DEFINING HABITAT RESTORATION FOR BOREAL CARIBOU IN THE CONTEXT OF NATIONAL RECOVERY:

A Discussion Paper

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NOTE

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EXECUTIVE SUMMARY

With many boreal caribou population ranges across Canada in non-self sustaining condition, habitat restoration has become an increasing imperative for recovery of this species at risk. With decades required to return disturbed areas to mature forest conditions required by caribou, this presents a significant challenge. The extent of habitat loss that is ongoing in large parts of the species' distribution is exacerbated by a legacy of inadequate attention to reclamation following development and associated linear features. The Recovery Strategy for boreal caribou under the federal *Species At Risk Act*, released in 2012, provides a framework for setting restoration priorities for boreal caribou, based on a well-established relationship between habitat disturbance and population condition. The reference state for boreal caribou habitat restoration efforts is defined as the relative amount of "undisturbed habitat" as a key part of Recovery Strategy's critical habitat definition, relative to the recovery goal of achieving self-sustaining local populations in all boreal caribou ranges throughout their current distribution in Canada, to the extent possible. This paper discusses and defines boreal caribou habitat restoration in the context of both national recovery efforts for this species at risk and insights from caribou ecology and the rapidly advancing field of ecological restoration.

The practice of ecological restoration tends to be dominated by local-scale efforts, yet effective restoration for boreal caribou will require explicit linkages between site-specific restoration actions and corresponding range-level effectiveness evaluations. Site-scale efforts directed towards restoring features (e.g., wellpads, cutblocks, linear features, etc.) are necessary to set a course for success, where work is defined on the basis of local (e.g., eco-site) conditions to establish the best potential areas, likely trajectories, and the end points of active efforts. And while it would be appropriate to credit restoration efforts in some fashion for work that has achieved interim success (i.e., establishment on a trajectory), this does not itself indicate that sufficient restoration has occurred to trigger permitting of disturbance elsewhere in a population range if it has not achieved self-sustaining status. Where required, habitat restoration at the range scale should prioritize areas for restoration effort, undertake strategic coordination of restoration activities, build large blocks of restored features with high connectivity, and monitor progress of range-scale restoration. Range plans, mandated by the Recovery Strategy, will provide a useful platform for guiding restoration efforts at appropriate scales and monitoring the success of all recovery efforts. Locally variable conditions and a lack of a true ecological threshold makes it necessary to adopt a cautious approach with deploying the management threshold of 65% "undisturbed habitat" as a restoration target, and heightens the importance of monitoring of population trends to test whether local populations are responding positively to restoration efforts. A framework offered in this paper establishes criteria for measuring progress toward the restoration goal and objectives. Each criterion is designed to be implemented at either the feature or range scales, all of which should be considered in tandem.

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INTRODUCTION

The restoration of degraded ecosystems has become a primary focus of global conservation efforts in terrestrial and aquatic environments (MEA 2005). With habitat loss, degradation, and fragmentation as the leading threat to biodiversity globally (Vitousek et al. 1997; Fischer & Lindenmayer, 2007) and in Canada (Venter et al. 2006), successful recovery of species at risk of extinction increasingly involves active habitat restoration as an essential activity paired with other conservation strategies. Boreal caribou (*Rangifer tarandus caribou*), which have been profoundly affected by ongoing anthropogenic habitat changes in large parts of their Canadian distribution, illustrate this need.

Generally speaking, habitat restoration "seeks to replace what has been lost" (Bedford 1999), yet there are multiple definitions of this concept (Jørgensen 2013). The process of restoration implies ecological repair, or an active reversal of land degradation. In most definitions, restoration is the endpoint of a continuum of human-facilitated improvement, but notions of success vary. The Society for Ecological Restoration (SER) defines the science of restoration ecology as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). Halme et al. (2013) point out that “assisting the recovery” implies active management with the goal of ecological restoration to return the system to some previous state.

The practice of restoration can have several levels of ambition (Figure 1), exemplified by other terms such as *revegetation*, *rehabilitation,* and *reclamation*. Whereas the ultimate ambition of 'restoration' tends to be the ‘original’, ‘initial’, or ‘pre-disturbance’ conditions (van Andel et al. 2012); other terms, which are often used interchangeably, have lesser goals. For example, 're-vegetation' is limited to the establishment of plant cover, and 'rehabilitation' refers to the improvement of ecosystem functions without necessarily seeking to achieve a full return to pre-disturbance conditions (van Andel et al. 2012; Burton & Macdonald 2011). 'Reclamation', on the other hand, is usually used to mean the return of the land to a useful (yet productive) purpose (Clewell & Aronson 2007); in silviculture the aim is to re-establish trees required for timber, fuel, or to increase carbon stocks (Burton and Macdonald, 2011; Suding, 2011).

Although ecological restoration is a rapidly developing field of research, poorly-defined targets and a lack of quality (or any) monitoring jeopardizes the critical enterprise of evaluation and learning from successes and failures (Gonzáles et al. 2013; Wortley et al. 2013). Despite broad agreement that comprehensive evaluations based on well-defined targets and appropriate monitoring would be key to future progress, these are rare among a multitude of restoration projects. Goal setting for restoration activities may be defined by permitting or legislative requirements or by aspirations to restore biodiversity and ecosystem function (Burton & Macdonald 2011). More often than not, however, it is undefined, or constrained by considerations of feasibility or economics (Hobbs 2007).

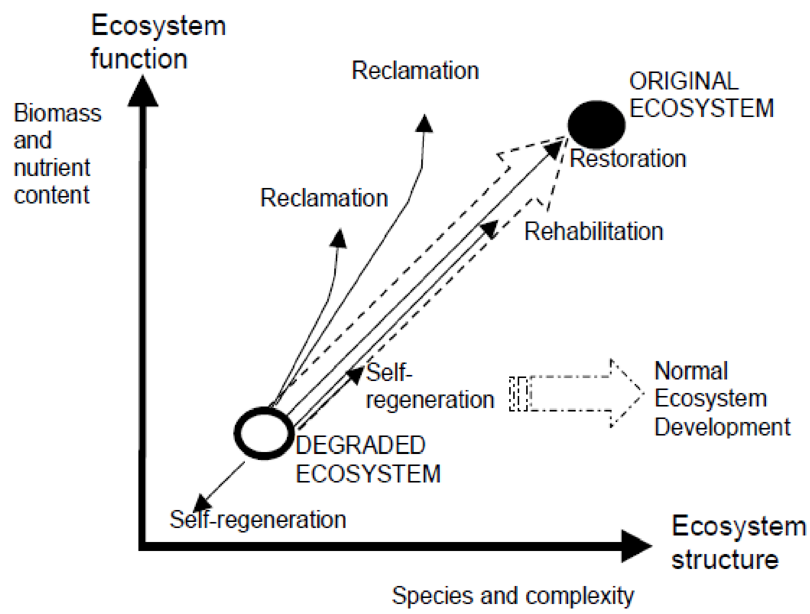

Figure 1. Degradation or loss of ecosystem structure and functions are the starting point for restoration activities. If nothing is done, self-regeneration may result in some recovery or may even erode the system. Active restoration activities can have several levels of ambition, ranging from reclamation to rehabilitation to restoration, which generally strives to achieve full recovery to a state resembling the original ecosystem. Source: Graf (2009), adapted from Bradshaw (1987).

Boreal caribou provide a measure of the intensity and extent of the cumulative effects of industrial activity, with declines of individual populations evident in many parts of their Canadian distribution, particularly where disturbance has been most extensive (Environment Canada 2011; 2012; Festa-Bianchet et al. 2011). Accordingly, habitat restoration will have to form a large component of recovery efforts for this species, which is currently listed as Threatened under the federal *Species At Risk Act* and under most provincial and territorial species at risk legislation within the species' distribution (Environment Canada 2012).

Habitat restoration for boreal caribou will necessarily be guided by whatever will be necessary to achieve the recovery goal of "self-sustaining"[1] local populations in all boreal caribou ranges throughout their current distribution, to the extent possible" (Environment Canada 2012). The goals of this discussion paper are to discuss and define boreal caribou habitat restoration in the context of both national recovery efforts for this species at risk and insights from the rapidly advancing field of ecological restoration, and to propose criteria for what constitutes restored habitat.

[1] A self-sustaining local population is "a local population of boreal caribou that on average demonstrates stable or positive population growth over the short-term (≤20 years), and is large enough to withstand stochastic events and persist over the long-term (≥50 years), without the need for ongoing active management intervention" (Environment Canada 2012:47).

HISTORY OF BOREAL CARIBOU HABITAT RESTORATION

Since the 1950s, resource extraction activities such as oil and gas exploration and development, combined with increased forestry and agricultural development have transformed the boreal forests in the western sedimentary basin of northwest Canada (Nitschke 2008, Price et al. 2010; Rooney et al. 2012). Likewise, in the southern portion of the boreal zone throughout Canada, industrial activities have replaced fire as the dominant disturbance agent (Cyr et al. 2009). Forestry has been the principal cause of land use change, but mining development and exploration, hydroelectric development, peat mining, and some agricultural development are increasing in intensity and scope in some areas (Brandt et al. 2013).

Many boreal caribou populations, particularly in southern and western Canada, have experienced high rates of landscape changes in their ranges over the past 10-20 years (Environment Canada 2011; 2012; Festa-Bianchet et al. 2011; Hervieux et al. 2013; COSEWIC in press). This strongly suggests that habitat protection and restoration has not kept pace with the rate of habitat loss. The gap is at least partially explained by the lack or inadequacy of reclamation standards that govern the oil and gas sector (e.g., Rooney et al. 2012). Although requirements and standards to regenerate boreal forest following disturbance from forestry operations have a much longer history in Canada (Buda & White 2007; Lieffers et al. 2009) than does the oil and gas industry, there is a general lack of success in renewing caribou habitat, as suggested by recent reviews on forestry standards from the perspective of caribou conservation (Dzus et al. 2010; Antoniuk et al. 2012).

The lack of post-development habitat restoration is particularly noteworthy where oil and gas development has been far reaching. For example, with operators not being required to return the land to its original state, there has been extensive conversion of wetland habitat to upland forest habitats where oil sands mining is taking place in Alberta; less than 35% of peatland is expected to remain in a post-mining landscape (Rooney et al. 2012). Until recently, the energy sector invested little in actively recovering vegetation on seismic lines in boreal forests, under the assumption that these sites would regenerate naturally, as occurs after fire or forest harvesting (Bayne et al. 2011). Lee and Boutin (2006) discovered that about 60% of seismic lines they assessed in western Canada had not recovered to woody vegetation within 35 years, and remained in a clear state with low forb cover; there was no natural recovery in lowland black spruce sites. Based on observed median recovery rates (defined as the percent cover return of woody vegetation detectable on aerial photography), they estimated the time to recovery of 112 years, with the highest prospects on upland aspen and white spruce sites. Continued human industrial and recreational use of lines hampered recovery.

To illustrate the consequences of this spread of activity to one boreal caribou population, the 300,000 ha Little Smokey caribou range in northwestern Alberta is blanketed by 11,277 km of linear features that include seismic lines, pipelines, well sites and other features (Nash 2010).

Among these, only about 28% had achieved sufficient vegetation growth to be indexed as “reclaimed”[2], while 59% had no or insufficient vegetation growth (Nash 2010). Most features were built well before construction practices had shifted to narrower "low impact" seismic lines (Lee & Boutin 2006, Bayne et al. 2011), but they illustrate the profound and lasting legacy of decades of intensive industrial disturbance exacerbated by a lack of attention to restoration.

Active restoration of boreal caribou habitat is a relatively new endeavour; restoration activities are not even listed among "actions already completed or currently underway" catalogued in Section 6.1 of the Recovery Strategy (Environment Canada 2012). Habitat restoration is, however, highlighted as a necessary component of boreal caribou recovery actions in the same document, as well as in provincial recovery strategies (e.g., Alberta Woodland Caribou Recovery Team 2005; BC MOE 2011), and regional (ALT 2009) plans. Although some larger-scale caribou restoration efforts were first initiated about 15 years ago, they have had mixed success (Golder Associates 2012). Most of the focus has been on establishing vegetation along linear corridors, and/or controlling human or predator access, with limited documented success from a caribou recovery perspective to date. This lack of success discussed above is compounded by lack of monitoring and time lag issues (Golder Associates 2012; 2014).

RESTORATION AS A COMPONENT OF BOREAL CARIBOU RECOVERY ACTIONS

The necessity of restoration is particular clear for those caribou ranges where local populations are small and/or declining and cumulative disturbance is at high levels (>50% of the range; e.g., Hervieux et al. 2013; COSEWIC in press). In such cases, population recovery will require a combination of habitat restoration, restriction of the future human footprint (i.e., full protection of some areas), and in many cases population management (e.g., predator and alternative prey control) as part of a broad land use planning framework (ALT 2009; Boutin 2010). To illustrate, the Athabasca Landscape Team, established in 2008 to develop "landscape management options" for four local populations in northeast Alberta, concluded that an "aggressive suite of management options" will be necessary to stave off extinction of resident caribou. Results from a series of simulations forecasting likely caribou populations and habitat conditions under various scenarios of land use change indicated that the combination of coordinated landscape-scale restoration and future footprint reduction focused on high-value caribou areas would have the greatest incremental benefit compared to other measures (ALT 2009).

[2] "Reclaimed" was defined by Nash (2010:7) as "The disturbance has suitable vegetation growing within acceptable parameters (i.e. density, distribution, species) to meet management objectives". This was measured in relation to an index based on “restored” criteria. A line would be considered “restored” once there was sufficient coniferous regeneration re-established on the line to: 1) prohibit access by ATV's and2) discourage any deciduous browse from growing in the understory.

