Caractérisation des impacts sur les écosystèmes, de l'utilisation des terres associées à la foresterie

Thèse

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Résumé

Un système basé sur le concept de naturalité, qui évalue la similarité par rapport à la forêt naturelle, a été élaboré dans le but d'évaluer les impacts de la foresterie. Ce système repose sur l'identification d'indicateurs de naturalité sensibles aux enjeux d'aménagement forestier reconnus et utilise des mesures disponibles à partir des cartes écoforestières, des études sur la modélisation des écosystèmes et des données historiques. Ce système fournit une valeur unique permettant de représenter l'effet conjugué de diverses pratiques, incluant la protection, sur les principales caractéristiques de l'écosystème forestier. D'abord développé pour la pessière, puis adapté pour la sapinière, ce système fonctionne de manière bidirectionnelle, permettant d'évaluer aussi bien la dégradation, que l'amélioration de la qualité des écosystèmes résultant d'objectifs de restauration et de mesures de mitigation. Ce système a été utilisé pour comparer l'impact sur la qualité des écosystèmes à l'échelle du paysage de divers scénarios sylvicoles considérés simultanément, comme dans la sapinière, où l'effet combiné de coupes progressives irrégulières et d'une réduction de la révolution de 70 à 50 ans pour les scénarios équiennes (coupe avec protection de la régénération et des sols et plantation) a été examiné. Son utilisation permet également d'éclairer la réflexion pour la détermination d'objectifs de protection aptes à limiter les pertes de biodiversité, tout en tenant compte de l'intensité de l'aménagement pour la production de bois. Ainsi, pour trois unités d'aménagement forestier de la pessière, considérant la combinaison de scénarios sylvicoles actuellement utilisés pour régénérer les forêts productives, le niveau de protection devrait être doublé et atteindre 35% de la superficie forestière afin de limiter d'éventuelles pertes d'espèces. Aussi, les résultats montrent qu'il serait plus avantageux au plan environnemental d'intensifier la production de bois d'espèces indigènes sur une petite proportion du territoire forestier tout en assurant une protection stricte sur la portion non productive, plutôt qu'un aménagement extensif sur la vaste majorité du territoire forestier. Dans le cadre du développement de l'analyse de cycle de vie (ACV) chapeauté par le Programme des Nations Unies pour l'environnement et la Société de toxicologie et de chimie de l'environnement (UNEP-SETAC), les impacts de produits ou services sur la qualité des écosystèmes sont évalués par le biais des impacts de l'utilisation des terres sur la biodiversité. Pour l'intégration à l'ACV, une courbe provisoire reliant l'indice de naturalité à la perte potentielle de biodiversité exprimée sur la base de la richesse en espèces provenant de la base de données PREDICTS est proposée. L'application de cette courbe a permis l'obtention de scores d'impact cohérents avec la proportion d'espèces disparues (PDF) estimée à partir de la naturalité et conformes aux connaissances relatives aux impacts de l'aménagement forestier. Toutefois, les résultats s'avèrent sensibles au paramétrage de la courbe et l'analyse de sensibilité a montré qu'il existait des risques de distorsion, voire d'obtention de résultats erronés. L'évaluation des scores d'impact de l'ACV résultant de l'application de trois scénarios sylvicoles distincts évalués concomitamment à l'application d'un gradient de la proportion du territoire forestier en protection stricte, apporte un éclairage sur le comportement du modèle utilisé pour l'évaluation de la qualité

des écosystèmes en ACV si l'on tient compte de l'intensité de l'aménagement. Le modèle ACV multiplie deux paramètres aux effets opposés et non-linéaires : le PDF qui augmente avec l'intensité de l'aménagement, alors que la superficie requise pour produire 1m^3 de bois diminue. Étant donné les risques associés à la présence d'effets non-linéaires non contrôlés, le modèle ACV peut fournir des résultats erratiques ne reflétant pas toujours l'effet sur l'aspect à protéger qui correspond ici à la qualité des écosystèmes. Conséquemment, dans l'état actuel des choses, le modèle ACV ne devrait pas être utilisé pour la prise de décision en matière d'utilisation des terres. De plus amples recherches relatives aux propriétés mathématiques des relations en cause sont nécessaires afin de vérifier la possibilité de contrôler ces effets de manière à assurer l'obtention de résultats reflétant la qualité des écosystèmes plutôt que celui de la superficie requise, déterminée par la productivité, et ainsi respecter la hiérarchisation des impacts associés à la qualité des écosystèmes évaluée à l'échelle d'un territoire et éviter des recommandations qui conduiraient à occasionner davantage de dommages.

Abstract

An evaluation system based on the concept of naturalness, which measures the similarity against natural forests, has been developed to assess the impacts of forestry. This assessment system relies on naturalness indicators sensitive to recognized forest management issues, and uses measures from eco-forest maps, results from ecosystem modeling and historical data. The naturalness assessment model provides a unique index allowing to assess the combined effect of different forest management practices including protection, on the main characteristics of forest ecosystems. Initially developed for black spruce forests, then adapted for balsam fir forests, the naturalness assessment model performs bi-directional evaluations allowing the assessment not only of ecosystem degradation but also of its improvement with restoration or mitigation measures. Among potential applications of the naturalness assessment model, its usefulness has been demonstrated for comparing the impact at the landscape level of different silvicultural scenarios combinations. In the balsam fir forest, we examined the combined effect of irregular shelterwood cutting along with the rotation reduction form 70 to 50 years for the even-aged scenarios of careful logging and plantation. The naturalness assessment model can also be used to shed light on protection levels needed to limit biodiversity losses. In three forest management units of the black spruce forest, considering the current mix of silvicultural scenarios for wood production, the protection level should be doubled to attain 35% of the forest area, to limit species losses. Results indicate that it would be better for the environment to intensify forest management using indigenous species over a small proportion of the forest territory while insuring strict protection over the remaining portion, compared with an extensive forest management applied over most of the forested area. Life cycle analysis (LCA) development under the guidance of the United Nations Environment Program and Society of Environmental Toxicology and Chemistry (UNEP-SETAC), provides impact evaluation of products or services on ecosystem quality through impact of land use on biodiversity. In order to include naturalness results in LCA, a provisional curve relating naturalness index to potentially disappeared fraction of species (PDF) has been developed using species richness data from the PREDICTS database. The provisional curve application lead to LCA impact scores consistent with the PDF estimated from naturalness and the existing knowledge about the effects of forest management. However, the sensitivity analysis showed that results are sensitive to the curve parametrization and there are risks of distortion and even contradictory results. LCA impact scores related to the application of three different silvicultural scenarios each combined with a gradient of the proportion of forest area in strict protection shed a light on the LCA model behaviour when considering management intensity. The LCA model multiplies two parameters having opposite non-linear effects: the PDF, which is rising with the intensification of the management, while the area required to produce 1m^3 of wood, is diminishing. Considering the risks related to the uncontrolled non-linear effects involved in the LCA model, this could lead to erratic results that do not reflect the effect on the safeguard subject corresponding here to the quality of ecosystems. Therefore, the LCA model should not be used for decision making related to land use decision. More research is required to investigate the mathematical relationships involved to verify if and how issues related to non-linear effects in LCA model could be properly addressed and insure that impact scores results reflect ecosystem quality instead of the area required for wood production, conserve the hierarchical structure of impacts and avoid recommendations that could produce more damage.

