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Risk Analysis, Ecology, and the Science/Policy Interface

Managers overseeing land and water resources encounter ecological risks daily. When these risks from diverse human and natural sources begin to overlap and interact (what ecologists call "Cumulative Effects"), decision-makers face the task of countering threats to resource management objectives. Risk analysis has much to contribute to understanding and managing cumulative effects for many types of ecological problems. A staple of high-hazard industries concerned with safety of services and processes, risk analysis is also relevant to understanding, analysis, research, and communication needed for ecological threats. For diverse activities and enterprises occurring on a land base it brings everyone (policy makers, regulators, and diverse stakeholders alike) to a common ground where technical and policy bias can be set aside and the same language can be spoken—the language of risk analysis. Appendix 1 summarizes a wide variety of risk analysis methods recognized by the International Organization for Standardization. This guide focuses on the application of one of those methods—the Bowtie Risk Analysis Tool (BRAT).

The Bowtie Risk Assessment Tool (BRAT)

Origins and Purpose

The Bowtie Risk Assessment Technique (BRAT) is a risk analysis approach that can be used to visualize and synthesize the key elements of an environmental risk assessment. BRAT owes its name to the shape of the key framework diagram, which often resembles a bowtie. It was developed in the late 1970s and initially used in high-hazard industries such as the oil and gas sector to manage risk events inherent to their operations (CGE Risk Management Solutions 2017). Because of its value to any risk assessment process, the International Organization for Standardization, which develops International Standards that provide solutions to global challenges, has listed BRAT as a method for selecting and applying systematic techniques for risk assessment (IEC/ISO 31010:2009 standard). BRAT is only recently beginning to be applied to identifying and managing environmental risk events (ICES 2014; Creed et al. 2016; Elliott et al. 2017; Kishchuk et al. 2018; Winder et al. 2020).

BRAT Frameworks

Qualitative Risk Assessment

The key component of BRAT is the bowtie diagram, which is a schematic concept of a risk event and its effects, of the threats that increase the likelihood of the risk event taking place, and of the barriers that can be put in place to prevent the risk event from occurring and to minimize its effects in case it does occur. The strength of the bowtie diagram lies in providing a visual synthesis of the key drivers of the problem and potential solutions.

The key elements of the bowtie diagram are shown in Figure 1, with further descriptors in Table 1. The circle in the centre is the risk event that is being assessed. To the left are the threats, which contribute to the likelihood of the risk event taking place. In industrial settings, threats and barriers are considered to be anthropogenic in origin, comprising a system regulated by human factors. However, in ecological problems it may be more appropriate to include natural threats and barriers, as their interaction with human elements may be key components of the overall system regulating risk. To the right are the effects, which would take place if the risk event occurs. Preventative barriers that decrease the likelihood of the risk event can be placed between a threat and the risk event. These are preventative and. It is also possible to add mitigative barriers between the risk event and the effects, which will reduce the overall impact of the risk event after it occurred. The square at the top of the diagram is the policy objective that provides a broader framework for the risk event and its effects.

It is readily apparent that risk in a BRAT framework "flows" from left to right (threats, modified by barriers, drive the potential occurrence of the Top Event; when it occurs, the Top Event, modified by mitigation factors, may trigger the consequence). However, beginning the development of a BRAT framework by first outlining threats may not be satisfactory—it may bias the risk assessment towards known and available data, avoiding knowledge gaps and poorly defining the Top Event. The preferred approach involves first determining and clearly defining the Top Event, hopefully in terms of a specific management objective found in a top-level consensus document or report. In conjunction with that, there can be an assessment of the critical "dreaded outcomes," such as the consequences to be avoided that might result from the occurrence of the Top Event. Finally, with these in hand, it is possible to identify key threats that specifically pertain to the outcomes. For example, if "predation lowers caribou populations" is a consequence, then "predation of caribou" is likely a key threat. Note that multiple threats can apply to one consequence, or conversely one threat can lead to multiple consequences. When BRAT frameworks are chained (consequences of one becoming threats for the next), it is not unusual to have a "multiple threat/one consequence" framework lead at the left, and a "one threat/multiple consequence" framework follow to the right (e.g., Figure 2). Complexity is an important consideration in chaining frameworks. Adding too many elements can reduce comprehension of the framework and its utility for portraying risk in a meaningful way. In cases where a threat or consequence appears to resolve as a series of closely related events, it may be that the element is poorly defined or in the wrong place (threats and consequences are sometimes confused). It is also possible that the Top Event might be poorly defined. Ideally, the Top Event should portray a technically well-defined threshold critical to the other elements of the framework.

Although this guide focuses on the use of BRAT frameworks in an ecological context, it should be noted that the consequences do not have to focus solely on ecological outcomes. It is also possible to incorporate financial, socioeconomic, political, or cultural consequences, either directly or in an adjunct analysis (per Winder et al. 2020).

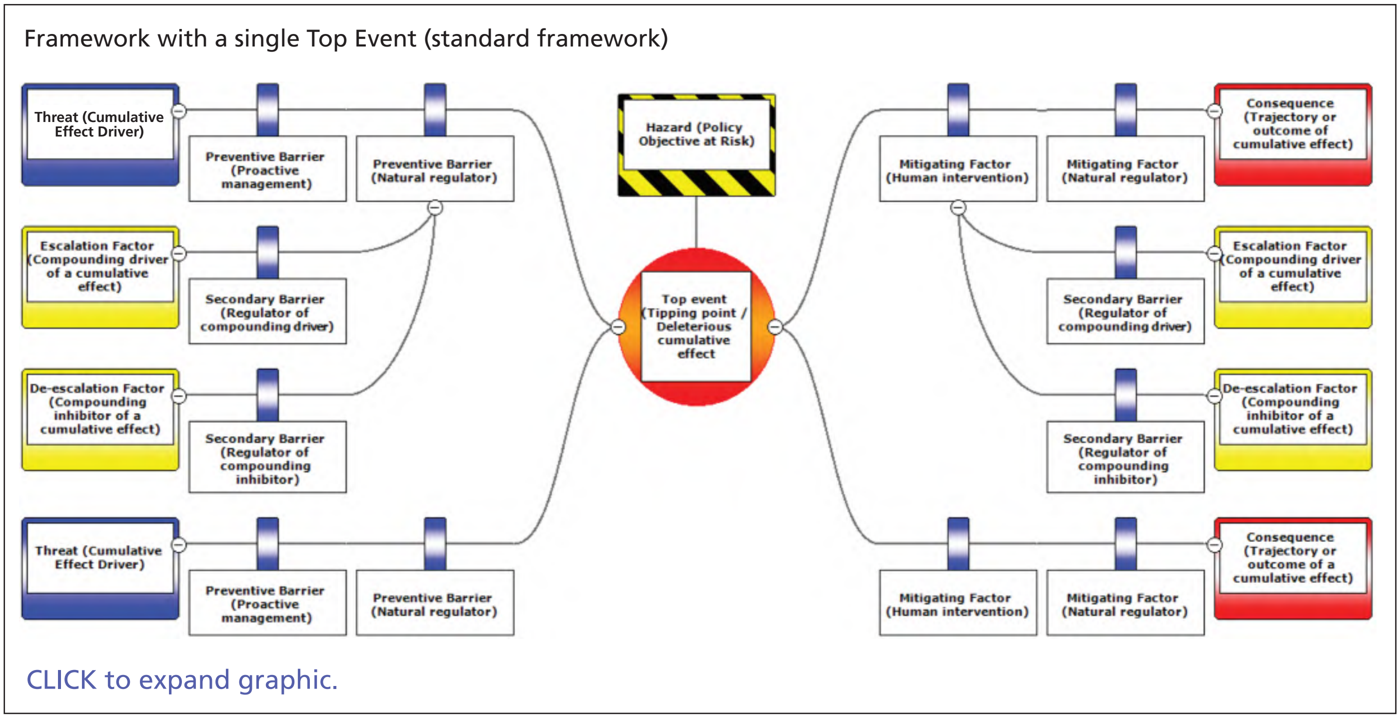


Figure 1. A generic BRAT framework, showing associated terms used in risk analysis (and equivalent ecological terms in parentheses). Excerpted from Winder et al. (2020). (See enlarged versions of these graphics in Appendix 2.)

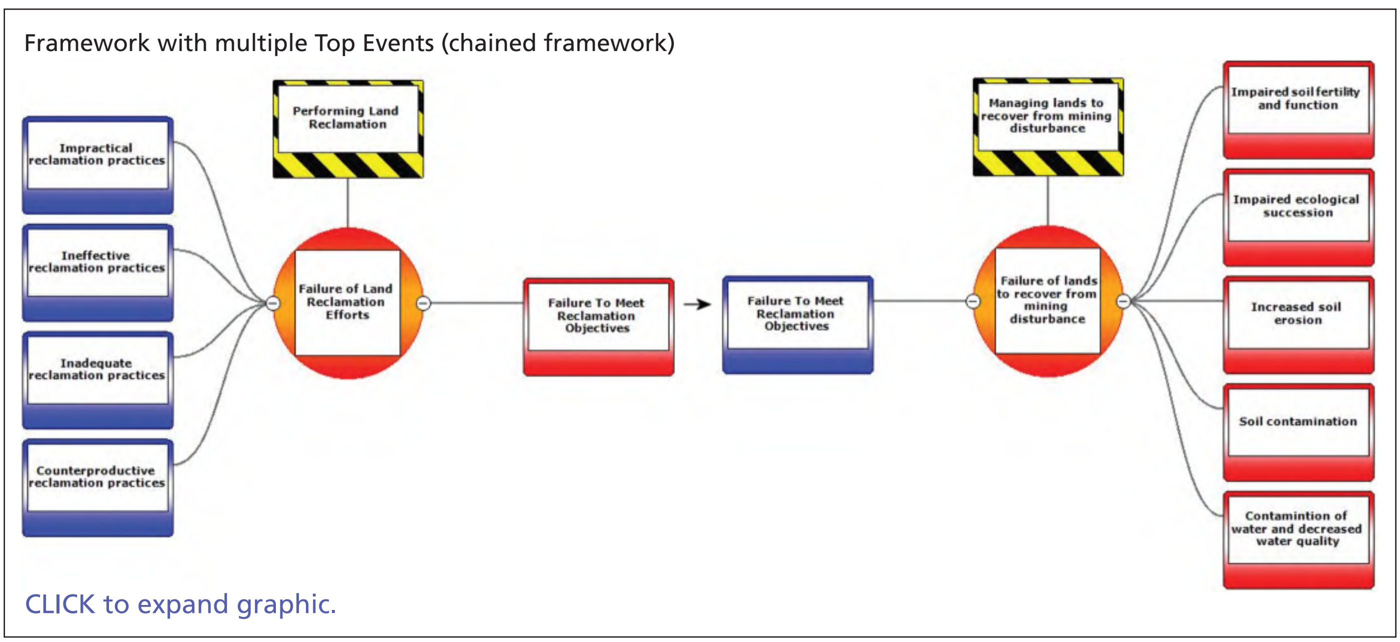


Figure 2. Two simplistic BRAT frameworks chained to show the relationship between two Top Events (failure of land reclamation efforts at left and failure of lands to recover from mining disturbance at right).