Although the need for habitat restoration in ranges of many non-self-sustaining caribou populations is clear in concept, the goals or desired endpoints are seldom explicitly defined. Definitions or goals of caribou habitat restoration are commonly identified as a knowledge gap (e.g., Nova Gas Transmission Ltd. 2012, Golder Associates 2012). Moreover, the emphasis of permits and regulations governing natural resource development taking place within the distribution of boreal caribou has been far removed from restoration in the service of caribou recovery. For most, the endpoint is reclamation, or the return to productive land. For example, the aim of Alberta's *2010 Reclamation Criteria for Wellsites and Associated Facilities* is to "obtain equivalent land capability", which is defined under provincial regulation as " the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical" (AESRD 2013:1). Ontario's *Forest Management Guide for Conserving Biodiversity at the Stand and Site Scales* offers as advice for best management practice only ("not mandatory direction") to "consider returning the road bed to the productive forest landbase" as long as the road is not slated for long-term use (OMNR 2010).

Despite the limitations of these and other reclamation regulations and policies with respect to boreal caribou habitat, the publication of the *National Boreal Caribou Recovery Strategy* (Environment Canada 2012) with its framework for critical habitat has sharpened the focus on habitat restoration within caribou ranges where habitat loss through development activities has been particularly pronounced. By drawing attention to restoration as an imperative component of boreal caribou recovery, it also raises questions about how the endpoint of this process should be defined relative to the overall recovery goal.

HABITAT RESTORATION IN THE CONTEXT OF BOREAL CARIBOU RECOVERY

Recovery of species at risk with large home ranges and complex habitat and life history requirements within dynamic ecosystems is challenging to implement because their requirements are not limited to discrete areas. Ensuring sufficient quality and quantity of habitat for such species demands consideration beyond individual habitat patches (Arkle et al. 2014). Caribou, for example, are broadly distributed across Canada's boreal forest biome, with individual animals requiring large expanses of mature conifer forest. They select habitat at multiple scales, move between seasonal ranges, and live at low densities relative to other ungulates (Festa-Bianchet et al. 2011; Environment Canada 2011; 2012). Their habitats are dynamic in nature and continually influenced by recurring large-scale disturbance events that lead to habitat changes in space and time.

A major driver of boreal caribou habitat selection is to reduce risk of predation by wolves and bears; as such, individuals are widely dispersed across the landscape, particularly in areas like mature forests and peatland complexes that contain poor habitat for alternative prey (moose and deer) and low numbers of predators (Rettie & Messier 2000; Bowman et al. 2010; Whittington et al. 2011). Individual animals can adjust to increasing disturbance levels by expanding their home ranges, but this adaptability has its limits. Once cumulative disturbance reaches a certain level, movements become constrained and individuals are restricted to sub-optimal habitats, with ultimate consequences to reproductive success and population-level viability (Faille et al. 2010; Beauchesne et al. 2014).

The identification of critical habitat in the national Recovery Strategy for boreal caribou (Environment Canada 2012) recognizes this complexity. Two successive scientific studies by Environment Canada to inform the identification of boreal caribou critical habitat[3] (Environment Canada 2008; 2011) demonstrated that habitat conditions at the scale of local population range[4] affect the productivity of boreal caribou. This work identified the local population range as the appropriate scale at which to identify critical habitat for this species. Specifically, critical habitat is the habitat that is necessary to maintain or recover self-sustaining local populations throughout their distribution, and is the fundamental concept underlying recovery of boreal caribou (Environment Canada 2012). Results from a meta-analysis of boreal caribou demographic data from across Canada concluded that the condition of boreal caribou local populations, as represented by calf recruitment, had a strong negative relationship with the total disturbance (calculated as the combined effects of non-overlapping human disturbance buffered by 500 m and fire within last 40 years, with no buffer) within boreal caribou ranges. In other words, the extent of cumulative disturbance in the range is a key determinant of whether or not a population is self sustaining over time (Environment Canada 2008; 2011).

In view of this strong relationship between overall habitat disturbance and caribou demography, the framework for critical habitat taken by the national Recovery Strategy is to consider disturbance as a proxy for population condition, relative to the recovery goal of achieving self-sustaining local populations in all boreal caribou ranges throughout their current distribution in Canada, to the extent possible (Schmiegelow 2013). As such, the Recovery Strategy identifies a minimum of 65% undisturbed habitat in a range as the “disturbance management threshold”, which provides a measurable probability (60%) for a local population to be self-sustaining (Figure 2). For boreal caribou ranges with less than 65% undisturbed habitat, the Recovery Strategy requires restoration of disturbed habitat to an undisturbed condition "over reasonable, gradual increments every five years" to a minimum of 65% undisturbed habitat. For boreal caribou ranges with ≥ 65% undisturbed habitat, the Recovery Strategy requires maintenance of a minimum of 65% undisturbed habitat (Environment Canada 2012).

[3] Critical habitat is defined by SARA as the habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species’ critical habitat in the recovery strategy or in an action plan for the species.
[4] The local population range is defined by Environment Canada (2012:47) as "the geographic area occupied by a group of individuals that are subject to similar factors affecting their demography and used to satisfy their life history processes (e.g. calving, rutting, wintering) over a defined time frame".

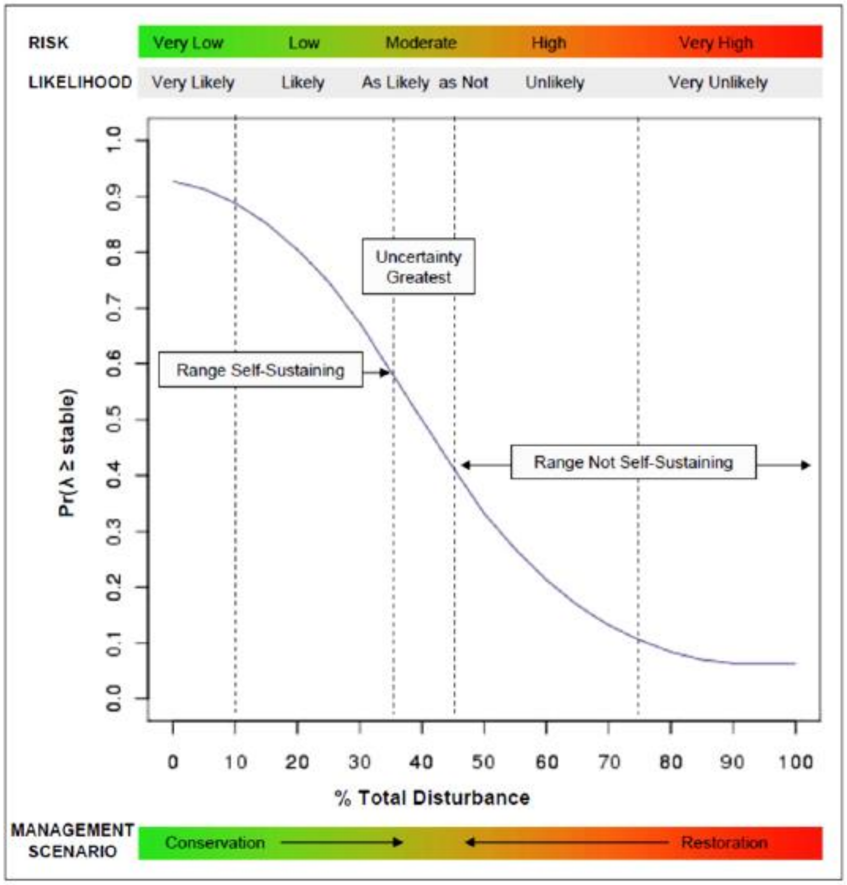

Figure 2. The disturbance-recruitment relationship derived from a meta-analysis of 24 boreal caribou populations. This demonstrates the probability of observing stable or positive growth (λ ≥ stable, i.e., self-sustaining) of caribou populations over a 20-year period at varying levels of total range disturbance (fires ≤ 40 years + anthropogenic disturbances buffered by 500 m). This served as a key component of critical habitat identification under SARA, whereby a disturbance management threshold of a minimum of 65% undisturbed habitat (i.e. 35% total disturbance) in a range was applied, with measurable probability (60%) for a local population to be self-sustaining. Source: Figure 71 in Environment Canada (2011).

The statistical strength of the disturbance-recruitment relationship has provided a robust scientific basis for identifying critical habitat and for defining the nature and extent of current recovery activities that focus on managing habitat change within boreal caribou ranges. Accordingly, the Recovery Strategy (Environment Canada 2012) sets up a framework with an explicit objective to reduce risk by limiting cumulative disturbance at the range scale. Although this offers a useful metric for defining critical habitat, it has raised questions as to how it can be applied in reverse in the service of recovery in general and habitat restoration in particular.

The management threshold and caribou habitat restoration

The disturbance-recruitment relationship is linear in nature (Environment Canada 2011), meaning that the more total disturbance in a population range the greater the probability of that caribou population being non self-sustaining. In other words, the relative amount of disturbance within the range of a local boreal caribou population is expressed across a wide range or continuum (Environment Canada 2011). Furthermore, although the underlying relationship is statistically strong (with total disturbance explaining 70% of population condition), it is characterized by variability. This means that the response to disturbance by individual local populations will vary according to unique characteristics operating at the range scale.

Accordingly, the outcome for a caribou population will be most certain at the lower and higher ends of the disturbance gradient, but there is substantial uncertainty in the middle (Figure 2). While based on Environment Canada's (2011) disturbance-recruitment relationship, the 65% / 35% undisturbed:disturbed management threshold identified in the Recovery Strategy is not an ecological transition point (*sensu* Ficetola and Denoel 2009). There is no evidence one exists for boreal caribou, so the threshold is instead an expression of management tolerance for risk to boreal caribou local population persistence. This introduces a scientifically arbitrary aspect that may fall short of the ecological objective (Hunter et al. 2009; Johnson 2013). After all, there are almost even odds that a given local population will not be self-sustaining when the range is 65% "undisturbed" (Figure 2; Environment Canada 2012).

The Recovery Strategy makes clear that those boreal caribou ranges that are below the 65% undisturbed habitat threshold will require restoration of habitat that has been lost in order to achieve recovery of the population. Because a population range that is characterized by more than 35% disturbance is deemed non-self-sustaining (where other lines of evidence, e.g., population size and trend, point in a similar direction), it is logical to infer that the corollary is also true, i.e., restoring habitat at sufficient levels to cross the line back again would ensure the recovery of that population. Indeed, the definition of "undisturbed habitat" provided in the glossary of the Recovery Strategy[5] is simply the opposite of "disturbed habitat". The "disturbed – non-disturbed" dichotomy is nevertheless problematic for predicting and measuring the point at which restoration will be achieved in a given population, due to a number of factors ranging from variability in local conditions to the particularities of the various datasets used to measure "disturbance". This illustrates well the key challenge arising from application of a prescriptive solution presented by a management threshold (Hunter et al. 2009; Johnson 2013), and the reason why performance indicators in the Recovery Strategy also include population condition. Accordingly, habitat targets are not to be met in isolation of population condition targets; not only does each range have to meet specific habitat condition targets, but they also have to meet specific population condition targets (e.g. achieve/maintain a stable to increasing pop trend over 5 years; Environment Canada 2012).

[5] "Undisturbed habitat" is defined as "habitat not showing any: i) anthropogenic disturbance visible on Landsat at a scale of 1:50,000, including habitat within a 500 m buffer of the anthropogenic disturbance; and/or ii) fire disturbance in the last 40 years..(without buffer)." (Environment Canada 2012:47).

As useful as the management threshold for disturbed/undisturbed habitat is for assessing relative risk to a caribou population in relation to the objectives set in the Recovery Strategy, it still leaves open a number of questions about how to apply this metric towards developing habitat restoration targets, and predicting or measuring the point at which these will be achieved. With this in mind, the remainder of this paper will explore these issues in further detail. I will first draw from the academic discipline of restoration ecology and best available information on caribou ecology to set goals and objectives for habitat restoration within boreal caribou ranges. The next step will be to develop specific criteria for application at appropriate scales that are relevant to boreal caribou recovery. This will be followed by a brief discussion on challenges and opportunities around implementation of caribou restoration using this proposed framework, and a summary of key findings.

DEFINING RESTORATION SUCCESS: INSIGHTS FROM RESTORATION ECOLOGY

Restoration ecology as an academic discipline has advanced considerably over the past 15 years, motivated in large part by the apparent urgency arising from the cumulative transformation of natural landscapes. This emergence is seeking to overcome the limitations of a traditional focus of restoration on ad hoc local-scale efforts (Hobbs & Norton 1996) by providing conceptual guidance, on-the-ground testing of various theoretical principles, and enhanced documentation of these endeavours, aimed at restoring ecosystems at landscape scales (Brudvig 2011).

A foundation document for the field -- produced by the Society of Ecological Restoration International -- is a widely-used and oft-cited Primer for ecological restoration (SER 2004). It provides a list of nine descriptive attributes as a guideline for measuring restoration success at a site: (1) similar diversity and community structure in comparison with reference sites; (2) presence of indigenous species; (3) presence of functional groups necessary for long-term stability; (4) capacity of the physical environment to sustain reproducing populations; (5) normal ecosystem-level functioning; (6) integration with the landscape; (7) elimination of potential threats; (8) resilience to disturbances; and (9) self-sustaining to the same degree as its reference ecosystem. These characteristics can be grouped into broader categories such as vegetation composition and structure, ecosystem function, landscape context or ecosystem stability (Ruiz-Jaen & Aide 2005; Shackelford et al. 2013).