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Liste des abréviations, sigles, acronymes

ACV: Analyse du cycle de vie

AF: Aménagement forestier

ANT: Anthropization

ANT_NDP: Naturalness degradation potential from anthropization

BIM : Building information modeling

CF: Close forests

CF_pni: partial naturalness for close forests

CIRAIG : Centre international de référence sur le cycle de vie des produits, procédés et services

CL: careful clearcut logging

Compo: composition

Compo_PNI: Partial naturalness for composition

Context: landscape context

Context_PNI: Partial naturalness for landscape context

CPRS : Coupe avec protection de la régénération et des sols

CRMR : Centre de recherche sur les matériaux renouvelables

CRSNG: Conseil de recherches en sciences naturelles et en génie

CS: Companion species

CS_NDP: Naturalness degradation potential related to companion species

CT: cover type

CT_pni: partial naturalness index for cover type

CTot: coupe totale

DEG: dégagement mécanique

DW: dead wood

DW_NDP: Naturalness degradation potential related to dead wood

DW_PNI: Partial naturalness index for dead wood

EC : Éclaircie commerciale

EICV : Évaluation des impacts du cycle de vie

ep: enhanced protection

exo: exotic species

exo_NDP: Naturalness degradation potential from exotic species

FMU: Forest management unit

for_area: forest or forested area

HS: horizontal structure

HS_NDP: Naturalness degradation potential related to horizontal structure

ip: initial level of protection

IR: irregular stands

IR_pni: Partial naturalness index for irregular stands

ISC: irregular shelterwood cutting

LCA: Life cycle analysis

LS: Late successional characteristic species (i. e. *Picea* spp.)

LS_pni: Partial naturalness index for late sucessionnal characteristic species

NDP: Naturalness degradation potential

NE: natural evolution

NI : Naturalness index

OF: Old forests

OF_pni: Partial naturalness index for old forests

PDF: Potential disappeared fraction of species / Fraction d’espèces potentiellement disparues

PL: Plantation

PNI: Partial naturalness index for a given characteristic of naturalness (characteristic_PNI)

Pni: Partial naturalness index for a given condition indicator (condition_pni)

Prod_area: productive area

PT: préparation de terrain

RP: regeneration process

RP_NDP: Naturalness degradation potential related to regeneration process

SAR: Species area relationship

Struc: Structure

Struc_PNI: Partial naturalness index for structure

TAR: Terrestrial area required to produce 1m^3 of wood

UAF: Unité d'aménagement forestier

UNEP-SETAC: United Nations Environment Program – Society of Environmental Toxicology and Chemistry

W_CC: Clearcuts on wetlands

W_CC_NDP: Naturalness degradation potential related to clearcuts on wetlands

Wm: Modified wetlands

Wm_NDP: Naturalness degradation potential related to modified wetlands.

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Avant-propos

Ces travaux de doctorat ont été réalisés sous la direction de Robert Beauregard et la codirection de Louis Bélanger, tous deux de l'Université Laval, ainsi que Manuele Margni de l'École Polytechnique de Montréal.

Ce projet de recherche résulte d'une collaboration entre le Centre de recherche sur les matériaux renouvelables (CRMR) de l'Université Laval et le Centre international de référence sur le cycle de vie des produits, procédés et services (CIRAIG), associé à l'école Polytechnique de Montréal. Il s'inscrit dans le cadre d'un projet plus large, désigné sous l'acronyme BIM (building information modeling), développé par l'équipe du CIRAIG, sous la direction de M. Manuele Margni, et financé par le Conseil de recherches en sciences naturelles et génie du Canada (CRSNG). Le volet développé dans le cadre de la présente recherche se concentre sur la caractérisation des impacts de l'aménagement forestier sur la qualité des écosystèmes. L'étudiante a également bénéficié d'un financement découlant d'une subvention à la découverte du CRSNG attribuée à Évelyne Thiffault, professeure à l'Université Laval, ainsi que d'un financement de la chaire de recherche du CRSNG sur la construction écoresponsable en bois (CIRCERB).

Les travaux ont été réalisés dans le cadre du programme de doctorat en sciences forestières et les résultats sont présentés sous forme d'une thèse par articles comprenant les trois articles suivants, dont l'étudiante, Sylvie Côté, est la principale auteure :

Article 1, publié le 11 avril 2019 :

Côté, S.; Bélanger, L.; Beauregard, R.; Thiffault, É.; Margni, M. A Conceptual Model for Forest Naturalness Assessment and Application in Quebec's Boreal Forest. *Forests* **2019**, *10*, 325, doi: https://doi.org/10.3390/f10040325.

Article 2, publié le 25 mai 2020 :

Côté, S.; Bélanger, L.; Beauregard, R.; Thiffault, É.; Margni, M. Naturalness Assessment of Forest Management Scenarios in Abies balsamea–Betula papyrifera Forests. *Forests* **2020**, *11*, 601, doi:https://doi.org/10.3390/f11050601.

Article 3, publié le 8 août 2021:

Côté, S.; Beauregard, R.; Margni, M. ; Bélanger, L. Using naturalness for assessing the impact of forestry and protection on the quality of ecosystems in Life Cycle Assessment. *Sustainability* **2021**, *13*, 8859, doi: https://doi.org/10.3390/su13168859.

Le troisième article a été modifié par rapport à la version initialement déposée pour faire ressortir l'importante incertitude associée à la courbe NI-PDF et retirer les subtilités induites par l'introduction de valeurs infinitésimales de PDF pour la classe quasi-naturelle afin de se limiter aux résultats quantifiables à partir des données disponibles. La version incluse au chapitre 5 de la version finale de la thèse est conforme à la version publiée. Toutefois, la section décrivant en détails la construction de la courbe NI-PDF a été déplacée du matériel supplémentaire de l'article pour être insérée à l'appendice 5.B dans la thèse. Une coquille a été repérée dans le graphique d'analyse de sensibilité présenté dans le matériel supplémentaire du second article (pour FM-A-100PL60_ep). La version finale du fichier inclut la version corrigée dudit graphique.

La contribution de chacun des co-auteurs est précisée au tableau 1. Le matériel supplémentaire associé à chacun des articles est disponible sur le site de la revue via le lien spécifié (Article 1 : http://www.mdpi.com/1999-4907/10/4/325/s1 ; Article 2 : http://www.mdpi.com/1999-4907/11/5/601/s1 ; Article 3 : https://www.mdpi.com/2071-1050/13/16/8859) et aussi auprès de la bibliothèque de l'Université Laval.

Les résultats de la recherche ont également fait l'objet de présentations orales à deux occasions :

- Aux intervenants et différents bailleurs de fonds participant au projet BIM, le 6 septembre 2018.
- Lors d'un atelier sur la naturalité, tenu par le Comité scientifique d'aménagement de la Forêt Montmorency, le 12 juin 2019.

