

Applied ecology in Canada's boreal: a holistic view of the mitigation hierarchy and resilience theory¹

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Abstract: Canada's boreal biome is a mosaic of forests and peatlands. These ecosystems have developed dynamically, periodically affected by disturbance events of significant spatial extent and variable severity, reducing ecosystem biomass. The same ecosystem types typically regenerate from biological legacies. However, concern is growing about the impact of these different anthropogenic disturbances, particularly compound disturbances including climate change, which open the door to shifts to alternate stable states. One strategy promoted to regulate anthropogenic disturbance is the "mitigation hierarchy" for development projects, where impacts on ecosystems are avoided, mitigated, restored, or compensated. This practical approach is not yet integrated into disturbance and resilience theory. Here, I develop an integrated view of the mitigation hierarchy, as well as resilience and disturbance theory, in a boreal context using ecosystem services to measure ecosystem state in a two-step process that first models loss of ecosystem function and then integrates the mitigation hierarchy and resilience theory. The application of this model is discussed in the context of restoration studies after different types of catastrophic anthropogenic disturbance. These studies, some of which are published in this special issue, highlight the important role of bryophytes and understory plants in setting restoration targets and developing criteria and indicators of success.

Key words: restoration, boreal forests, boreal peatlands, anthropogenic disturbance.

Résumé : Le biome boréal canadien est une mosaïque de forêts et de tourbières. Ces écosystèmes se sont développés dynamiquement, affectés périodiquement par des événements perturbateurs d'une étendue spatiale significative et de sévérités variables, réduisant la biomasse des écosystèmes. Les mêmes types d'écosystèmes se régénèrent typiquement à partir des systèmes biologiques antérieurs. Cependant, il y a de plus en plus d'inquiétude quant à l'impact de ces perturbations anthropiques différentes, particulièrement les effets cumulatifs des perturbations dont les changements climatiques, qui ouvrent la porte à des déplacements vers des états stables alternatifs. Une stratégie favorisant la régulation des perturbations anthropiques est la « hiérarchie des mesures d'atténuation » lors de projets de développement, où les impacts sur les écosystèmes sont évités, atténués, réhabilités ou compensés. Cette approche pratique n'est pas encore intégrée dans la théorie de la perturbation et de la résilience. L'auteur développe ici une vision intégrée de la hiérarchie d'atténuation et de la théorie de la résilience et de la perturbation, en contexte boréal, en utilisant des services écosystémiques pour mesurer l'état de l'écosystème dans un processus à deux étapes qui modélise d'abord la perte de la fonction de l'écosystème et qui intègre ensuite la hiérarchie des mesures d'atténuation et la théorie de la résilience. L'application de ce modèle est discutée dans un contexte d'études de la réhabilitation après différents types de catastrophes anthropiques. Ces études, dont certaines sont publiées dans ce numéro spécial, soulignent le rôle important des bryophytes et des plantes de sous-étage pour établir des cibles de réhabilitation et développer des critères et des indicateurs de succès. [Traduit par la Rédaction]

Mots-clés : réhabilitation, forêts boréales, tourbières boréales, perturbations anthropiques.

Introduction

Since deglaciation, the terrestrial component of Canada's vast boreal biome (5 519 790 km² in total; Brandt 2009) has been made up of a mosaic of forest stands and peatlands (currently 55% and 13%, respectively;

Brandt 2009; Tarnocai et al. 2011). Over approximately 7000 years (Ritchie 2004; Williams et al. 2004), these ecosystems have developed dynamically because they are periodically affected by disturbance events of significant spatial extent and variable severity (e.g., fire, insects,

Received 9 May 2016. Accepted 10 June 2016.

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floods, drought; [Holling 1992](#); [Payette 1992](#); [Vile et al. 2011](#)). Typically these disturbances, such as forest or peatland fires or insect outbreaks, reduce biomass present in the ecosystem and locally disrupt substrates ([Shetler et al. 2008](#); [Bergeron and Fenton 2012](#)). As all of the biomass or substrates are rarely removed, the same ecosystem types typically regenerate from biological legacies spared by the natural disturbance event ([Rowe 1983](#); [Brumelis and Carleton 1989](#), [Schimmel and Granström 1996](#)). Consequently ecosystem functions (e.g., carbon fixation, nitrogen cycling) are maintained across the landscape as individual ecosystems are disturbed and regenerate.