Beyond defining technical terms, the SER (2004) offers no specifics on how success for these attributes can be measured, indicating instead that performance standards must be conceived from an understanding of the reference ecosystem, which defines the restoration goal. The document is also careful to state that it is not essential to achieve the full expression of all of these attributes, although it is necessary to "demonstrate an appropriate trajectory of ecosystem development towards the intended goals or reference" (SER 2004:3). Evaluations can be conducted through 1) direct comparisons of selected parameters measured in the reference and restoration sites, 2) attribute analysis, which involves an assessment of the nine attributes listed above relative to the restoration objectives, or 3) trajectory analysis, where trends from periodically collected data are evaluated to confirm that the restoration is following its intended trajectory towards the desired reference condition.

In the decade since the publication of the SER International Primer on Ecological Restoration (SER 2004), a number of literature reviews of published restoration work have focused primarily on the extent to which published restoration projects (which have grown substantially over the past decade) have defined and achieved success, many using the Primer attributes as a foundation (e.g., Ruiz-Jaen & Aide 2005; Brudvig 2011; Hallett et al., 2013; Halme et al., 2013, Jørgensen 2013, Morsing et al. 2013, Shackelford et al. 2013, Wortley et al. 2013). In practice, definitions of successful restoration for most projects tend to concentrate on vegetation structure and composition or diversity, which tend to be useful for predicting the direction and speed of succession (Ruiz-Jaen and Aide 2005). There is increasing attention to assessments of ecological function (Morsing et al., 2013; Wortley et al. 2013), but resilience (attribute 8) and self-sustainability (attribute 9) are rarely measured or achieved (Morsing et al. 2013).

Central to implementing ecological restoration must be consideration of the desired state or condition or trajectory to be moved to, commonly referred to as the reference state or ecosystem. This is both necessary for goal setting and diagnostic purposes (i.e., deviations from the trajectory), and serves as the foundation for planning and evaluation (SER 2004; van Andel 2012). Restoration criteria are commonly set by looking backwards to a condition resembling the past structure or composition. Because it is difficult to reconstruct the past in many cases, reference sites match as much as possible nearby sites with similar environmental conditions or more broadly to an estimated historical range of variability (SER 2004, Suding 2011).

DEFINING HABITAT RESTORATION FOR BOREAL CARIBOU

The nine SER (2004) attributes are site-based criteria that emphasize assisting the recovery of ecosystems, yet are valuable if species habitat is defined at similar scales. The few available conceptualizations of boreal caribou habitat restoration have been similar to SER (2004), extending beyond vegetation composition and structure and emphasizing functional habitat in terms that are complementary to range-level recovery goals articulated in the National Recovery Strategy for boreal caribou. For example, the Athabasca Landscape Team (ALT 2009) described reclaimed habitats in terms of their role to help achieve "functional habitat" over the long term for four population ranges in northeast Alberta. This was defined as "caribou habitat that is sufficiently old (>50 years in lowlands and >80 years in uplands), and had comparatively small areas of young forest (<30 years old) and anthropogenic footprint (e.g., corridors and clearings). Functional habitat provides caribou with sufficient food and opportunities to space away from predators." Restoration (for caribou) was defined by participants of a Woodland Caribou Restoration Workshop (Golder Associates 2014) as "disturbed caribou range is returned to habitat that can support a self-sustaining caribou population without ongoing management intervention (e.g., predator control)". Antoniuk et al. (2012) offered "the return of habitat to a state suitable for caribou use and reduced mortality risk, comparable to that which existed prior to disturbance" as a definition for caribou habitat restoration.

The exercise of mapping the nine SER (2004) attributes of restored ecosystem with characteristics that define successful boreal caribou conservation (Table 1) provides a basis for the formulation of boreal caribou habitat restoration goals and objectives. Attributes of restored boreal caribou habitat bear similarities with those of a fully conserved species (Redford et al. 2011), where populations with secure conservation status are self-sustaining, genetically robust, ecologically functional, and resilient to climate and other changes.

Table 1: The Nine Attributes of Restored Ecosystems (SER 2004) applied to boreal caribou habitat.

SER Attribute	**Relevance for Boreal Caribou Habitat**	**Category**
1. *The restored ecosystem contains a characteristic assemblage of the species that occur in the reference ecosystem and that provide appropriate community structure.*	Boreal caribou habitat is composed of large, contiguous tracts of muskegs and peatland or mature coniferous forests. Individuals generally avoid mixedwood and deciduous forests that provide habitat for other ungulates.	Vegetation structure and composition
2. *The restored ecosystem consists of indigenous species to the greatest practicable extent.*	Invasive plant species can impede regeneration success of coniferous forests and wetland habitat. Northward expansion of coyote and white-tailed deer, facilitated by industrial activity and climate change, would lead to increased predation beyond natural range of variability.	Vegetation structure and composition
3. *All functional groups[6] necessary for the continued development and/or stability of the restored ecosystem are represented.*	Ranges that support self-sustaining boreal caribou populations are characterized by a relatively high ecological intactness with all functional groups indicative of natural boreal ecosystem present at natural levels of abundance and diversity.	Ecosystem function
4. *The physical environment of the restored ecosystem is capable of sustaining reproducing populations of the species necessary for its continued stability or development along the desired trajectory.*	The likelihood of a caribou population to have reproductive and survival rates that will result in a stable or increasing population is a function of disturbance levels and amount and arrangement of biophysical attributes required to carry out life processes within the range.	Ecosystem structure and function
5. *The restored ecosystem apparently functions normally for its ecological stage of development, and signs of dysfunction are absent.*	High range-scale disturbance levels ultimately result in increased predation levels and population declines. This is indicative of a dysfunctional habitat state from a boreal caribou perspective, in contrast to one that supports a self-sustaining population where predation levels lie within the bounds of natural variability.	Ecosystem function
6. *The restored ecosystem is suitably integrated into a larger ecological matrix or landscape, with which it interacts through abiotic and biotic flows and exchanges.*	Individual biophysical features used for calving, rutting, and wintering, etc. are important for life processes; sustainability of a caribou population is ultimately contingent on the overall condition of the range, as dictated by cumulative disturbance and habitat supply.	Landscape context
7. *Potential threats to the health and integrity of the restored ecosystem from the surrounding landscape have been eliminated or reduced as much as possible.*	Key threats to the integrity of boreal caribou habitat are tied to direct and functional habitat loss brought about by cumulative industrial activities. These lead to increased predation risk for individuals, and overall high levels of predation. Threats to regeneration success include off-road vehicle access.	Landscape context
8. *The restored ecosystem is sufficiently resilient to endure the normal periodic stress events in the local environment that serve to maintain the integrity of the ecosystem.*	Disturbance levels affect range condition and can lead to population declines. With the known relationship between cumulative disturbance and population condition, a precautionary approach limiting disturbance levels can confer resilience.	Ecosystem stability
9. *The restored ecosystem is self-sustaining to the same degree as its reference ecosystem, and has the potential to persist indefinitely under existing environmental conditions.*	The ability of a range to support a self-sustaining local population of boreal caribou is a function of disturbance levels and amount and arrangement of biophysical attributes required to carry out life processes	Ecosystem stability

[6] functional group is an assemblage of organisms that is recognized by its functional roles in an ecosystem (SER 2004).

Goal and objectives of caribou habitat restoration

The reference state for boreal caribou habitat restoration efforts is defined by the national Recovery Strategy, which has relative amount of "undisturbed habitat" as a key part of its critical habitat definition. Restoration must seek to regenerate forests of sufficient quality to sustain the caribou population in that range, and be of similar character to undisturbed tracts that still exist within the range or in similar ranges. "Undisturbed habitat" is defined in the glossary as the corollary of "disturbed habitat" (Environment Canada 2012). Although the specific habitat characteristics (e.g., species composition, age, etc.) will vary across the distribution of boreal caribou (Environment Canada 2008; 2011), each local population range represents the pathway to the species' recovery goal and population and distribution objectives, which in turn guide critical habitat definition, and hence the habitat restoration targets.

Restoration Goal: Restore habitat where necessary to assist recovery of a boreal caribou local population range to a) support a self-sustaining population and b) prevent range recession.

The following five objectives collectively describe the desired outcomes that support and demonstrate achievement of the restoration goal:

1) Sufficient habitat is restored to maintain or attain a minimum of 65% of the range as undisturbed habitat;
2) Undisturbed (including restored) habitat is arranged in large tracts of conifer-dominated forests and muskegs that facilitate seasonal movements of individual caribou across the range and include biophysical attributes needed to carry out life processes;
3) Predator and alternate prey occurrence and abundance in areas of restored habitat are reduced to pre-disturbance levels;
4) Human access to areas being restored is prevented to reduce incidental mortality and disturbance to regenerating vegetation.
5) Priorities and associated timelines of individual restoration activities are sufficient to achieve conditions likely to support a self-sustaining local population within a time period that is suitable to the level of risk it currently faces;

Scale of attention

The practice of ecological restoration tends to be dominated by local-scale efforts, yet landscape-scale factors must influence site-scale restoration outcomes (Brudvig 2011; Kouki et al. 2011). From a species' recovery perspective, there is abundant evidence that amount and spatial configuration of habitat at the landscape level is critical (Fahrig, 2003; Lindenmayer et al., 2006). With ecosystems serving as a central focus of ecological restoration (SER 2004), there is increasing recognition of how essential it is for restoration activities to adopt a 'landscape perspective' (see van Andel 2012). "Landscape success" reflects how restoration has contributed to maintaining or improving the ecological integrity of the region, necessary for the achievement of goals like the maintenance of biodiversity (Kentula 2000).

Similarly, defining habitat restoration for boreal caribou has relevance at multiple scales. Restoration activities are ultimately implemented through a multitude of individual decisions about land-use disturbances that range from roads, seismic lines, pipeline, and transmission lines, to cutblocks, well pads, facilities, timber harvesting and more. Yet from a caribou perspective, just as risk to a population cannot be evaluated from one road or clearing, an individual development feature cannot be deemed restored for caribou in isolation. This is because individual sites are biologically linked to the landscapes in which they occur and are functionally interdependent (Bedford 1999). Landscape context will strongly influence whether or not a site is occupied by the species (Arkle et al. 2014). Nevertheless, while functional habitat for caribou is a range-scale concept, the work of restoration has to be focused at the scale of the individual feature. Similar to the two dimensions of the critical habitat framework in the national Recovery Strategy (ecological condition of the range and biophysical attributes), this underscores the need for both perspectives (Figure 3), which are discussed here in turn.

Restoration efforts at the site (feature) scale

For boreal caribou, the physical restoration work necessarily occurs at the site scale, feature by feature (i.e., seismic line, cutblock, well pad, etc.). As mentioned earlier, it is only in the last decade or so that the aim of reclamation activities following industrial disturbance have focused on restoring boreal caribou habitat, with a particular impetus provided by the publication of the national Recovery Strategy (Environment Canada 2012). Recent efforts at habitat restoration at the site scale have accelerated in Alberta in particular, where restoration needs are obvious for most local populations (Hervieux et al. 2013). These activities have focused on the re-establishment of native vegetation and controlling human and wildlife access (see Golder Associates 2012; 2014; Nova Gas Transmission Ltd. 2012).

Techniques adopted in boreal caribou habitat restoration programs have been aimed at increasing recovery speed relative to natural regeneration. Preparation of sites, creation of microsites using woody material, winter planting, and seeding are receiving significant attention (e.g., OSLI 2012; Vinge & Lieffers 2013). Although existing published scientific literature that evaluates the success or failure of intensive silviculture efforts leading to restored caribou habitat is still limited (Golder Associates 2012; Racey et al. 2011; Woodlands North 2013), considerable advances have been made in the development of effective techniques to promote re-vegetation, understanding which plant species to use, identifying priority sites for regeneration and determining where efforts are less likely to be successful; some progress has been made in controlling human access (Golder Associates 2012; Nova Gas Transmission Ltd. 2012; Vinge & Lieffers 2013).

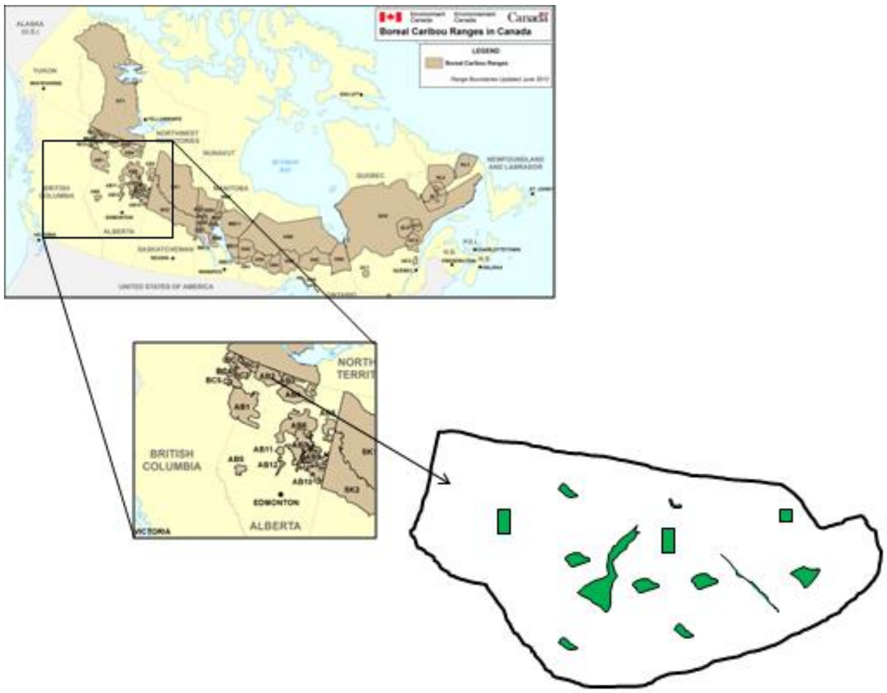

Figure 3. Multi-scale perspectives of caribou habitat restoration: population range and feature. The green polygons illustrate hypothetical examples of undisturbed habitat at the feature scale within a local population range. Figure courtesy of Environment Canada.