Tableau 1: Contribution des co-auteurs à chacun des articles

Auteurs Titre des articles	Sylvie Côté	Robert Beauregard	Louis Bélanger	Manuele Margni	Évelyne Thiffault
A Conceptual Model for Forest Naturalness Assessment and Application in Quebec's Boreal Forest.	1, 2, 3, 4, 5, 6, 7, 8, 9,10	1, 9	1, 2, 3, 5, 8, 9	1, 9	4 (données de bois mort), 9
Naturalness Assessment of Forest Management Scenarios in Abies balsamea–Betula papyrifera Forests.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	1, 9	1, 2, 3, 9	1, 9	4 (données de bois mort), 9
Using naturalness for assessing the impact of forestry and protection on the quality of ecosystems in Life Cycle Assessment.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	1, 6, 8, 9	6, 8, 9	2, 6, 8, 9	

Légende :

1. Définition des problématiques
2. Élaboration des méthodes
3. Revue de littérature
4. Acquisition de données
5. Développement et adaptation du modèle
6. Validation
7. Présentation des résultats
8. Analyse des résultats
9. Écriture et révision du document
10. Communications avec l'éditeur

Introduction

Le bois est souvent présenté comme un matériau écologique, or la crédibilité d'une telle affirmation repose sur l'obtention d'une éco-étiquette résultant d'une analyse d'impact environnemental de la production et de l'utilisation du matériau. Pour ce faire, on procède généralement à une analyse de cycle de vie (ACV) qui est une méthode utilisée en ingénierie pour « évaluer l'impact environnemental d'un produit, d'un service ou d'un système en considérant toutes les étapes de son cycle de vie » (Jolliet et al. 2010). L'élaboration de cette méthode à l'échelle internationale est encadrée par une initiative conjointe du SETAC (Society of Environmental Toxicology and Chemistry) et du PNUE (Programme des nations unies pour l'environnement), selon une démarche multidisciplinaire visant à évaluer les impacts environnementaux en se basant sur la science.

L'ACV peut notamment être utile pour comparer l'impact environnemental de divers matériaux de construction dont le bois. L'ACV permet d'évaluer l'impact d'un produit ou d'un service selon quatre grandes catégories de dommages correspondant à des sujets de protection soient : la santé humaine; les ressources naturelles; les changements climatiques et la qualité des écosystèmes (Jolliet et al. 2010). Cependant, à l'heure actuelle, l'évaluation des impacts sur la qualité des écosystèmes représente un volet qui n'est généralement pas couvert dans l'interprétation des résultats des ACV (Maier et al. 2019). Parmi les raisons expliquant cette situation mentionnons notamment le manque de considération du type d'utilisation des terres et des paramètres caractéristiques associés à l'aménagement, ainsi que du besoin de tenir compte de l'intensité d'aménagement (Maier et al. 2019). La présente étude vise à développer une méthode d'évaluation de l'impact de la foresterie sur les écosystèmes. Il est ensuite prévu d'en tester l'intégration au modèle de l'ACV dans la perspective d'appuyer la réflexion des concepteurs de bâtiments désireux de prendre des décisions écoresponsables, en permettant de mesurer les impacts relatifs de l'utilisation de 1m^3 de bois en construction, sur la qualité des écosystèmes en tenant compte du régime d'aménagement forestier, par rapport aux autres options de matériaux tels que le béton ou l'acier. Le projet « Life cycle whole building design tool for energy efficient innovative building » de l'École Polytechnique du Montréal auquel contribue le Département des sciences du bois et de la forêt de l'Université Laval, s'inscrit dans cette perspective. Ce projet est financé par le CRSNG, avec la participation de Cecobois et du Conseil canadien du bois. La présente étude constitue un des volets de ce projet et porte sur la caractérisation des impacts de l'utilisation des terres associées aux pratiques d'aménagement forestier au Canada, de façon à permettre une différenciation en fonction du régime d'aménagement.

Chapitre 1. Revue de littérature

La présente étude se concentre sur l'évaluation des impacts de la foresterie en forêt boréale, dans la perspective d'être utilisée dans l'ACV. Les lignes directrices proposées par l'initiative sur le cycle de vie du PNUE-SETAC proposent une évaluation des impacts potentiels de l'utilisation des terres sur la qualité des écosystèmes fondée principalement sur l'évaluation des dommages potentiels à la biodiversité (Koellner et al. 2013), comme en témoigne l'unité proposée pour évaluer l'impact sur la qualité des écosystèmes qui correspond à la fraction d'espèces potentiellement disparues multipliée par la superficie et par année (PDF*m^2*an) (Milà i Canals et al. 2007). Il est cependant reconnu que l'intégration des considérations relatives à la biodiversité dans les ACV représente un défi à maints égards, notamment en raison de son caractère multidimensionnel (Gaudreault et al. 2016), qui rend difficile l'expression des impacts de l'utilisation des terres reliées à un produit en utilisant la valeur d'un seul indicateur (de Souza et al. 2013; de Baan et al. 2013a). De plus, il n'existe pas de suivi général de la biodiversité associé au type d'utilisation des terres, ce qui limite le développement de modèles basés sur la biodiversité et fait en sorte que de tels modèles comporteront inévitablement un fort niveau d'incertitude (Yamaguchi et al. 2016). Les données relatives aux impacts des différents types d'utilisation des terres s'avèrent variables à l'échelle de la planète et il existe toujours à ce jour des manques de connaissances importants quant aux chaînes de cause à effets (de Baan et al. 2013a). La biodiversité est même désignée par certains comme une ressource précieuse non mesurable (Michelsen et al. 2014). Malgré la multitude de modèles proposés au cours des 20 dernières années (Winter et al. 2017), la prise en compte de la qualité des écosystèmes dans l'analyse d'impact ACV de produits et services demeure limitée (Maier et al. 2019). Généralement, ces modèles se basent soit sur les écosystèmes, soit sur la biodiversité, laquelle est souvent ramenée à la seule richesse en espèces (i.e. le nombre d'espèces) (Coelho & Michelsen 2014; Lindqvist et al. 2016), faute de données disponibles pour quantifier les autres aspects de la biodiversité (p. ex. diversité génétique, populations). Cependant, les données de richesse relative en espèces en forêt boréale sont rares, plus rares que dans les autres écosystèmes (Alkemade et al. 2009; Newbold et al. 2015). Dans ce contexte, une approche fondée sur l'application du concept du filtre brut, selon lequel le maintien de la diversité des écosystèmes naturellement présents au sein des paysages aménagés permet de répondre aux besoins de la vaste majorité des espèces (Hunter et al. 1988), semble appropriée. Toutefois, pour s'assurer que cette diversité d'écosystèmes soit similaire à celle affichée en milieu naturel, il est important de tenir compte de leur niveau d'altération, ces deux aspects pouvant être estimés à l'aide des concepts de naturalité et d'hémérobie.

La première partie de cette revue de littérature porte sur les aspects entourant l'élaboration d'un système d'évaluation de la qualité de l'écosystème : les concepts sur lesquels il repose, soit la naturalité et l'hémérobie. La seconde partie porte sur la démarche conceptuelle ayant sous-tendue l'élaboration du modèle d'évaluation de la naturalité. La troisième partie présente un court portrait de la méthode proposée en ACV pour l'évaluation des impacts de l'utilisation des terres sur la qualité des écosystèmes. La quatrième partie relate plusieurs études ayant proposées diverses méthodes pour l'évaluation de la qualité des écosystèmes dans les ACV. Étant donné qu'il s'agit d'intégrer les effets de l'aménagement forestier à l'ACV, la cinquième section porte sur les effets de l'aménagement forestier sur les écosystèmes. Enfin, dans la perspective de fournir des éléments de réflexion pertinents pour la discussion des résultats, la dernière section porte sur les effets non-linéaires et effets de seuil.

