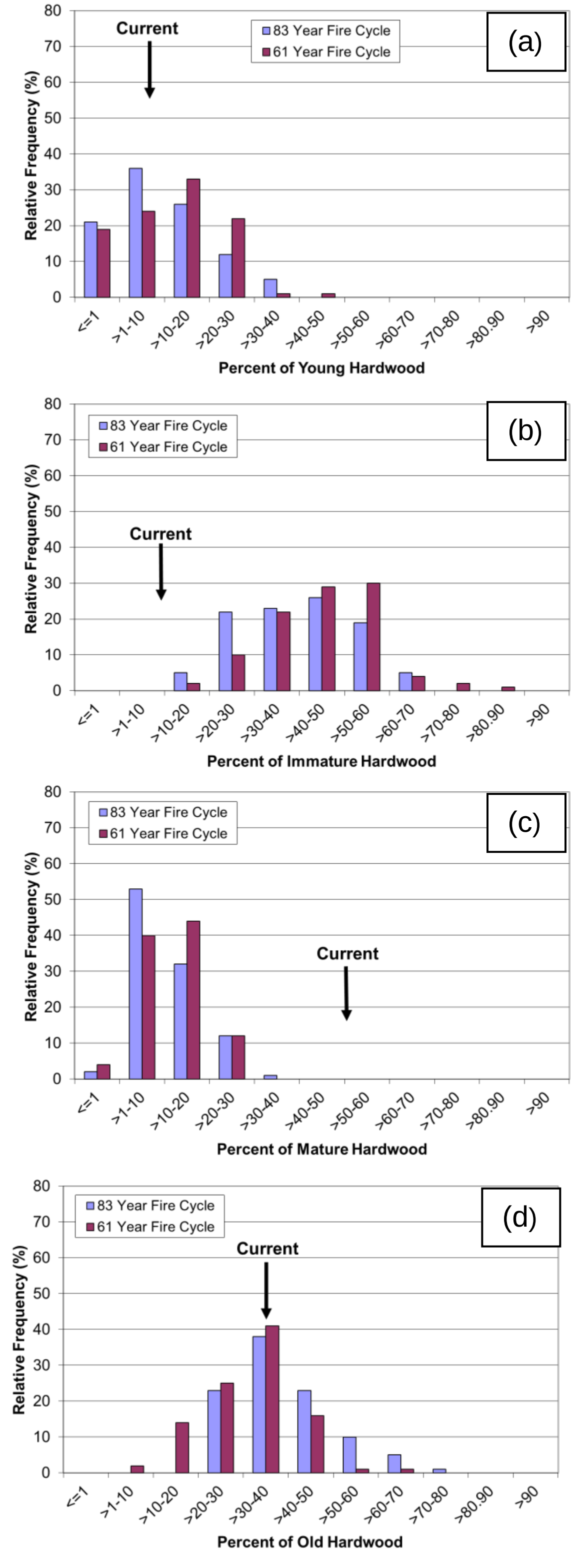


Figure 11. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands on the Alpac's west FMU area

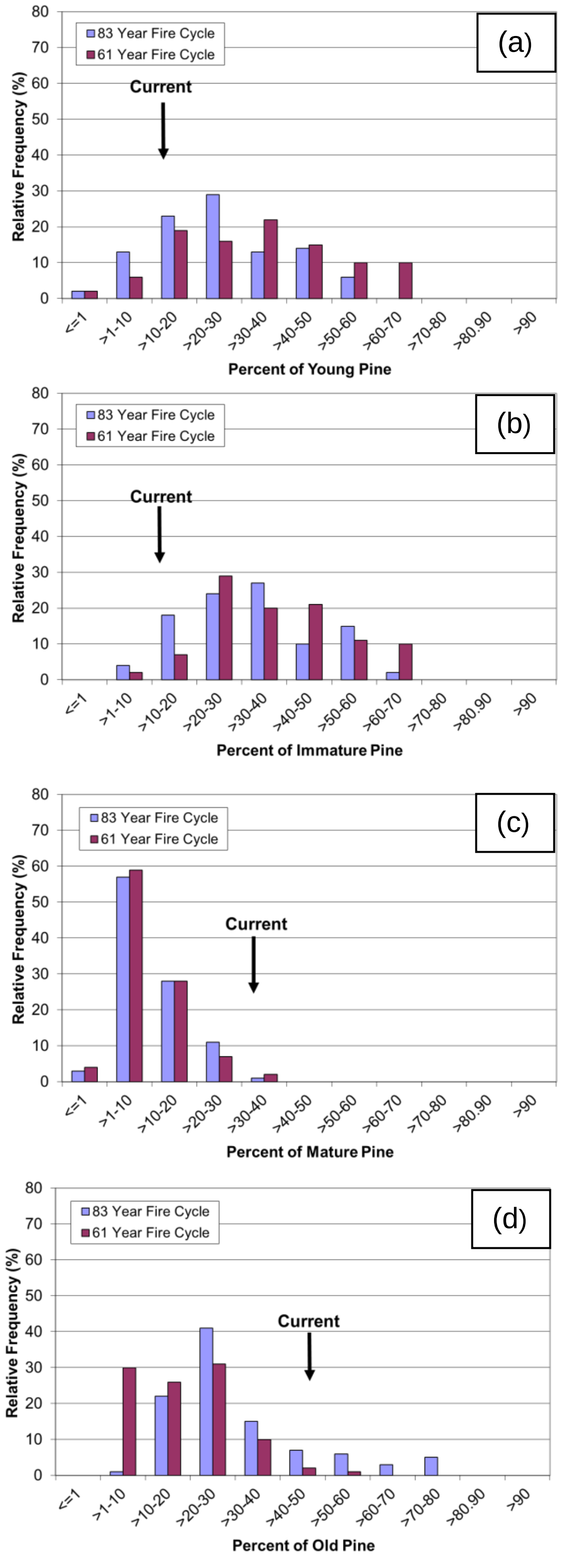


Figure 12. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands on Alpac's south FMU area.

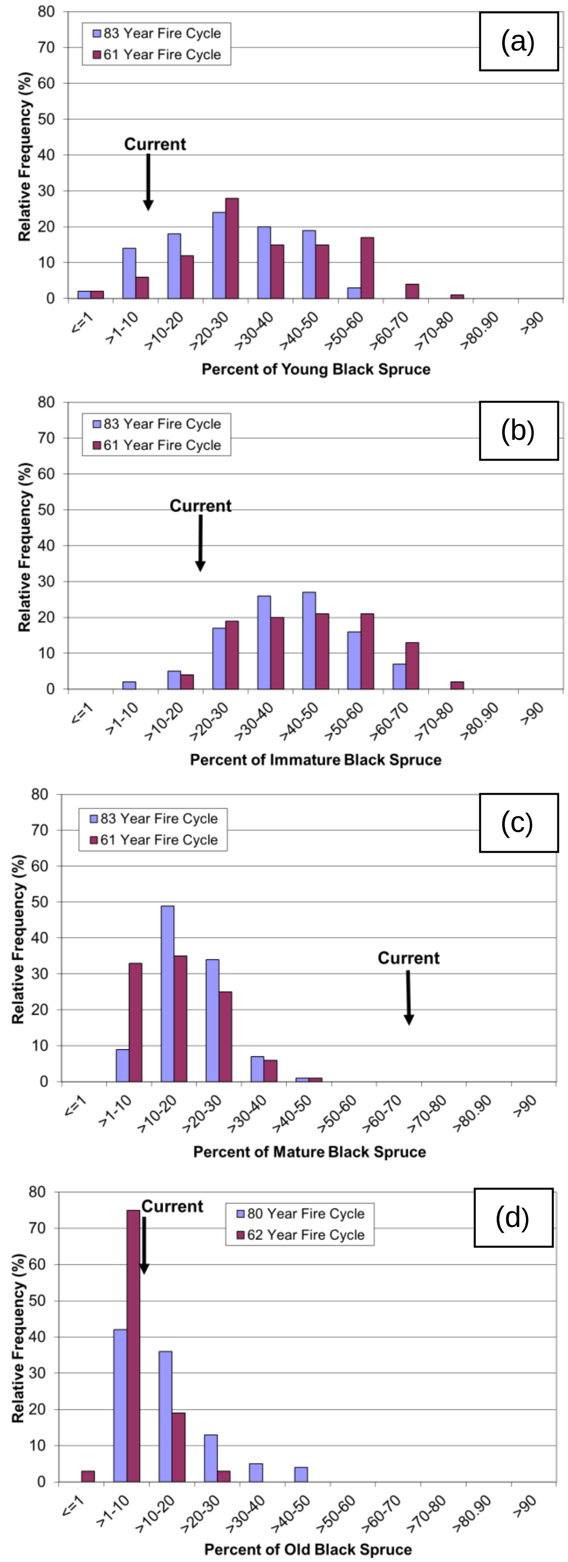


Figure 13. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands on Alpac's south FMU area.

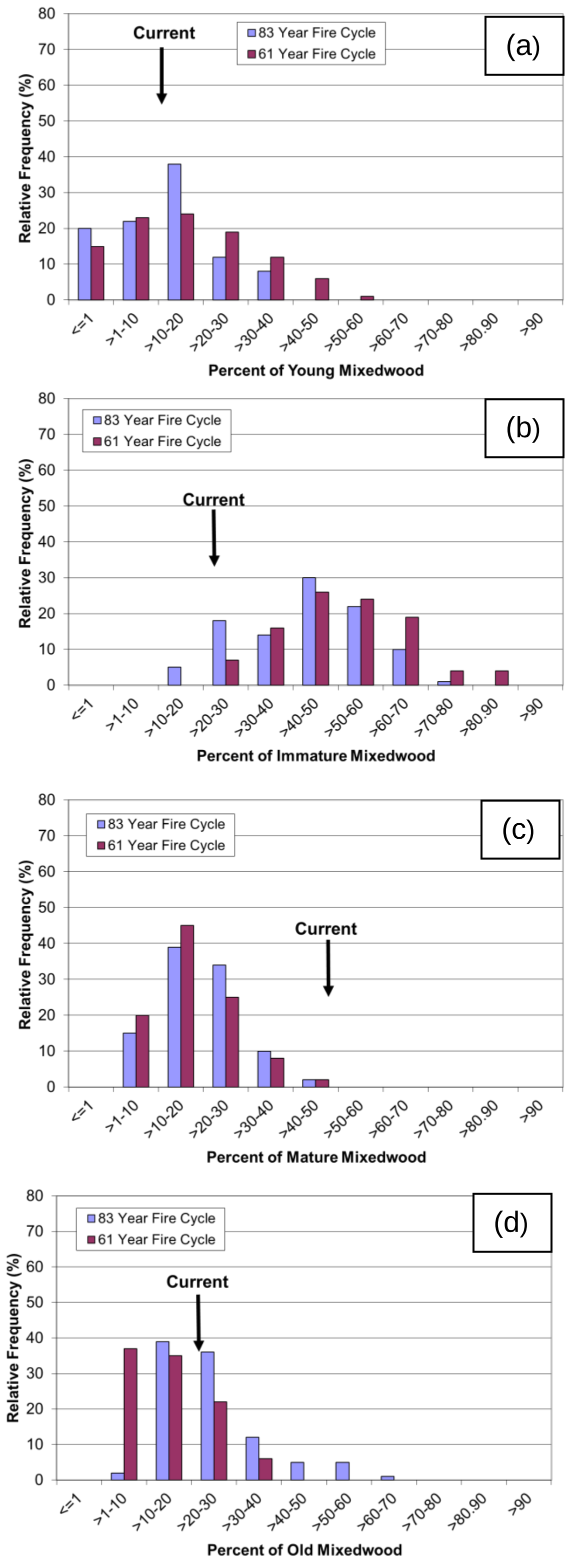


Figure 14. Frequency distribution of young (a), immature (b), mature (c), and old (d) mxedwood stands on Alpac's south FMU area.

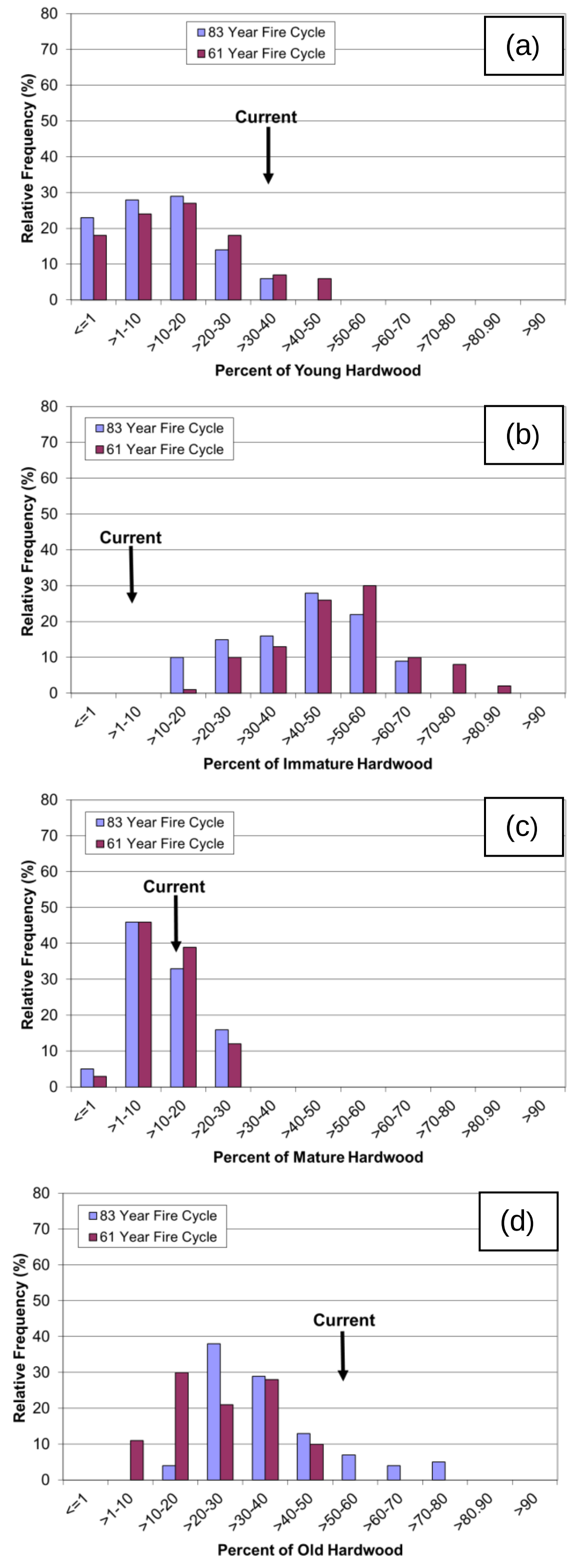


Figure 15. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands on Alpac's south FMU area.