Restoration methodologies and actions appropriate for the unique characteristics of boreal forests must be guided by principles of ecological succession and an understanding of how ecosystems and communities change over time through both natural and anthropogenic disturbances (Vitt and Bhatti 2012). To begin with, forest composition is influenced by landform, topography, parent material, soils, and local climate (Bergeron 2000; Macdonald et al. 2012). The nature of disturbance (i.e., severity, frequency, spatial pattern, and seasonal timing) determines which and how many viable propagules will survive to remain on-site following the disturbance. Soil type has a strong influence on the speed of recovery as well as what type of forest recovers in a site (Macdonald et al. 2012). Once established, ecological properties of individual species and their interactions with other species largely determine the succession trajectory. Generally speaking, shade-intolerant species capable of rapid regeneration are dominant at first, and shade-tolerant conifers eventually take over (Bergeron 2000). However, post-disturbance forest composition outcomes are not necessarily predictable (Lieffers et al. 2003). For example, restoration potential will be negatively affected if the disturbance results in removal of organic matter or otherwise affects soil chemical properties, as will the availability of suitable microsites for plant germination (references in Macdonald et al. 2012). This is a particularly relevant issue in many boreal caribou population ranges where extensive networks of seismic lines have experienced poor natural regeneration due to extensive root damage, soil compaction and removal of mineral soil horizon, and repeated disturbance (e.g., re-clearance or human access; Lee & Boutin 2006; Bayne 2011; Nova Gas Transmission Ltd 2012; Vinge & Lieffers 2013).

All boreal forest ecosystems have evolved into "eco-sites" in response to the parent materials, topography, climate, and natural disturbance regimes (e.g., Beckingham and Archibald 1996; OMNR 1997). Closely associated with landform complexes and broad overstorey composition, the underlying characteristics of these environments are central to understanding and predicting potential boreal forest restoration trajectories following disturbance. According to Macdonald et al. (2012), suitable soil conditions, reestablishment of the original plant community, and continuing development of, and interactions between, soils and vegetation constitute the key to rebuilding boreal forest ecosystems after industrial disturbance. Mammalian assemblages change considerably between the major successional stages that characterise boreal forests: the initiation stage (0–10 years post disturbance), establishment stage (11–25 years), aggradation stage (26–75 years) and mature/old growth stage (76–125+ years) (Fisher & Wilkinson 2005). Boreal caribou respond to such successional changes primarily by shifting their ranges, such that the occupancy and relative abundance of caribou, other ungulates, and predators differs between each stage (Appendix 1). With respect to caribou selection and avoidance patterns, variability across boreal ecozones is not so evident (Appendix 2).

Generally speaking, there are some particular challenges when it comes to achieving site-scale habitat restoration in the service of boreal caribou conservation and recovery. Examples include:

- Wetland ecosystems are dominant components of Canadian boreal forests. Peatland complexes (i.e., bogs and fens) constitute prominent habitat features for boreal caribou (Rettie & Messier 2000; Bowman et al. 2010). Yet restoring wetland habitats can be a more complex and challenging enterprise than regenerating upland habitats. To illustrate, Alberta's first set of reclamation guidelines for wetlands stated that "reclamation of fens or bogs in the oil sands has not been attempted" (Alberta Environment 2008). In large areas of Alberta, reclamation activities (from oil sands mining) are resulting in the replacement of low productivity fens and bogs by higher-productivity upland forests (Rooney et al. 2012). Natural regeneration on cutover peatlands occurs very slowly and is often insufficient to restore its key ecological functions (e.g., peat-accumulating or hydrologic functions), with many peatlands void of vegetation after more than 30 years (Poulin et al., 2005). Fens have a particularly complex hydrology (and thus even more significant restoration challenges) because of their direct links to the surrounding environment (Graf et al. 2012).

- The type of disturbance can also have significant influence on the potential for restoration success. For example, linear features (e.g., roads and seismic lines) tend to be more difficult to restore than cutblocks. This can be explained by a variety of factors, including the removal of organic layer and the tendency to bisect many different soil and ecosystem types over relatively short distances (Vinge and Lieffers 2013). Their recovery also appears to be faster when they are narrower (Bayne et al 2011). Linear features are associated with access, either into or through areas. The development of roads, railways, pipelines, power lines and seismic lines results in direct disturbance, but also creates entry points for continued human access and further development activities, negatively impacting overall restoration success (Bayne et al. 2011; Golder Associates 2012, Nova Gas Transmission Ltd. 2012).

- Landscape context will also have bearing on restoration success at the site level. A high quality site embedded in a low quality landscape is unlikely to serve as habitat for species with broad area requirements (Arkle et al. 2014). For example, in three case studies in Ontario, Racey (2014) documented caribou use of regenerated clearcut sites about 40 years after forest harvesting. They attributed this in large part to the broader landscape conditions that allowed some caribou to persist in the area following harvest activities, taking advantage of key habitats such as large peatlands or calving areas while the forest matured.

Defining caribou habitat restoration at the feature scale

Even in areas where there has been no anthropogenic disturbance, caribou habitat at the range scale is characterized by a mosaic of conditions that includes unsuitable or otherwise poor habitat for caribou. This challenges our ability to evaluate each feature by itself as restored (or not) from a caribou perspective and whether or not it serves as good habitat on its own. Nevertheless, there is no question that techniques applied at small scales are essential for ultimate restoration success.

In a general review of how success had been evaluated in restoration projects, Ruiz-Jaen & Aide (2005) found that for most studies, the recovery of vegetation structure or diversity was the key focus. Reasons for this include: 1) laws requiring restoration always include vegetation monitoring, 2) recovery of species and ecological processes is generally assumed to follow vegetation establishment, and 3) metrics associated with vegetation structure are easy and quick to measure. For caribou, there has been additional attention to the concept of restoring habitat functionality, defined by ALT (2009:xiii) as providing caribou "with sufficient food and opportunities to space away from predators". Recent restoration efforts have placed large focus on preventing or ameliorating ease of access for humans, predators, and alternate prey on individual linear features (e.g., Golder Associates 2009; 2012; Nova Gas Transmission Ltd. 2012).

Habitat function

With predation as the lead proximate cause of caribou mortality and documented use by wolves of seismic lines as movement corridors (Latham et al. 2011; Whittington et al. 2011), recent efforts have focused on measures aimed at reducing predator and alternate prey presence and mobility, such as line blocking by tree felling, stem bending, and slash placement (Neufeld 2006; Golder Associates 2009; Woodlands North 2013). This has been carried out with an assumption that when a given linear feature is no longer used by these species, habitat for caribou will have been improved, or restoration even achieved. Accordingly, work has focused on measuring use of regenerating or physically blocked corridors by various predators and alternative prey through cameras or snow tracking as a means of testing success. However, evidence of effective blocking techniques that lead to adjustment of predator movements has been lacking (e.g., Neufeld 2006). Moreover, even if predators stop using a given feature, this does little to address the numerical response of predators to deer and moose population levels within the population range. Alleviation of predation risk, which is strongly tied to the distribution and abundance of forage for early seral ungulates across the range, will demand a more comprehensive approach than managing predator movements in the name of restoration.

With respect to human access, repeated disturbances caused by ATV's and other vehicles associated with both recreation and continued exploration and development activities have a demonstrated negative impact on regeneration success, retarding re-vegetation by damaging seedling growth and compacting soil (Lee & Boutin 2006). Physical access control measures have, however, had mixed success in blocking human use of linear corridors undergoing restoration, and tend to lose their effectiveness over time (CLMA & FPAC 2007; Nash 2010; Nova Gas Transmission 2012; Vinge & Lieffers 2013). Decommissioning practices that quickly re-establish natural vegetation and other ecological processes should ultimately lead to longer-term vehicular access control once a certain degree of woody vegetation growth can be achieved (CLMA & FPAC 2007; Vinge & Lieffers 2013).

Habitat structure/composition

While some degree of effective predator and human access control will be beneficial within the early stages of site-scale restoration activities, this should not distract focus from the need to rapidly re-establish forest vegetation with compositional and structural characteristics of caribou habitat. Typically, measures of habitat suitability for wildlife species would be derived from field-based vegetation and other metrics to quantify such characteristics as ground and canopy cover, vegetation height, plant composition, etc. Such attributes that accurately predict a species' occupancy can in turn be used to define and demonstrate restoration success (e.g., Arkle et al. 2014).

In the case of boreal caribou, most habitat descriptions and selection or suitability models are based on more broadly-defined habitat types, e.g., upland tundra, treed bogs, peatlands, conifer-rich forests, etc. (Environment Canada 2011). An exception is habitat supply mapping for industrial forest management where forest stands are assigned a habitat class (e.g., suitable, capable, unsuitable), based on attributes such as tree composition and age, using data available from forest resource inventories (FRI; OMNR 2014a). While useful for forest management purposes, the extent to which this approach can be used to develop targets for caribou habitat restoration will be limited by issues such as: 1) the narrow set of vegetation characteristics that can be measured by FRI, particularly for the understory; 2) the poor predictive power of FRI for some caribou habitat (e.g., winter forage; Boan et al. 2013) and 3) the unavailability of FRI in a large portion of caribou distribution in Canada.

The focus on habitat types rather than plot-based vegetation measures, even to characterize "fine-scale" caribou habitat (Rettie & Messier 2000), reflects both the enormous home ranges of this animal and the overarching importance of broader-scale features in predicting caribou occurrence and productivity discussed here. Also of note, is the differential habitat use by caribou between or even within seasons for various life processes, and to a certain extent between ecoregions (Environment Canada 2011). For example, important lichen-rich habitat used for winter foraging tends to be characterized by boreal forest habitats with open canopies (McMullin et al. 2013), whereas densely-stocked conifer stands serve as refuge habitat from predators and deep snow during the same season (reviewed in Environment Canada 2011). The biophysical attributes of calving sites and rutting areas exhibit further differences (Environment Canada 2011).

In sum, our ability to come up with generic descriptors of caribou habitat at the site scale is complicated by the broad-scale habitat selection and variability across the distribution of this wide-ranging species. Having said that, the following attributes hold some promise, although each has its caveats:

- *Canopy species composition*: In light of the established deleterious effects for caribou of landscape-scale conversion to mixedwood forests with increased amount and distribution of early seral habitat for other prey species, it is important to maintain or restore relatively pure stands of conifer habitat (Dzus et al. 2010). Eco-site conditions dictate how significant a certain proportion of hardwood will be from a caribou perspective. For example, an Ontario eco-site with deep coarse dry sand (and jack pine dominant) would likely be of far less concern than the same proportion of hardwood on a richer eco-site with moist coarse loamy soils (black spruce, jack pine), the latter with a higher potential for richer understory browse (Racey et al. 2011). Forest stands or units with > 90-99% pine and spruce are similar to the "natural" (e.g., pre-harvest) or "pre-industrial" conditions (PIC) that are used as a benchmark within boreal caribou range in Ontario (OMNRF 2014a; G. Hooper, OMNR, in litt.). This underscores the "conifer purity objective" that has been adopted as Ontario regional guidance within the caribou zone (OMNRF 2014b).

- *Forest age*: The association of boreal caribou with "mature" or "old growth" boreal forest habitats is well established, although these descriptors are often not quantified with respect to age, due at least in part to the variability across the distribution (see Environment Canada 2012). Discussions of caribou habitat restoration acknowledge the long time scales that will be necessary in order to achieve success (e.g., ALT 2009; Golder 2014). The forest must become "old enough to be considered low quality for other prey, and suitably old to be used by caribou" (ALT 2009). When defined, it ranges from 40 to 80 years, and there is variability across boreal caribou distribution (Appendix 1; Environment Canada 2011).

- *Tree height*: Although not typically used to characterize caribou habitat, tree height is a common indicator of restoration or reclamation success, e.g., in silviculture. It will be most useful for determining end point of initial stages of restoration (see below) rather than indicative of restored habitat per se.

- *Lichen cover or abundance*. The importance of lichen as winter forage for caribou is well-documented, and recent studies have improved the ability to predict favourable conditions for lichen that provide caribou forage (T.McMullin, in prep.). However, with predator-related issues being the most critical terms of caribou recovery, the reduction in lichen forage is not a significant limiting factor for caribou in most cases, and not all caribou habitat is lichen-rich. Nevertheless, the establishment of arboreal or terrestrial lichen can be a useful indicator of the return of caribou habitat (Racey 2014).

- *Shrub/understory cover*. Shrubs are preferred forage for alternate prey, and high abundance of deciduous trees corresponds with shrub abundance; shrub-rich regeneration can create unsuitable conditions for boreal caribou. For example, Boan et al. (2011) recommended moose forage abundance in younger forests as a monitoring criterion for evaluating silvicultural effectiveness in multiple-ungulate systems where caribou occur or may recover.

Although the above attributes could serve as the basis for indicators of restoration success to guide restoration efforts at the feature scale, it would not be possible to come up with distribution-wide generic indicators of any; most thresholds would have to be devised in accordance with eco-site conditions. Even so, any conversation about site-level habitat attributes for caribou will be overwhelmed by considerations of both landscape context and overall range condition.

Stage of restoration

The above discussion underscores the difficulty of declaring the success of feature-scale restoration efforts from a caribou perspective. Therefore, it would be appropriate for some criteria that define feature-scale restoration to signify the establishment of a restoration trajectory, rather than the end point of restoration per se. This would correspond with the point at which active on-the-ground efforts can cease. For example, the free-to-grow concept (FTG) used in forest management is a working example of meeting a standard for progress along a vegetation recovery trajectory. When applied to forestry operations, attaining FTG means that the trees have good growth rates, are free from any insects, diseases, and high levels of competing vegetation, and are likely to reach the desired future forest condition without additional effort (e.g., OMNR 2009).