While most boreal ecosystems are resilient as they regenerate to their initial state after disturbance, situations where ecosystems shift to an alternate stable state ([Beisner et al. 2003](#)) are present (e.g., [Jasinski and Payette 2005](#); [Boiffin and Munson 2013](#)). Typically, these are compound disturbances that eliminate the propagules (sexual or asexual reproductive structures) that permit regeneration; for example, two successive fires in a short period that eliminate available tree seed may shift a forest stand to an open heath. In these cases, ecosystem functions are not maintained or are reduced across the landscape as the alternate stable state fulfills different functions. For example, when a forest fails to regenerate and is replaced by a heath, biomass production drops, among other consequences.

Large scale anthropogenic disturbances appeared on the Canadian boreal landscape as European colonists extracted natural resources from boreal ecosystems. In particular, since 1800, forest harvest and mining of different types of substances such as peat, coal, oil and gas, metals, and minerals ([Brandt et al. 2013](#)) have had significant impacts on the boreal biome. Despite the size of the boreal biome in Canada, concern is growing about the impact of these different anthropogenic disturbance types on the boreal biome ([Venier et al. 2014](#)). This is particularly true in the context of compound disturbances including climate change ([Yamasaki et al. 2008](#); [Kettridge et al. 2015](#)), opening the door to shifts to alternate stable states that may stop providing some of the ecosystem functions and services that society depends upon ([Oliver et al. 2015](#)).

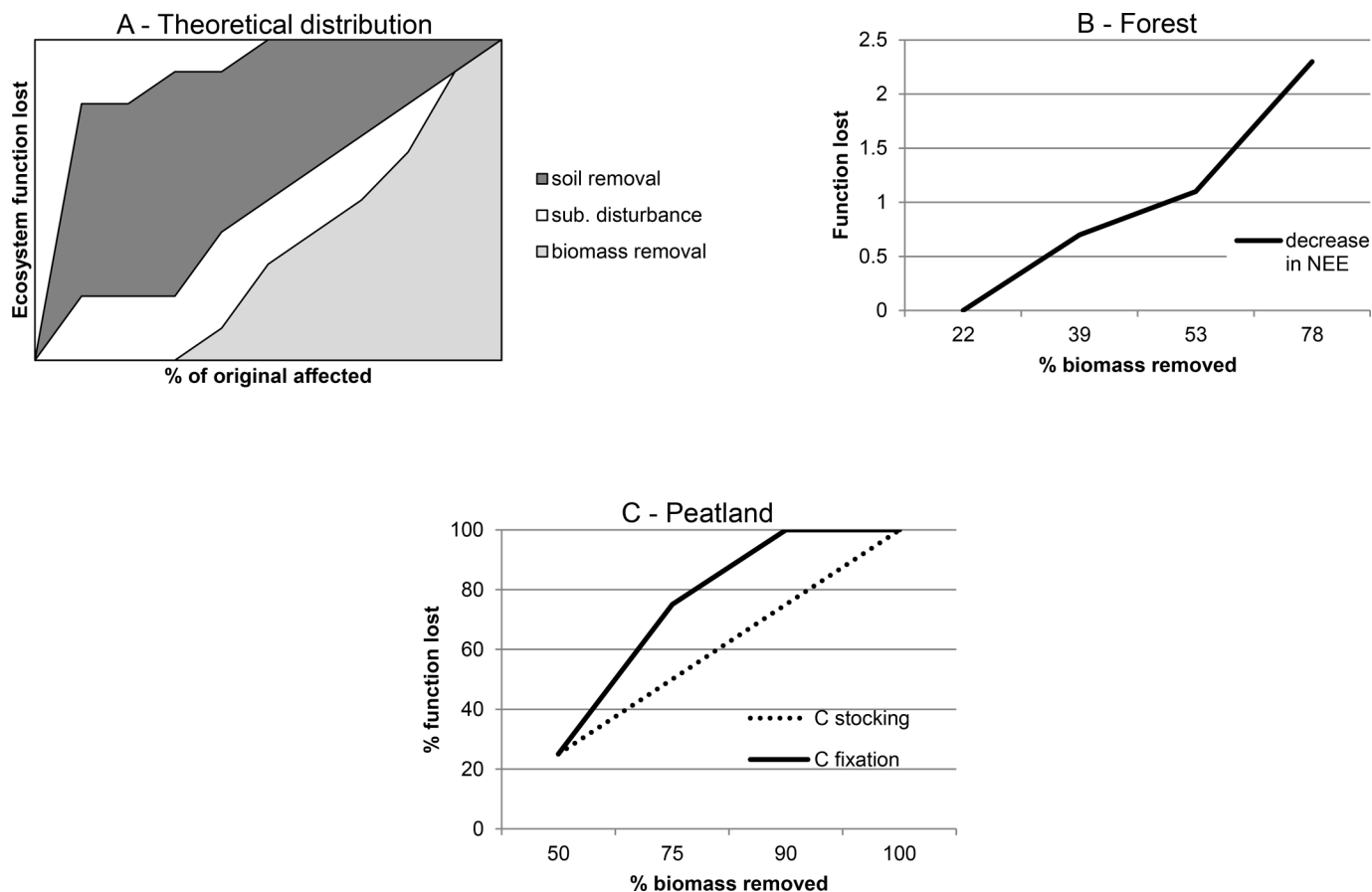
Faced with social concern for the state of local and global ecosystems, industries and governments have adopted different programs to regulate anthropogenic disturbance and preserve ecosystem functions. One strategy promoted to regulate anthropogenic disturbance is the “mitigation hierarchy” for development projects, where impacts on ecosystems (generally considered to be due to habitat loss) are avoided, mitigated, restored, or compensated, in that order ([McKenney and Kiesecker 2010](#)). While the application of this hierarchy has been criticised, as it is typically applied only to local habitat loss and the avoidance step is frequently ignored