1.1 Les concepts de naturalité et hémérobie

L'hémérobie correspond à une mesure intégrée de l'impact humain sur les écosystèmes (Winter 2012). Elle réfère à un gradient d'influence anthropique qui, dans sa portion moins altérée se définit plus précisément grâce au concept de naturalité (Figure 1.1), laquelle correspond à la distance relative par rapport à l'état naturel (Winter 2012). Les concepts d'hémérobie et de naturalité sont complémentaires et permettent de caractériser plus finement les deux extrêmes d'un même gradient (Winter 2012). Sur le plan de la biodiversité, une plus grande naturalité se caractérise par une plus grande quantité d'espèces adaptées et spécialisées incluant souvent des espèces vulnérables ou en danger (Winter 2012). Si bien qu'en mettant l'emphase sur le maintien ou la restauration de la naturalité il serait possible de limiter la perte de biodiversité forestière (Winter 2012).

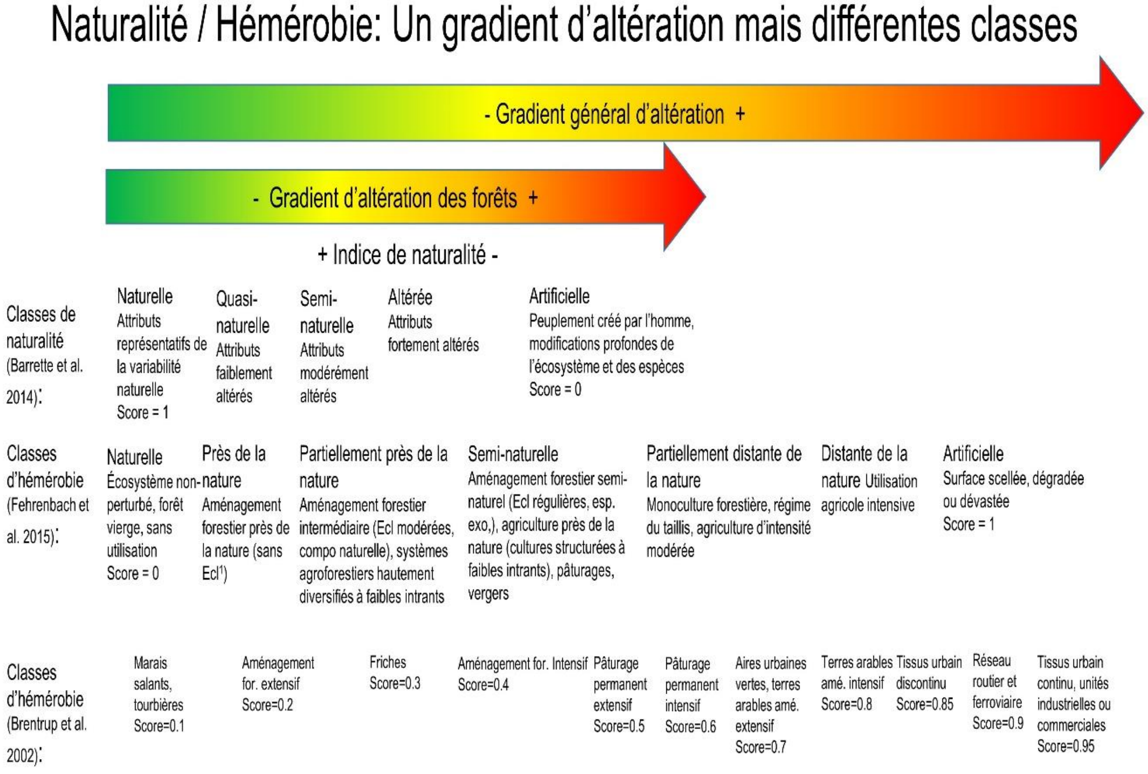


Figure 1.1 : Position relative le long du gradient général d'altération des classes de naturalité des forêts utilisées par Barrette et al. (2014), des classes d'hémérobie utilisées par Fehrenbach et al. (2015) et des classes d'hémérobie associées aux différentes utilisations des terres utilisées par Brentrup et al. (2002). [1] **: Ecl : éclaircie**

1.2 Un modèle conceptuel pour l'évaluation de la naturalité

Le modèle conceptuel représente un outil permettant de définir de manière explicite et de mettre en relation les différents phénomènes d'intérêts et les indicateurs pertinents (Newton & Kapos 2002). Les fondements du modèle conceptuel, qui correspondent ici aux concepts d'hémérobie/naturalité, permettent d'identifier les variables pertinentes pour l'évaluation (Newton & Kapos 2002). Plus précisément, il s'agissait de développer un modèle permettant d'évaluer le degré d'altération de l'écosystème forestier, en se basant sur des indicateurs de naturalité/hémérobie dont l'état peut être évalué à partir de données disponibles, lesquelles correspondent essentiellement à la cartographie et aux données d'inventaire écoforestier.

Un modèle conceptuel permet notamment d'articuler la réflexion sur un domaine donné, faciliter la communication et documenter le domaine pour référence future (Gemino & Wand 2004). Dans le domaine de la biologie de la conservation, l'utilisation du modèle conceptuel permet de se pencher sur la complexité existant à la fois au niveau des détails et sur le plan dynamique (Margoluis et al. 2009). La complexité des détails résulte du grand nombre de variables impliquées dans le système, alors que la complexité dynamique découle des interactions, parfois imprédictibles, entre les variables. Compte tenu de la complexité inhérente au concept de biodiversité, les modèles conceptuels développés dans le domaine de la biologie de la conservation s'attardent à la fois aux espèces, aux écosystèmes et aux processus écologiques (Margoluis et al. 2009), ou encore aux trois principaux attributs des écosystèmes forestiers (Franklin et al. 1981): les espèces, la structure et les processus (Noss 1990; Roberge et al. 2008; Brümelis et al. 2011). Le modèle conceptuel facilite l'identification des facteurs clés et fournit une base pour la sélection des paramètres à mesurer pour l'évaluation (Margoluis et al. 2009).

De façon générale, les modèles conceptuels développés en écologie considèrent les effets écologiques des éléments moteurs (« drivers » en anglais) et des facteurs de stress (Ogden et al. 2005; Tierney et al. 2009). Dépendamment du contexte et des besoins, les effets écologiques peuvent être évalués sur divers types d'attributs tels que des espèces indicatrices, comme dans les travaux d'Ogden et al. (2005) portant sur la restauration des écosystèmes humides du Sud de la Floride, ou encore sur des caractéristiques des écosystèmes, comme dans l'étude de Tierney et al. (2009) portant sur l'évaluation de l'intégrité écologique développée dans le cadre du programme de suivi des signes vitaux du Service national des parcs américains.