Although this signifies the point where restoration work can end and the regenerating forest is re-entered in the inventory, it is well understood that it may be many years before the wood is once again harvestable. By the same token, applying this concept to feature-scale caribou restoration means that while some degree of success can be declared well before the range is restored, new disturbance may not be permitted if it has an additive effect until the range-scale criteria have been satisfied. Generally speaking, initial successes achieved at the small scale (features) should be viewed as a long-term investments collectively aimed at restoring large contiguous habitat patches within the population range (see below). This will necessarily take time.

Achieving recovery for boreal caribou at the range scale

Both critical habitat assessments undertaken by Environment Canada (2008; 2011) emphasized the importance of the range scale for driving population condition and habitat quality. The ultimate measure is a self-sustaining caribou population, defined in the Recovery Strategy as "a local population of boreal caribou that on average demonstrates stable or positive population growth over the short-term (≤20 years), and is large enough to withstand stochastic events and persist over the long-term (≥50 years), without the need for ongoing active management intervention". Results from population viability analyses suggested that >300 animals in a population is necessary for long-term population viability, given moderate rates for calf and female survival (Environment Canada 2008). Whether a range can support a self-sustaining local population is also a function of both the amount and quality of habitat available for boreal caribou. Preferred habitats vary throughout their range but generally include peatland complexes composed of bogs and fens, and upland conifer-dominated lichen-rich areas (Rettie and Messier 1998, Brown et al. 2003). Environment Canada (2011) estimated that ranges needed to 10,000 to 15,000 km^2 to support 300 individuals. Boreal caribou maintain low population densities throughout these large range areas as a means of reducing predation risk (Rettie and Messier 2000; Brown et al. 2003; Whittington et al. 2011).

Habitat quality is often related to forest age, i.e., old enough to be considered low quality for other prey and containing sufficient forage for caribou (e.g., lichens). Relative size of continuous tracts of undisturbed habitat with required biophysical attributes such as particular calving locations are also important. While size and configuration of habitat patches are obviously an important influence on population sustainability (Arsenault & Manseau 2011; Nagy 2011), metrics for such attributes are still elusive and are affected by extent and intensity of unsuitable habitat. It appears, therefore, that the empirical basis for quantifying non-habitat in relation to the population recovery goal is considerably stronger than that any quantification of "sufficient" habitat quality, e.g., size of habitat tracts or degree of connectivity, etc.

Where required, habitat restoration at the range scale should include the following elements in sequence (Figure 4):

1. *Prioritize areas for restoration effort*. Because not all sites can be restored easily or at all, areas or features that receive restoration attention in the context of the range scale must be prioritized, such that the most effort is placed on those that have the best chance of success due to their capability to respond quickly or to their strategic location relative to caribou conservation (van Rensen et al. 2013; Vinge 2014). If a portion of a range is heavily disturbed, it will take a large amount of rehabilitation efforts to get it to a functional state. In contrast, a relatively small amount of effort on a range that has little disturbance can help bring the entire area into a functional state. The Recovery Strategy (Environment Canada 2012:27) provides direction for identifying areas to focus restoration efforts in highly disturbed ranges that will be prioritized for boreal caribou recovery within a timely fashion. The relative necessity of this strategic effort will differ according to the relative condition of the range to ensure that the total amount prioritized is likely to be sufficient to achieve self-sustaining status for the population.

2. *Undertake strategic coordination of restoration activities*. Rather than implement restoration efforts independently with respect to individual features, a coordinated strategy with an aim towards building large tracts of suitable caribou habitat should be undertaken. This would require organized efforts of multiple actors to collectively define the restoration objectives in relation to the caribou range plan, come up with appropriate methods, and track amount of restoration that actually occurs (ALT 2009). The Recovery Strategy (Environment Canada 2012:26) itself mandates range plans, with one instruction to "undertake coordinated actions...through restoration efforts".

3. *Build large blocks of restored features with high connectivity***.** Extensive areas of relatively undisturbed mature forest as habitat provide food, movement corridors and refugia from predation. These provide additional targets of active restoration and define where such activities should be focused or where new activity restrictions and limitations apply as restoration is proceeding. Particularly in ranges with an extensive human footprint, such areas should aim to be as large as possible. ALT (2009) identified the size of targets as "thousands of square kilometers" and Antoniuk et al. (2012), 5,000 km^2. Ensuring for connectivity means that it is necessary to strive for configuration that allows animals to move between different habitats that are needed to satisfy life history requirements.

4. *Monitor progress of range-scale restoration***.** During and after site-scale restoration work the trend of disturbed:non-disturbed/fully restored habitat should be measured together with the caribou population response (as defined by recruitment, females survival, and/or lambda). If feasible, predator and alternate prey numbers and trends should also be included in any monitoring framework, however, it is noted that the best measures of predation ultimately lie in boreal caribou demographic rates. This will be necessary anyway in many caribou population ranges that require habitat restoration, because predator and or alternate prey control may be required and therefore monitored (ALT 2009; Boutin 2010; Hervieux et al. 2014). The relatively risky 65% management threshold defined in the Recovery Strategy requires precaution to ensure restoration is sufficient before removal of additional habitat occurs. Otherwise, if the assumption that habitat is sufficient is wrong, restored habitat can be inappropriately counted as offsets for additive, new, and unsustainable disturbance. This underscores the importance of population information to verify success, which may also come prior to the management threshold (FSC Canada 2014).

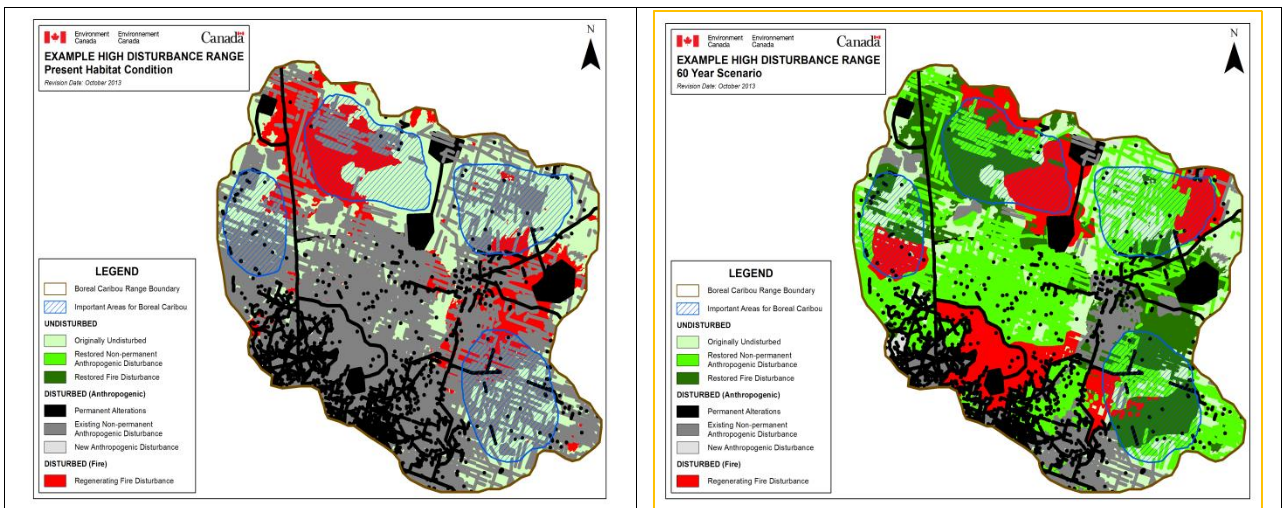

Figure 4. Restoration of a high-disturbance range over 60 years, from a) 22% undisturbed habitat to b) 65% undisturbed habitat. Restoration will be targeted in: important areas for boreal caribou and the centre of the range to improve connectivity between these areas. Figure courtesy of Environment Canada.

CRITERIA FOR BOREAL CARIBOU RESTORATION

In the 10 years since the publication of the SER Primer (2004), attention to evaluation of success has been growing, with an increasing focus on ecological functionality. This is important in light of the fact that regulations governing renewal or reclamation of lost or degraded lands have been either slow to develop at all, or woefully inadequate from an ecological perspective. However, the nine attributes of restored ecosystems identified by SER (2004) are not themselves widely used and do not naturally give rise to caribou-specific criteria. Even renewal standards in forestry, which have the longest history, are left to the discretion of individual forest management planning processes -- largely determined through negotiation without a scientific bottom line or identified thresholds. These tend to be variable across and even within planning areas (with different plans) (Buda & White 2007), and silvicultural ground rules tailored to serve caribou conservation are seldom in evidence (Racey et al. 2011).

The previous discussion of caribou restoration at the site (feature) and range scales concluded that although most of the actual work is being conducted at the site scale, the evaluation of ultimate success mostly occurs at the range scale (Figure 5). Metrics associated with the former should limit themselves for the most part to describing localized vegetation structure and composition, whereas functional attributes of the restored system are most appropriately tracked at the caribou population range scale. At least some criteria for proceeding with and ending restoration actions at the feature scale will not be the same as the criteria for evaluating whether a feature is functionally and structurally restored from a boreal caribou (range scale) perspective. Site-level objectives should be established in reference to both the trajectory -- the point at which site-specific field restoration activities can cease -- as well as fully restored habitat that can be counted as restored (or not) in range-scale disturbance metrics. Attaining free to grow may not give license to disturb new habitat elsewhere in the range, or claim restoration success, until range scale recovery targets have been achieved. Proposed criteria and indicators for restoration activities conducted at both site and landscape scales are presented in Table 2.

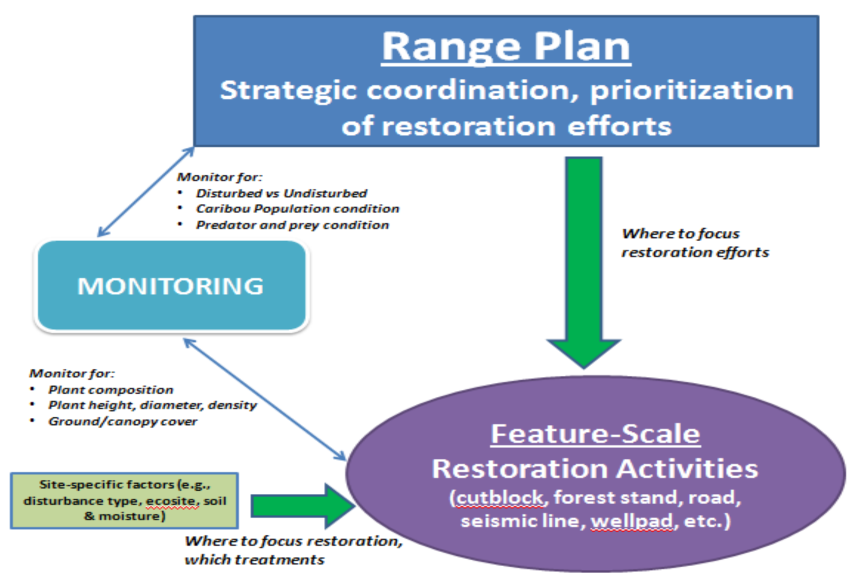

Figure 5. Although restoration is focused at the feature scale, boreal caribou habitat restoration must begin with a range plan, whereby on-the-ground activities are prioritized and coordinated within the context of recovery of the population range. Both the range plan and site-specific (eco-site) factors will dictate where feature-scale restoration activities should be conducted within the range and appropriate treatments. Monitoring is necessary at both scales.

Table 2. Criteria for caribou habitat restoration at the range and feature scales.

Scale	Criterion	Objective(s)[7]	Notes (including potential indicators)
Range	Areas for restoration effort are prioritized for maximum effectiveness and benefit to caribou	1, 2, 5	Priorities consistent with best available science in all cases, even when taking into account socioeconomic considerations, to ensure bottom line of caribou survival and recovery is not jeopardized.
Range	Proportion of disturbed:undisturbed habitat is maintained at a minimum of 35:65% for self-sustaining local populations and where necessary, undisturbed (restored) habitat is augmented over reasonable, gradual increments every five years	1, 5	It is not sufficient for this criterion to be met on its own, as it is of no value to caribou if the population continues to decline, emphasizing the importance of the following criterion. It is also possible for a caribou population to recover even before some of the ecosystem responses have occurred.
Range	Caribou population is stable or increasing	2,3	Given the variability around the disturbance-recruitment relationship that underpins the previous criterion, it is necessary to directly measure caribou population condition.
Range	Restoration is strategically coordinated to focus activities towards rebuilding and maintaining contiguous interconnected large blocks of undisturbed habitat	1, 2, 5	Large blocks in the process of restoration remain into the future, with new disturbance permitted accordingly.
Range	The distribution and abundance of forage for early seral ungulates is similar to mature forest and within natural bounds of variability	2, 3	This criterion relates to predation being the key driver of caribou declines, rather than reduction in lichen forage.
Range	The habitat no longer contributes to a higher rate of predation than what would occur in natural boreal forest conditions	2, 3	This criterion shifts the focus of managing predator movements at the feature scale to restoring habitat to minimize predation risk at the range scale.
Feature	Vegetation is established on a performance trajectory appropriate to eco-site conditions to a state that no longer requires active site preparation and tending	1,2, 5	Indicators are eco-site specific, including tree height, plant composition, ground cover, diameter, density, etc.
Feature	Seedling establishment and regeneration is not compromised by ATV and other vehicles	4	Human vehicle access must be actively managed at the beginning stages of restoration work.
Feature	Native vegetation is compatible with adjacent areas	1, 2	Conifer "purity" (e.g., > 90%), age, vegetation composition and structure equivalent to natural boreal forest condition.
Feature	Restored area functions as biophysical feature supporting caribou life processes	2	Evidence of caribou using area for calving, wintering, rutting, foraging, etc.