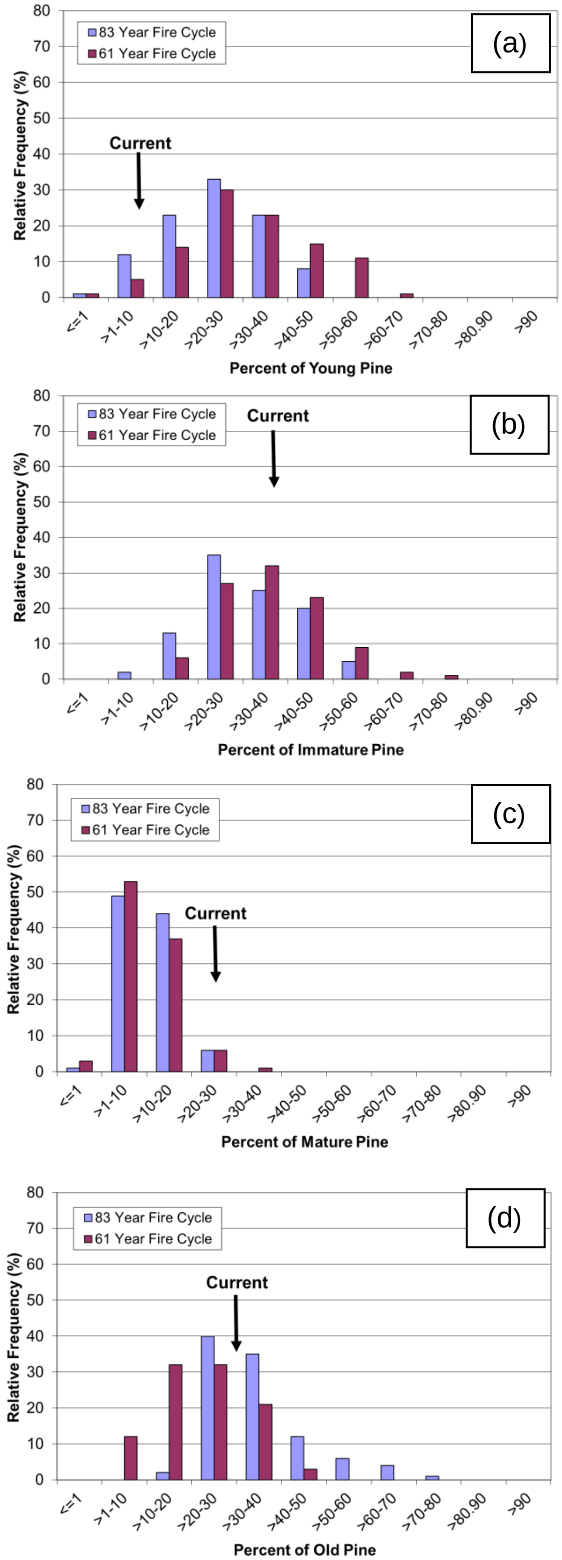


Figure 16. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands on Alpac's east FMU area.

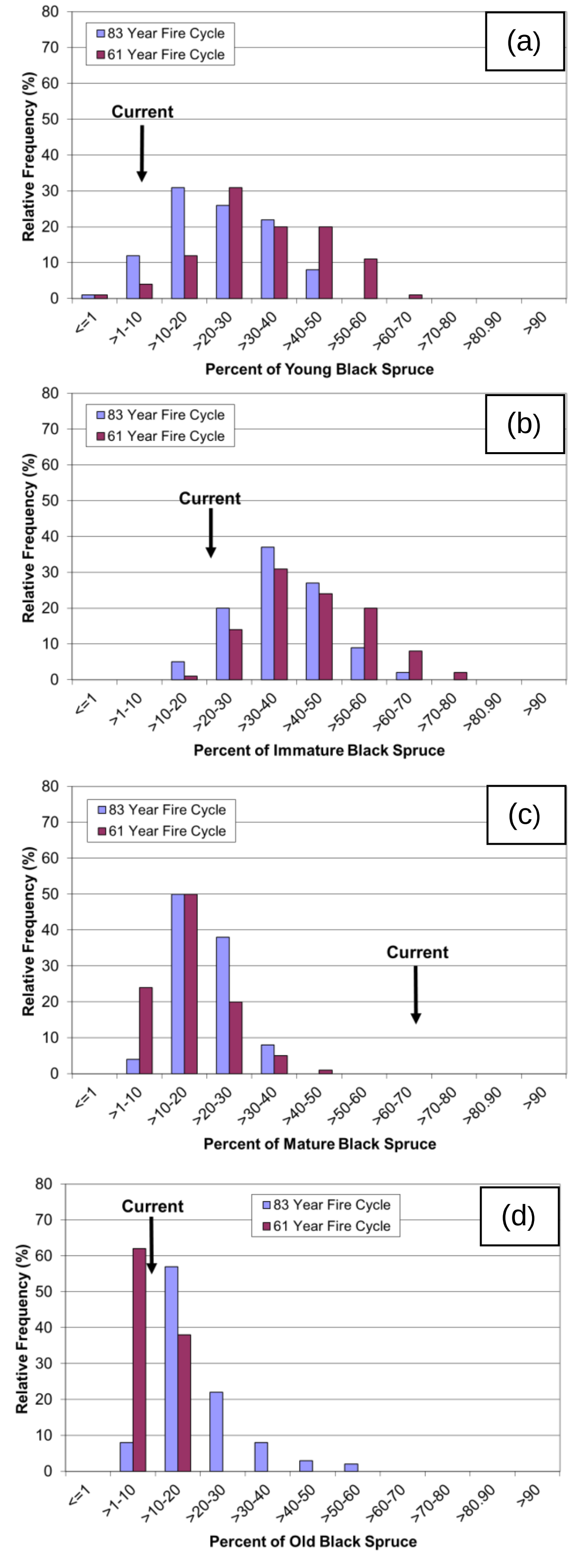


Figure 17. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands on Alpac's east FMU area.

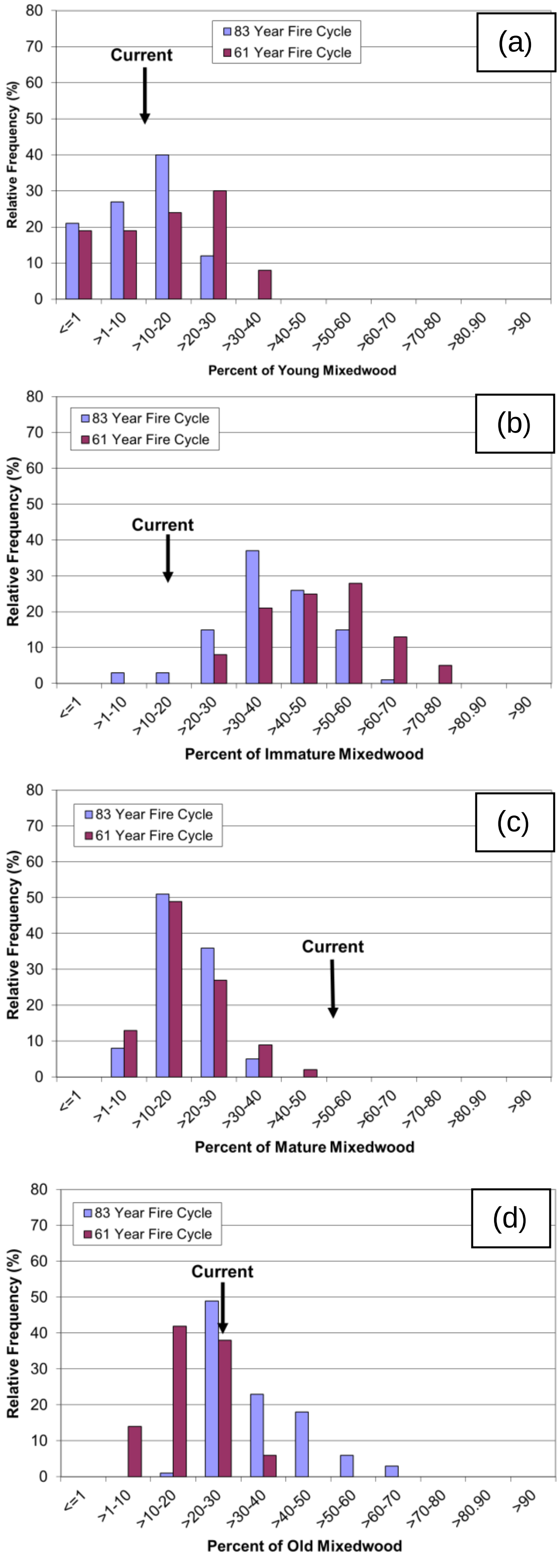


Figure 18. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands on Alpac's east FMU area.

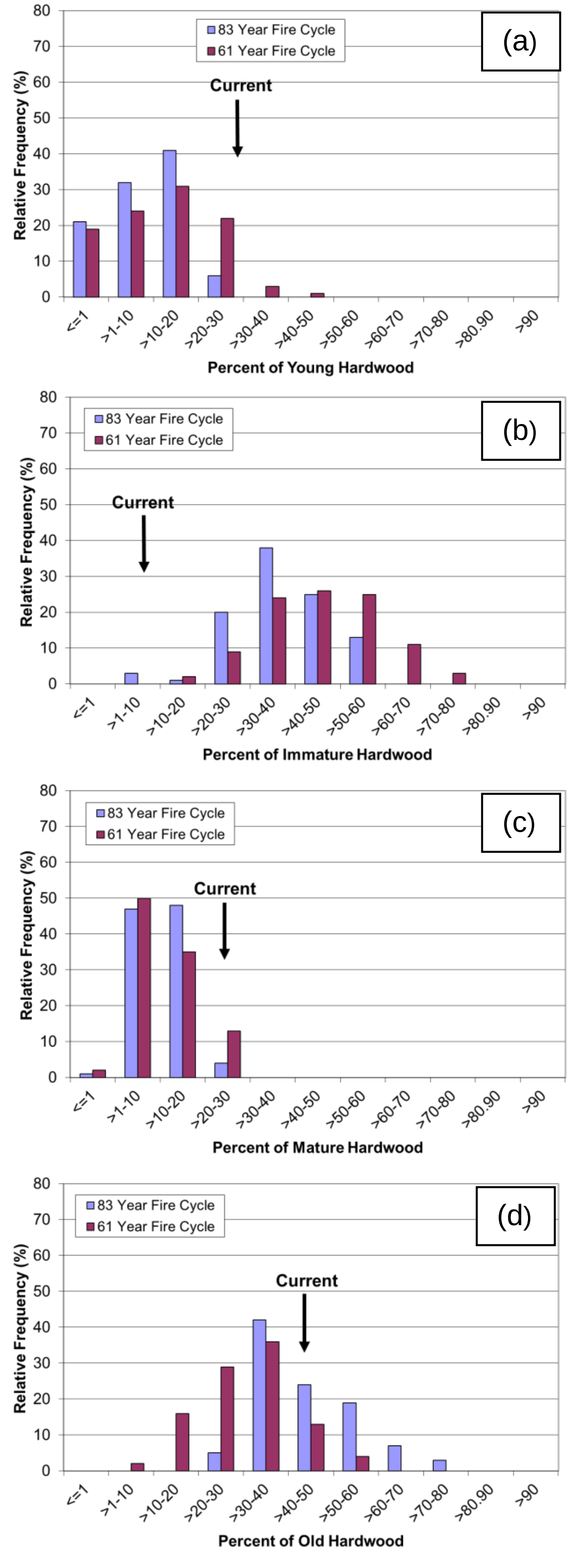


Figure 19. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands on Alpac's east FMU area.