Table 1. Terminology used in the Bowtie Risk Assessment Tool (BRAT) with definitions and analogous terms, excerpted from Winder et al. (2020)

BRAT term	Definition (in ecological context)	Analogous term(s)
Hazard	Key policy developed to achieve a desired outcome, found in the grey literature or high-level peer-reviewed studies and syntheses.	Policy objective at risk
Top Event[a]	Result of the failure of the *Hazard*, can be triggered by the cumulative effects of single or multiple *Threats*.	Tipping point/deleterious cumulative effect
Threat	A cause of anthropogenic and/or natural risks that can trigger the *Top Event*.	Cumulative effect driver
Consequence	Outcome of policy failure due to occurrence of the *Top Event* (specific condition that the key policy seeks to avoid).	Trajectory or outcome of a cumulative effect
Preventive Barrier[b]	Anthropogenic or natural factors that limit *Threats* and thereby control or prevent the occurrence of the *Top Event*.	Proactive management or natural regulator
Mitigation Factor[b, c]	Anthropogenic or natural factors that could potentially mitigate the severity of a *Consequence*.	Human intervention or natural regulator
Escalation Factor[d]	Influences regulating/elevating risks by limiting the effectiveness of *Barriers* and *Mitigation Factors* (if several, acting in synchrony).	Compounding driver of a cumulative effect
De-escalation Factor	Influences regulating/reducing risks by increasing the effectiveness of *Barriers* and *Mitigation Factors* (if several, acting in synchrony).	Compounding inhibitor of a cumulative effect
Secondary Barrier[e]	Interventions and influences that could potentially limit the effect of *Escalation Factors* or *De-escalation Factors*.	Regulator of compounding. drivers/inhibitors

a A.K.A. *Risk Event* in some BRAT frameworks.

b A.K.A *Layer of Protection* in some BRAT frameworks.

c More generally, a *Recovery Barrier* controls (or prevents) a *Consequence*. It might also mitigate the impact and/or severity of a *Consequence*. In Winder et al. 2020, the term *Mitigation Factor* specifies a *Recovery Barrier* that mitigates consequences.

d This can have a dual role, acting as a *De-escalation Factor* with effects ranging from risk elevation to risk reduction.

e A.K.A. *EF Barrier (Escalation Factor Barrier)*

Used for the frameworks included in this guide, BowTieXP (CGE Risk Solutions, Leidschendam, The Netherlands) is an example of software that can be used to design and analyze BRAT frameworks. However, many of the features are designed for industrial use. Simple qualitative frameworks can be plotted with various graphics programs; it is also possible to build a quantitative BRAT framework using a statistical computer language like R (q.v. Winder et al. 2020).

Semi-quantitative Risk Assessment

Risk matrices

It is often possible to initially quantify risk at a basic level using various types of risk matrices (Figure 3). For BRAT frameworks, a risk matrix can be developed for each barrier, assessing its importance within the overall framework. This can serve as a prelude to an in-depth sensitivity analysis of the framework. For example, barriers with very high hazard ratings might be prioritized for further evaluation of their influence on the Top Event and consequence likelihoods.

Layers of protection analysis

Risk can be quantified within a BRAT framework using Layers of Protection Analysis (LOPA). Threat incidence and barrier effectiveness are the main inputs to the analysis. In standard LOPA, barrier effectiveness is expressed as a percent probability of barrier failure (i.e., the percent chance that the barrier fails to prevent the threat from contributing risk to the Top Event and/or consequence). Although this approach is not fully stochastic, it captures and portrays the quantitative nature of risk as it flows through the BRAT framework. Software such as BowTieXP can incorporate LOPA into a bowtie framework for easy calculation. To briefly describe the method, a probability of failure on demand (PFD) is estimated based on published literature or the best available information. Threat incidence (or Top Event likelihood) is multiplied by the PFDs for intervening barriers (per individual threat or consequence) to produce a likelihood of occurrence (corresponding to the Top Event and consequences). Much more information on the use of LOPA in industrial settings is available in the literature and online (e.g., Summers 2003; Willey 2014; Johnson 2015).

There are some shortcomings of standard LOPA, as probabilities ranging from 0–1 (0–100%) are difficult to reconcile with continuous variables that might also be used to produce and reconcile estimates of barrier effectiveness. Winder et al. (2020) used a modified LOPA, wherein the probabilities exceeded 1 (100%). They termed these probabilities "LOPA Factors" to distinguish them from standard PFD values. In effect, failure estimates greater than 100% indicate risk that must be reduced before a barrier begins to be effective. Employing a modified LOPA may be necessary to quantify risk, because ecological and demographic data used to estimate barrier effectiveness may otherwise be difficult to map as simple probabilities.

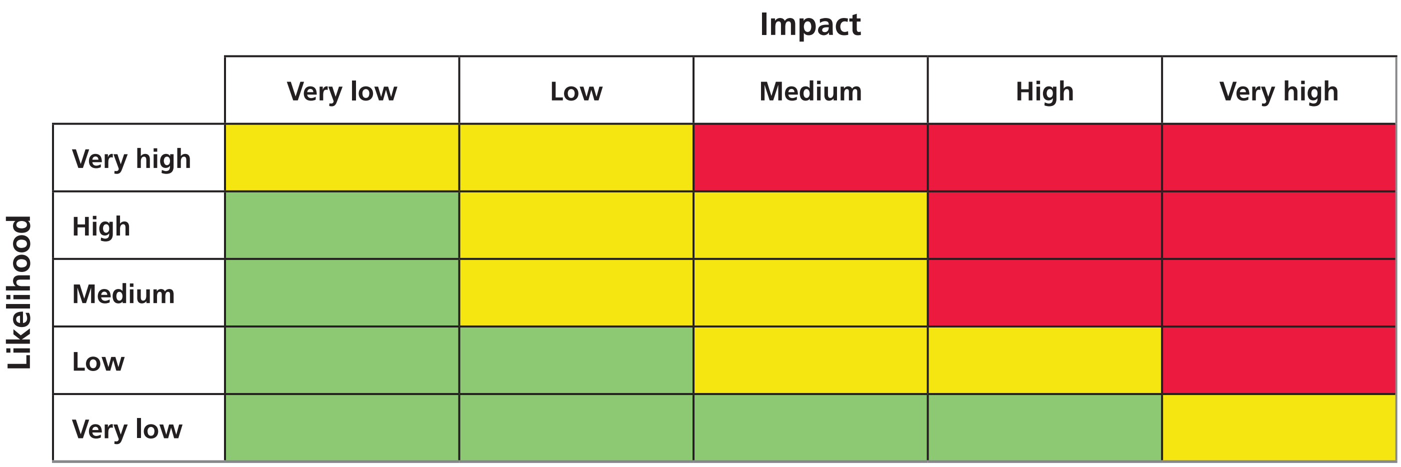


Figure 3. Example of a risk matrix that could be used in various risk analysis methods, such as simple hazard analysis or BRAT frameworks. The colours denote an assigned level of risk tolerance. For example, green could mean "sufficiently controlled and no intervention is needed, continue monitoring," yellow could mean "caution—assess need for improvement and consider where intervention may be needed," and red could mean "unacceptable outcome where active intervention and control are needed." By assigning probabilities to the "Likelihood" categories and severity values to the "Impact" categories, then plotting the quantified risk for a particular barrier, it is possible to determine barrier effectiveness in the context of risk tolerance.

BRAT Suitability for Ecological Problems

General Suitability

BRAT can be useful in certain, but not necessarily all environmental risk assessment scenarios. To decide whether plotting the risk event and associated threats, barriers and consequences onto a bowtie is helpful, we offer a BRAT Suitability Score:

1. Assign-scores (0 = no, 1 = yes) to the following criteria:
    a) Multiple threats present and significant
    b) Multiple consequences present and significant
    c) Interacting threats present
    d) Threat barriers present
    e) Risk quantification is possible with some type of compliance data
2. Suitability = sum of sub-scores.
3. We suggest that a score of 3 or more indicates that a BRAT framework might be a useful tool in an environmental risk assessment scenario.

Environmental Risk Assessment: Cumulative Effects

An Environmental Risk Assessment is a process for estimating the likelihood of an adverse outcome due to changes in environmental conditions resulting from human activities (Ministry of Environment, Lands and Parks 2000). Some human activities aggravate the effects of other past, present, or future human activities, resulting in so-called "cumulative environmental effects" (Government of Canada 2019). Considering cumulative effects therefore requires practitioners to look beyond the incremental impacts of a single decision, which may be individually insignificant but may cumulatively contribute to significant environmental change (Schultz 2009).

Identifying the following key elements is useful for assessing an environmental risk: the risk event that can lead to adverse effects, the threats that can trigger the risk event, and the effects that the risk event would have. Often, measures that can prevent the risk event and those that can mitigate its effects can also be identified. Deciding on the most effective preventative or mitigative measures in a complex scenario with cumulative effects is difficult without an appropriate structure to adequately capture all elements that play a role. Over the past 25 years, cumulative environmental effects have received considerable attention from practitioners, academics, and legislators, but their accurate assessment and management at broader landscape scales remains challenging (Sinclair et al. 2017).

Several jurisdictions in Canada have developed cumulative effects frameworks. The Province of British Columbia uses a cumulative effects framework that consists of three components (Government of British Columbia 2014). The first component establishes the "values foundation," which includes identifying the relevant values and objectives, choosing the appropriate methods for the assessment, collecting the necessary data, and defining the geographic area for the assessment of cumulative effects. The second one is the assessment itself, which involves evaluating the current condition of values relative to the objectives, and identification of current and future risks. The third component is decision support for the stakeholders. BRAT can contribute to the third component of this framework for cumulative effects. The visual synthesis of the threats, barriers and impacts demonstrates gaps and redundancies in the management system, which helps to better understand and manage the risk event.

The Canadian Federal Government has published a "Framework for Addressing Cumulative Environmental Effects in Federal Environmental Assessments" (Government of Canada 2019). This framework consists of five steps: Scoping, Analysis, Mitigating, Determining Significance and Follow-up. Bowtie diagrams could provide a useful tool in the decision-making process particularly for Step 2: Analysis (Assess the status of the receiving environment; Assess the cumulative environmental effects of the project; and Assess the cumulative environmental effects of the project in combination with future projects and activities) and Step 3: Mitigating (Identify mitigation measures for cumulative environmental effects).

Other Ecological Risk Assessment

Aside from general cumulative effects problems at the landscape level, BRAT frameworks could be used to understand interactive risks for a variety of ecological problems at the site level. For example:

- Containment of invasive species
- Adaptive forest management
- Climate change adaptation
- Pest management
- Fire management
- Wildlife management

However, even at the site level, a close examination of these problems likely requires an accounting of cumulative anthropogenic effects to fully assess risks.

BRAT and Addressing Environmental Risks

To address environmental or other risks, there are three categories or phases of activity:

Threat Identification

This activity precedes the BRAT framework development described in this guide. Before the BRAT can utilize compliance data for the most significant threats, there must be a consensus that identifies and prioritizes those threats. Data such as field observations and monitoring are compiled and analyzed by researchers and stakeholders, and ideally listed in an agreed executive summary or top-level document.

Risk Analysis

The first step described in this guide is the use of the BRAT framework or some other type of risk analysis to qualify and quantify risks. Critically, data on the incidence and severity of threats is needed to begin this activity. Figure 4 shows a standard approach to qualification of risks to the protection of caribou habitat, where barriers can be organized and classified according to their overall characteristics such as scope or degree of control. This can help visualize gaps in risk regulation, such as showing which barriers have legal consequences, versus those that only provide recommendations or guidelines. Figure 5 shows a more detailed type of analysis; in this case, risks pertaining to the decline of caribou populations are quantified. Quantification of risk requires information on the incidence of threats and compliance data (data describing the performance of real-world threat barriers). In addition to the field observations and monitoring used to identify threats, examples of compliance data might include license and permit figures, summary information for legal actions, and geospatial data. Note that incomplete data do not necessarily negate the relevance of a risk analysis. Assembling a BRAT framework to quantify risk is equally useful in identifying knowledge gaps, policy gaps, and compliance gaps where improvements are needed if eventual decisions for risk management are to be well-informed and credible.