[7] See p. 13.

WHEN IS A DISTURBANCE NO LONGER A DISTURBANCE?

With development (and restoration) activity focused at the site scale, a key question in the context of evaluating the success of range plans under the national Recovery Strategy that is often asked is: at what point an individual disturbance is no longer counted as a disturbance, hence allowing for the removal of the 500 m buffer? To a certain extent, the Recovery Strategy already addresses this through its definition of undisturbed habitat as "habitat not showing any...anthropogenic disturbance visible on Landsat at a scale of 1:50,000, including habitat within a 500 m buffer of the anthropogenic disturbance". This simply means that in future mapping exercises that quantify disturbance through national datasets (e.g., Pasher et al. 2013 in the context of measuring progress in section 8 of the Recovery Strategy in five-year increments), sub-range components will be scored as either disturbed or undisturbed by these types of analyses. It is important to note that the removal of a 500m buffer from a single feature will have little consequence to measures of total disturbance when there are other buffered disturbances in proximity.

With individual jurisdictions in charge of implementing caribou recovery and formulating range plans (as outlined in the Recovery Strategy), they have turned to using their own mapping sources to define disturbance. A disturbance layer is made up of compiled resource inventory datasets, such as roads layers, forest harvest blocks, or mining claims that are aggregated to represent cumulative anthropogenic disturbance (e.g., OMNR 2013). However, various decision rules that have no relationship to caribou may be applied during mapping or removal of features. For example, standards for road decommissioning made with respect to a roads dataset for transportation purposes may result in disturbance being removed from that layer before features have achieved characteristics indicative of caribou habitat. On the one hand, turning towards provincial/territorial datasets allows range plans to include more up to date information on disturbance levels and should eventually encourage the development of region-specific recruitment-disturbance models. On the other, because decisions will be made by others as to when, for example, a road shows up or not in the inventory, there will be little control by caribou managers in "scoring" some individual features as disturbed or undisturbed.

Given the perfectly reasonable use of these datasets as a means to track disturbance and accumulation of restored habitat tracts over time (and therefore changes in relative risk to a caribou population), the details of individual features may not be significant. Although this conclusion may seem unsatisfying, the need to emphasize range-scale parameters for determining the ultimate success of restoration efforts is widely acknowledged (e.g., Golder Associates 2014). Site-scale efforts are necessary to set a course for success, where work is defined on the basis of local (e.g., eco-site) conditions to establish the best potential areas, likely trajectories, and the end points of active efforts. And while it would be appropriate to credit restoration efforts in some fashion for work that has achieved this key stage, it may not mean that sufficient restoration has occurred to trigger permitting of disturbance elsewhere in a population range that has yet to achieve self-sustaining status as expressed in a range plan.

THE PATH FORWARD: CHALLENGES AND OPPORTUNITIES

There will be multiple challenges associated with implementing the framework presented here, many of which are identical to those facing caribou recovery in general, particularly in ranges that are currently not self-sustaining. The suite of challenges related to caribou habitat restoration are offset to a certain extent by opportunities that have been more recently opened by the introduction of the national Recovery Strategy and some increasing technical advances and insight in restoring boreal forest ecosystems.

Challenges

- Many boreal caribou local population ranges in Canada lack regular population monitoring that will be necessary to enable and measure ultimate success of range-scale recovery;
- Spatial layers used to quantify disturbance tend not to be regularly updated, may be scaled differently, and will have differing (and usually non caribou-centric) rule-sets governing when a disturbance appears or not (e.g., a road);
- Provincial policies and guidelines driving restoration activities and requirements are usually not consistent with caribou survival and recovery, as they tend to be primarily focused on return to a productive land base;
- Local population range boundaries are inconsistently defined across Canada and can and do get modified, challenging the ability to track changes in disturbance and recovery over time within some ranges;
- Technical challenges persist with restoring boreal caribou habitat, particularly in peatlands.
- Re-establishing caribou habitat, if successful, will take several decades to achieve in a given area, and will not immediately compensate for the loss of habitat caused by the ongoing and future projects. This means that embarking on restoration now will not lead to immediate improvements in range condition in highly disturbed population ranges in particular;
- Although impacts of individual disturbances are lessening (see below), cumulative disturbance (the additive impact of all individual disturbances) has escalated during the same time period and jurisdictions' capacity to measure, track, and regulate cumulative disturbance is incipient at best.

Opportunities

- There has been an increase in attention paid to caribou habitat restoration needs brought about by the national boreal caribou Recovery Strategy, and enhanced awareness that recovery of this species will require a considerably higher standard than most reclamation policies and guidelines that are presently in place.
- The Recovery Strategy has also brought attention to the importance of measuring and tracking cumulative disturbance, and the regulatory gaps that exist to manage this effectively.
- There has been significant progress in restoration made in a relatively short period of concerted effort (about 5 years) with respect to enhanced knowledge, techniques, and speed towards establishment of vegetation after human disturbance;
- Seismic exploration has moved to minimal disturbance e.g., narrowing of lines has reduced the impact of individual disturbances and increased restoration potential (Bayne et al. 2011), but this is offset by increasing cumulative disturbance (see above);
- Empirical research into restoration outcomes is clearly expanding, and the field of Restoration Ecology is flourishing, with closer ties to conservation biology (Wortley 2013).

KEY FINDINGS

At the 2010 meeting of the Convention on Biological Diversity in Nagoya, Japan, countries committed to a new target of restoring 15% of the degraded ecosystems worldwide by 2020 (Aichi Target 15; CBD 2010). This was done without any clear definition of "restored" or "degraded ecosystem", or articulation of desired outcomes of restoration activities (see Jørgensen 2013). This set of circumstances illustrates well the growing imperative for restoration activities as part of the political agenda for conservation, while at the same time demonstrating that definitions of success in this endeavour remain elusive. As Jørgensen (2013:2981) warned recently: "These commitments will route money and resources toward restoration.... yet funds might end up used in arbitrary, useless, or even harmful ways if what counts as ecological restoration is left unclear."

When it comes to habitat restoration in the service of species at risk recovery, boreal caribou serve as a prime example for how challenging this can be to achieve. Not only will decades be needed to return disturbed areas to mature forest conditions that exemplify suitable habitat, but the extent of habitat loss that has been suffered in large parts of the species' distribution combined with a legacy of inadequate (or no) attention to reclamation adds a further daunting dimension to the task. Many boreal caribou local populations have lost much ground in short time periods and minimal remedial action, with current disturbance levels in their ranges far exceeding thresholds directed in the Recovery Strategy (Environment Canada 2012). Although the well-established relationship between habitat disturbance and population condition provides a solid means to frame restoration priorities for boreal caribou, locally variable conditions and a lack of a true ecological threshold magnifies the risk of irreversible harm to local populations of adopting the management threshold of 65% "undisturbed habitat" as a restoration target. Hence, a cautious approach is merited, particularly in the case of ranges with intermediate levels of disturbance, as well as monitoring of population trends to test whether local populations are responding positively to restoration efforts.

Effective restoration for boreal caribou will require explicit linkages between site-specific restoration actions and range-level effectiveness evaluation. This underscores the importance of planning at the population range scale to organize and prioritize on-the-ground restoration efforts. This should improve prospects for overall effectiveness not only because it will focus efforts on the parts of the range that have the best chance for success, but also in areas that will provide the greatest benefit per unit of effort. The Recovery Strategy (Environment Canada 2012) mandates range plans, albeit not explicitly to guide restoration strategies. These should provide a platform for coordination of multiple actors in the same landscape in all endeavours related to boreal caribou recovery, including restoration. Management activities must be placed in the proper context. For example, line-blocking strategies on linear features aimed at reducing wolf use or access are actions and strategies that are not going to achieve site-specific habitat restoration or contribute to long-term range restoration on their own. Because the objective of caribou range planning is to manage cumulative disturbance in the face of significant jurisdictional regulatory gaps, interim success with feature-scale restoration cannot be used to offset increasing disturbance elsewhere without regard to the range plan as a whole.

In spite of the primacy of range-scale planning to guide and evaluate boreal caribou habitat restoration, most or all the ground work will be conducted at the scale of the individual feature, i.e., cutblock, linear corridor, oil pad, etc. Accordingly, the framework offered in this paper establishes criteria for success at both the feature and range scales, all of which must be considered together. In addition, it recognizes a degree of interim success once a trajectory of recovery has been established, the details of which need to be worked out in keeping with eco-site conditions and the overall state of the range and/or population. In spite of the use of a management threshold for identifying critical habitat in the Recovery Strategy, habitat in the process of recovery does not suddenly switch to a restored state as if disturbance is a binary, rather than continuous variable. Decisions about how to give recognition for gradual improvements in range condition as a result of restoration efforts without undermining this work (i.e., by prematurely allowing new disturbance) will have to be considered in the context of individual range plans.

It is useful to listen to the warnings of some restoration ecologists, including those made in reference to biodiversity offsetting, which relies heavily on the science and practice of ecological restoration to compensate for biodiversity loss caused by development projects. The promise of effective restoration increases the chance of permitting damage to biodiversity, yet many expectations and underlying assumptions about how restoration will succeed are unsupported by evidence. This can exacerbate the negative consequences of failure to restore (Maron et al. 2012). In spite of some promising results, restoration often does not go as well as planned (Suding et al. 2011). Because criteria are often not set, restoration goals tend to be unrealistic (Hobbs 2007). Restoration ecology is a young discipline, "one still pre-occupied with trees and plants rather than taking a true ecosystem-based approach, and one in which success in meeting objectives is not yet routine. In many cases, we can say restoration practitioners are employing the 'build it and they will come' model, with faith placed in establishing tree cover as a means of facilitating all aspects of forest ecosystem recovery and restoration" (Burton & Macdonald 2011:855-6).

For boreal caribou, there are no examples of successful restoration at the range scale. This can be explained in part by the fact that intensive human activity in many caribou ranges has taken place over a shorter period of time than it takes to regenerate caribou habitat. But it is also clear that an ever-increasing footprint provides little chance for sufficient habitat to both re-grow and be maintained. The best opportunities for learning how to effectively restore caribou habitat will be offered by population ranges where overall disturbance levels are maintained at relatively low or intermediate levels while restoration of individual tracts is allowed to proceed.

Habitat restoration on its own will not achieve success for boreal caribou recovery in heavily disturbed ranges, because unmanaged predation by wolves will cause ongoing declines for some time (ALT 2009). By the same token, predator control for the purposes of increasing caribou survival may help caribou persist, but will have to continue with no end to keep caribou if no efforts are made to restore habitat at the same time (Hervieux et al. 2014). All evidence points to the conclusion that it will be exceedingly difficult to recover boreal caribou populations once they are in decline and disturbance levels are high. Restoring ecosystems is typically a highly expensive process that requires substantially more effort than prevention of ecological damage in the first place.

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APPENDIX 1. Literature review of associations of boreal caribou, predators, and alternative prey with major boreal forest successional phases. Sources for first five columns: Larsen (1980); Kasischke & Stocks (2000); Song (2002); Fisher & Wilkinson (2005). Sources for columns 6 and 7 in Appendix 3. Compiled by Lucy Poley (University of Calgary).

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
Initiation stage **0 - 10 yrs** Low shrub canopy; high density of recolonizing deciduous trees; establishment of early shrub and herbaceous communities; regenerating soils; parkland appearance	Burned without residual trees	- delay of 5-10 years before lichen colonization is not unusual - lichen succession generally difficult - ground lichens appear first - crustose, foliose, fruticose - lichen succession impeded by highly competitive herbaceous vegetation	- woody shrub species show rapid growth, increased flower production, and greater abundance than pre-fire conditions - fire-dependant species appear and disappear in this stage	Aspen – -Fire triggers regeneration, particularly moderate-intensity fires - Aspen suckers appear quickly -Aspen roots can be damaged by repeated traffic, impeding regeneration White spruce – -if organic material is burned away by high-intensity fires, spruce seeds colonize more easily - majority of seedlings recruit within a few years of fire - slow growth - white spruce seed source can be maintained through selective harvesting - retention of mature spruce after harvesting ensures strong seed source Black spruce – Low frequency, out-competed by mosses, herbaceous plants Jack pine – - seedlings can produce cones within 3-5 years of a fire, reproductive success after 10 years	Although young burns may be an abundant source of regenerating vegetation from summer browse, lack of lichen for winter forage makes these areas unsuitable, leading to caribou abandoning burned sites (Schaefer & Pruitt, 1991) Deadfall accumulating in young burns provides movement barriers (Schaefer & Pruitt, 1991) British Columbia: caribou selected burns and sites with regenerating woody vegetation in the spring (Boonstra & Sinclair, 1984) Newfoundland: caribou used clearcuts in this stage significantly less than any other stand ages (Mahoney & Virgl, 2003) Newfoundland: 50% of collared caribou moved away from timber harvesting operations, but returned one year later (Chubbs et al., 1993) Alberta subalpine/upper foothills: caribou moved away from active cutblocks but part of the herd returned after first-pass logging; on average, telemetry locations were significantly farther from cutblocks 1-12 years old than were random points, indicating caribou avoid these areas (Smith et al., 2000)	Moose, white-tailed deer, black-tailed deer, and elk make use of young seral stages (with regenerating vegetation) for foraging (Fisher & Wilkinson, 2005) Alaska: moose occupied sites immediately after fire and used them more than expected up to 4 years post-fire; shifted home ranges to include burned sites post-fire; when an area within a moose home range burned, moose increased time spent in burned locales (Gasaway et al., 1989) Moose use young clearcuts extensively, selecting over other habitat types (Fisher & Wilkinson, 2005) Cuts age 7-10 years provided most winter forage and cutes 4-50ha in size were utilized most by moose (Thompson & Curran, 1993) Ontario: Moose with calves avoided younger cutblocks – cover may be important when young are present (Thompson & Vukelich, 1981) BC: moose used burns and cuts 5-11 years old more than any other forest age and preferred partial cuts over clearcuts (Eastman, 1977) Quebec: Moose densities increased >50% in harvested blocks 10 years post-harvest (combined with stricter hunting regulations ; Potvin et al., 2004)
	Harvested without residual trees	- cutover habitat does not support growth of terrestrial and epixylic lichens - species found on branches and trunks dramatically reduced and experience photoinhibition and cessation of growth - post-harvest stands have substantially lower mass of lichen epiphytes	- less severely disturbed than burned sites and recolonized by plants surviving harvest, (aster, Salix, Alnus, aspen, etc.) - plants requiring fire do not fare well - post-harvest deciduous stands have greater vascular diversity than coniferous stands - tall shrubs grow vigorously and out-compete conifer seedlings			
	Burned with residual trees	- some suitable habitat is retained but remaining species exposed to changes in microclimate and will be reduced	- species found in unburned patches resemble pre-fire communities			