Le modèle conceptuel développé par Ogden et al. (2005), dont le diagramme simplifié est présenté à la Figure 1.2, inclut tous les principaux éléments moteurs qui se définissent comme étant les forces externes au système naturel qui ont une influence à grande échelle sur les systèmes. Ces éléments moteurs regroupent aussi bien les forces naturelles (p. ex : régime de perturbations naturelles) qu'anthropogéniques (p. ex : pratiques d'aménagement). Les facteurs de stress correspondent aux changements physiques ou chimiques occasionnés par les éléments moteurs provoquant des changements significatifs des composantes biologiques, ainsi que des patrons et interrelations dans les systèmes naturels. Les effets écologiques réfèrent aux réponses physiques, chimiques et biologiques causées par les facteurs de stress. Enfin, les attributs correspondent à un sous-ensemble représentatif de tous les éléments ou composantes biologiques du système naturel. Il s'agit souvent d'espèces ou de groupes d'espèces, de populations ou encore de processus, généralement désignés comme indicateurs. Ces attributs sont choisis pour représenter un effet connu ou présumé des facteurs de stress et qui représentent des éléments du système ayant une valeur importante pour les humains (Ogden et al. 2005). Dans la documentation écrite accompagnant le modèle conceptuel, les informations de base relatives aux facteurs de stress et aux attributs sont généralement fournies avant la discussion sur les effets écologiques et les relations critiques servant de base pour établir les liens servant de base à l'élaboration des hypothèses causales (Ogden et al. 2005).

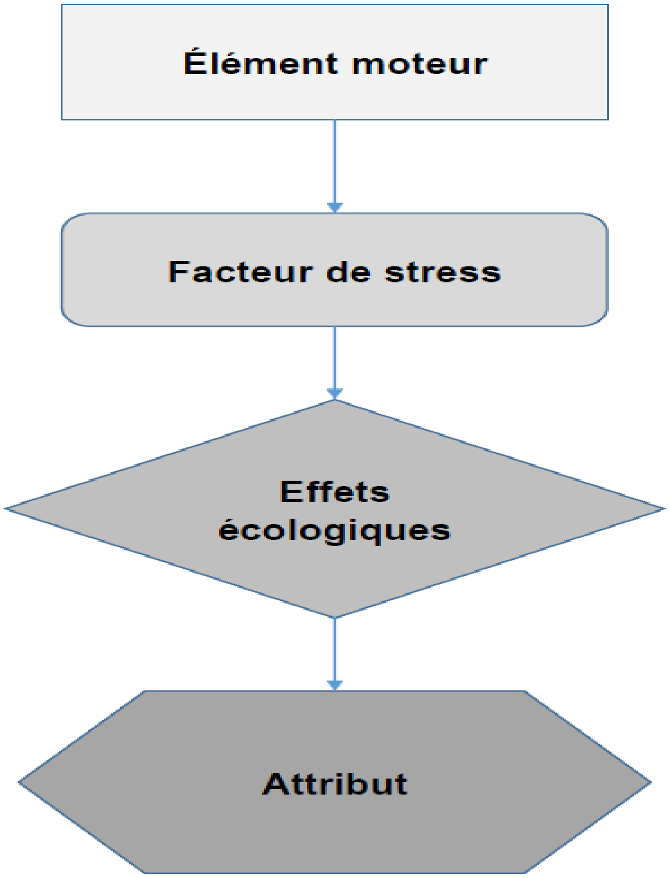


Figure 1.2 : Diagramme simplifié d'un modèle conceptuel écologique (adapté de Ogden et al. 2005).

Le modèle conceptuel développé par Tierney et al. (2009) pour évaluer l'intégrité écologique fournit un autre exemple (Figure 1.3). L'intégrité écologique se définit comme étant la capacité à supporter et maintenir une communauté d'organismes balancée, intégrée et capable de s'adapter, caractérisée par une composition en espèces, une diversité et une organisation fonctionnelle comparables à celles de l'habitat naturel de la région considérée (traduit de la définition de Frey et al. 1975, citée dans McRoberts et al. (2012)). La mesure de l'intégrité écologique se base sur la composition, la structure et les fonctions d'un écosystème, mises en relation avec les limites de variabilité historiques ou naturelles du système, ainsi que les perturbations causées par les agents de changements anthropogéniques ou naturels (traduction de la définition de Karr et Dudley, 1981, fournie dans Mitchell et al. (2014)).

Ce modèle conceptuel identifie les principaux agents moteurs et facteurs de stress influençant les forêts du Nord-Est de l'Amérique du Nord, ainsi que les mesures de structure, de composition et de fonction qui varient sous l'influence des facteurs de stress (Tierney et al. 2009). L'utilisation d'un modèle conceptuel de type « driving force-state-reponse » reconnait que les impacts d'un développement durable peuvent être négatifs ou positifs (Newton & Kapos 2002), ce qui permet une évaluation bidirectionnelle. Ce dernier modèle peut être appliqué via l'identification d'indicateurs de condition (p. ex. la proportion de la superficie occupée par des groupements de fin de succession), de pression (p. ex. la proportion de superficie sujette à un scenario sylvicole appliqué sur une révolution trop courte pour permettre le développement des caractéristiques des peuplements de fin de succession) et de réponse politique (p. ex. existence de politiques visant l'aménagement ou la conservation de groupements de fin de succession) (Hagan & Whitman 2006). En principe, les effets conjugués de l'application de la réglementation et des pressions appliquées, aussi bien négatives ou positives, devraient éventuellement se répercuter sur les indicateurs de condition.

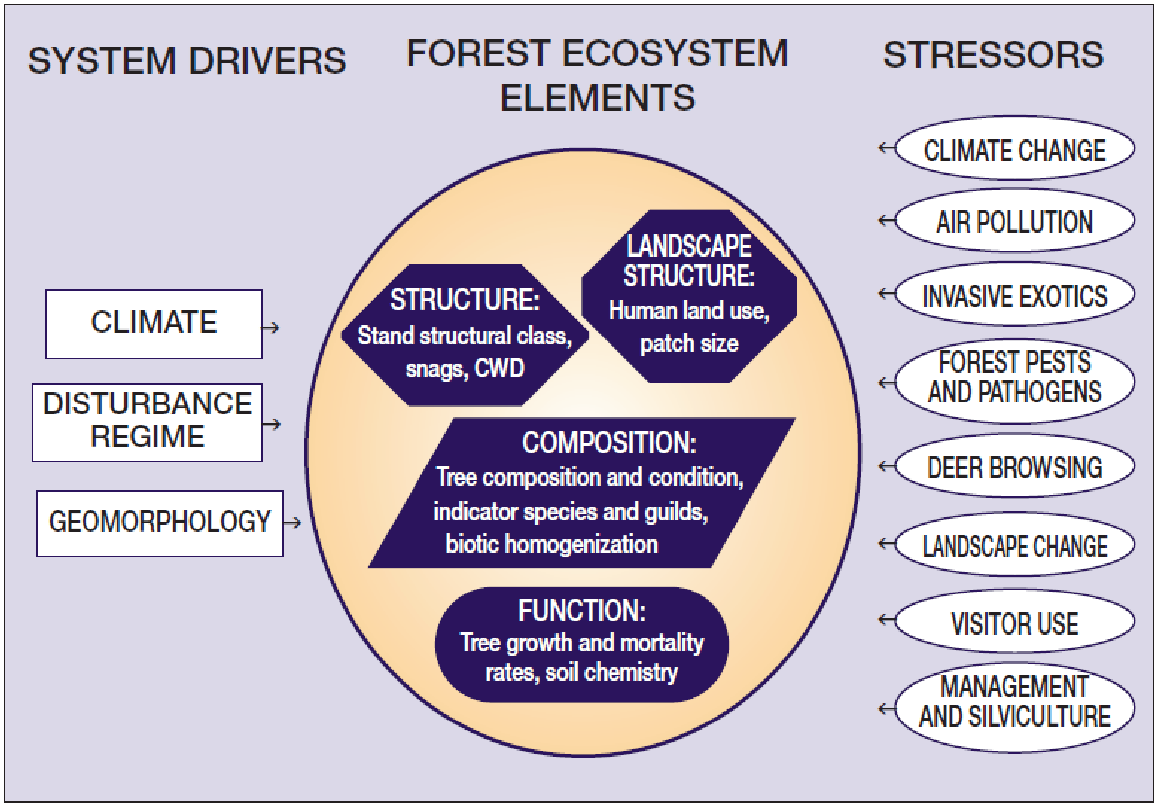


Figure 1.3 : Modèle écologique conceptuel utilisé pour évaluer l'intégrité écologique des forêts du nord-est des États-Unis (tiré de Tierney et al. 2009).