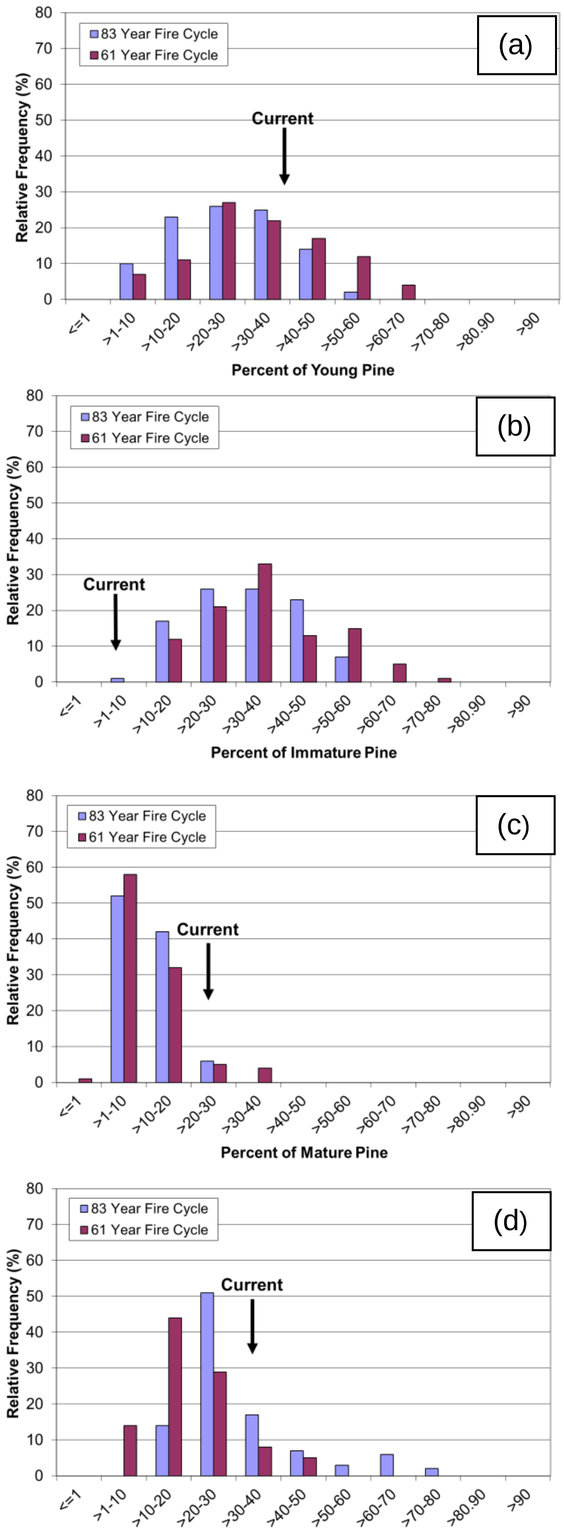


Figure 20. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands for the East Side Athabasca River caribou herd on the Alpac FMA

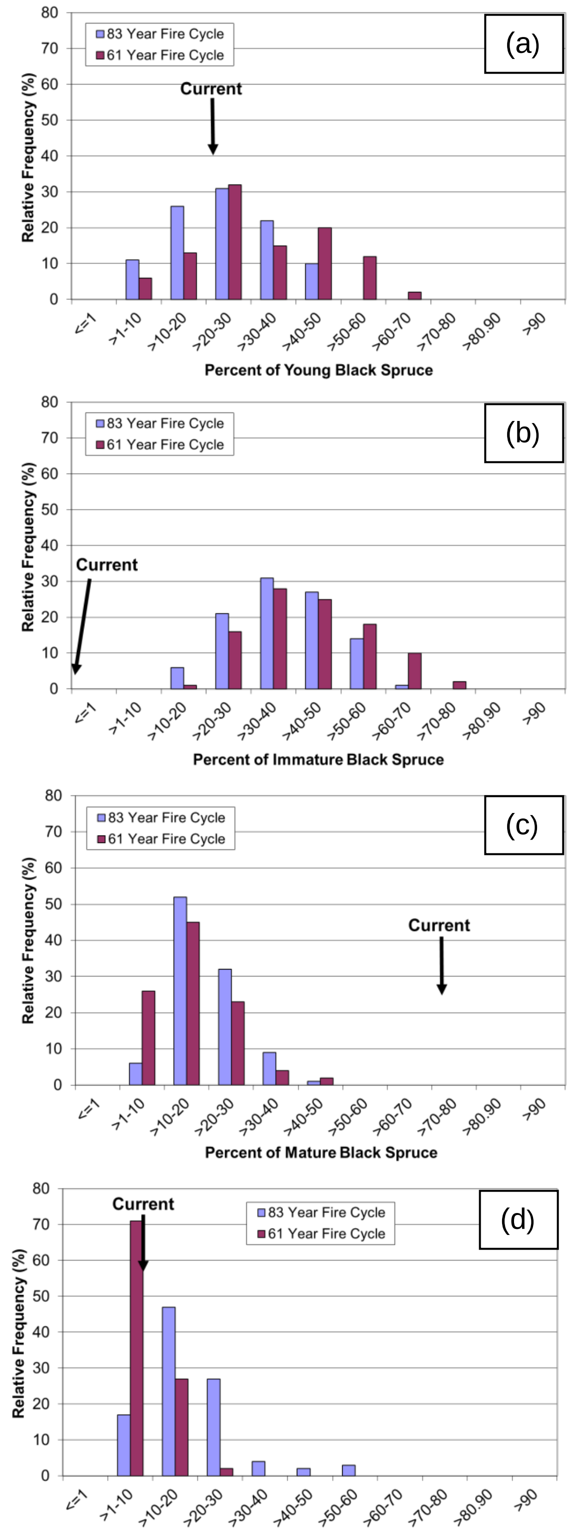


Figure 21. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands for the East Side Athabasca River caribou herd area on the Alpac FMA.

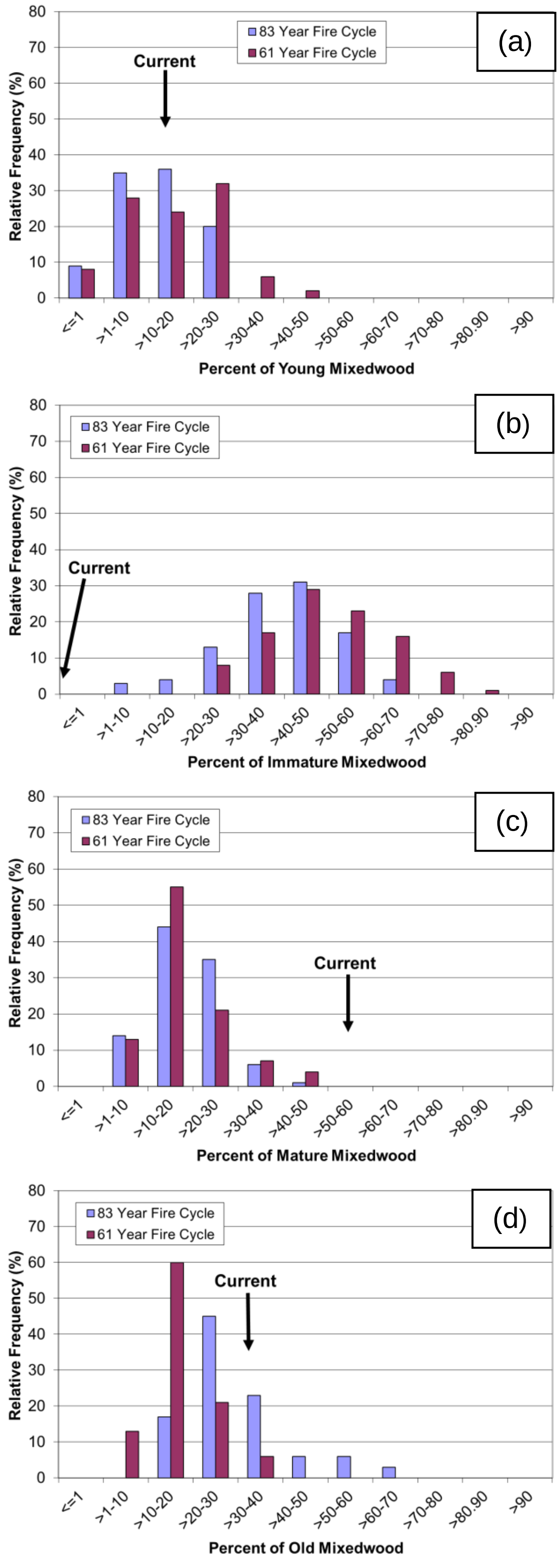


Figure 22. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands for the East Side Athabasca River caribou herd on the Alpac FMA.

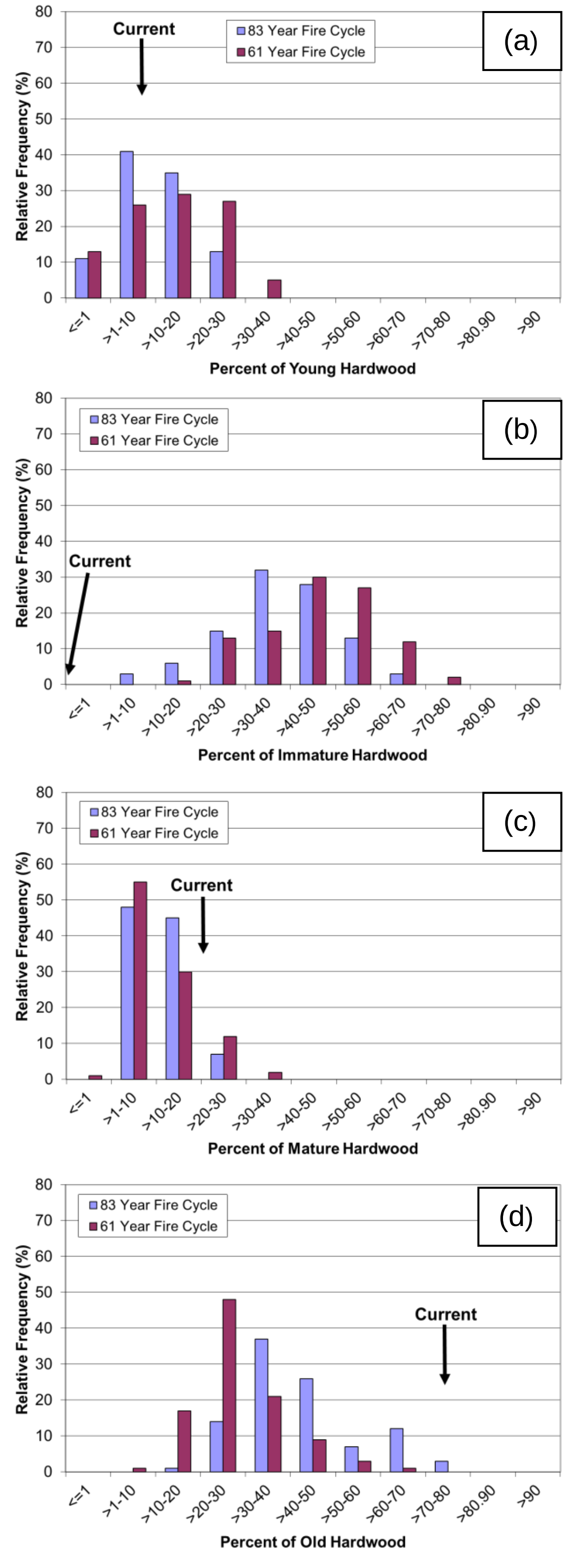


Figure 23. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands for the East Side Athabasca River caribou herd area on the Alpac FMA.

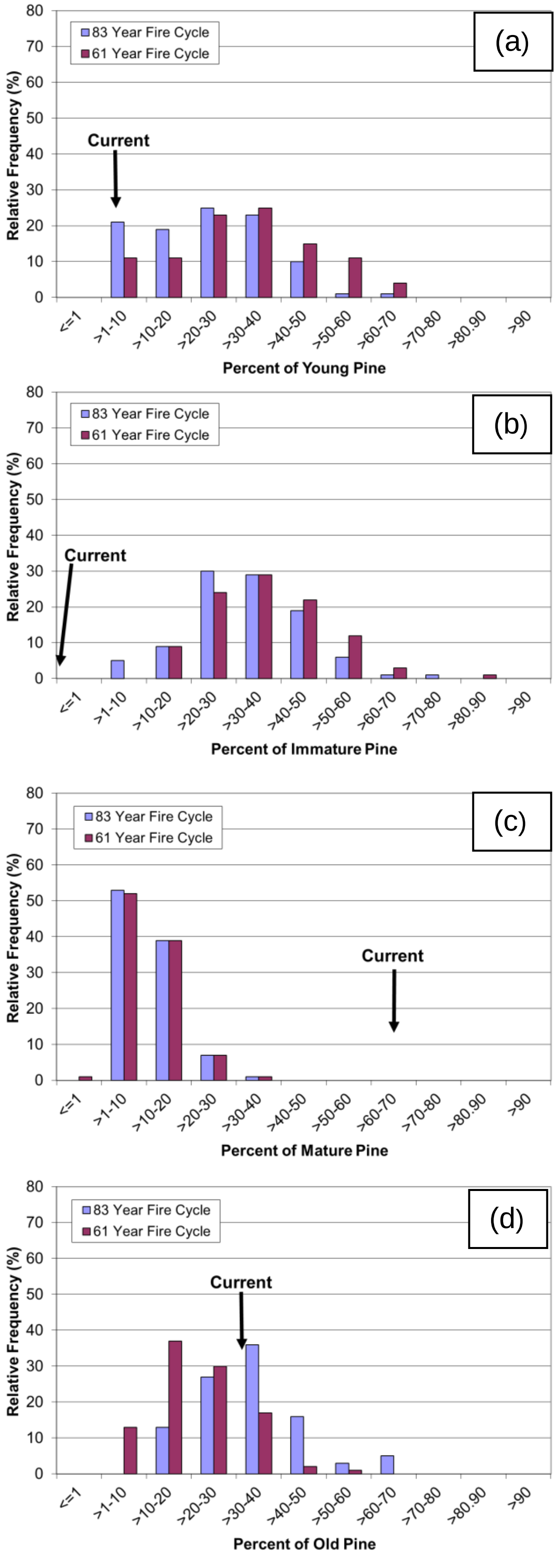


Figure 24. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands for the West Side Athabasca River caribou herd on the Alpac FMA

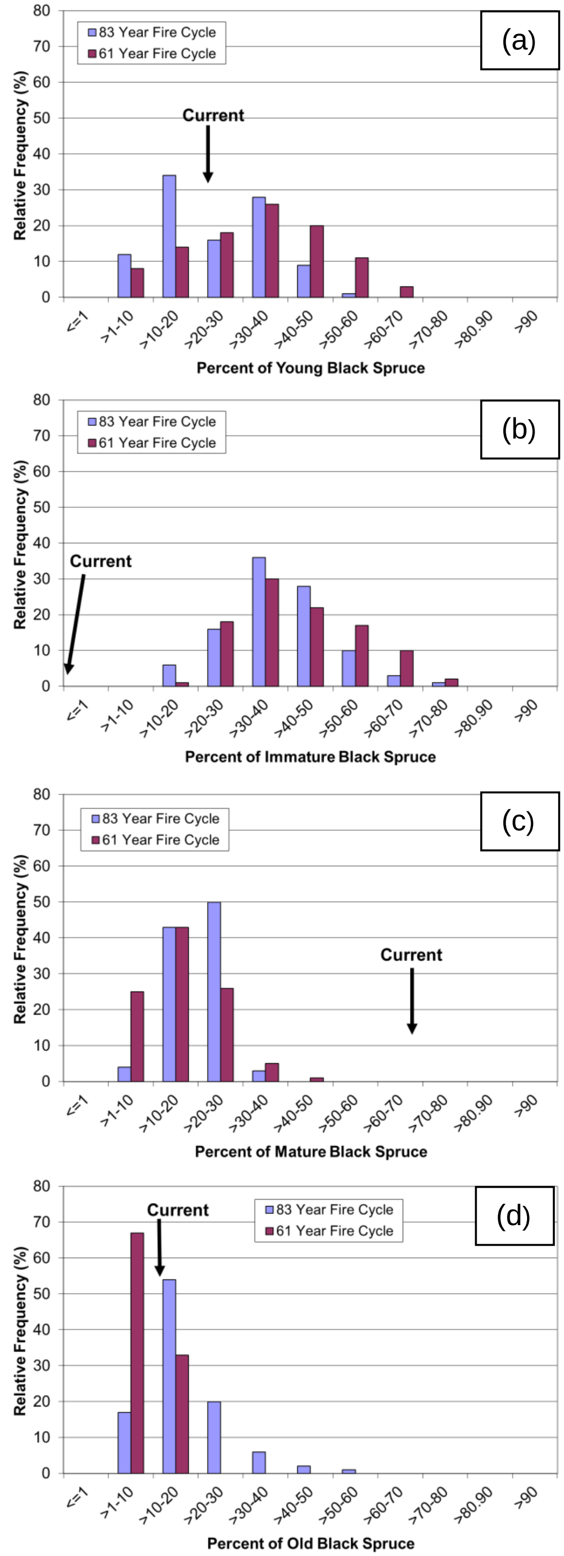


Figure 25. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands for the West Side Athabasca River caribou herd area on the Alpac FMA.