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
	Harvested with residual trees	- residual trees provide substrate but changes in microclimate, including wind exposure, increases mortality - residual forest patches of larger size allow greater chances of survival	- post-harvest residuals mimic post-fire residuals - larger, more, or more connected patches of residuals means faster convergence to pre-harvest community	- requires fire to reduce organic soils Lodgepole pine – - seedlings can produce cones within 3-5 years of a fire, reproductive success after 10 years - requires fire to reduce organic soils Balsam poplar – - harvest operations may set up conditions suitable for balsam poplar regeneration	Caribou tended to use clearcut areas the least in comparison to other boreal habitat types (Rettie & Messier, 2000) Caribou are more likely to occupy a cutblock if lichen is still present in adequate amounts – lack of ground treatment during harvesting preserves lichen growth (Rettie et al., 1997) Sharp decline in caribou within 5 years following timber harvest in NW Ontario, and 75% decline in caribou numbers within 11 years (Wiwchar & Mallory, 2012) Rocky Mountains: Caribou avoided areas burned within the last 60 years (Robinson et al., 2012)	Fewest empty stomachs found in wolves in logged areas 0-7 years post-harvest, indicating high prey (mainly moose) availability (Wiwchar & Mallory, 2012) Rocky Mountains: Wolves strongly selected areas burned within the last 60 years (Robinson et al., 2012) Alaska: wolves avoid burned areas for two years post-fire but re-colonize within 3 years (Fisher & Wilkinson, 2005)
Establishment Stage **11-25 years** Dense canopy of regenerating shrubs and trees a few metres high; patches of residual trees provide vertical structure; regenerating cohort of trees completes initial stocking; loses parkland appearance	Burned without residual trees	- slow colonization by shade-tolerant lichen species on fallen snags - reindeer lichens begin to colonize	- tall shrubs and deciduous tree species reach maximum cover during this stage - decreasing number of forbs, grasses, and lower shrubs	Aspen – -rapidly develops towards maximum leaf area and canopy density -self-thinning continues -no more recruitment White spruce – -occasional recruitment only after fire and harvest Black spruce – -in spruce forests, seedlings are slowly becoming established -in spruce-lichen woodlands, resprouted shrubs still dominate as seedlings grow -trees are producing cones Jack pine – -trees can reproduce successfully after 10 years	Caribou avoided sites 5-37 years post-burn because of inhibition of movement by deadfall (Schaefer & Pruitt, 1991) Caribou select stands <20 years old significantly less than older stands (Mahoney & Virgl, 2003) Rocky Mountains: Caribou avoided areas burned within the last 60 years (Robinson et al., 2012) Quebec: lower caribou density in landscapes disturbed <30 years ago than in undisturbed landscapes (Courtois et al., 2007)	Moose have higher reproductive rates in stands of this age than older (30+ years) burns (Schwartz & Franzmann, 1989) 14 year old burns produce more moose forage than 60-80 year old forests (Lautenschlager et al., 1997) Alaska: highest moose density in areas where fire occurred between 11 and 30 years ago (Maier et al., 2005) Alaska: high wolf density in large burns 11+ years old, but not significantly different from use of 30+ year old burns (Schwartz & Franzmann, 1989) Black bear adult mean weight, reproductive success, and cub survival greater in 11+ year old burns than 30+ year old burns (Schwartz & Franzmann, 1989)
	Harvested without residual trees	- still few nonvascular plant species - pioneer lichens now disappear - terrestrial lichens restricted to moist shady areas	- similar to burned stands - tall shrubs and deciduous tree species reach maximum cover during this stage - decreasing number of forbs, grasses, and lower shrubs -overall lower diversity due to lack of post-fire-adapted plants; resembles later seral stages of post-fire communities			

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
	Burned with residual trees	- residual patches support higher species diversity and biomass than surrounding cut areas - epiphytic lichen survival lower closer to patch edges due to wind	- residual trees provide patches of pre-disturbance habitat for vascular plants - patches provide sources for recolonization - patch fringes subject to edge effects	-maturity at 25 years Lodgepole pine – -seedlings and saplings are growing -produce viable seeds		Rocky Mountains: Wolves strongly selected areas burned within the last 60 years (Robinson et al., 2012)
	Harvested with residual trees	- residual patches support higher species diversity and biomass than surrounding cut areas - epiphytic lichen survival lower closer to patch edges due to wind	residual trees provide patches of pre-disturbance habitat for vascular plants - patches provide sources for recolonization - patch fringes subject to edge effects -overall lower diversity due to lack of post-fire-adapted plants; resembles later seral stages of post-fire communities			
Early Aggradation Stage 26-40 years Canopy cover is uniform; generally more open canopy in conifer stands than deciduous; dominance of regenerating trees; canopy lifts from forest floor; deadwood has mainly rotted	Burned without residual trees	- highest density of Cladonia sp. is found in stands 20-60 years old - abundant lichen biomass accumulates on trunks and branches	- overall stem density of shrubs decreases - shade-intolerant shrubs start to disappear -shade-tolerant shrubs increase in density gradually - annual and biennial forbs disappear - overall decrease in richness, diversity and evenness in vascular understory species	Aspen – -residual mature aspen have died -regenerating aspen have self-thinned and largely controlled understorey vegetation in aspen-white spruce forests White spruce – -various age and size in spruce due to continual, slow post-fire recruitment in canopy gaps Black spruce – -25-50 years: black spruce begins to dominate as feather mosses and sphagmum appear on ground in spruce forest -canopy is dense in both spruce forest and spruce-lichen woodlands	Caribou in Newfoundland used 21-40 year old stands more than they used 0-20 year old stands but less than they used 41+ year old stands (Mahoney & Virgl, 2003) Rocky Mountains: Caribou avoided areas burned within the last 60 years (Robinson et al., 2012) Quebec: lower caribou density in landscapes disturbed <30 years ago than in undisturbed landscapes (Courtois et al., 2007)	Moose abundance decreases compared to younger stands (Fisher & Wilkinson, 2005) Moose abundance declines dramatically after 30 years and reproductive success drops (Schwartz & Fransmann, 1989) Moose in Ontario found to use cutblocks 25-33 years old more often than expected based on availability (Thompson & Vukelich, 1981) Alaska: positive but not significant relationship between moose and forests burned 30-40 years ago (Maier et al., 2005) Northern Alberta: moose selected sites burned within the last 40 years (Wasser et al., 2011) High wolf density in stands aged 30+ years but not different from 11-29 year old stands (Schwartz & Franzmann, 1989) Rocky Mountains: Wolves strongly
	Harvested without residual trees	- terrestrial lichens in moist areas only - Cladonia sp. found on stumps - less substrate for lichens than burned stands - epiphytic lichens start to accumulate but biomass lower than post-fire stands due to interruption in stand continuity	- begins to resemble post-fire communities			

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
	Burned with residual trees	- same species as burned without residuals but higher diversity and biomass due to increased substrate availability, especially in moist areas - epiphytic lichen survival lower closer to patch edges due to wind	- residual patches add heterogeneity to a stand - residual patches maintain a level of continuity to old-growth stands	Jack pine – -maturity after 25 years -after ~30 years, shade-tolerant species become codominant with jack pine Lodgepole pine – -maturity after 25 years -after ~30 years shade-tolerant species become codominant with lodgepole Balsam poplar -may become codominant with aspen in stands with large canopy gaps		selected areas burned within the last 60 years (Robinson et al., 2012)
	Harvested with residual trees	-- same species as burned without residuals but higher diversity and biomass due to increased substrate availability, especially in moist areas - epixylic species remain limited due to removal of fibre during harvesting - epiphytic lichen survival lower closer to patch edges due to wind	- residual patches add heterogeneity to a stand - residual patches maintain a level of continuity to old-growth stands			
Late Aggradation Stage 40-75 years Canopy cover is uniform; generally more open canopy in conifer stands than deciduous; dominance of regenerating trees; canopy lifts from forest floor; deadwood has mainly rotted	Burned without residual trees	- highest density of Cladonia sp. is found in stands 20-60 years old - abundant lichen biomass accumulates on trunks and branches	- overall stem density of shrubs decreases - shade-intolerant shrubs start to disappear -shade-tolerant shrubs increase in density gradually - annual and biennial forbs disappear - overall decrease in richness, diversity and evenness in vascular understory species	Aspen – - clones and/or individuals begin to die, leaving gaps in canopy White spruce – -significant recruitment begins between 40 and 60 years -various age and size in spruce due to continual, slow post-fire recruitment in canopy gaps Black spruce – -optimum seed production after 50 years Jack pine – -co-dominant with or beginning to be replaced by more shade-tolerant species Lodgepole pine – -co-dominant with or	Caribou in Ontario eat more lichen in >50 year old stands than in 1-15 year old or 31-50 year old stands (Arsenault et al., 1997) Caribou in Newfoundland used 40-60 year old stands more than younger-aged stands but less than barrens or mature forest (Mahoney & Virgil, 2003) Rocky Mountains: Caribou avoided areas burned within the last 60 years (Robinson et al., 2012)	"Less moose forage" in stands 60 – 80 years old than in younger stands (Lautenschlager et al., 1997) Rocky Mountains: Wolves strongly selected areas burned within the last 60 years (Robinson et al., 2012)
	Harvested without residual trees	- terrestrial lichens in moist areas only - Cladonia sp. found on stumps - less substrate for lichens than burned stands - epiphytic lichens start to accumulate but biomass lower than post-fire stands due to interruption in stand continuity	-post-fire and post-harvest succession begins to converge after ~ 60 years			

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
	Burned with residual trees	- same species as burned without residuals but higher diversity and biomass due to increased substrate availability, especially in moist areas - epiphytic lichen survival lower closer to patch edges due to wind	- residual patches add heterogeneity to a stand - residual patches maintain a level of continuity to old-growth stands	beginning to be replaced by more shade-tolerant species Balsam poplar -may become co-dominant with aspen in stands with large canopy gaps		
	Harvested with residual trees	-- same species as burned without residuals but higher diversity and biomass due to increased substrate availability, especially in moist areas - epixylic species remain limited due to removal of fibre during harvesting - epiphytic lichen survival lower closer to patch edges due to wind	- residual patches add heterogeneity to a stand - residual patches maintain a level of continuity to old-growth stands			
Mature Stage 76 - 125 years Similar canopy cover to previous stage; deciduous content reduced; canopy rises; near the end of this stage gaps begin to appear in canopy; "ideal harvest stage"; incremental growth of trees declines; increased deadwood	Burned without residual trees	- feather mosses begin to dominate ground cover - abundance of terrestrial lichen - epiphytic lichens dominate trunks and branches	- by this stage changes in vascular plant composition is a result of overstory canopy species composition and structure and less so age since disturbance - high species diversity in herbaceous and shrubby plants - dominance begins to shift to nonvascular plants	Aspen – -aspen stand break-up occurs -aspen lose vigour and rapidly decline in canopy dominance White spruce – -original cohort of white spruce emerges as canopy dominants or co-dominants -more frequent recruitment of white spruce Black spruce – -canopy closes and begins to thin -after 100 years gaps appear in canopy in spruce forest - in spruce-lichen woodlands, open canopy forms after 100 years Jack pine – -increasingly replaced by shade-tolerant species	Caribou tend of be associated with older forests, as there is a steady increase in lichen mat thickness as stands progress from young burns to burns >90 years of age (Arseneault et al., 1997) In Newfoundland, caribou selected old stands significantly more than any other stand age (Mahoney & Virgl, 2003) Northern Alberta: caribou select open black spruce and pine-lichen stands (Wasser et al., 2011)	Moose tend to avoid old/mature stands (Cederlund & Okarma, 1988)
	Harvested without residual trees	- terrestrial lichens resemble pre-harvest conditions and have regenerated adequately - epiphytic lichen biomass is high but diversity is lower due to dominance by most competitive species - harvesting again after 70-80 years reduces chance of slow-growing lichens remaining in community	-- stands develop understorey and shrub plant communities that resemble plant communities occurring naturally - gaps in canopy create opportunities for shade-intolerant species to reappear - burned and cut stands begin to converge			

Age (years) and description	Disturbance and Structure	Lichen	Vascular plants	Trees	Caribou (overview)	Predators and alternate prey (overview)
	Burned with residual trees	- residual patches are sources of old-growth adapted species	- residual patches increase community heterogeneity through vertical and horizontal structure	Lodgepole pine – -increasingly replaced by shade-tolerant species Balsam poplar – -may become increasingly abundant in older deciduous stands without much conifer		
	Harvested with residual trees	- residual patches are sources of old-growth adapted species - at this stage species adapted to deciduous trees no longer found in conifer stands and vice versa	- residual patches increase community heterogeneity through vertical and horizontal structure			
Old-Growth Stage >125 years Heterogeneity in canopy closure; presence of large trees; diverse microhabitats; largest size and highest density of large trees; late-stage conifers dominate; increased gaps in canopy; vascular plants show up in gaps; slow-growing non-vascular plants reach maturity	Burned without residual trees	- diverse microhabitats means increased species diversity - epiphytic species thrive on trees due to changes in bark chemistry - resembles pre-fire communities	- loss of dominance of vascular species; species richness remains generally the same or increases but reduced biomass and cover - shade-intolerant species reappear due to gaps in canopy	Aspen – -continue to decline in dominance -individuals and clones die off -gaps in canopy grow White spruce – -dominates canopy after 150 years Black spruce – -open spruce canopy after 100 years -ecosystem begins to degrade without fire Jack pine – -jack pine disappears in ~170 years without fire Lodgepole pine – -lodgepole pine replaced by shade-tolerant species after 50-200 years without fire (depending on ecosystem)	Same as above	Moose made use of 120+ year old stands, exploiting early seral vegetation in canopy gaps (Stelfox et al., 1995) Alberta: white-tailed deer used 120+ year old stands in winter more than any other successional stage but not in summer (Stelfox et al., 1995)
	Harvested without residual trees	- recovery to pre-harvest communities complete - monocultures support less diversity than multi-species mixes	- shade-intolerant species reappear due to gaps in canopy			
	Burned with residual trees	- residual legacy absorbed in overall heterogeneity; similar to other post-fire stands	- residual patches increase community heterogeneity through vertical and horizontal structure			
	Harvested with residual trees	- residual legacy absorbed in overall heterogeneity; similar to other post-harvest stands	- residual patches increase community heterogeneity through vertical and horizontal structure			

APPENDIX 2. Evidence for avoidance and selection of boreal caribou habitats characterised by major boreal forest successional stages. Sources in Appendix 3. Compiled by Lucy Poley (University of Calgary).