Newton & Kapos (2002) proposent des indicateurs de biodiversité, pouvant être associés aux inventaires nationaux, potentiellement utiles pour fournir des informations quant au statut et aux tendances en matière de biodiversité forestière. Les indicateurs proposés à cet effet sont : 1) proportion du territoire par type forestier et stade successionnel; 2) proportion de la superficie forestière par stade successionnel en forêts protégées; 3) degré de fragmentation par type forestier; 4) taux de conversion du couvert forestier (par type) vers d'autres utilisations; 5) superficie et pourcentage de forêt affectées par les perturbations anthropiques et naturelles; 6) complexité et hétérogénéité de la structure forestière; 7) nombre d'espèces dépendantes des forêts; 8) statut de conservation des espèces dépendantes des forêts. Leur démarche propose de combiner l'état des forêts évaluées sur la base des données de l'inventaire forestier et l'identification des espèces dépendantes des forêts. Cependant, le statut actuel de ces espèces ne tient pas compte du délai de réponse existant entre la perte d'habitat et l'extinction d'espèces (Brooks et al. 1999; Hanski 2005), ce qui fait en sorte qu'une estimation des effets potentiels sur les espèces, comme celle que l'on vise à faire dans le cadre des ACV, comportera inévitablement un niveau d'incertitude très élevé.

Gauthier et al. (2008) identifient cinq attributs clés pour préserver la résistance et la résilience des écosystèmes : la composition forestière, la structure forestière, le bois mort, la matière organique au sol et la nécessité de planifier sur de grands espaces et à long terme. Les caractéristiques de naturalité retenues dans le modèle d'évaluation proposé dans la présente étude reconnaissent ces mêmes attributs (composition, structure, bois mort, contexte à l'échelle du paysage) en ajoutant la prise en compte de la provenance de la régénération (naturelle ou artificielle, considérant le processus de sélection génétique opéré), de la disponibilité de semences dans les peuplements naturels (en lien avec l'âge de révolution et les espèces présentes, en considérant les processus impliqués dans la dynamique naturelle, dépendamment du régime de perturbation en cause), en plus des lits de germination pour le processus de régénération (Côté & Bélanger 1991). Un modèle basé sur la condition et la pression possèderait un bon potentiel explicatif car il se fonde sur des faits : la condition pouvant être observée au fil du temps via l'utilisation des cartes forestières et la pression qui résulte de nos actions pouvant être quantifiées à travers le suivi des interventions intégré à la cartographie forestière.

1.3 Évaluation des impacts de l'utilisation des terres en ACV

Le cadre conceptuel associé à l'évaluation de la qualité des écosystèmes en lien avec l'utilisation des terres dans l'ACV découle des travaux de l'initiative UNEP-SETAC (Milà i Canals et al. 2007; Koellner et al. 2013). Ce cadre considère une transformation initiale instantanée résultant de l'utilisation des terres, suivie d'une phase d'occupation des terres pendant laquelle la qualité demeurerait constante, puis d'une période de relaxation associée à un hypothétique abandon de l'utilisation pendant laquelle s'effectue une transformation post-utilisation conduisant à un nouvel état d'équilibre qui se stabiliserait à un niveau de qualité inférieur par rapport au niveau historique (Figure 1.4).

Selon les lignes directrices établies par l'UNEP-SETAC pour l'évaluation des impacts de l'utilisation des terres sur la qualité des écosystèmes dans les ACV (Koellner et al. 2013), l'impact de l'utilisation des terres (IO) correspond à la différence de qualité (ΔQ) entre la situation faisant l'objet de l'évaluation et la situation de référence, multipliée par le temps (t) et la superficie occupée (S).

$$IO = \Delta Q \times t \times S$$

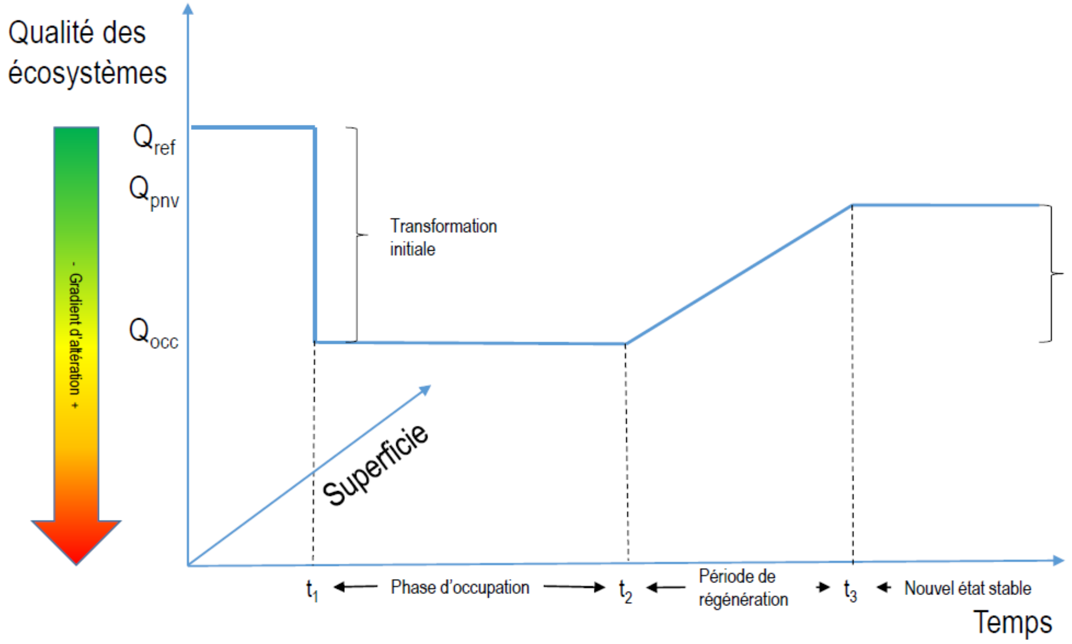


Figure 1.4 : Modèle d'évaluation de la qualité des écosystèmes en fonction du temps dans l'ACV (adapté de (Milà i Canals et al. 2007; Koellner et al. 2013)). Qhis : Niveau historique de qualité des écosystèmes; Qpnv : Niveau de qualité associé à la végétation naturelle potentielle (pnv); Qocc : Niveau de qualité pendant la phase d'occupation; t1 : changement d'utilisation des terres; t2 : arrêt de l'utilisation; t3 : atteinte d'un nouvel état d'équilibre.