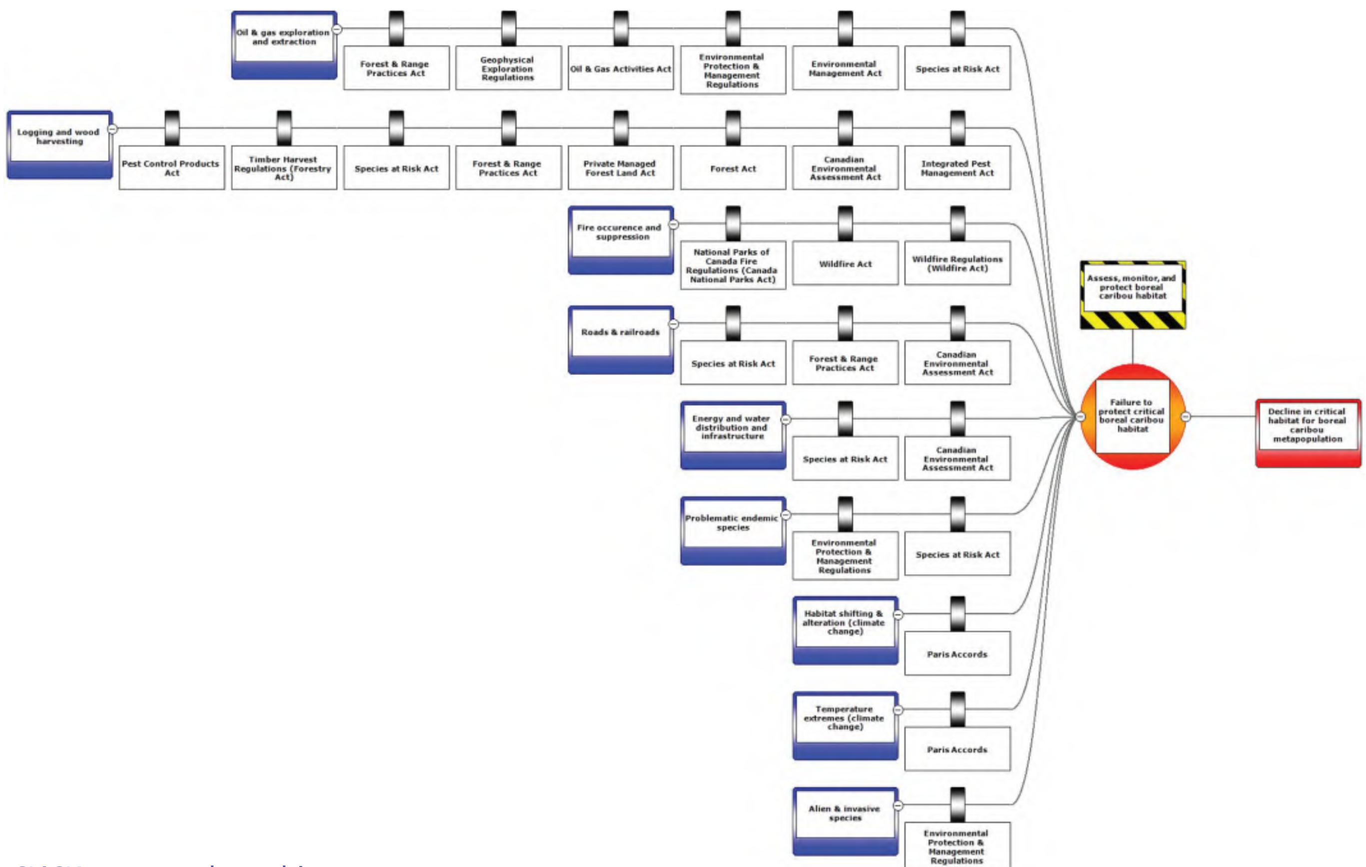
Risk Management

To support decision making for managing environmental risks, it is necessary to forecast risks. The BRAT framework shown in Figure 5 includes escalation and de-escalation factors with a temporal dimension; these are factors expected to change over time, depending on the level of interventions and how factors may respond. Without making changes, risk is still only considered from a contemporary viewpoint. However, risks can be forecast by forcing a change to risk quantification for both threats and barriers, based on a scenario that changes threat incidence or the effectiveness of a barrier. For example, Winder et al. (2020) forecast the cost of protecting caribou by changing assumptions regarding specific risk barriers.

The framework in Figure 5 also departs from the industrial view of risk regulation in that it incorporates natural barriers to risk along with those that are more directly anthropogenic. In land management, natural barriers to risk often provide important points of control via human escalation or de-escalation of risks. To take this analysis a step further, important risk escalation factors found in Figure 5 (disturbances related to climate change and linear features) are emphasized and reconfigured in Figures 6 and 7 within BRAT frameworks allowing more detailed input into barrier effectiveness (via the risk escalation factors). The framework in Figure 5 incorporates a parallel demographic metric (lambda) to reconcile and rationalize the risk quantification. If an area-based parallel metric were used to reconcile barrier effectiveness and quantify risk in Figures 6 and 7, it might eventually be possible to map the associated risk levels to aid decision-making in a spatial context. However, caution is warranted. The demographic data used to reconcile barrier effectiveness in Figure 5 was gathered at the herd level; variance of demographics at the sub-herd level (difficult to assess) would be needed to map the risk portrayed in Figure 5. For instances where more detailed variance might be available, Figure 8 represents an idealized situation where the risk of policy failure might be mapped to aid land management.

Example Ecological BRAT Frameworks

Qualitative Analysis of a Single Top Event



CLICK to expand graphic.

Figure 4. A qualitative "single Top Event" BRAT Framework. This framework follows the standard industrial approach, solely portraying the human regulatory framework that protects critical habitat for boreal woodland caribou in northeastern British Columbia. Threats are ranked according to their level of contribution to the risk event. Barriers are the acts and regulations that exist on the provincial (British Columbia) and federal level to protect caribou habitat (Ministry of Environment 2010). The effect of the failure to protect the habitat is a decline in critical habitat for the boreal caribou meta-population.