Forest Stage	Ecozone	Caribou avoidance	Caribou selection	Reference(s)
Initiation stage 0 - 10 yrs	**Taiga Shield**	Avoidance of burned areas <40 years old		EC (2011)
	Hudson Plains	Avoidance of herbaceous areas and burned areas <40 years old; avoidance of forest abundant in deciduous species		EC (2011); Brown et al. (2007)
	Boreal Shield	Avoidance of burned areas <40-50 years old; avoidance of deciduous and mixed forests, jack pine <40 years old; avoidance of shrub-rich stands; strong avoidance of recently logged areas and recently burned areas	Selection of deciduous shrubs and ericaceous species in NF & L;	EC (2011); Crete et al. (2004), Courbin et al. (2009); Courtois et al. (2007); Bergerud (1972); Schaefer & Pruitt (1991); Antoniak & Cumming (1998); Arseneault et al. (1997); Beguin et al. (2013); Leclerc et al. (2012)
	Boreal Plains	Avoid aspen-dominated and immature stands; avoid areas with abundant shrubs, avoid recent burns; avoid burns <40 years		Neufeld (2006); James (1999); EC (2011); Hirai (2006)
	Montane Cordillera	Avoidance of aspen stands		Neufeld (2006)
	Taiga Plains	Avoidance of forest stands <10 years old in summer;	Select for recent burns in northern extreme of NT range during summer; regenerating burns and sparsely vegetated areas	Dalerum et al. (2007); Nagy et al. (2006)
	Boreal Cordillera			
Establishment Stage 11-25 years	**Taiga Shield**	Avoidance of burned areas *<40 years old*		EC (2011)
	Hudson Plains	Avoidance of herbaceous areas and burned areas *<40 years old*; avoidance of forest abundant in deciduous species	Regenerating conifer stands used to a lesser degree than mature stands;	EC (2011); Courtois (2003); Brown et al. (2007)
	Boreal Shield	Avoidance of burned areas *<40-50 years* old; avoidance of deciduous and mixed forests, avoidance of jack pine *<40 years old*; avoidance of birch and aspen forests; avoidance of shrub-rich stands; *low proportion of regenerating forests (20 – 40 years)* in Quebec caribou home ranges	Selection of deciduous shrubs and ericaceous species in NF & L; weak selection for regenerating conifer stands; *caribou in Quebec showed selection for areas disturbed within 6-20 years during spring , calving, some winter*	EC (2011); Crete et al. (2004), Courbin et al. (2009); Courtois et al. (2007); Bergerud (1972); Courtois (2003); Schaefer & Pruitt (1991); Antoniak & Cumming (1998); *Beguin et al. (2013); Leblond et al. (2011); Leclerc et al. (2012); Hins et al. (2009)*
	Boreal Plains		Young jack pine and upland jack pine-black spruce selected during summer	Rettie (1998); Rettie & Messier (2000); Metsaranta & Mallory (2007)
	Montane Cordillera	Avoidance of aspen stands	Selection of mixed lodgepole pine-black spruce	Neufeld (2006); Edmonds (1988,1993); Johnson (1980)
	Taiga Plains			
	Boreal Cordillera	Avoidance of closed deciduous and closed mixed forests throughout the year		Nagy et al. (2006)
Early aggradation Stage 26-40 years	**Taiga Shield**	Avoidance of burned areas *<40 years old*		Brown et al. (1986)
	Hudson Plains	Avoidance of herbaceous areas and burned areas *<40 years old*; avoidance of forest abundant in deciduous species		Courtois (2003; Pearce & Eccles, (2004); Brown et al. (2007)
	Boreal Shield	Avoidance of burned areas *<40-50 years* old; avoidance of deciduous and mixed forests, avoidance of jack pine *<40 years old*; avoidance of birch and aspen forests; avoidance of shrub-rich stands; *low proportion of regenerating forests (20 – 40 years)* in Quebec caribou	Dense and mature conifer forest of spruce, tamarack, jack pine, between 30 – 50 years; jack pine dominated uplands; dense jack pine and spruce stands;	Crete et al. (2004); Courtois (2003); Courbin et al. (2009); Courtois et al. (2007); Lefort et al. (2006); Duchesene et al. (2000); Hillis et al. (1998); Aresenault et al. (1997); Lesmerises et al. (2013); Moreau et al. (2012); Hins et al.

Forest Stage	Ecozone	Caribou avoidance	Caribou selection	Reference(s)
		home ranges; avoidance of mixed-deciduous forest <40 years old		(2009); EC (2011); Bergerud (1972); Schaefer & Pruitt (1991); Antoniak & Cumming (1998); *Beguin et al. (2013); Leblond et al. (2011); Leclerc et al. (2012);*
	Boreal Plains			
	Montane Cordillera		Mixed conifer lodgepole pine-black spruce and treed muskeg	Edmonds (1988); Edmonds (1993); Johnson (1980)
	Taiga Plains			
	Boreal Cordillera	Avoid closed spruce forest and conifer forests without lichens in mid-winter;		Nagy et al. (2006)
Late aggradation Stage 41-75 years	**Taiga Shield**		Caribou use dense mature conifer and open conifer forests with abundant lichen	Brown et al. (1986)
	Hudson Plains		Large patches of intermediate (50 – 99 years) black spruce	Courtois (2003; Pearce & Eccles, (2004); Brown et al. (2007)
	Boreal Shield		Mixed spruce-fir forests *>40 years*; Dense black spruce stands; Mature conifer forests with lichen; dense jack pine and spruce stands; dense mature conifer forests; caribou select for closed-canopy mature conifer forests throughout most of the year; 50 – 70 year old forests used during calving and summer in Quebec	Crete et al. (2004); Courtois (2003); Courbin et al. (2009); Courtois et al. (2007); Lefort et al. (2006); Duchesene et al. (2000); Hillis et al. (1998); Aresenault et al. (1997); Lesmerises et al. (2013); Moreau et al. (2012); Hins et al. (2009); EC (2011); Bergerud (1972); Schaefer & Pruitt (1991); Antoniak & Cumming (1998); *Beguin et al. (2013); Leblond et al. (2011); Leclerc et al. (2012);*
	Boreal Plains		Mature forest > 50 years old; black spruce-dominated stands and lowland black spruce stand within muskeg used for calving	Neufeld (2006); Dalerum et al. (2007); Rettie (1998)
	Montane Cordillera		Mixed conifer lodgepole pine-black spruce and treed muskeg	Edmonds (1988); Edmonds (1993); Johnson (1980)
	Taiga Plains		Upland and lowland black spruce forests with abundant lichens ; large patches of spruce peatland	Culling et al. (2006); McLoughlin et al. (2005)
	Boreal Cordillera	Avoid closed spruce forest and conifer forests without lichens in mid-winter;		Nagy et al. (2006)
Mature Stage 76 - 125 years	**Taiga Shield**		Caribou use dense mature black spruce and open black spruce forests with abundant lichen; Some use of mature white spruce and fir stands	Brown et al. (1986); Schaefer et al. (2000)
	Hudson Plains		Dense and mature black spruce forest with lichens; Large patches of intermediate (50 – 99 years) and mature (100 – 200 years) black spruce	Courtois (2003; Pearce & Eccles, (2004); Brown et al. ()2007)
	Boreal Shield		Mature conifer forests with lichen, spruce-fir stands 80+ years; late seral stage spruce-dominated lowlands; open conifer (spruce, jack pine, fir, tamarack) stands >70 years old; low-density black spruce forests and black spruce-tamarack peatlands with abundant lichen; strong selection for open lichen woodlands in winter; forests aged 90 – 120 years old used year-round by caribou in Quebec	Courtois (2003); Courbin et al. (2009); Courtois et al. (2007); Lantin et al. (2003); Bergerud (1985); Vors (2006) Wilson (2000); Leblond et al. (2011); Hins et al. (2009)
	Boreal Plains		Treed peatlands with high abundance of lichens	Anderson (1999); Bradshaw et al. (1995); Anderson et al. (2000); Areseneault (2003); Rettie & Messier (2000)
	Montane Cordillera		Open, lodgepole pine-dominated stands of 80 years or more	Thomas et al. (1996); Szkorupa (2002)

Forest Stage	Ecozone	Caribou avoidance	Caribou selection	Reference(s)
	Taiga Plains		In Dehcho prefer forest stand ages of 100 years or older; prefer open coniferous habitat with abundant lichens	EC (2011); Culling et al. (2006); Nagy et al. (2006)
	Boreal Cordillera		Select for open upland and lowland spruce forests with abundant lichen	Culling et al. (2006); Nagy et al. (2006)
Old-Growth Stage >125 years	**Taiga Shield**		Caribou use dense mature conifer and open conifer forests with abundant lichen; Some use of mature white spruce and fir stands	Brown et al. (1986); Schaefer et al. (2000)
	Hudson Plains		Mature conifer stands used ; Large patches of mature black spruce (100 – 200 years)	Courtois (2003); Brown et al. (2007)
	Boreal Shield		Mature conifer forest with lichen; dense and open mature conifer forests; open canopy mature conifer forests with abundant lichen; high abundance of arboreal lichens important for foraging in some areas; open lichen woodlands used year-round	Courtois (2003); Courbin et al. (2009); Courtois et al. (2007); Bergerud (1985); Wilson (2000); Lantin et al. (2003); Vors (2006); Hillis et al. (1998); Lander (2006); Hins et al. (2009)
	Boreal Plains		Treed peatlands with high abundance of lichens	Anderson (1999); Bradshaw et al. (1995); Anderson et al. (2000); Areseneault (2003); Rettie & Messier (2000)
	Montane Cordillera	Avoid white spruce stand with low abundance of lichens		Saher (2005)
	Taiga Plains		In Dehcho prefer forest stand ages of 100 years or older; prefer open coniferous habitat with abundant lichens	EC (2011); Culling et al. (2006); Nagy et al. (2006)
	Boreal Cordillera		Select for open upland and lowland spruce forests with abundant lichen	Culling et al. (2006); Nagy et al. (2006)
Other habitat (non-forest)	**Taiga Shield**		Upland tundra and sand flats in proximity to water; Treed and open wetlands, small bogs, large open muskeg; Lakes for loafing and ruminating ; Glacial and bedrock erratics with lichen	Schmelzer et al. (2004); Brown et al. (1986)
	Hudson Plains		Fens, bogs and lakes; Poorly drained areas dominated by sedges, mosses and lichens; Peatlands dominated by open bogs and terrestrial lichens (20 – 60 years)	Pearce & Eccles (2004); Magoun et al. (2005); Brokx (1965)
	Boreal Shield	Avoidance of active logging*; strong avoidance of habitat patches embedded in disturbed habitat (cutblocks and regenerating stands);* avoided recently logged areas twice as strongly as avoided recently burned areas in Quebec	Water bodies and wetlands; Open wetlands, peninsulas, islands; Upland tundra for loafing; Areas with dry to moist sandy to loamy soils and shallow soils over bedrock Cutovers and regenerating stands promote caribou concentration in residual forest patches when found at high densities in the area surrounding forest patches	Courtois (2003); Brown et al. (1986); EC (2011); Wilson (2000); Schaefer & Pruitt (1991); Cumming & Hyer (1998); *Lesmerises et al. (2013)*; Beguin et al. (2013)
	Boreal Plains	Avoid areas with main roads, seismic lines, well sites, high density of cutblocks;	Select peatland complexes in N. Alberta	EC (2011); Dyer (1999); Stuart-Smith et al. (1997)
	Montane Cordillera	Avoid areas with a large proportion of cutblocks and seismic lines		Neufeld (2006)
	Taiga Plains	Avoid edge habitat	Small islands, old burns at edges of wetlands, lakeshores; riparian habitat	Culling et al. (2006); Nagy et al. (2006); McLoughlin et al. (2005)
	Boreal Cordillera	Avoid water during the rut, calving, winter		Nagy et al. (2006)

APPENDIX 3. Literature Sources for Appendix 1 and Appendix 2.

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