([Clare et al. 2011](#); [Gardner et al. 2013](#)), it offers a practical framework for action. Ecological landscape planning, where ecological or socially important sites are identified before development, is an example of an “avoidance” strategy ([Clare et al. 2011](#)). Forest certification (e.g., the National Boreal Standard, [Forest Stewardship Council Canada Working Group 2004](#)) is an industry-specific program that sets out guidelines on how to avoid and mitigate impacts of forest management on the ecosystems and the people inhabiting the forest region. Restoration/reclamation techniques are currently being developed for boreal landscapes following large catastrophic anthropogenic disturbances ([Vitt and Bhatti 2012](#); [Burton 2014](#); [Kuuluvainen et al. 2015](#); [Macdonald et al. 2015](#)). The main challenge is defining the restoration or reclamation target and indicators of success. [Burton \(2014\)](#) and [Stanturf et al. \(2014\)](#), and the articles featured in this special issue suggest using ecosystem functions to define endpoints and indicators of success. The focus on function rather than ecosystem composition is important, because community composition is transitory (on a millennial scale) as species respond individually to the environment ([Williams and Jackson 2007](#)).

While not explicitly specified, the aim of the mitigation hierarchy is essentially to ensure or generate ecosystem resilience. Theoretical models of ecosystem resilience have multiplied (e.g., [Hodgson et al. 2015](#)) as we aim to determine how far we can alter natural systems without destroying their capacity to recover and thus provide ecosystem services. When the capacity for recovery of an ecosystem is lost, it may pass into an alternate stable state ([Oliver et al. 2015](#)). Resilience and recovery have been defined in a variety of ways; however, here I follow [Hodgson et al. \(2015\)](#) and use resilience as the global term encompassing both the ability of a system to resist change in the face of disturbance and its ability to recover to its original state after disturbance. The concept of resilience is inherent in most disturbance models as they generally incorporate the concept of increasing recovery time after for disturbances of increasing severity and frequency. Similarly, system resilience will decrease as disturbances eliminate or reduce elements important for recovery.

Here, I propose an integrated view of the mitigation hierarchy, and resilience and disturbance theory, in a boreal context using ecosystem services to measure ecosystem state in a two-step process that first models loss of ecosystem function and then integrates this with the mitigation hierarchy and resilience theory. This model provides a framework for the articles describing restoration and reclamation in the boreal context that follow as part of this special issue. It can also give a holistic view of research and actions being undertaken in the boreal context beyond the special issue, with the theoretical underpinnings that provide links among studies and suggest hypotheses. More practically, this holistic view could be

Fig. 1. Modelling ecosystem function loss. (A) Theoretical representation of a composite disturbance variable, ecosystem function lost, generated from three disturbance variables, biomass removal, substrate degradation, and substrate removal. (B) Application of the model using data from Webster et al. (2016) on biomass harvesting in boreal forest stands. As more biomass is lost, ecosystem function (difference in net ecosystem exchange) is lost. (C) Application of the model using data from peatlands (Robert et al. 1999; House et al. 2012; Gonzalez and Rochefort 2014). As biomass is removed, two ecosystem functions (carbon stocking and carbon fixation) are lost.



useful for evaluating and comparing the effects of different disturbance events on different ecosystems. This comparison can then be used in landscape and regional development planning, to prevent ecosystem service loss due to less desirable alternate stable states following disturbance events.