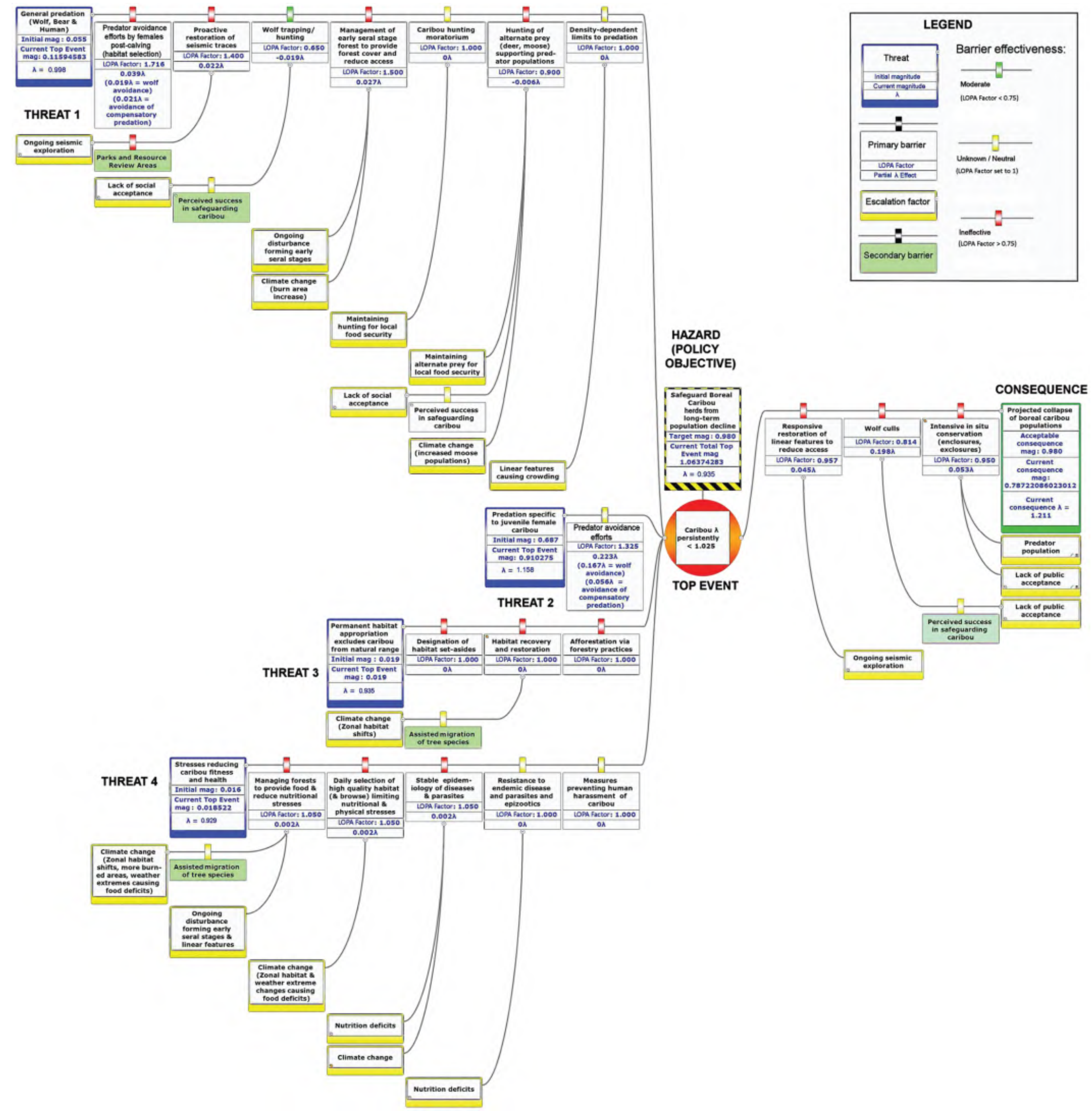


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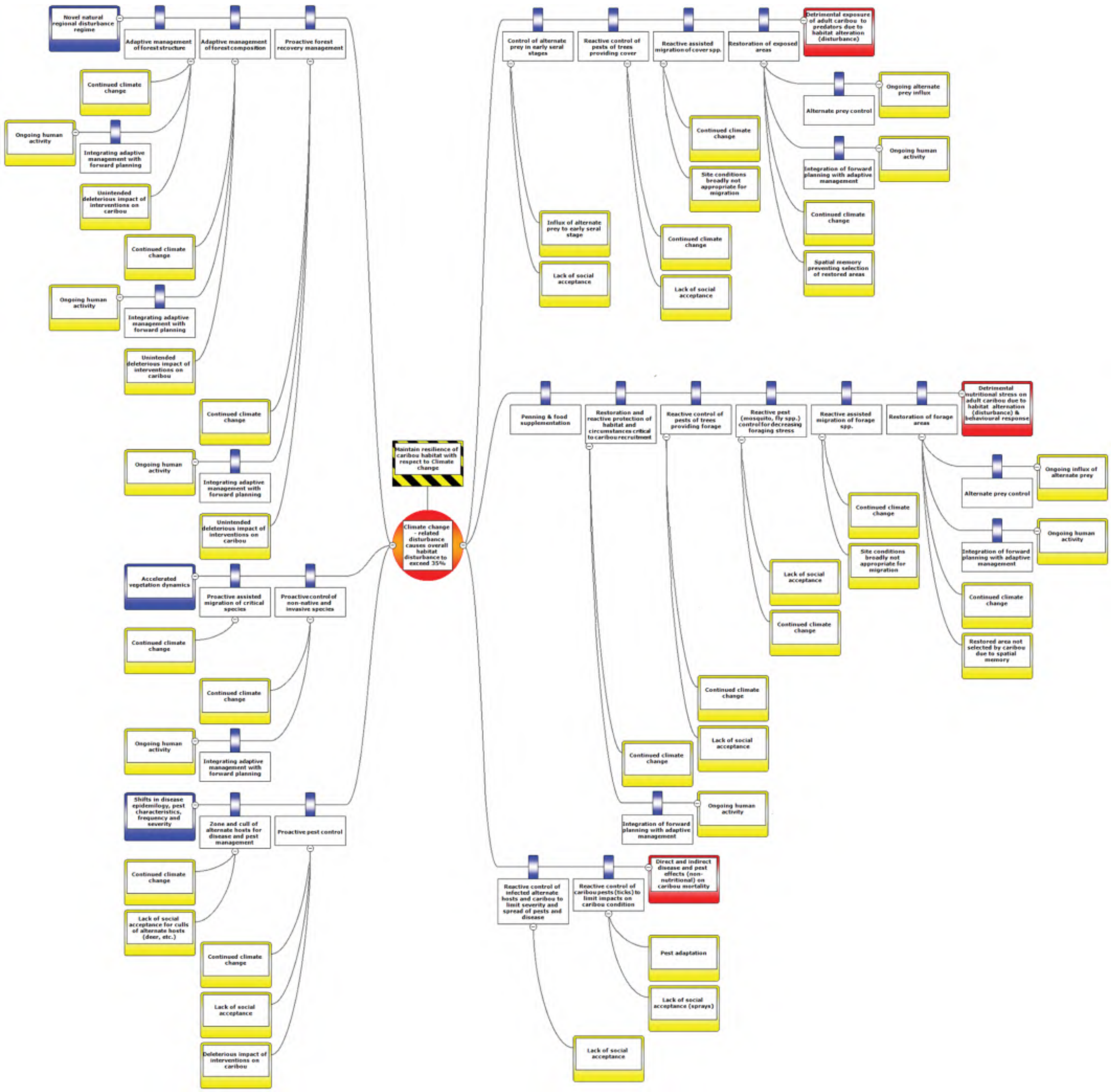
Figure 5. A "single Top Event" BRAT framework (per Winder et al. 2020) that qualifies and quantifies cumulative effects and risks to sustainability of caribou in northeastern British Columbia, Canada. Threat incidence is not shown. The upper blue numbers in threat barrier boxes correspond to the probability (1 = 100%) of barrier failure (to block the threat). In this case, probabilities > 100% correspond to risk levels that must be overcome before barriers can become effective; this also permits the probabilities to be reconciled with other continuous measures of risk. The lower blue numbers in the barrier boxes are lambda (population growth rate) values characterizing the demographic response of a caribou herd to risk reduction for that barrier. Parallel risk metrics were necessary because it was impossible to estimate the effectiveness of all barriers solely in terms of one parameter. It was necessary to use two parallel parameters (probabilities and lambda) to reconcile gaps in quantitative estimates of risk. In a full-featured framework, numbers can also be shown pertaining to the likelihood of occurrence for the Top Event (central red circle) and consequence (red box at right).



CLICK to expand graphic.

Figure 6. A "single Top Event" BRAT framework with risks related to climate change and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.

Multiple Top Events (Chained Frameworks)

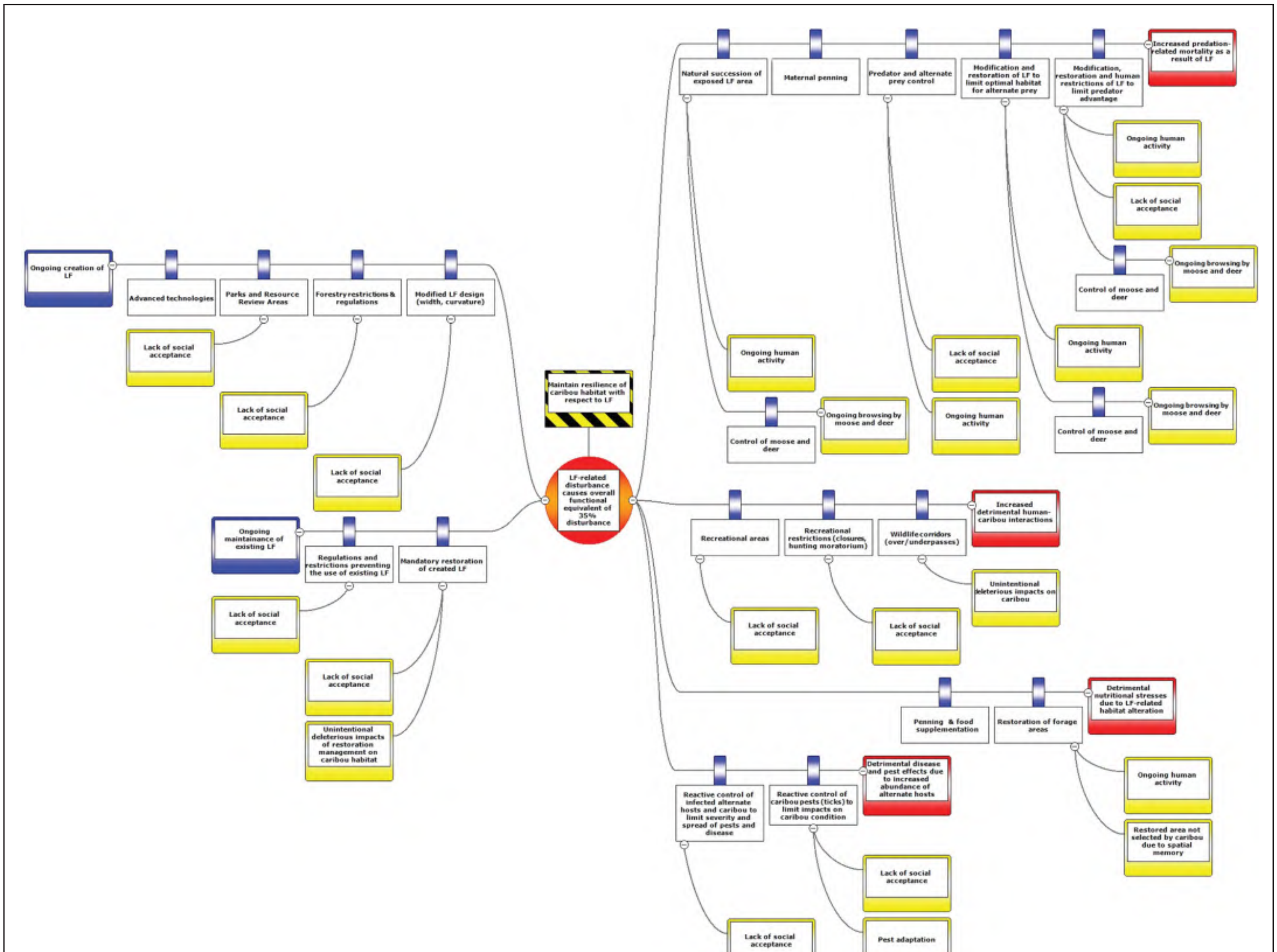


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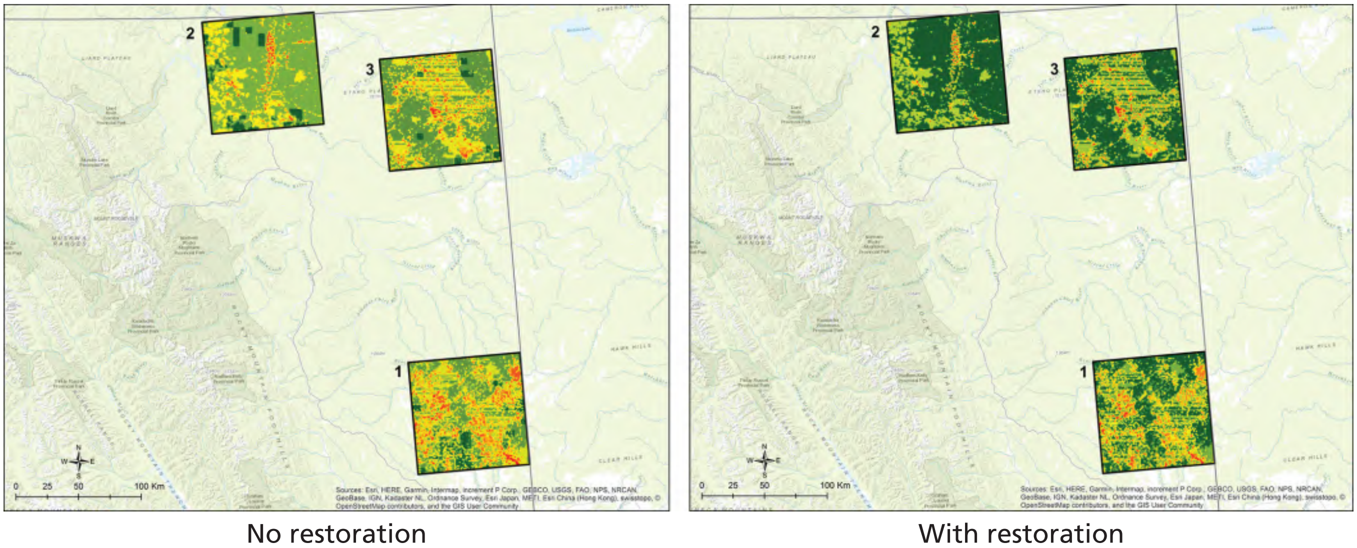
Figure 7. A "single Top Event" BRAT framework portraying qualitative risks related to linear features (linear disturbances such as seismic exploration traces, pipelines, hydroelectric lines, roads, and trails) and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.



CLICK to expand graphic.

Figure 8. Preliminary heat maps show the intensity of some anthropogenic threats highlighted as critical for boreal caribou within several BRAT frameworks for northeastern British Columbia, Canada. Orange-red is more intense, yellow-green is less intense. The current situation (L) is contrasted with a future scenario where all seismic traces have been rehabilitated (R).

Implications for Decision-making and Managing Risk

Risk events such as the effects of mining on the surrounding ecosystem or forestry operations on population growth of a protected species are well-suited to the visual representation of the pathway of the risk event using BRAT. The bowtie diagram easily captures several threats and impacts at once and shows the barriers that can be put in place to prevent potential negative impacts. Typically, however, in the case of complex environmental risk events, the relative contributions of each threat to the occurrence of the risk event or the effectiveness of any given barrier are more challenging to quantify. Standard semi-quantitative risk analysis (e.g., using the standard LOPA) is best suited for less complex scenarios in closed systems, for which BRAT was originally developed. For more complex scenarios, parallel metrics (e.g., demographic data per Winder et al. 2020) can be used to reconcile the probabilities used in LOPA to produce an estimate of risk values.

In some cases, when it is difficult to assess changes in the probability that a risk event will occur (as a function of threats and barriers), it may suffice to categorize the severity of the threats and effectiveness of the associated barriers (using risk matrices for example). Incorporating these into a bowtie diagram would allow policymakers to assess where the main threats lie, whether adequate barriers are in place, where data gaps should be addressed, and which barriers should receive a more detailed risk analysis.

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Appendices

Appendix 1: Types of risk analysis

The use of any one particular risk assessment method may incorporate a mixture of approaches. This appendix lists a range of standard approaches that might be applicable to ecological problems (specifically, in the context of cumulative effects). There are 31 Risk Assessment Techniques listed by the International Organization for Standardization in their "ISO.IEC 31010:2009 – Risk management – Risk assessment techniques." Keeping in mind that many of these methods were developed for industrial or business settings, we list these techniques below along with commentary on their potential relevance to ecological problems such as cumulative effects.