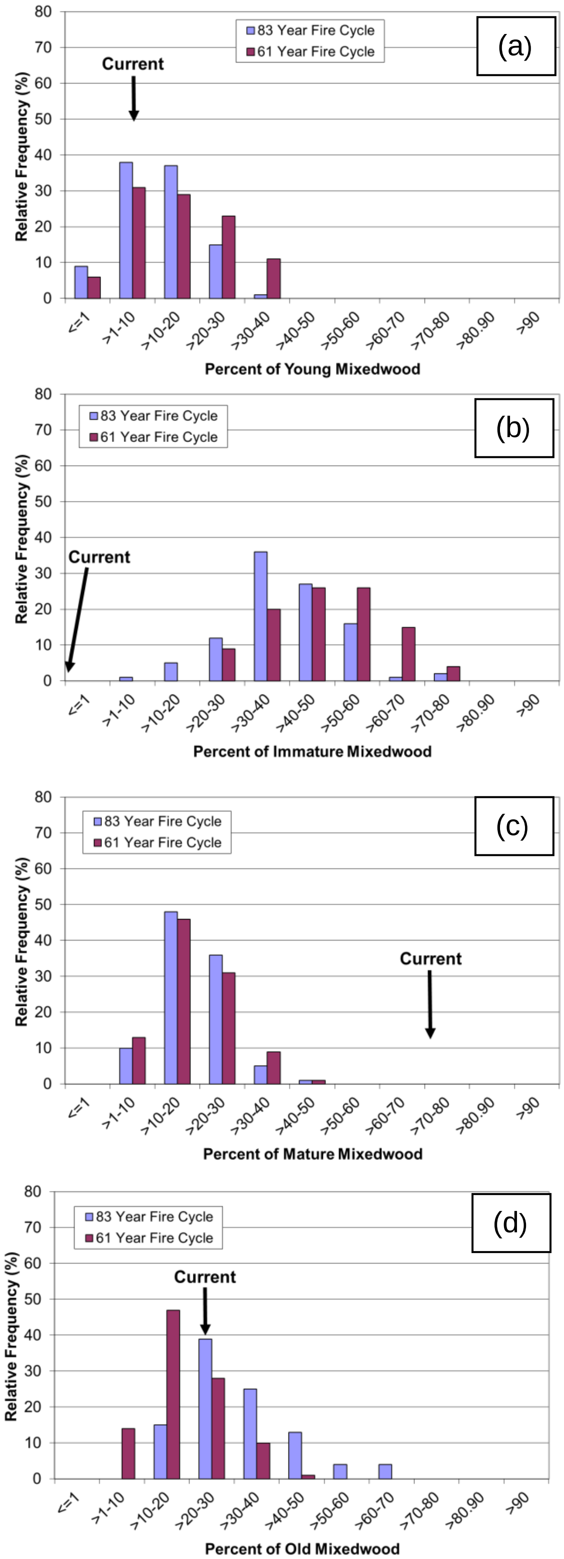


Figure 26. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands for the West Side Athabasca River caribou herd on the Alpac

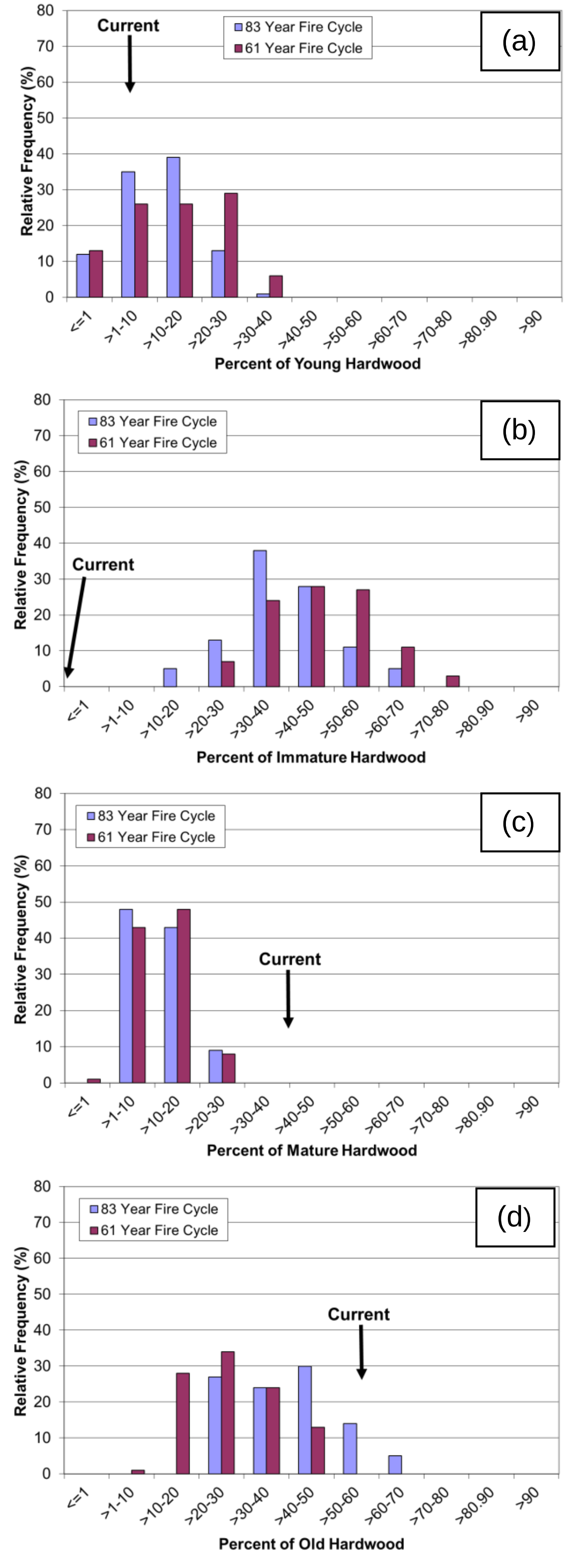


Figure 27. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands for the West Side Athabasca River caribou herd area on the Alpac FMA.

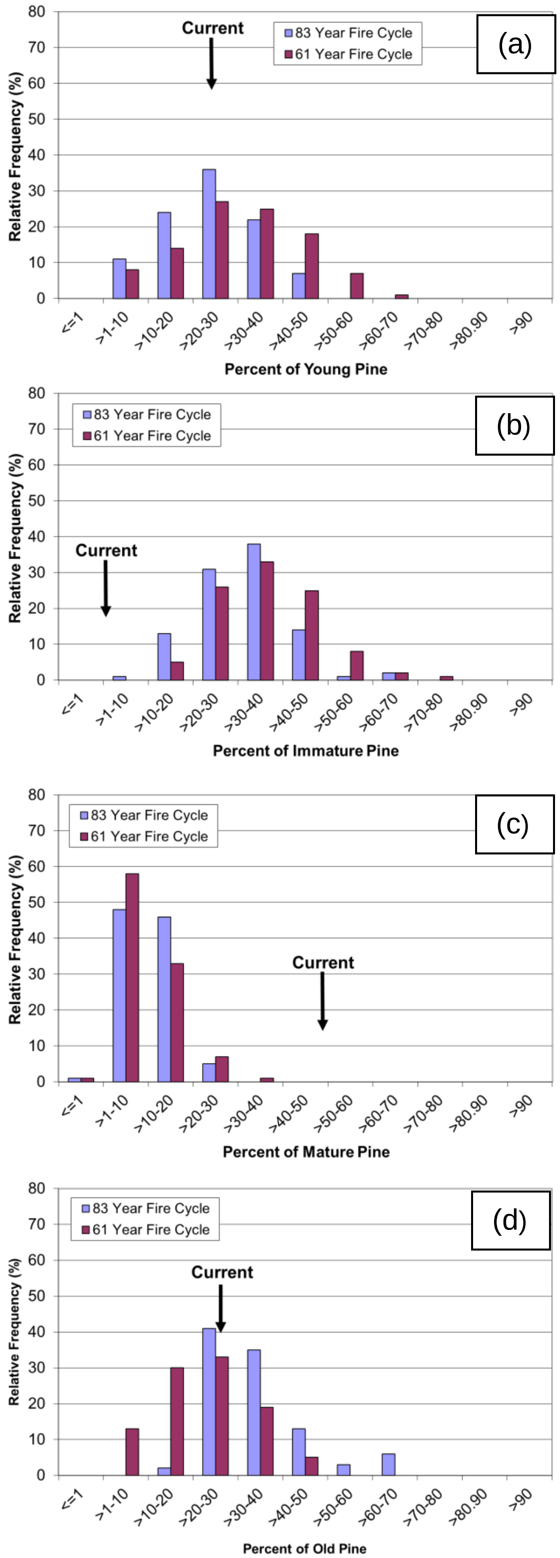


Figure 28. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands for the Forest Wetlands caribou habitat type on the Alpac FMA.

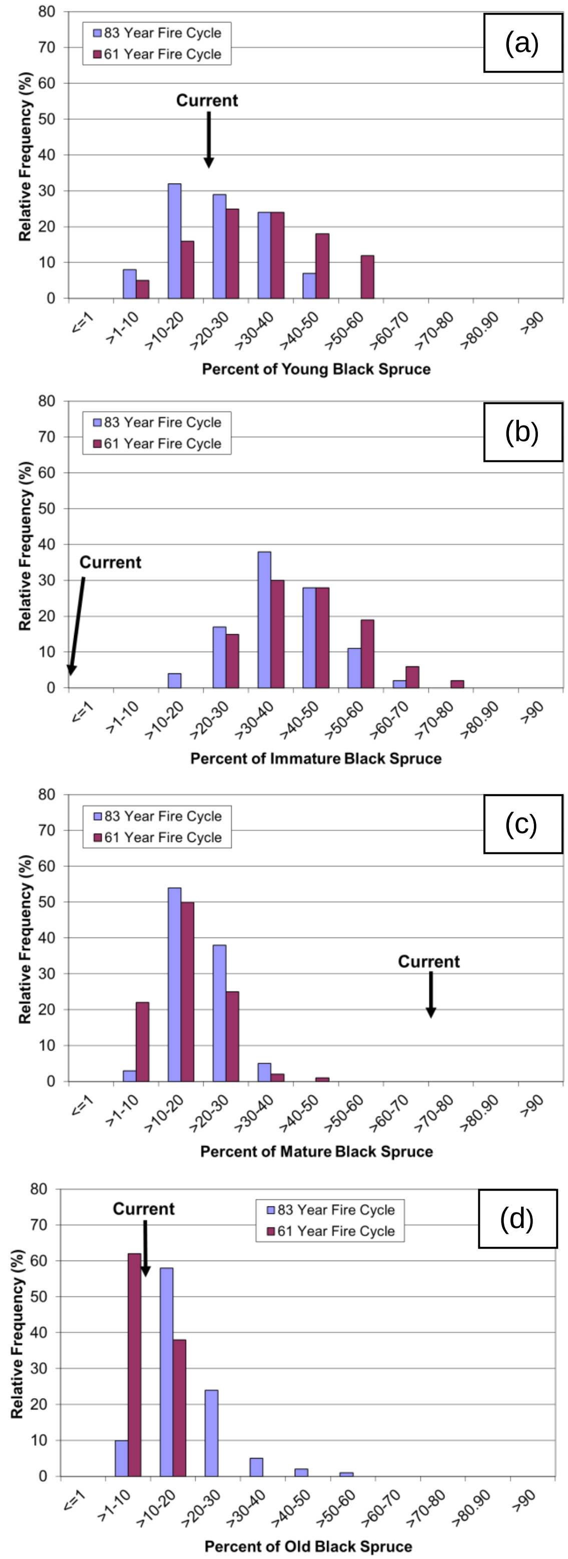


Figure 29. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands for the Forest Wetlands caribou habitat type on the Alpac FMA.