Modelling loss of ecosystem function

Most disturbances impact many parts of an ecosystem at once. This model, like Roberts' (2004) and Ryan's (2002), incorporates impacts on both the aerial biomass and the substrate (mineral soils and peat soils). Disturbance severity, measured as a loss of ecosystem function, is determined using three proposed variables from Pickett and White's seminal book (Pickett and White 1985): biomass and propagule removal, substrate degradation/disturbance, and mineral and peat soil removal (presented with theoretical distributions in Fig. 1a). These variables are determined as the percent of the original biomass or substrate removed or degraded in terms of area and depth. Biomass here includes both living and dead material, and implies that when all or nearly all of

the biomass is removed, propagules (sexual and asexual reproductive structures) are also removed. Therefore, as the amount of biomass removed increases, there are fewer biological legacies to facilitate recovery and the ecosystem is increasingly dependent on the dispersal of propagules from outside sources for regeneration (Seidl et al. 2014). For example, when peatlands are mined below 30 cm from the surface, no viable *Sphagnum* spp. propagules remain in the system, and colonization is dependent on outside propagules (Robert et al. 1999; Gonzalez and Rochefort 2014). Similarly, when salvage logging is undertaken before seed abscission, few tree seeds are available for natural regeneration of the forest (Splawinski et al. 2014).

Biomass removal is a common event in natural disturbances in boreal ecosystems, and as such large amounts of biomass need to be removed before there is a sizeable effect on ecosystem function, or recovery. For example, harvest of forest trees alone does not significantly affect ecosystem function. However, when trees are harvested, and stumps and top soil are removed, net ecosystem ex-

change changes from a sink to a source (Fig. 1B; data estimated from Webster et al. 2016). Similarly, if the ecosystem functions of C fixation and C stocking for peatlands are examined, significant amounts of peat need to be removed before these functions are completely lost (Fig. 1C; data collated from Robert et al. 1999; Gonzalez and Rochefort 2014; House et al. 2012).

Substrate degradation refers to changing the mineral and peat soils that are the foundations of terrestrial ecosystems. When the nature of the substrate is degraded it can no longer support the same biomass, resulting in a change in ecosystem state. An example is the change in peat soils after forest harvest, which results in reduced growth rates for the regenerating trees (Lafleur et al. 2010).

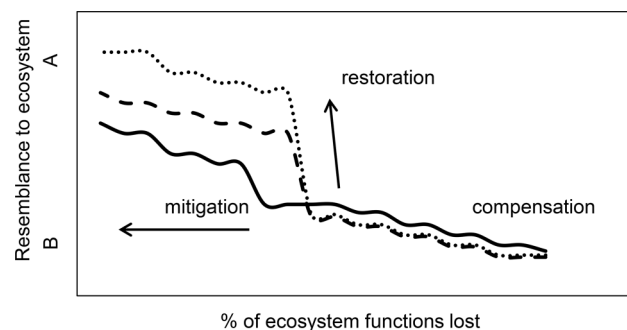
Finally, when the mineral and peat soils are not degraded but simply removed, there is a profound impact on the ecosystem, as it implies that all of the biomass is also removed, and no biological legacies are left to promote recovery. The foundation of the ecosystem is profoundly altered. Examples of this are in situ or open-pit mining of oil or minerals. These very severe disturbances very rarely occur naturally in the boreal context, with the possible exception of deglaciation. However, even then some biological legacies may remain (La Farge et al. 2013). These three variables are nested because a disturbance that degrades or removes substrate will also remove biomass (Fig. 1A). Together these three variables give an overall view of the effect of a disturbance event on the ecosystem as the composite variable, change in ecosystem state.