1. Brainstorming. Structured brainstorming discussions may be suitable for developing consensus during the initial development of a qualitative risk assessment; the approach is open-ended and therefore not suitable for detailed refinement and quantification of risks.
2. Structured/Semi-structured interviews. This method is potentially useful for building and achieving consensus on the important elements of risk; the approach presumes foreknowledge of relevant questions and framework structure to guide input.
3. The Delphi Method. As above, an interview of an expert panel is potentially suitable for building consensus and prioritizing threats but requires significant foreknowledge of the risk landscape.
4. Checklist. Can potentially be used to assess risks once risk scenarios are well understood.
5. Preliminary Hazard Analysis. This method is potentially useful for determining which hazards are important to include in a more thorough risk analysis. A preliminary determination of risk levels is made where risk is a combination of probability and severity, assessed in a matrix. Matrix probabilities range from "Extremely improbable," to "extremely remote," "remote," and "probable" (although it seems one might also add "certain" to this spectrum). Severity values range from "minor" to "major," "hazardous," and "catastrophic." A hazard analysis might also be instrumental in the context of cumulative effects if incorporated into a framework accounting for interactive effects. See the more generic "Risk Matrix" or "Consequence/Probability matrix (item 29).
6. Hazard and Operability study (HAZOP). A structured and systematic method for examining potential deficiencies in complex planned or operational systems. Systems are broken into individual components or "nodes" and multidisciplinary expert teams examine and analyze each node using guide words to prompt discussion. Providing there is sufficient information about design and implementation, this method might have some value in examining land management methods addressing cumulative effects (e.g., the sufficiency of planning around contingencies).
7. Hazard analysis and critical control points (HACCP). In this approach, every hazard is viewed as a tipping point where controls can eliminate the hazard. In the context of ecological tipping points, this might apply to an array of risk barriers in a framework for cumulative effects, but the method in and of itself is about linear processes and end-point control.
8. Toxicity. A simple assessment of the risk for toxic substances, based on dose-response models or other indices. Relevance to ecological and cumulative effects studies would likely be in the context of pollution assessment and modeling.
9. Structured What-if Technique (SWIFT). Designed to be quicker than more intensive methods like FMEA (#13 below), SWIFT uses structured brainstorming with guide words and prompts to identify risks. In the context of cumulative effects, this might have some relevance where threats and risks are poorly studied or relatively unknown, as an initial step in threat and risk identification supporting a more detailed subsequent analysis,
10. Scenario analysis. This method develops a branched tree of paths leading to potential "alternate futures," based on extrapolation of past or current trends. In the context of environmental problems, this might be useful to see where trade-offs to different consequences will occur as a component of a more comprehensive framework. A limitation of the approach is that path elements are not synchronized and thus the stochastic aspects become questionable.
11. Business impact analysis. This method evaluates the resilience of business operations and processes in the face of change. Although this approach could be adapted to examine risks in the context of natural disturbance and ecosystem resiliency, the methodology is heavily reliant on compliance data and auditing processes. This type of data may not be possible to acquire or implement in a research or regional land management context.
12. Root cause analysis. A linear analysis that examines the events leading up to a problem to identify the true root cause and establish the causal relationship. There can be several root causes; it might therefore be possible to use this tool to examine threats and reactive, proactive control measures for those threats. However, the approach is *ex post facto* (i.e., the problem has already happened once, reasons are investigated and well described, and the point of the analysis is to prevent future occurrence). For that reason, it may be unwieldy if applied to emerging cumulative effects problems or future scenarios.

13. Failure mode and effects analysis (FMEA). This method focuses on potential modes of failure where the failure modes, causes, effects, and criticality of many components in an engineered system must be understood. A strength in the context of cumulative effects is that it could be a quantitative or qualitative analysis. However, the view of multiple event paths leading to different failure modes would seem to be incompatible with the view of a current risk scenario having essentially one mode of failure (via a tipping point).

14. Fault tree analysis. This method uses Boolean logic to understand the lower-level events leading to an undesired "system failure condition" (Top Event). In the context of cumulative effects, it does not look at mitigation of the Top Event; it analyzes the logical connection of events leading to some problem. This makes its application to cumulative effects versus other methods somewhat limited.

15. Event tree analysis. Essentially the flip side of #14 (Fault tree analysis), Event tree analysis looks at the success or failure of consequences from an initiating event. In the context of cumulative effects, the initiating event would equate to a Top Event. Event trees are probabilistic, and so might have better application to cumulative effects than fault tree analysis. However, multiple threats leading to the triggering event are not addressed, so the emphasis is effectively on mitigation or prevention controls after the triggering event happens.

16. Cause and consequence analysis (CCA). A merger of Fault tree and Event tree analysis. An advantage of this approach is that it allows for risk quantification and addresses many of the aspects found in a bowtie analysis. Moreover, CCA permits the analysis of event sequences that may be much more descriptive of ecological processes in some ways. Unlike bowtie analysis, however, universal escalation factors are not addressed. Another problem is that each event is essentially a tipping point. This might be challenging for complicated/interacting paths—it might, for example, lead to a form of Braess's Paradox (i.e., path improvement leads to poorer performance). In this case, if risk barriers are interrelated and not truly independent, decreasing the number of events on one path could actually lead to risk being increased because the deletion of associated risk barriers for those events might also adversely affect risk on the other paths.

17. Cause and effect analysis (Ishikawa diagram). A visual tool for the simple portrayal of causes for negative events or defects – good for brainstorming, but poor at portraying interactions and may become too cluttered in more complex situations. In the context of cumulative effects, it might be a good way to group or categorize or cluster threats, but its use as a decision-making tool would be limited to identifying root causes of Top Events.

18. Layers of Protection Analysis (LOPA). A tool for quantitative screening of risk, a weapon of choice for quantifying bowtie risk analysis in CGE's Bowtie XP software. It is a hybrid approach, incorporating aspects of both qualitative and quantitative risk assessment. This article indicates that industry often uses risk matrices (see #5 Preliminary Hazard Analysis) to prioritize or indicate which elements of risk analysis should be included or explored in a LOPA.

19. Decision tree. Basically, a flowchart-like algorithm to support decision-making; where information is complete, it should be paired with a probabilistic model. In the context of cumulative effects, an advantage of this method is that it can parse scenarios into worst, best, and expected. They are also relatively easy to communicate. A disadvantage is that they are somewhat unstable to small changes in variance, leading to poorer predictive power. Comments about Braess's Paradox at #16 above might also apply here.

20. Human reliability analysis. A form of Probabilistic Risk Analysis (PRA) that looks at human risk factors. A PRA asks what can go wrong, what are the consequences (and how severe), and what are the probabilities of occurrence (using #14 Fault tree and #15 Event tree analysis). This could probably be adapted for cumulative effects frameworks, but bowtie frameworks eclipse this type of PRA by having a more explicit structure.

21. Bowtie (BRAT). A "weapon of choice" for cumulative effects analysis. BRAT frameworks incorporate many of the preceding elements in a simple, straightforward design that is not overly complicated; it shows the confluence of threats or elements of risk and consequences pertaining to a single important tipping point. While it is well-suited for portraying interactive threats, the approach does have limitations (e.g., there is no accommodation for complex interactions such as feedback loops).

22. Reliability-centred maintenance. An engineering strategy focused on risk management rather than a prediction of risk outcomes. In the context of cumulative effects, this might be an endpoint to pursue once regional- or landscape-level management of risk is implemented, especially in the context of verifiable indicators of habitat condition.

23. Sneak circuit analysis. An electrical engineering method for determining the potential for unexpected (sneak) functions in electrical circuitry. Conditions for the establishment of sneak circuits must be understood and accounted in this approach. In the context of cumulative effects, principles from this tool might help detect the potential for incipient (unaccounted) risks, or perhaps for example detect where Braess's Paradox might increase risks in more complex systems.

24. Markov analysis. A predictive method based on knowing the stochastic linkages of chained events in their current state, with no need to consider historic trends. The method is linear and relies on a deep knowledge of the probability that one event will cause another – something that might not be fully achievable (yet) in most situations with cumulative environmental effects.

25. Monte Carlo simulation. Using randomness to solve deterministic problems. This could possibly be used in conjunction with different LOPA scenarios to portray uncertainty in risks found in BRAT frameworks.

26. Bayesian statistics and networks. A statistical modelling method based on prior knowledge or belief concerning the probability of events. The resulting analysis can be hierarchical or, if the elements interact, they can form a Bayesian Belief Network. A BRAT framework can be transformed into a Bayesian Belief Network – an obvious advantage would be that interactions between elements lacking in the BRAT could be portrayed in the belief network, using the BRAT framework as a starting point that could be expanded. However, caution pertaining to Braess's Paradox might still apply.
27. FN Curve. A plot of cumulative frequency versus consequences. Perhaps useful for communicating aspects of mortality effects in BRAT frameworks dealing with demographic data.
28. Risk index. A simple categorical form of quantitative risk assessment. It can take various forms, including a risk matrix (see below).
29. Consequence/Probability Matrix. A.K.A. "Risk Matrix," of which (#5) Preliminary Hazard Assessment is a form.
30. Cost/benefit analysis. A systematic approach to assessing the strengths and weaknesses of various alternatives, with a view to selecting the most optimal alternative. This type of analysis can be an adjunct to BRAT frameworks.
31. Multi-criteria Decision Analysis. Supports decision analysis where multiple criteria must be weighed. This is a rich sub-field in risk assessment with a diverse set of methodologies (see link). For cumulative effects, using one of these approaches might be a good way to evaluate trade-offs, assuming the preferences of decision-makers regarding outcomes are already well-understood and defined.

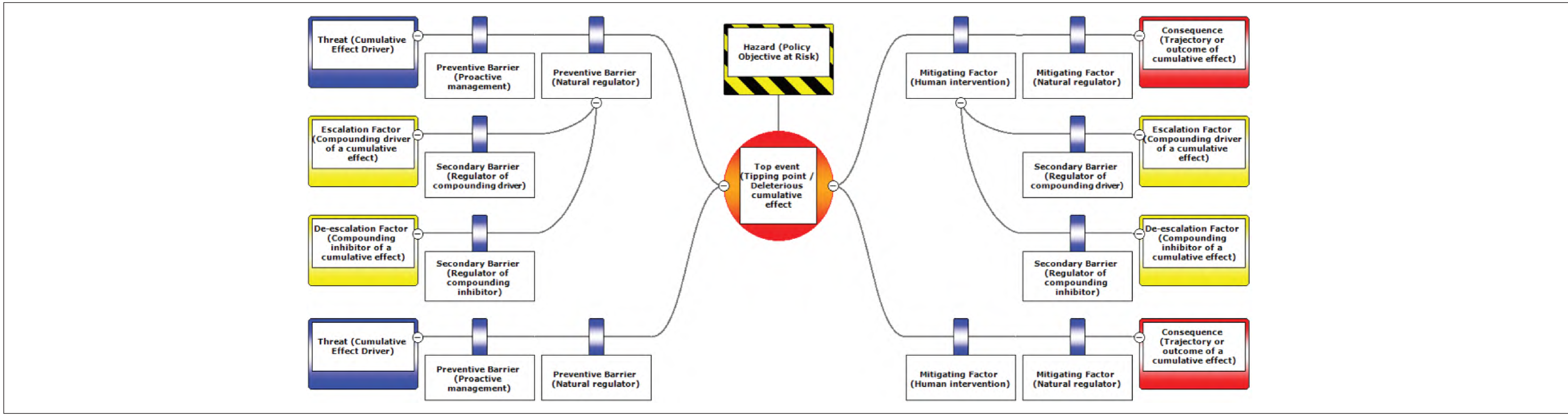

Figure 1. A generic BRAT framework, showing associated terms used in risk analysis (and equivalent ecological terms in parentheses). Excerpted from Winder et al. (2020).