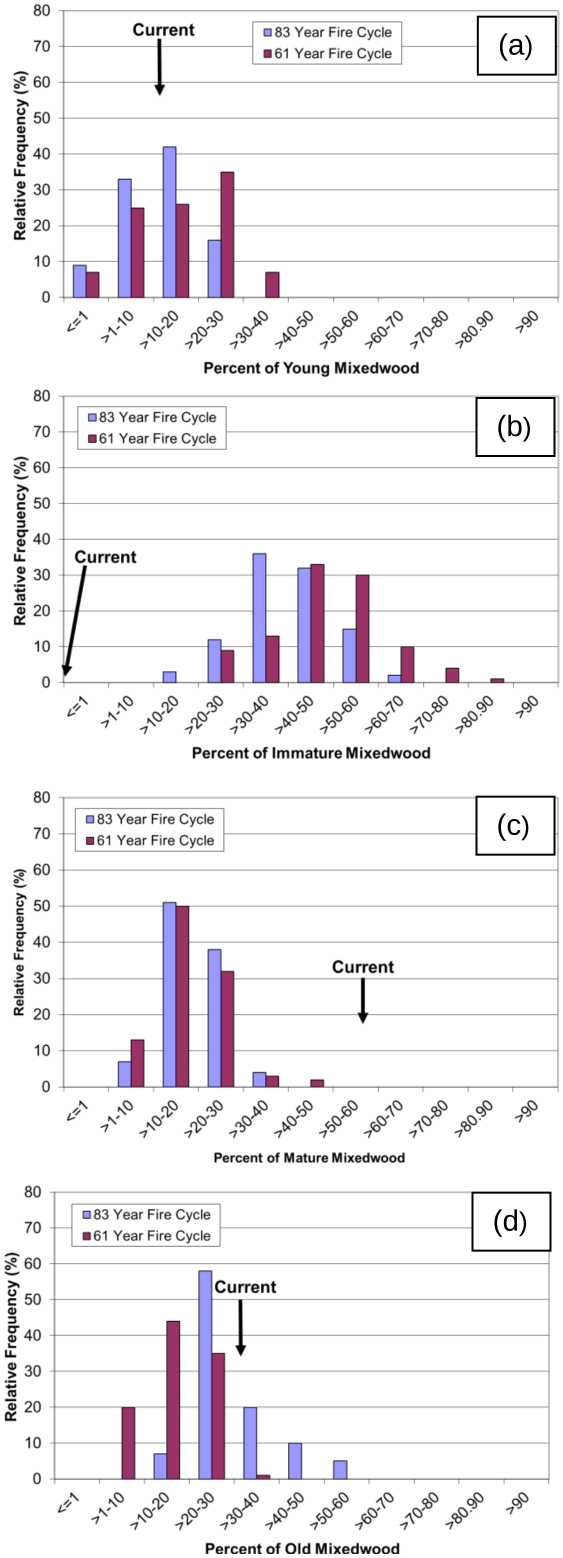


Figure 30. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands for the Forest Wetlands caribou habitat type on the Alpac FMA.

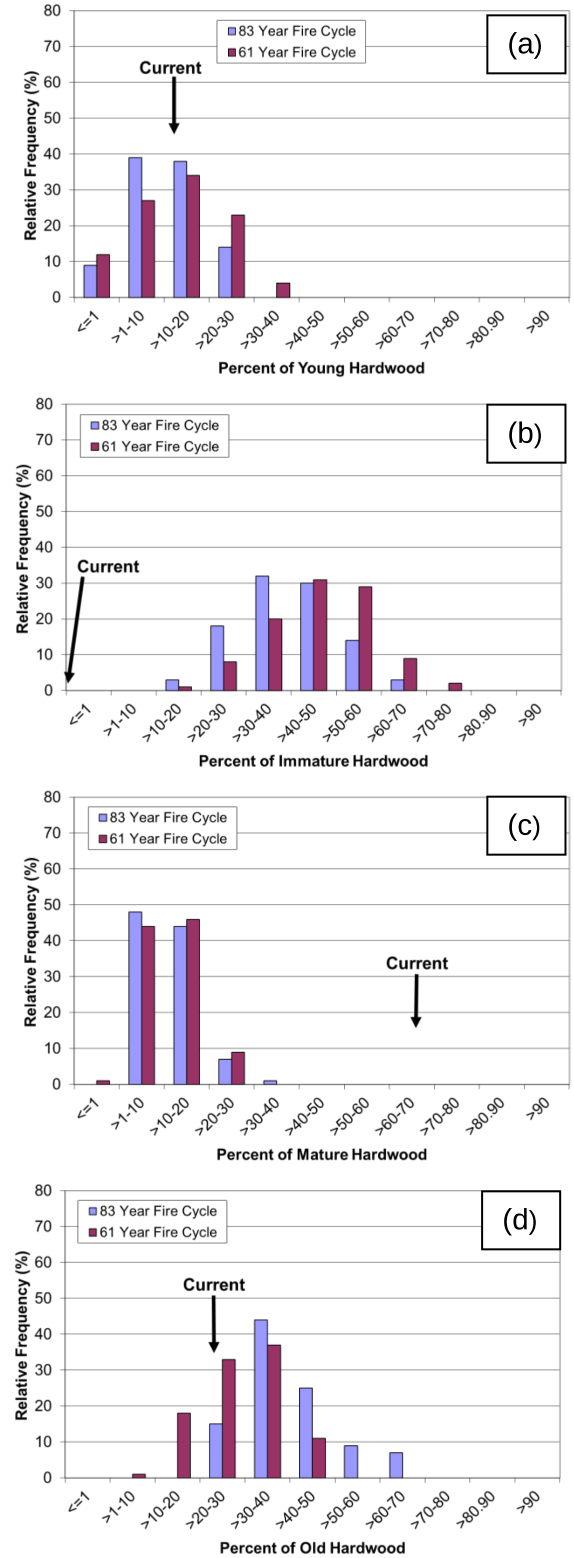


Figure 31. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands for the Forest Wetlands caribou habitat type on the Alpac FMA.

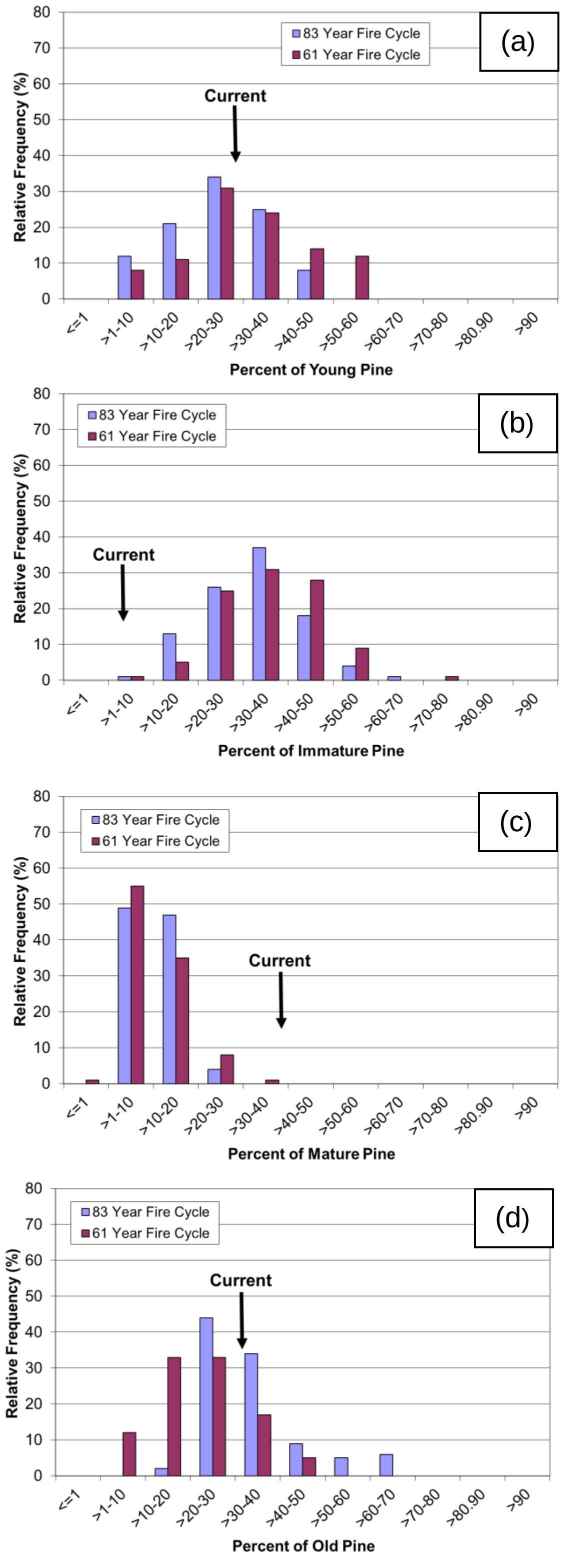


Figure 32. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands for the Upland Shrub, Sb, and Pine caribou habitat type on the Alpac FMA.

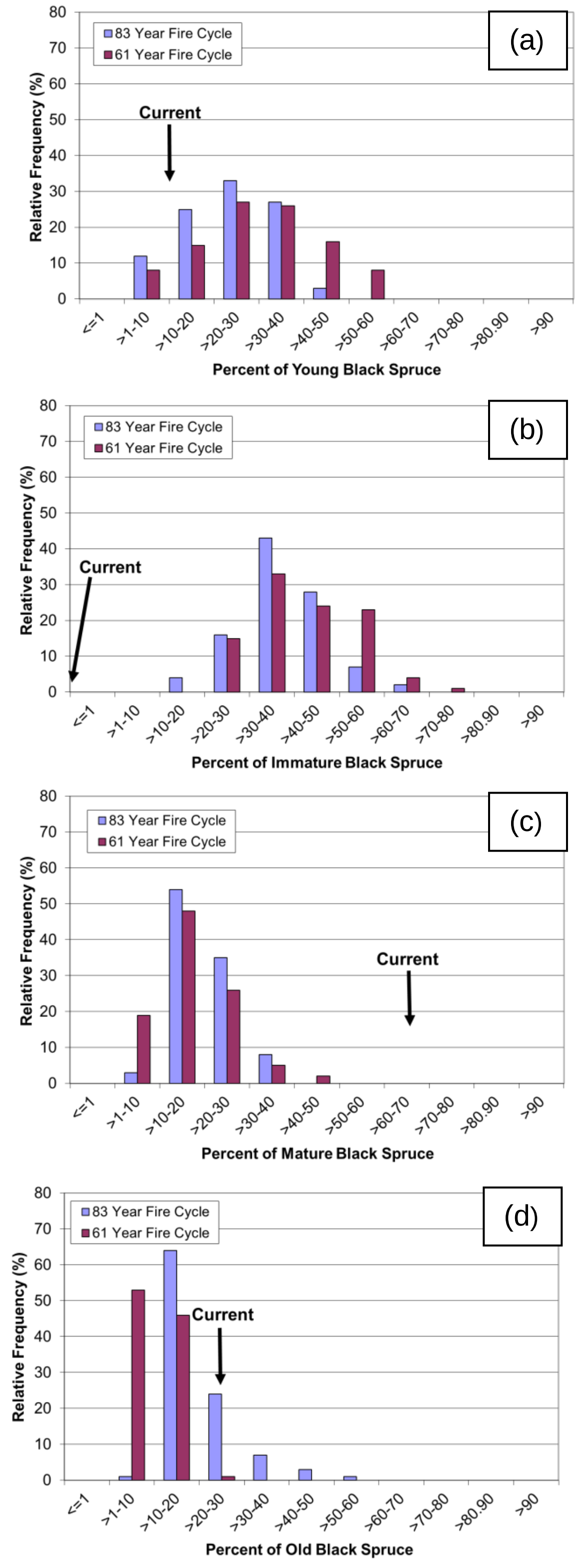


Figure 33. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands for the Upland Shrub, Sb, and Pine caribou habitat type on the Alpac FMA.

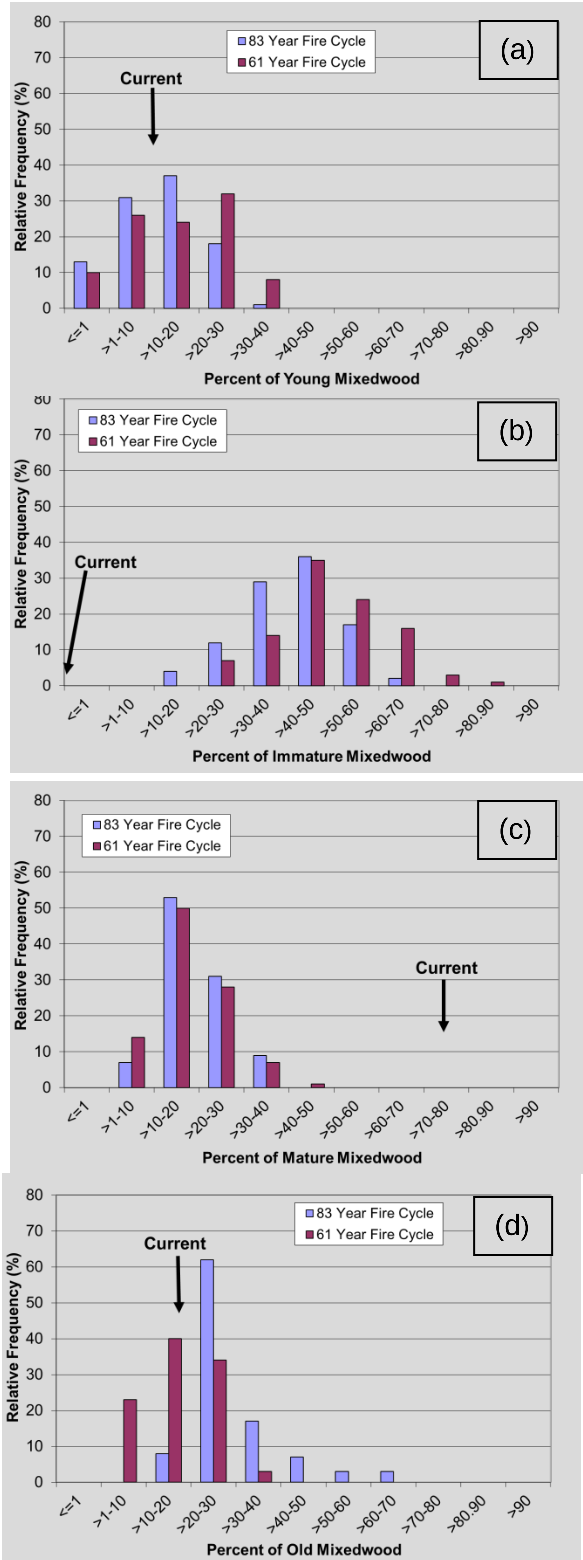


Figure 34. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands for the Upland Shrub, Sb, and Pine caribou habitat type on the Alpac