Modelling resilience, mitigation, and restoration

The relationship between the composite change variable in ecosystem state and the chance of recovery for different ecosystems can also be modelled. An ecosystem that experiences sufficient change in ecosystem function such that it is unable to recover would transition to an alternate stable state (Fig. 2). The amount of ecosystem functions lost that are required to switch between stable states would vary among ecosystems (compare solid and dashed lines in Fig. 2). An example would be the development of treeless peat bogs after winter forest harvest in paludifying black spruce boreal forests (Lafleur et al. 2010). Even though only ecosystem functions associated with tree growth are lost, a new ecosystem now exists. However, as indicated by the small difference between ecosystems A and B in Fig. 2, restoring the initial ecosystem will be simpler than in a system where there is a greater difference between alternate stable states (e.g., peatland forest vs. agricultural field (e.g., Figure 2, solid or dotted lines).

In this model, mitigation refers to the actions taken to reduce the chances of switching stable states. This may include changing the disturbance characteristics, such as reducing severity for example, using the same cases as those listed above, by limiting the depth of peat distur-

Fig. 2. Theoretical model illustrating the shift between two alternative stable states (Ecosystem A vs. B) for three different systems (solid, dashed, and dotted lines). As ecosystem functions are lost, the system loses resemblance to Ecosystem A, until it shifts to Ecosystem B. Actions taken before the state shift mitigate the effects of loss of ecosystem functions and facilitate recovery to ecosystem A. Once the state shift has been determined, restoration or compensation are required.



bance to permit natural regeneration from in situ biological legacies, or logging a burned forest after seed drop (Splawinski et al. 2014). Restoration and reclamation are actions undertaken to force the system back to the initial state, such as the forest and wetland reclamation that is presently occurring in Alberta (MacDonald et al. 2015; Borkenhagen and Cooper 2016; Vitt et al. 2016 (this issue); Hartsock et al. 2016 (this issue)). Compensation is accepting the fact that it is impossible to return to Ecosystem A, and paying for the loss of ecosystem functions.

Implications and the special issue

Research over past decades has focussed on how to manage our boreal ecosystems (forest and peatland) for resilience, with different studies on the impacts and suggested management modifications to silvicultural practices (e.g., Fenton et al. 2009, 2013; Caners et al. 2013).

However, research now needs to focus on anthropogenic disturbances that cross the line and force ecosystems into a new stable state, to develop techniques to restore them to their initial state. In this special issue of *Botany*, four articles discuss the restoration of peatland and forest ecosystems after disturbances that resulted in high levels of change in state of the original system: in situ mining of oil sands (Vitt et al. 2016 (this issue); Hartsock et al. 2016 (this issue)), open-pit gold mining (Guittouny-Larcheveque et al. 2016 (this issue)), and peat extraction (Rochefort et al. 2016 (this issue)). Individually these studies represent case studies of restoration, where the authors document efforts to restore the original systems after individual anthropogenic disturbances. However, together they illustrate the different issues facing this process: how do you choose your endpoint for restoration? Here different cases are discussed, fen, forest, and agricultural field. How do you determine whether you have a “normal” example of this endpoint? Species composition, soil characteristics, or ecosystem function

(e.g., nitrogen fixation)? Questions of technique but also of theory need to be further developed in the future to ensure that restoration rebuilds the appropriate ecosystem in the appropriate landscape, and that success is measured in a multi-criteria environment (Burton 2014; Stanturf et al. 2014).

These studies also highlight the importance of understory species (in many cases, bryophytes) as keystone species for the regeneration of boreal ecosystems. Bryophytes dominate most boreal systems and drive many ecosystem services in these ecosystems (Turetsky et al. 2012; Macdonald et al. 2015) and have been suggested as foundation species for restoration (Daly et al. 2012; Vitt et al. 2016 (this issue)). While the presence of charismatic mega flora such as trees are seen as a symbol of restoration success, the presence and composition of the ground layer may be more important in determining endpoint and success. With this special issue, composition is emphasized in the context of different environments (continental fens, coastal bogs/fens, boreal forests) with a focus on restoration end points and criteria for success.

Acknowledgements

This special issue, and the inspiration for this commentary follow from the symposium “Ecological impacts and restoration of industrial sites: roles of bryophytes and graminoid vascular plants” organised by Dr. Line Rochefort (Université Laval) and myself at the international conference Botany 2015 held in Edmonton, Alberta, Canada, in July 2015. I thank all the symposium presenters for their very stimulating conferences and the discussions that followed. In particular I thank Dr. Rochefort for agreeing to organise the symposium with me. It was a pleasure to work with her. Funding for the symposium was provided by the Canadian Botanical Association and the Botanical Society of America.

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