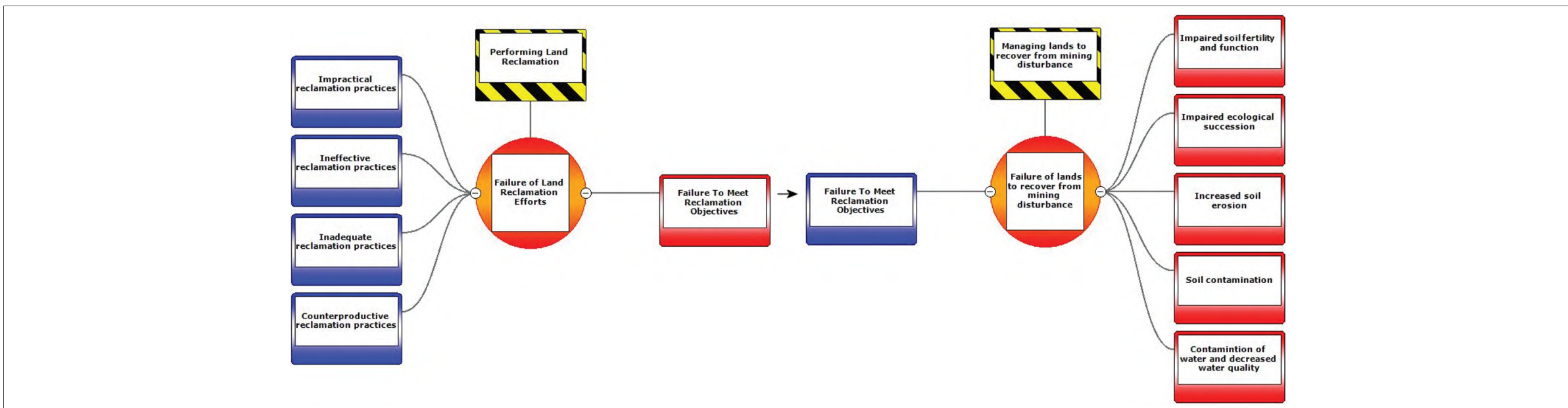

Figure 2. Two simplistic BRAT frameworks chained to show the relationship between two Top Events (failure of land reclamation efforts at left and failure of lands to recover from mining disturbance at right).

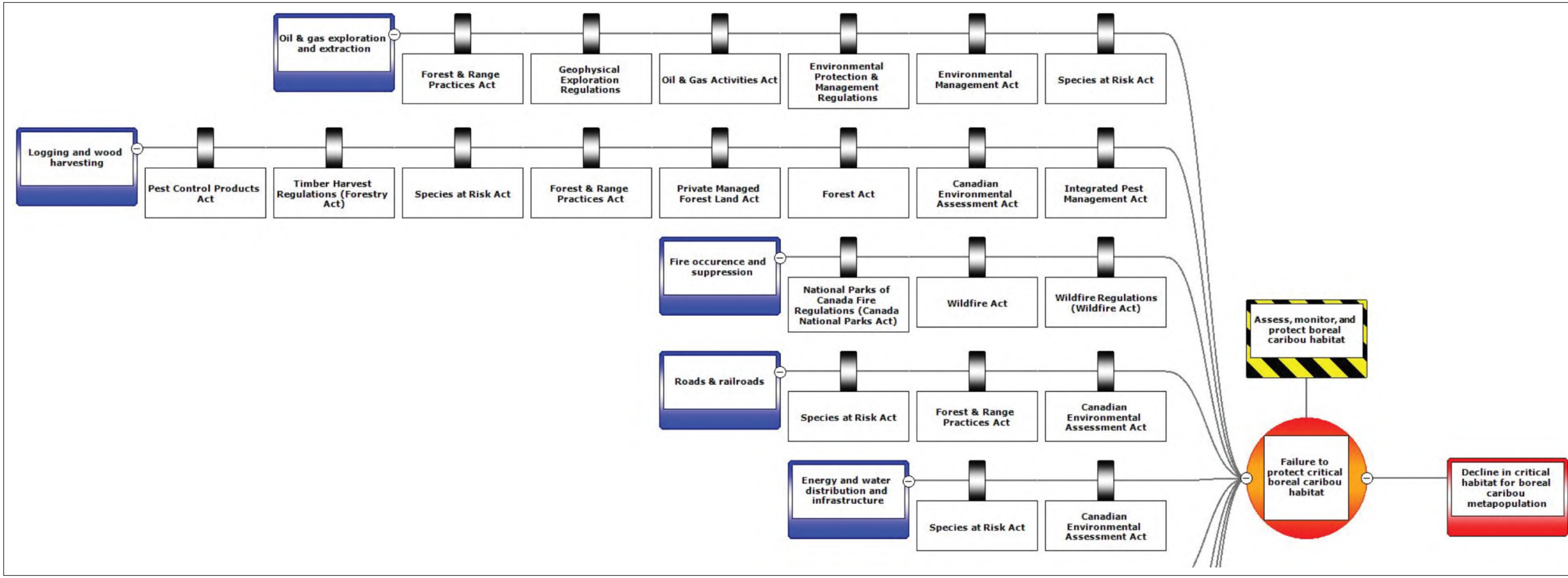

Figure 4 top. A qualitative "single Top Event" BRAT Framework. This framework follows the standard industrial approach, solely portraying the human regulatory framework that protects critical habitat for boreal woodland caribou in northeastern British Columbia. Threats are ranked according to their level of contribution to the risk event. Barriers are the acts and regulations that exist on the provincial (British Columbia) and federal level to protect caribou habitat (Ministry of Environment 2010). The effect of the failure to protect the habitat is a decline in critical habitat for the boreal caribou meta-population.

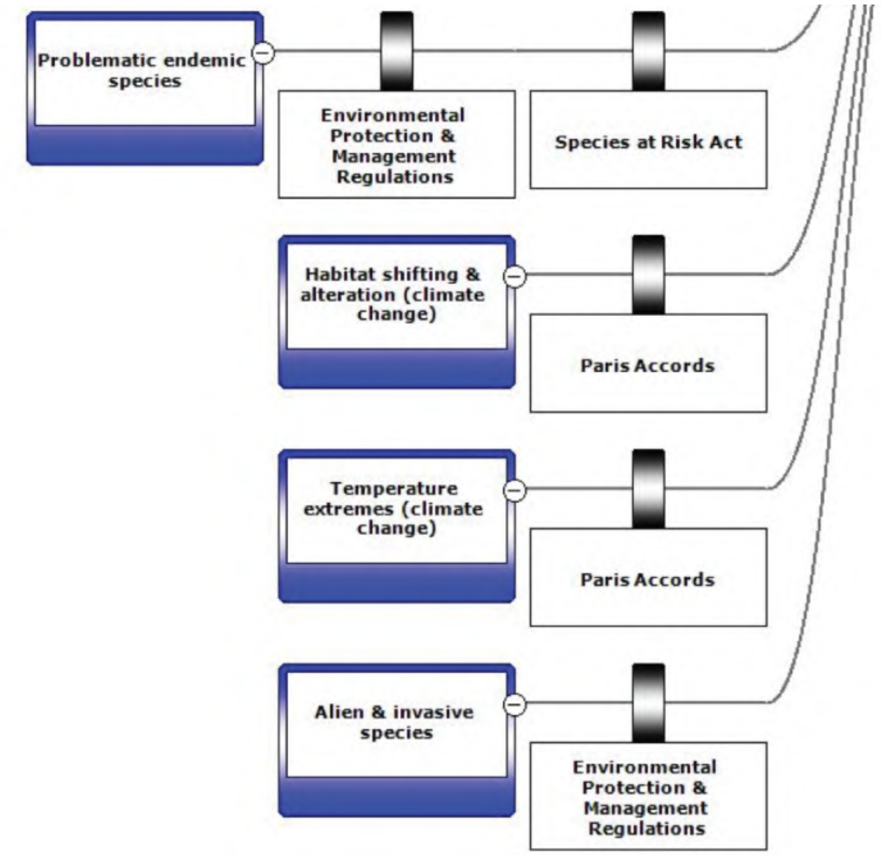

Figure 4 bottom. A qualitative "single Top Event" BRAT Framework. This framework follows the standard industrial approach, solely portraying the human regulatory framework that protects critical habitat for boreal woodland caribou in northeastern British Columbia. Threats are ranked according to their level of contribution to the risk event. Barriers are the acts and regulations that exist on the provincial (British Columbia) and federal level to protect caribou habitat (Ministry of Environment 2010). The effect of the failure to protect the habitat is a decline in critical habitat for the boreal caribou meta-population.

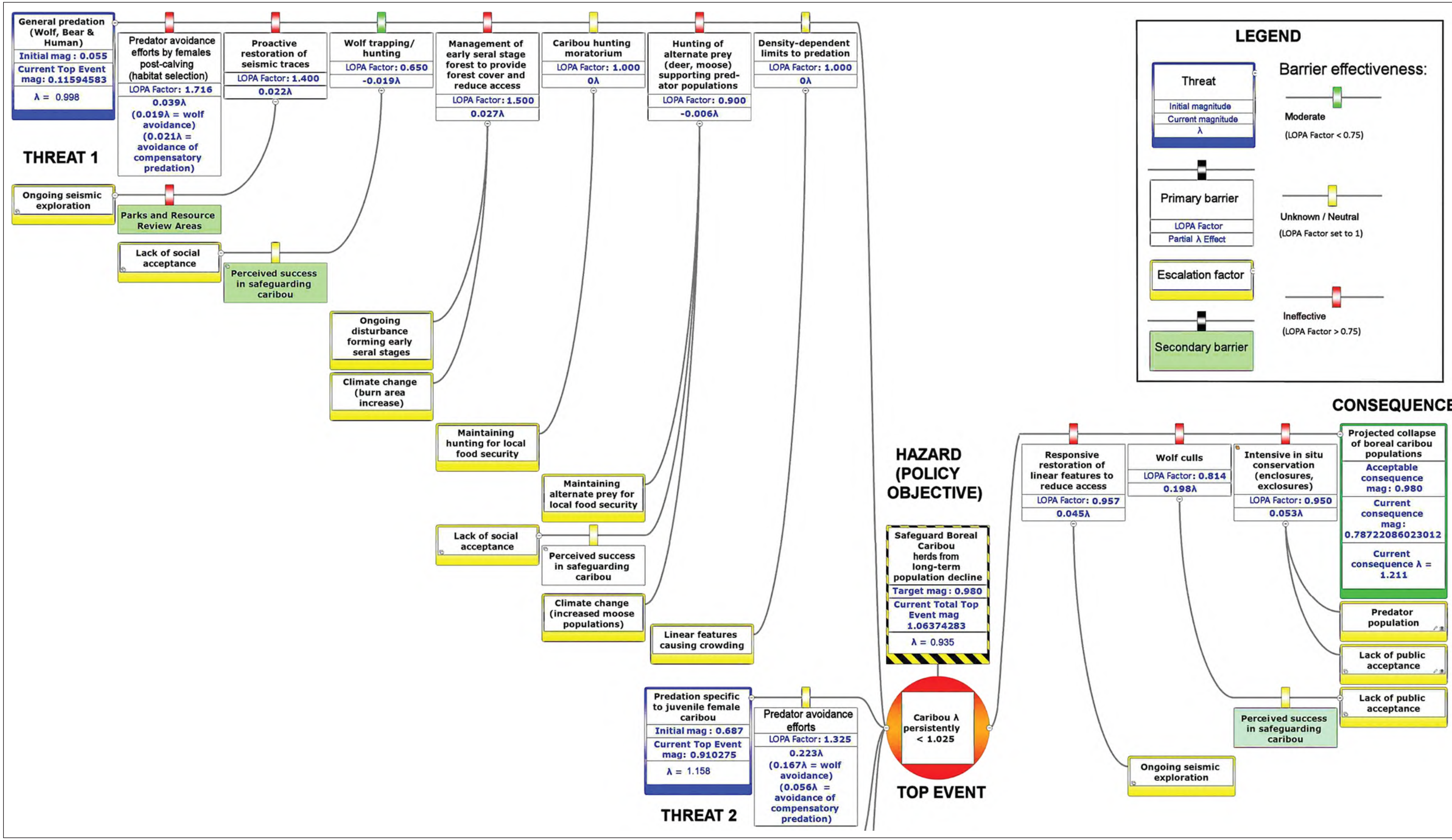

Figure 5 top half. A "single Top Event" BRAT framework (per Winder et al. 2020) that qualifies and quantifies cumulative effects and risks to sustainability of caribou in northeastern British Columbia, Canada. Threat incidence is not shown. The upper blue numbers in threat barrier boxes correspond to the probability (1 = 100%) of barrier failure (to block the threat). In this case, probabilities > 100% correspond to risk levels that must be overcome before barriers can become effective; this also permits the probabilities to be reconciled with other continuous measures of risk. The lower blue numbers in the barrier boxes are lambda (population growth rate) values characterizing the demographic response of a caribou herd to risk reduction for that barrier. Parallel risk metrics were necessary because it was impossible to estimate the effectiveness of all barriers solely in terms of one parameter. It was necessary to use two parallel parameters (probabilities and lambda) to reconcile gaps in quantitative estimates of risk. In a full-featured framework, numbers can also be shown pertaining to the likelihood of occurrence for the Top Event (central red circle) and consequence (red box at right).