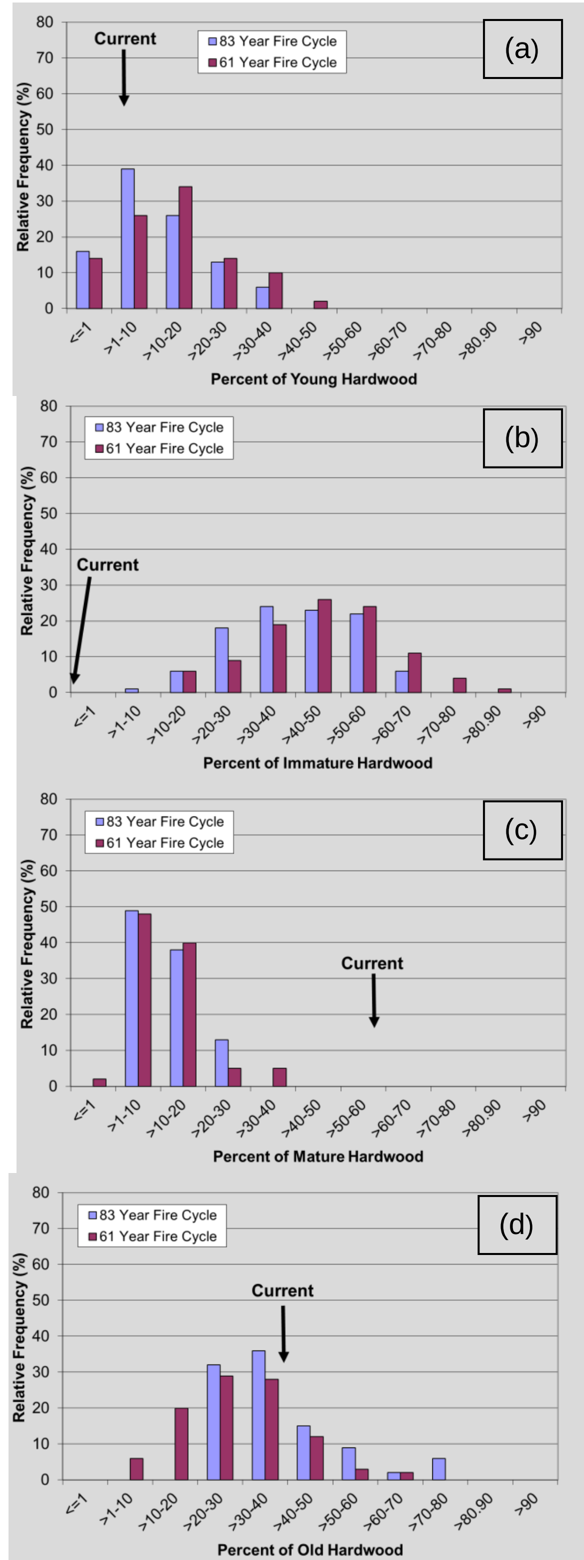


Figure 35. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands for the Upland Shrub, Sb, and Pine caribou habitat type on the Alpac FMA.

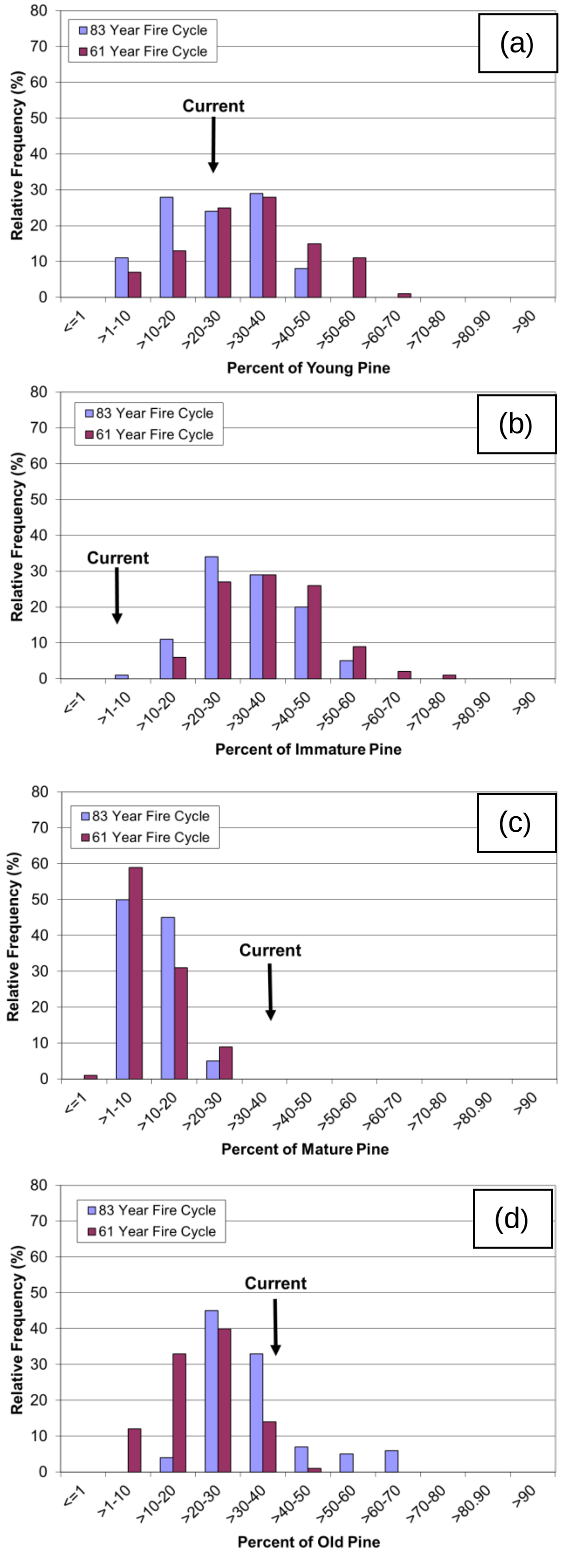


Figure 36. Frequency distribution of young (a), immature (b), mature (c), and old (d) pine stands for the Other Mesic caribou habitat type on the Alpac FMA.

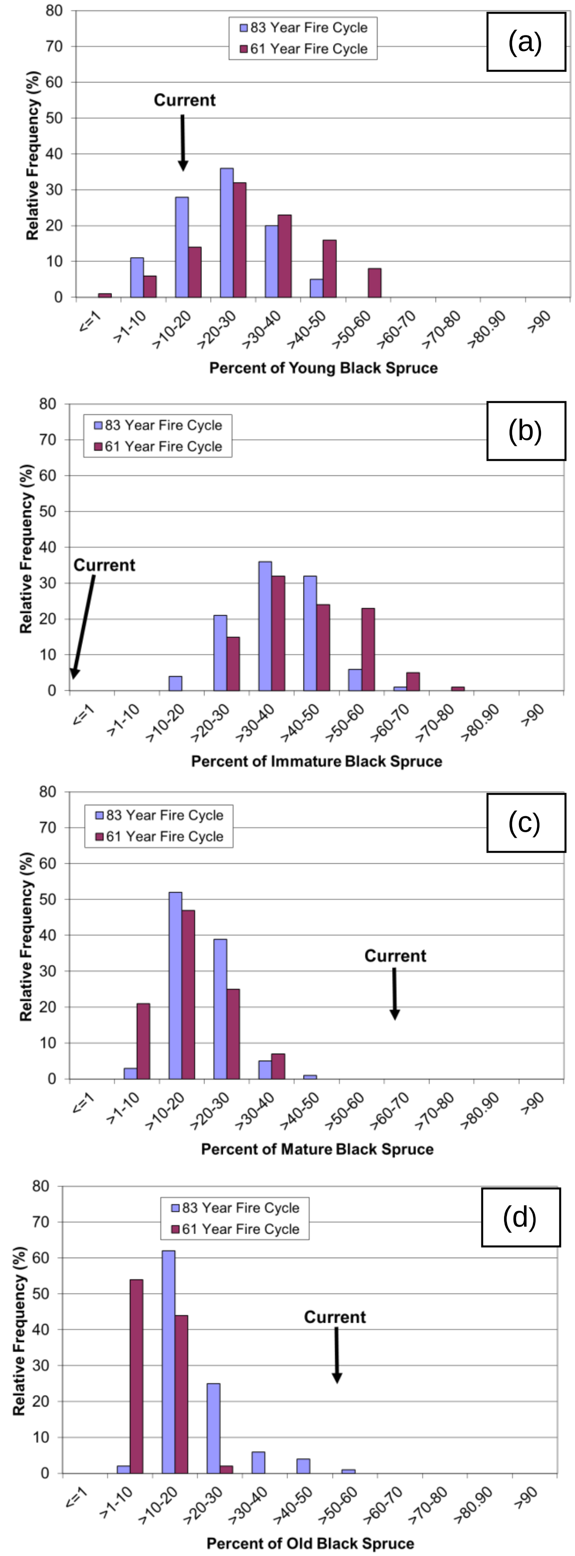


Figure 37. Frequency distribution of young (a), immature b), mature (c), and old (d) black spruce stands for the Other Mesic caribou habitat type on the Alpac FMA.

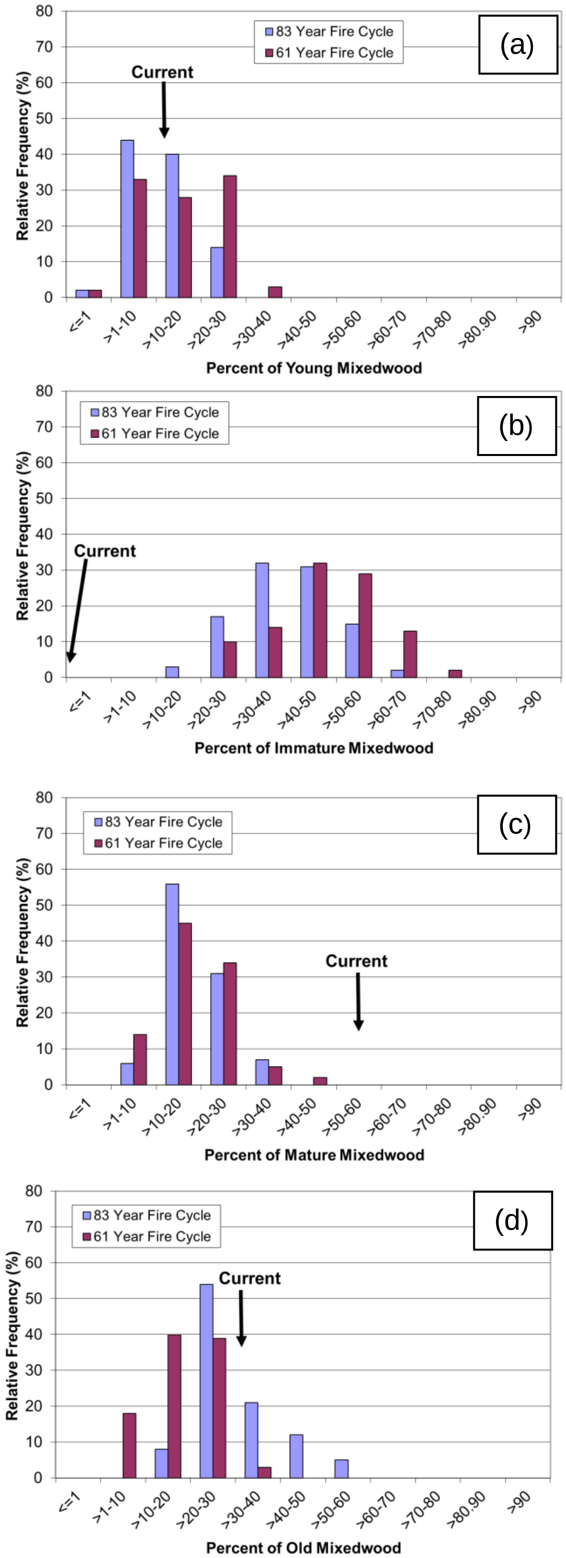


Figure 38. Frequency distribution of young (a), immature (b), mature (c), and old (d) mixedwood stands for the Other Mesic caribou habitat type on the Alpac FMA.