Étant donné le choix d'exprimer les impacts sur la qualité des écosystèmes dans les ACV en termes de perte potentielle d'une fraction d'espèces par unité de surface et par année (Milà i Canals et al. 2007), le modèle désiré doit prévoir une mise en relation entre le niveau de naturalité/altération associé aux pratiques forestières et la perte potentielle d'une fraction d'espèces. Or, les suivis de l'effet des pratiques, ou de l'aménagement sur la perte potentielle d'une fraction d'espèces sont très rares (Newton & Kapos 2002; Yamaguchi et al. 2016), d'où la nécessité de faire appel à des concepts pouvant être évalués sur la base des données disponibles. Toutefois, aux fins de l'ACV, si l'évaluation se base sur une autre mesure, il est recommandé de fournir des facteurs de conversion en PDF, lesquels devraient préférablement être validés (Verones et al. 2017). Au chapitre 5, une courbe provisoire mettant en relation de façon préliminaire l'indice de naturalité avec le PDF a été élaborée et la sensibilité des valeurs utilisées pour son paramétrage a été testée.

1.4 Qualité des écosystèmes dans les ACV

Les études réalisées dans le domaine de l'évaluation de la qualité des écosystèmes dans les ACV ont exploré diverses méthodes basées sur la richesse relative en espèces évaluée à partir de méta-analyses (De Baan et al. 2013a), sur la relation entre la superficie occupée par un type d'utilisation des terres et le nombre d'espèces (De Baan et al. 2013b; Chaudhary et al. 2015) ou encore sur des modèles d'habitat (De Baan et al. 2015), en intégrant la prise en compte des spécificités régionales associées aux grands domaines bioclimatiques. Certains ont aussi inclus la vulnérabilité des espèces (De Baan et al. 2013b; De Baan et al. 2015; Chaudhary et al. 2015), ou des écosystèmes (Michelsen, 2008). Plusieurs de ces méthodes traduisent les impacts en termes de nombre d'espèces ou de proportion du nombre d'espèces potentiellement disparues, alors qu'il est reconnu que la diversité α, exprimée par le nombre d'espèces, ne représente pas à elle seule un bon indicateur de la biodiversité (MEA, 2005). Pour répondre à cette problématique, une étude a récemment proposé une mesure de la biodiversité incorporant la diversité fonctionnelle (De Souza et al. 2013); cependant cette approche ne permet pas toujours de bien cerner les impacts sur la biodiversité puisque certaines espèces ou groupes d'espèces peuvent être remplacés par d'autres ayant une fonction similaire. L'ajout d'indicateurs de ressources critiques associées aux écosystèmes a également été tenté (Michelsen, 2008), sans toutefois permettre de couvrir l'ensemble des facettes de la biodiversité. Les méthodes élaborées jusqu'à maintenant comportent toujours diverses lacunes, notamment en matière de cohérence avec le cadre de référence utilisé dans les ACV qui se traduit dans certains cas par une intégration difficile avec les autres catégories d'impacts sur la qualité des écosystèmes (comme par exemple, l'écotoxicité terrestre ou l'écotoxicité aquatique), lesquelles sont exprimées en PAF*m2*an qui correspond à la fraction d'espèces potentiellement affectées multipliée par la superficie et par année (Woods et al. 2018). Il s'avère que la recherche d'un proxy approprié constitue un objectif de recherche depuis de nombreuses années (De Baan et al. 2013; Curran et al. 2016).

Le choix d'exprimer les impacts en termes de biodiversité suscite également certains questionnements considérant les délais existant entre les changements d'utilisation des terres et leurs effets sur la disparition d'espèces qui peut s'étendre sur plusieurs décennies voire plus d'un siècle (Rompré et al. 2009; Krauss et al. 2010). Les effets sur les espèces étant sujet à un décalage dans le temps (Angelstam et al. 2004), une évaluation portant sur la fraction d'espèces potentiellement disparues peut conduire à une sous-estimation des impacts (de Souza et al. 2013) et comporte un niveau élevé d'incertitude.

Certaines méthodes proposées (Chaudhary et al. 2015; de Baan et al. 2015) considèrent le statut des espèces (menacées ou vulnérables). Cependant, ces listes actuelles ne tiennent pas compte des disparitions futures qui résulteront des actions présentes en raison du délai de réponse. L'existence de ce délai de réponse dans le processus disparition d'espèces, fait aussi en sorte de remettre en question l'hypothèse d'un effet constant de l'occupation des terres dans le temps, utilisé en ACV (Koellner et al. 2013). Le suivi des populations d'espèces spécialisées permettrait possiblement d'être mieux en mesure d'anticiper les pertes éventuelles mais, les données sont rares et partielles (limitées à certaines espèces ou groupe d'espèces). Par ailleurs, les populations d'espèces peuvent fluctuer selon certains cycles (Kawaguchi & Desrochers 2018), ce qui complique l'utilisation des résultats obtenus sur de courtes périodes. Plus récemment, Chaudhary & Brooks (2018) ont proposé une méthode combinant l'utilisation de la SAR (de l'anglais Species-Area Relationship) modifiée pour le milieu rural (qui estime la proportion d'espèces qui subsistent après une conversion de l'habitat (Pereira et al. 2014)) et d'un score de vulnérabilité des écosystèmes pour cinq catégories d'utilisation de terres (forêts aménagées, plantations, pâturage, agriculture et urbaine) selon trois niveaux d'intensité (minimale, légère et intensive) de manière à évaluer l'impact sur cinq taxa (mammifères, oiseaux, amphibiens, reptiles et plantes). Cette méthode qui mesure les impacts à l'échelle globale, suscite cependant des questionnements relatifs aux échanges entre régions ou taxa pouvant en découler, lesquels sont susceptibles de fournir des résultats contre-productifs, dans la perspective d'identifier les meilleures pratiques (Gaudreault et al. 2020).

Les premiers essais d'intégration du concept d'hémérobie aux ACV utilisaient des classes générales attribuées aux différents types d'utilisation des terres, en contexte Européen, en fonction du niveau d'altération qui leur était associé, ce niveau étant considéré comme déterminant de la capacité de l'écosystème de maintenir ou regagner un certain niveau de naturalité (Brentrup et al. 2002). Cette méthode, qualifiée de largement subjective (Curran et al. 2016), n'établissait cependant pas les liens existant entre les catégories d'utilisation des terres et les différentes caractéristiques écologiques susceptibles d'avoir une influence sur la biodiversité et ne permettait pas de nuancer à l'intérieur des différentes classes proposées. Récemment, le concept d'hémérobie a été à nouveau proposé pour servir d'indicateur de catégorie d'impact pour l'utilisation des terres dans les ACV (Fehrenbach et al. 2015). La méthode, développée dans le contexte Européen, utilisait sept classes d'hémérobie pour caractériser deux types d'utilisation des terres : la foresterie et l'agriculture, et associait des critères et mesures permettant l'évaluation de la naturalité. Pour la foresterie, les critères considérés étaient : la naturalité du sol, la naturalité de la végétation forestière et la naturalité des conditions de développement (Fehrenbach et al. 2015). Les concepts de naturalité et d'hémérobie ont également été récemment utilisés pour incorporer la biodiversité marine dans l'ACV pour les fruits de mer (Farmery et al. 2017).