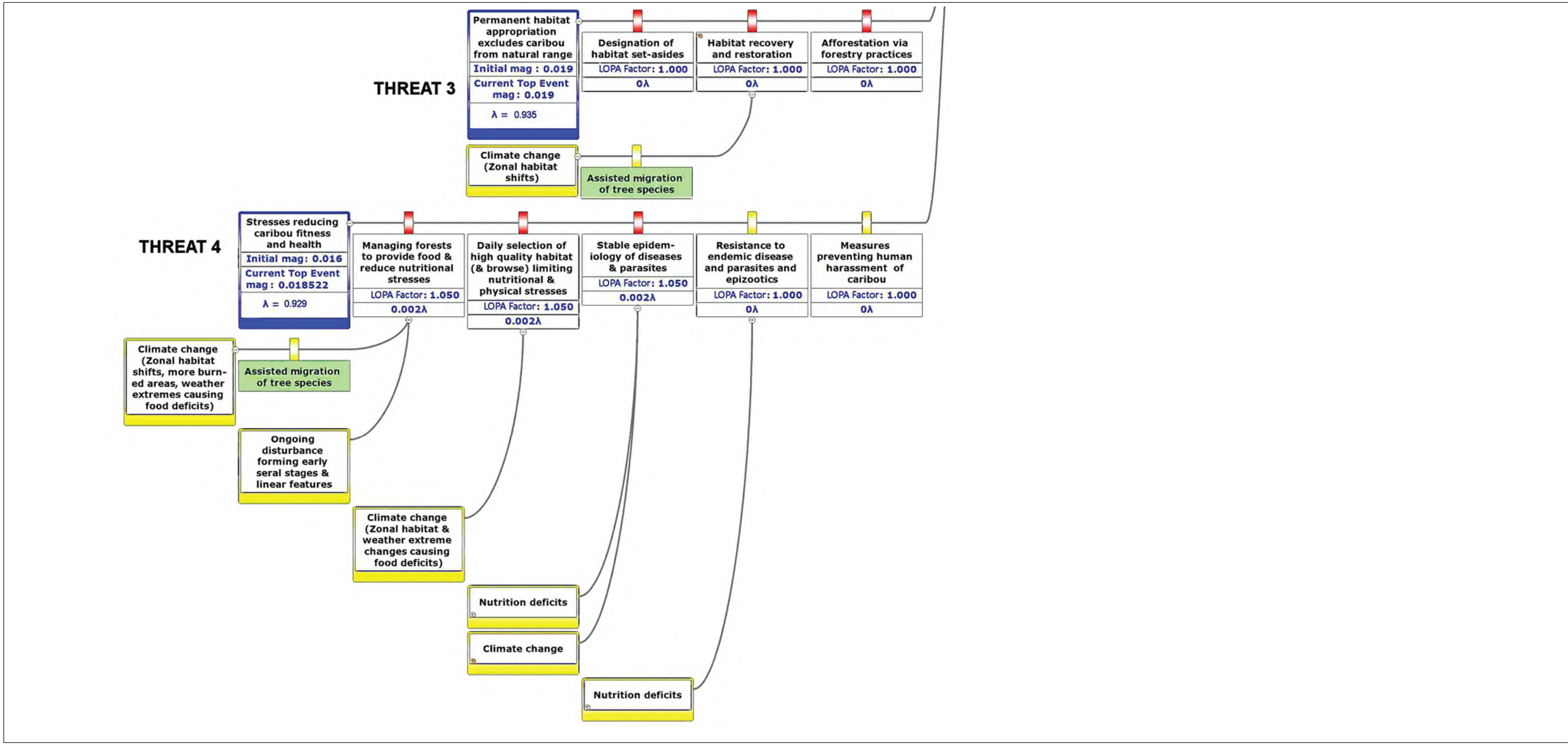

Figure 5 bottom half. A "single Top Event" BRAT framework (per Winder et al. 2020) that qualifies and quantifies cumulative effects and risks to sustainability of caribou in northeastern British Columbia, Canada. Threat incidence is not shown. The upper blue numbers in threat barrier boxes correspond to the probability (1 = 100%) of barrier failure (to block the threat). In this case, probabilities > 100% correspond to risk levels that must be overcome before barriers can become effective; this also permits the probabilities to be reconciled with other continuous measures of risk. The lower blue numbers in the barrier boxes are lambda (population growth rate) values characterizing the demographic response of a caribou herd to risk reduction for that barrier. Parallel risk metrics were necessary because it was impossible to estimate the effectiveness of all barriers solely in terms of one parameter. It was necessary to use two parallel parameters (probabilities and lambda) to reconcile gaps in quantitative estimates of risk. In a full-featured framework, numbers can also be shown pertaining to the likelihood of occurrence for the Top Event (central red circle) and consequence (red box at right).

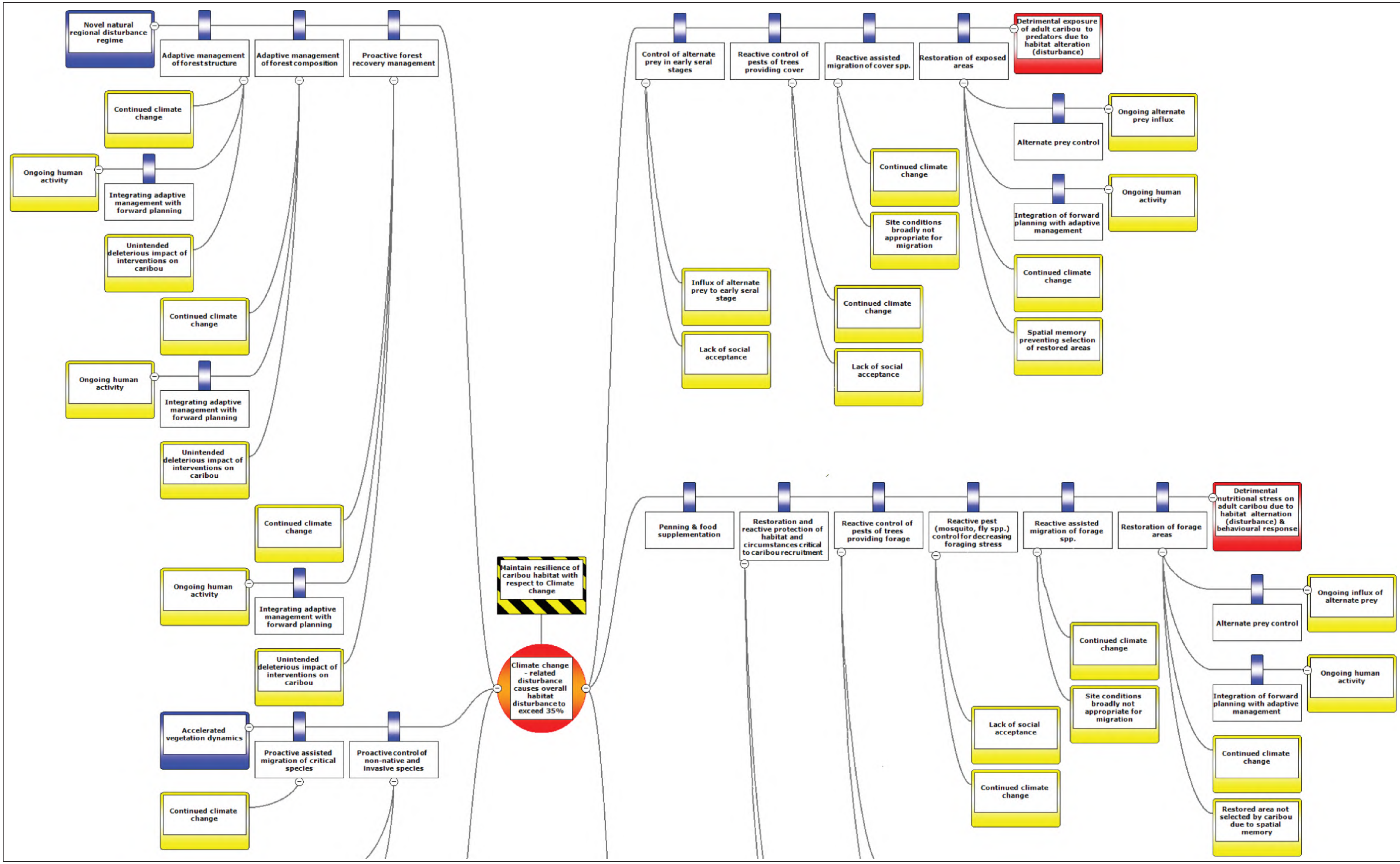

Figure 6 top half. A "single Top Event" BRAT framework with risks related to climate change and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.