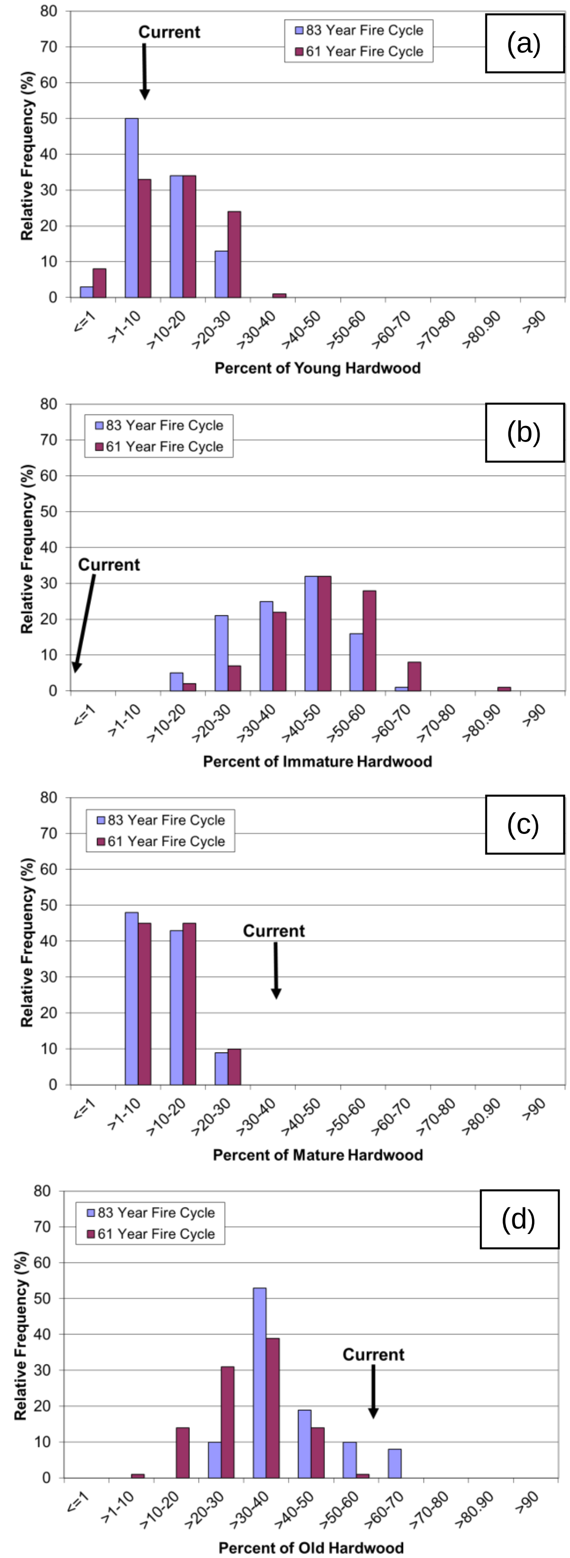
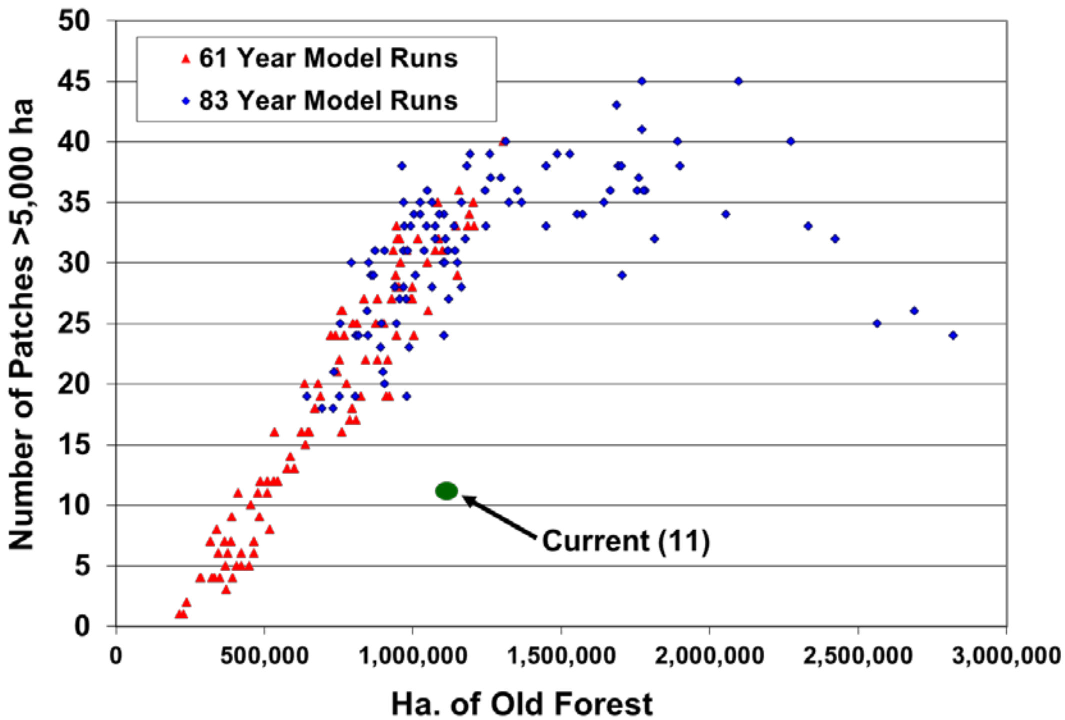


Figure 39. Frequency distribution of young (a), immature b), mature (c), and old (d) hardwood stands for the Other Mesic caribou habitat type on the Alpac FMA.

4.4 Spatial Results

Old forest patch sizes are significantly related to the amount of old forest – to a point. For example, the expected number of old forest patches larger than 5,000 ha is about 30 when there is 1,000,000 ha of old forest on the FMA (or 19% of the forest area), but only 12 when old forest accounts for 500,000 ha (or 10% of the forest area) (Figure 40). Note that there is a fairly strong linear relationship between the number of old patches >5,000 ha and old forest area (in hectares) up to about 1.3 million ha (Figure 40). After *circa* 1.3 million ha (or about 25% of the forested area), the relationship deteriorates - almost becoming random. The reason for this is that at some critical proportional threshold, the probability of pixels of a similar type joining into very large contiguous patches increases dramatically (Gardner et al. 1987). So, although the number of large patches levels off, or even declines, the total area within those patches increases significantly. For example, the eight landscape scenes that created more than 2 million ha of old forest all had at least one old forest patch at least 400,000 ha in size, and the three landscapes with more than 2.5 million ha had old forest patches larger than 900,000 ha.

Figure 40. Historical and current old forest patches larger than 5,000 ha on the Alberta-Pacific FMA.



It is interesting to note that the relationship between old forest levels and large old forest patch density is consistent across both model scenarios. This follows logically; regardless of the circumstance by which it occurred, as the amount of old forest increases across a landscape, the chances of creating more large old forest patches increases.

There are currently 1,136,000 hectares of old forest and 11 old forest patches larger than 5,000 ha on the AlPac FMA, regardless of leading species. The largest old forest patch is just over 9,600 hectares. The average number of old forest patches larger than 5,000 ha according to the NRV simulations was 30 (Figure 40). However, this is only part of the story. The 61-year modelling scenario created old forest patches larger than 50,000 ha 35% of the time, and larger than 10,000 ha 91% of the time. The 83-year scenario never created a landscape with less than five old forest patch smaller than 10,000 ha, and 71% of the time it created landscapes with old forest patches in excess of 50,000 ha. In other words, the largest, rarest, old forest patches that one would expect based on the modelling output do not exist on the AlPac FMA today.

A similar historical relationship between old forest area and old forest patch size is found when "old" is defined by vegetation type. Pine and hardwood leading forest types tend to have fewer large old forest patches than either black spruce or mixedwood because they have significantly less area (Figure 41). It is also interesting that the relationship differs by species type. The slope of the line for both black spruce and mixewood types is steeper than that for the pine and hardwood types (Figure 41). This may be the result of lower overall amounts of pine and hardwood translating into greater levels of spatial disaggregation for those particular vegetation types across the landscape, thus making it more difficult to create a large contiguous patch of any single seral-stage. In other words, vast areas of contiguous pine or hardwood forest do not exist on the FMA. In contrast, very large contiguous blocks of black spruce and mixedwood types are common on the AlPac FMA.

The largest old patch of mixedwood forest was 386 ha, black spruce forest 1,765 ha, deciduous forest 295 ha, and pine-leading forest 399 ha. The NRV for each species group from simulation suggested species-specific old forest patches in excess of 10,000 ha in each case. This suggests that cultural activities have significantly influenced natural old forest patterns at the forest-type scale.

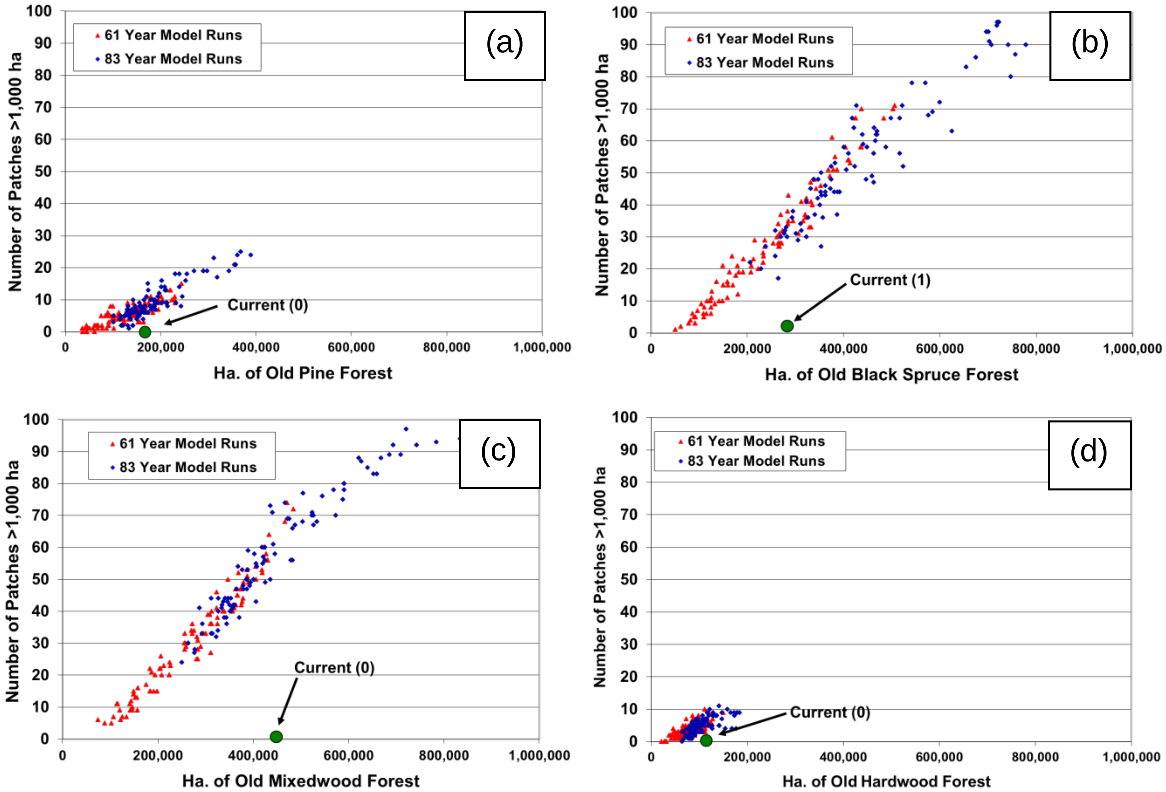


Figure 41. Number of old forest patches >1,000 for (a) pine, (b) black spruce, (c) mixedwood, and (d) hardwood forest, relative to the amount of old forest in each species type, for the AlPac FMA.

4.5 Woodland caribou habitat NRV results

The boreal population of woodland caribou (*Ranigifer tarandus caribou*) is a threatened species under the Species At Risk Act (SARA). The AlPac FMA includes parts of four recognized caribou ranges according to Environment Canada (2011); 1) the Cold Lake (361 hectares), 2) the East Side Athabasca River (1,388,000 hectares), 3) Richardson (25,000 hectares) and 4) the West Side Athabasca River (1,498,000 hectares). The population trends of the Cold Lake, East Side Athabasca River, and West Side Athabasca River herds are declining and all four herds are defined as "*not self sustaining*". (Environment Canada 2012).

The recently published woodland caribou recovery strategy includes very specific guidelines concerning potential caribou habitat. The strategy defines sustainable caribou habitat as that which "…*maintains a perpetual state of a minimum of 65% of the area as undisturbed habitat*…", where undisturbed habitat is "… *the combined effects of fire that has occurred in the past 40 years*.." (Environment Canada 2012).

Figure 42. NRV of the percent of the West Side Athabasca Woodland caribou herd zone forest that is >40 years of age.

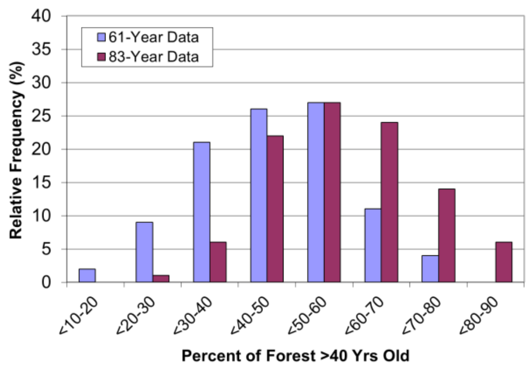
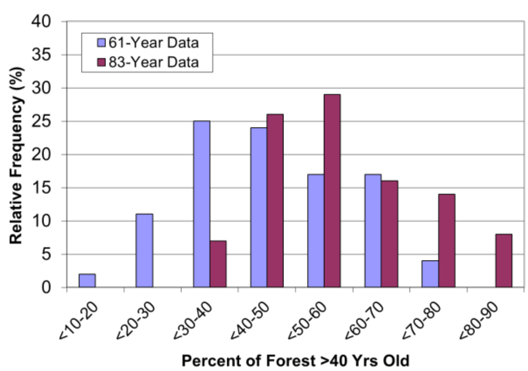


Figure 43. NRV of the percent of the East Side Athabasca Herd woodland caribou zone forest that is >40 years of age.



The implicit assumption in these statements is that the natural landscape, prior to significant human intervention, provided sufficient habitat of this type for caribou. Fortunately, this study provides an opportunity to test that assumption against the existing requirements.

The 83-year modelling scenario suggested that the minimum level of 65% of "undisturbed" forest was generated only 8% for the 61-year scenario (Figure 42), and 29% of the time under the 83-year scenario (Figure 43).

Adopting a sensitivity analysis approach (using the 61-year scenario), if the 65% threshold were reduced to 60%, the modelling exercise generated 23 successful landscape scenes out of 100, and at 50%, there were 39 landscapes that would support caribou. To get to a situation where the probability of having a suitable supply of caribou habitat, the maximum allowable amount of forest <40 years of age would have to be 45% (instead of 65%).