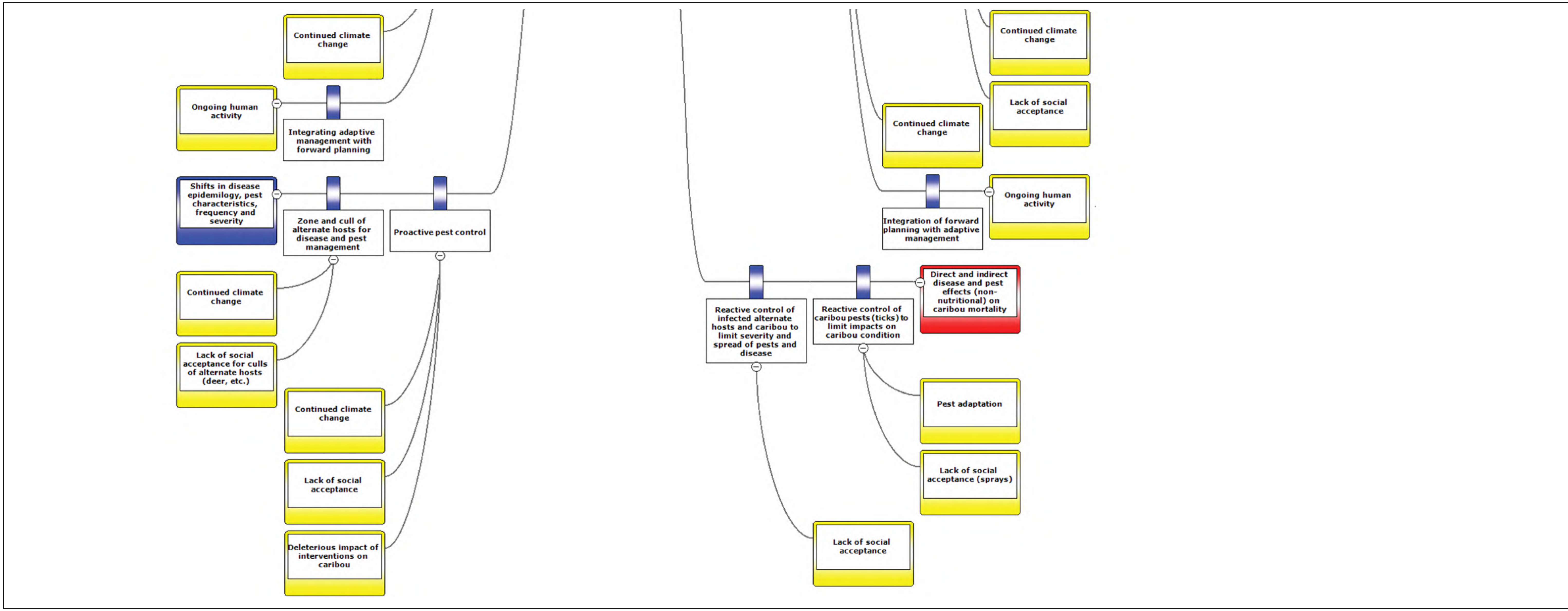

Figure 6 bottom half. A "single Top Event" BRAT framework with risks related to climate change and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.

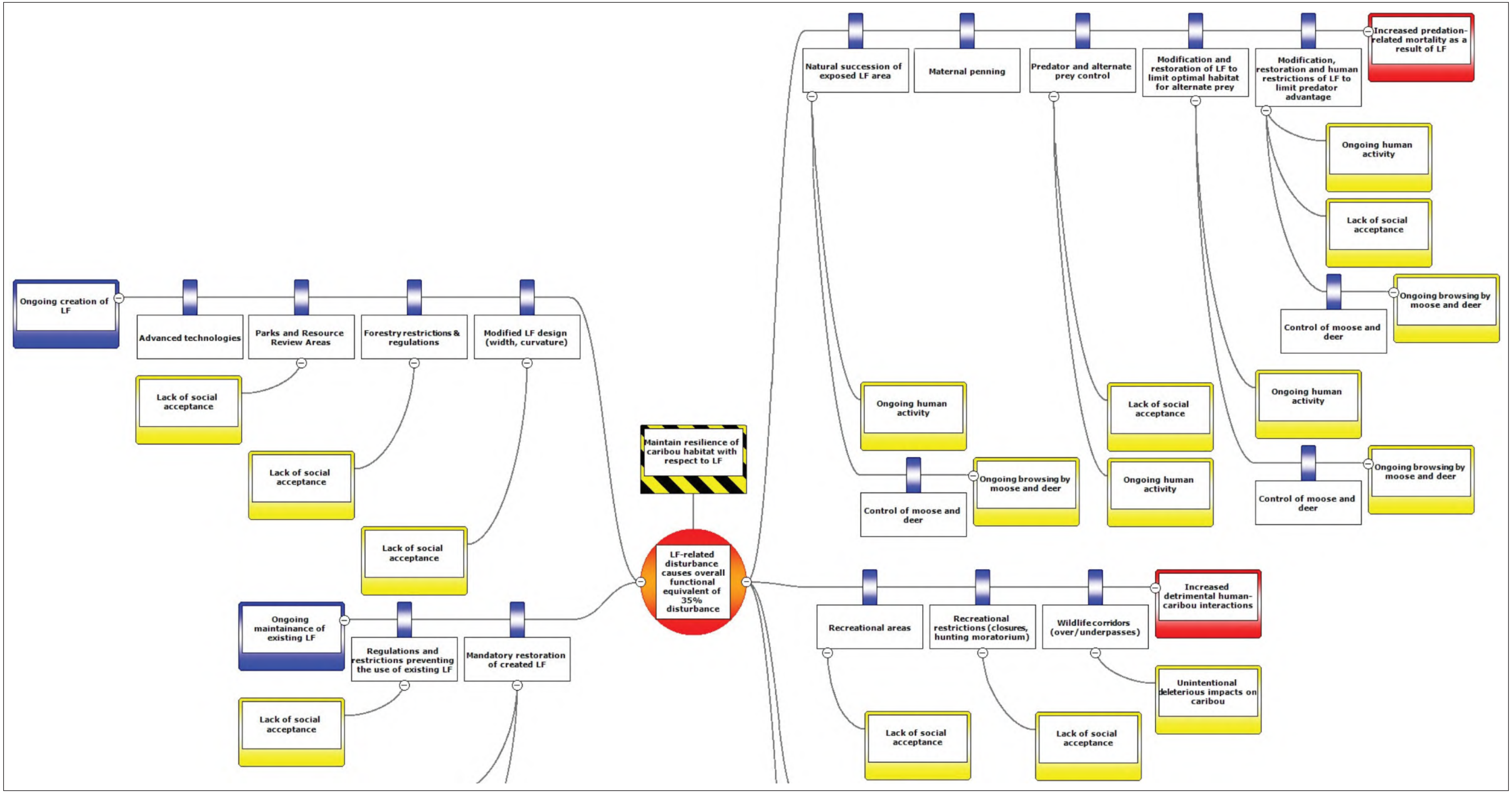

Figure 7 top half. A "single Top Event" BRAT framework portraying qualitative risks related to linear features (linear disturbances such as seismic exploration traces, pipelines, hydroelectric lines, roads, and trails) and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.

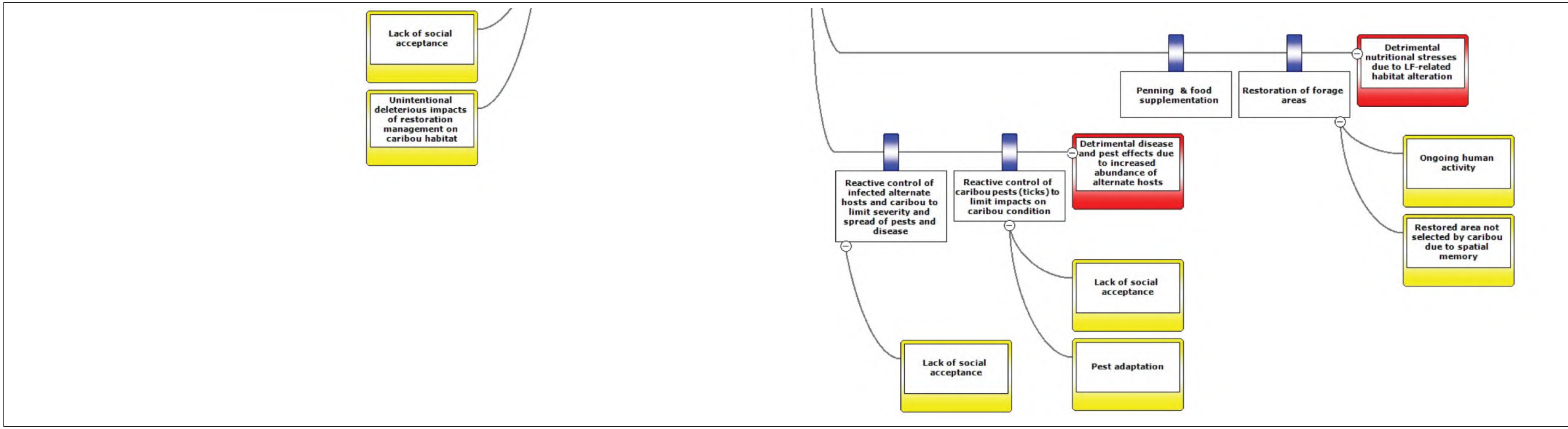

Figure 7 bottom half. A "single Top Event" BRAT framework portraying qualitative risks related to linear features (linear disturbances such as seismic exploration traces, pipelines, hydroelectric lines, roads, and trails) and cumulative effects on caribou habitat in northeastern British Columbia, Canada. For quantification of risk, it would likely be necessary to reconcile barrier failure probabilities with a parallel metric, such as flux in disturbed area.

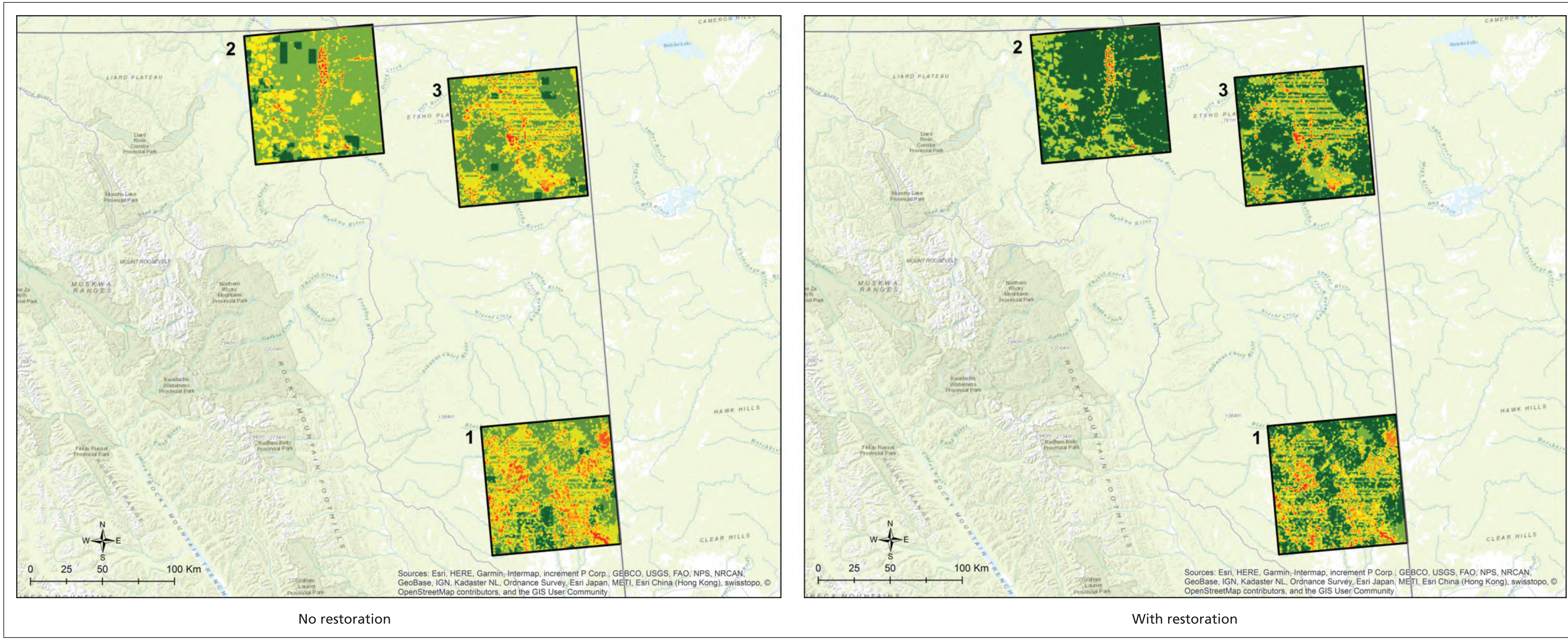

Figure 8. Preliminary heat maps show the intensity of some anthropogenic threats highlighted as critical for boreal caribou within several BRAT frameworks for northeastern British Columbia, Canada. Orange-red is more intense, yellow-green is less intense. The current situation (L) is contrasted with a future scenario where all seismic traces have been rehabilitated (R).

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