5.0 Discussion

5.1 NRV and current condition of the FMA

The main messages associated with the results of this study hold for both LT fire cycle assumptions. This study identified two concerns as regards the current landscape condition; 1) an historically unprecedented age-class imbalance, and 2) the absence of very large old forest patches. To the first point, overall disturbance levels on the AlPac FMA landscape have been on the lower end of, or below, NRV for several decades. This has pushed the amount of mature forest well beyond the upper bounds of NRV. Today, mature forest accounts for more than half of all forest on the FMA. Although in most cases the amount of old forest is currently well within the historical range, the proportion of old will start to increase rapidly as the massive bulge in the mature seral-stage ages. This conclusion holds true for both LT fire cycle scenarios.

Since it is unfamiliar, a shift beyond NRV is often associated with (negative) biological consequences. In this case, the current landscape is simpler and less diverse than that observed historically. Diverse ecosystems provide a sort of temporal buffer against external shocks without fundamentally changing the nature of the ecosystem. This is often referred to as *resilience* (Drever et al. 2006). More homogenous landscape are less resilient to external perturbations (Methven and Feunekes 1987) such as mountain pine beetle and wildfire (Odum et al. 1987, Romme 1982) and more likely to be affected by climate change.

A simplified landscape mosaic also potentially translates into less biodiversity. One of the more obvious threats to this landscape is the loss of young forest habitat in some vegetation types. Boreal landscapes boast a significant spike in diversity for the first several years after wildfires, favouring a large number of specialists that are not just adapted to fire, but depend on it. Similarly, the removal or abating of disturbance as a process from some ecosystem types will potentially have significant consequences. For example, disturbances such as wildfires are critical for creating pulses of dead wood that ultimately become important functional elements in small streams (Jones and Daniels 2008).

Another potential risk associated with a landscape with a continually aging forest is the fate of the large pulse of older forest. Over the next one or two decades, a large part of the AlPac forest will be transitioning from mature to old, eventually pushing the amount of old forest beyond NRV. On the AlPac FMA no evidence of fire *refugia* (e.g., areas that repeatedly avoid wildfire) has been found. In other words, historically, only a very small portion of the landscape escapes fires for more than 2-250 years, and then so, only randomly so. For example, using the simple negative exponential model introduced earlier, an average of 9% of forest greater than 200 years of age is expected on a landscape with an 83-year LT fire cycle, and just 4% assuming a 61-year LT fire cycle.

The dynamics of these very old parts of the landscape is largely unknown. In parts of boreal Quebec, where fire cycles exceed 200 years, Old forest dynamics include gap dynamics caused by the death of individual trees which create gaps allowing for the regeneration and/or release of younger trees (Gauthier et al. 1996). Gap dynamics are also thought to occur in the western boreal mixedwood (Cumming et al. 2000) where short-lived aspen are replaced by shade tolerant white spruce and abies. Thus, a likely future landscape scenario that involves more old forest would shift from mixedwood to conifer dominated, and from even-aged to all-aged.

The second NRV-related concern raised by this study is the lack of large and very large old forest patches. At the current level of old forest on the FMA, there should be at least double the number of old patches larger than 5,000 ha, including at least one that is >25,000 ha. However, the current condition situation for old forest patches is only part of the story.

There are at least two sources of old forest patch partitioning on this landscape; 1) fragmentation from cultural disturbance activities such as harvesting, and 2) linear features. The two sources arguably create two different ecological situations as well; old forest edge against younger forest versus old forest edge against a long-term disturbance. One might presume that linear feature edge is "harder". A further complication is that all linear features were treated equally for the current condition calculation. Thus, a 15-year old 3m seismic line is treated the same as a 50m highway right of way. "Edge" can mean different things to different species under different circumstances (Ries et al. 2004).

Not only does the current condition estimate not consider the source of patch isolation, it also considers all "old" boundaries equal. Given the history of industrial activity on this landscape, it is safe to assume that linear features such as roads and seismic lines are almost certainly a major cause of patch isolation (Pickell et al. 2015). We can further safely assume that there are many different types and ages of linear features. So a more thorough exploration of the influence of different types and ages of linear features on the patch sizes of old forest would be a valuable addition to this research. The 11 patches identified by the first iteration of this calculation is inclusive and thus represents the most conservative estimate of large old forest patch numbers.

5.2 NRV of caribou herd zones

The low to very low probability of achieving the 40yr-65% Environment Canada threshold of caribou habitat type historically suggests either/or a) caribou were dynamic over space and time in response to the highly active wildfire regime, or b) our assumptions about what constitutes suitable caribou habitat are in error. Either way, the results suggest that our understanding of woodland caribou is missing at least one critical ingredient. One of the likely candidates is the assumption that typical boreal wildfires are stand-replacing (Johnson 1992). Recent evidence suggests that only 10% of the historical wildfires would technically qualify as *stand-replacing*. Rather, on average, almost 40% of the area within wildfires in the boreal plains survive to some degree (Andison and McCleary 2014), and 25% of the time, more than 60% of the area within natural wildfires survives. Presumably, as the survival level within disturbances increases, the time to create a viable lichen population decreases, as does the danger from predation due to increased hiding cover. In other words, the 40 year threshold may be much lower. This is a testable hypothesis.

LITERATURE CITED

Andison, D.W. 2012a. The influence of wildfire boundary delineation on our understanding of burning patterns in the Alberta foothills. Can. J. For. Res. 42: 1253–1263.

Andison, D.W. 2012b. Pre-Industrial Seral-Stage Natural Range of Variation Simulation Analysis on the Alberta Newsprint Company FMA Area**.** Bandaloop Landscape-Ecosystem Services, Vancouver, BC. May 2012. 42p.

Andison, D.W. 2007a. Pre-Industrial Forest Condition Analysis and Integration of Natural Disturbance Patterns on the Mistik Management Ltd. FMA Area in Saskatchewan. Bandaloop Landscape-Ecosystem Services, Vancouver, BC. March 2007. 30p.

Andison, D.W. 2007b. Pre-industrial seral-stage natural range of variation simulation analysis on the Tolko Industries and Footner Forest Products joint FMA area in Alberta. Bandaloop Landscape-Ecosystem Services, Vancouver, BC. Sept. 4, 2007. 85p.

Andison, D.W. 2005a. Natural levels of forest age-class distribution on the Alberta-Pacific FMA. Bandaloop Landscape-Ecosystem Services, Vancouver, BC. Nov. 17, 2005.

Andison, D.W. 2005b. Natural levels of forest age-class distribution on the RSDS landscape of Alberta. Bandaloop Landscape-Ecosystem Services, Vancouver, BC. Dec, 2005.

Andison, D.W. 2004. Natural Levels of Forest Age-class Variability on the Sunpine FMA. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. August 18, 2004. 34p.

Andison, D.W. 2003. Patch and event sizes on foothills and mountain landscapes of Alberta. Alberta Foothills Disturbance Ecology Research Series, Report No. 4. March, 2003. Foothills Model Forest, Hinton, Alberta.

Andison D.W. 1999a. Validating age data on the Mistik FMLA: Laying the groundwork for natural disturbance research. Bandaloop Landscape-Ecosystem Services, Belcarra, BC.

Andison, D.W. 1999b. Assessing age data in foothills and mountain landscapes of Alberta: Laying the groundwork for natural disturbance research. Alberta Foothills Disturbance Ecology Research Series Report No. 1. Foothills Model Forest, Hinton, Alberta.

Andison, D.W. 1998a. Patterns of temporal variability and age-class distributions on a Foothills landscape in Alberta. Ecography 21:543-550.

Andison, D.W. 1998b. Age-class distributions and fire cycles on the Mistik FMLA: A preliminary analysis. Bandaloop Landscape-Ecosystem Services, Coal Creek Canyon, Colorado, March, 1998.

Andison, D.W. 1996. Managing for landscape patterns in the sub-boreal forests of British Columbia. Ph.D. thesis, UBC, Vancouver, BC. 197p.

Andison, D.W. and P.L. Marshall. 1999. Simulating the impact of landscape-level biodiversity guidelines: A case study. The Forestry Chronicle. 75(4): 655-665.

Andison, D. W., and K. McCleary. 2014. Detecting differences in regional wildfire burning patterns in western boreal Canada. *The Forestry Chronicle, 90*(1), 59–69.

Andison, D.W., R. Shulz, and P.L. Marshall. 2005. Comparing Stand Origin Ages with Forest Inventory Ages on a Boreal Mixedwood Landscape. University of BC, Vancouver, BC. 59p.

Athabasca Landscape Team. 2009. Athabasca caribou landscape management options report. Alberta, Canada. May 2009.

Booth, D.L., D.W.K. Boulter, D.J. Neave, A.A. Rotherham, and D.A. Welsh. 1993. National forest landscape management: A strategy for Canada. The For. Chron. 69(2):141-145.

Brassard, B.W., H.Y.H. Chen, J.R. Wang, and P.N. Duinker. 2008. Effects of time since stand-replacing fire and overstory composition on live-tree structural diversity in the boreal forest of central Canada. Can .J. For. Res. 38(1):52-62.

Clarke, K.C., J.A. Brass, and P.J. Riggan. 1994. A cellular automaton model of wildfire propagation and extinction. Photo. Eng. & Remote Sensing. 60(11): 1355-1367.

Cumming, S.G., F.K.A. Schmiegelow, and P.J. Burton. 2000. Gap dynamics in boreal aspen stands: Is the forest older than we think? Ecological Applications 10:744-759.

Davis, W. 1993. The global implications of biodiversity. M.A. Fenger et al. (eds.), Our Living Legacy. Proc. of a Symp. on Biological Diversity. Victoria, BC. pp. 23-46.

Drever, C.R., G. Peterson, C. Messier, Y. Bergeron, and M. Flannigan. 2006. Can forest management based on natural disturbances maintain ecological resilience? Can. J. For. Res. 36: 2285-2299

Environment Canada. 2011. Scientific assessment to support the identification of critical habitat for woodland caribou (Rangifer tarandus caribou), boreal populations in Canada. Ottawa, Ontario. 115pp + appendices.

Environment Canada. 2012. Recovery strategy for the woodland caribou (Rangifer tarandus caribou), Boreal populating in Canada. Species at Risk Act Recovery Strategy Series. Environment Canada, Ottawa, xi+138pp.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? Ecol. Appl. 3: 202-205.

Gardner, R.H. B.T. Milne, M.G. Turner, and R.V. O'Neill. 1987. Neutral models for the analysis of broad-scale landscape patterns. Landscape Ecology. 1(1): 19-28.

Gauthier, S., Leduc, A. and Y. Bergeron. 1996. Forestry dynamics modelling under a natural fire cycle: A tool to define natural mosaic diversity for forest management. *Environmental Monitoring and Assessment, 39*, 417-434.

Grumbine, E.R. 1994. What is ecosystem management? Conservation Biology. 8(1):27.38.

Johnson, E.A. 1992. Fire and vegetation dynamics: Studies from the North American Boreal Forest. Cambridge U. Press, Great Britain. 129 p.

Jones, T. A., and L.D. Daniels. 2008. Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills. *Forest Ecology and Management, 256*(10), 1751–1759.

Kabzems, R. and O. Garcia. 2004. Structure and dynamics of trembling aspen / white spruce mixed stands near Fort Nelson, BC. Can. J. For. Res. 34(2):384-395.

Lieffers, V.J., K.J. Stadt, and S. Navratil. 1996. Age structure and growth of understory white spruce under aspen. Can. J. For. Res. 26(6): 1002-1007.

Long, J.N. 2009. Emulating natural disturbance regimes as a basis for forest management: A North American view. For. Ecol. and Manage. 257: 1868-1873.

Methven, I. and V. Feunekes. 1987. Fire games for park managers: Exploring the effect of fire on landscape vegetation patterns. In: Moss, J.M. (ed), Landscape Ecology and Management. Proceedings of the first symposium of the Canadian Society for Landscape Ecology and Management. U. of Guelph, Ontario. p. 101-109.

Odum, W.E., T.J. Smith III, and R. Dolan. 1987. Suppression of natural disturbance: Long term ecological change on the outer banks of North Carolina. In: Goigel-Turner, M. (ed), Landscape Heterogeneity and Disturbance. Ecol. Stud. 64. Springer-Verlag, Germany. p. 123-135.

Payette, S. 1993. Fire as a controlling process in North American boreal forest. In: West, D.C., H.H. Shugart, and D.B. Botkin (eds.), Forest Succession: Concepts and Applications. Springer-Verlag, New York. pp.144-169.

Pickell, P.D., Andison, D.W., N. Coops, S. E. Gergel, and P.L. Marshall. 2015. Transition of the anthropogenic disturbance regime in western Canadian boreal forest following oil and gas development. Can. J. For Res. doi: 10.1139/cjfr-2014-0546.

Ries, L., R.J. Fletcher, Jr., J. ZBattin, and T.D. Sisk. 2004. Ecological responses to habitat edges: Mechanisms, models and variability explained. Ann. Rev. Ecol. Evol. Sys. 35: 491-522.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecological Monographs. 52(2): 199-221.

Taylor, S.W., K. Kepke, N. Parfitt, and C.C. Ross. 1994. Wild fire frequency in Yukon ecoregions. Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. 22 p.

Turner, M.G., and V.H. Dale. 1991. Modelling landscape disturbance. In: Turner, M.G. and R.H. Gardner (eds), Quantitative methods in landscape ecology. Ecol. Studies 82, Springer-Verlag. p. 322-351.

Van Wagner, C.E. 1978. Age class distribution and the fire cycle. Can. J. For. Res. 8(2):220-227.

Ward, P.C. and A.G. Tithecott. 1993. The impact of fire management on the boreal landscape of Ontario. OMNR, Aviation, Flood and Fire Management Branch Pub. No. 305. 12 p.

Wilken, E.B. 1986. Terrestrial Ecozones of Canada. Ecological Land Classification No. 19. Environment Canada, Hull, Quebec. 26p.

Yarie, J. 1981. Forest fire cycles and life tables: A case study from interior Alaska. Can. J. For. Res. 11: 554-562.