Une autre méthode propose l'utilisation de fonctions de contribution reliant la valeur de chacun des paramètres considérés à leur contribution à la biodiversité (exprimée entre 0 et 1). Ces fonctions sont développées sur la base de la littérature et d'interviews d'experts, dont les résultats sont ensuite agrégés pour fournir une valeur de potentiel de biodiversité, laquelle est ensuite pondérée par un facteur associé à la spécificité de l'écosystème régional (Michelsen 2008; Lindner et al. 2014; Winter et al. 2018). Cette démarche, qui inclut les différents aspects de la biodiversité (gènes, espèces et écosystèmes), a récemment été à la base du développement d'une proposition d'un nouveau cadre méthodologique pour l'évaluation des impacts sur la biodiversité dans les

ACV considérant la distribution inégale de la biodiversité sur la planète, le besoin de régionaliser les impacts de l'utilisation des terres et de nuancer les différents impacts sur la biodiversité associés aux différents types d'utilisation des terres, ainsi que la pertinence d'analyser les impacts associés à divers paramètres d'aménagement et leur influence sur l'intensité de l'utilisation (Maier et al. 2019).

Ce besoin d'améliorer la prise en compte de l'effet des pratiques d'aménagement ressort également d'une publication récente mettant en relation les pratiques forestières et les caractéristiques des écosystèmes jugées importantes pour la biodiversité (Rossi et al. 2018). Dans le cadre de cette étude, des cotes partielles de biodiversité basées sur le degré d'hémérobie résultant des pratiques forestières ont été évaluées pour 4 indicateurs de biodiversité (composition, structure, protection et bois mort), en utilisant des relations généralement non-linéaires. Ces cotes partielles ont été regroupées en appliquant un effet multiplicatif, dans une cote globale de dégradation potentielle de la naturalité, ensuite utilisée comme proxy pour évaluer la perte potentielle de biodiversité dans les ACV.

Malgré que pour l'ACV, les classes élaborées sur la base des concepts d'hémérobie/naturalité comportent l'avantage de conserver la complexité inhérente à l'utilisation des terres et éviter la sur-simplification résultant de l'utilisation d'un indicateur écologique unique (tels que la biodiversité α, ou le contenu en carbone des sols) (Fehrenbach et al. 2015), il n'est pas possible, dans l'état actuel des connaissances, d'établir avec précision des liens entre le niveau d'hémérobie/naturalité des écosystèmes et la richesse en espèces, faute de données disponibles et aussi en raison du caractère dynamique de la biodiversité impliquant un délai dans la réponse entre la pression et le résultat en termes de pertes d'espèces, ce qui accroît la difficulté d'avoir une donnée probante. Par contre, le degré de naturalité peut tout de même être évalué et il apparait comme un outil approprié pour permettre la réalisation d'évaluations bidirectionnelles par rapport à un état actuel ou modélisé.

À cet égard, le choix de la période de référence peut induire des facteurs de caractérisation présentant des différences importantes (Lindqvist et al. 2016; Verones et al. 2017; Vrasdonk et al. 2019). Pour l'ACV, la période de référence peut correspondre soit à la végétation historique, soit à la végétation naturelle potentielle (i.e. la végétation après re-naturalisation, impliquant une réduction permanente de la qualité des écosystèmes) ou encore au mélange de végétation actuelle, dépendamment des objectifs de l'analyse (Milà i Canals et al. 2014; Verones et al. 2017; Winter et al. 2018). Toutefois, la végétation naturelle potentielle implique une certaine perte de qualité permanente qui peut être difficilement quantifiable dans certaines parties du monde en raison de la longue période d'utilisation des terres combinée à l'absence de données sur les conditions initiales (Vrasdonk et al. 2019). La naturalité implique une référence à la situation historique (McRoberts et al. 2012). Son évaluation basée sur les données actuelles correspond aux résultats des actions passées jusqu'au moment de l'évaluation. Dépendamment des besoins de l'ACV, le modèle d'évaluation de la naturalité peut être appliqué à la situation correspondant à la période de référence requise qui peut être différente de la situation naturelle; dans ce cas l'effet sera représenté par la différence entre les deux cotes de naturalité évaluées pour la période à considérer. Dans ce contexte, l'utilisation de la naturalité intègre de plus une estimation des pertes permanentes.

Selon Teixeira et al. (2016), la richesse en espèces représente un bon point de départ en tant qu'indicateur pour les modèles ACV d'impact sur la biodiversité, mais l'évaluation devrait également tenir compte de l'intensité de l'utilisation et de la configuration d'habitat. Dans les ACV, l'intensité de l'utilisation est généralement prise en compte au moyen de classes (p. ex. intensive et extensive), alors qu'il serait judicieux d'exprimer l'intensité selon un gradient (Maier et al. 2019). La base de données de biodiversité PREDICTS (de l'anglais: Projecting Responses of Ecological Diversity in Changing Terrestrial Systems) (Hudson et al. 2017) est considérée comme potentiellement intéressante pour l'intégration au cadre établi par l'UNEP-SETAC (Maier et al. 2019). Cette base fournit diverses données de biodiversité (richesse, abondance et raréfaction basée sur la richesse), selon différents niveaux de pression définis sur la base du type d'occupation et de l'intensité d'utilisation. La configuration de l'habitat représente un facteur important, particulièrement dans un contexte où les types d'utilisation des terres sont diversifiés, ce qui n'est généralement pas le cas en forêt boréale au Québec, et il s'avère que cet aspect n'est habituellement pas intégré à l'interprétation des résultats d'ACV (Kuipers et al. 2019).

1.5 Aménagement forestier, protection et biodiversité

L'aménagement forestier consiste à contrôler ou réguler le patron de distribution des stades de développement des peuplements dans l'espace et dans le temps, à travers la sylviculture et la protection, afin d'assurer des bénéfices constants en qualité et en quantité permettant d'atteindre les buts fixés pour la forêt aménagée (Baskerville 1986). Considérant les multiples ressources et fonctions de la forêt, les objectifs d'aménagement sont généralement variés et différents modèles d'aménagement peuvent être envisagés, tels que la sylviculture intensive de production (systèmes sylvicoles à haut-rendement à l'instar de ceux appliqués en agriculture), la foresterie extensive (récolte opportuniste dépendamment des produits en demande), la production à rendement soutenu (ajuste la révolution et normalise les classes d'âge), l'aménagement intégré (la forêt est aménagée pour répondre à plusieurs valeurs), ou l'aménagement écosystémique (inspirée par les régimes de perturbations naturelles) (Hunter 1999). En réponse aux défis posés par l'aménagement intégré des ressources et des inévitables incompatibilités pouvant en résulter, certaines stratégies proposent un zonage du territoire forestier. C'est le cas de la Triade, qui prévoit la division du territoire en trois zones ayant chacune leurs objectifs spécifiques : conservation, production intensive et aménagement écosystémique (Seymour & Hunter 1992; Messier et al. 2009; Ward & Erdle 2015). Ce type de stratégie suscite des questionnements relatifs aux effets de l'aménagement extensif à grande échelle, versus ceux associés à une production plus intensive, ainsi qu'à une éventuelle compensation possible des impacts négatifs associés à une intensification de la production de bois par les effets positifs associés à une protection stricte accrue (Messier et al. 2009; Ward & Erdle 2015).

Sur le plan sylvicole, la coupe avec protection de la régénération et des sols (CPRS) représente le mode de régénération des forêts principalement utilisé en forêt boréale québécoise (plus de 90% des superficies touchées par la récolte en forêt boréale font l'objet de coupes totales) (MFFP 2020a), avec pour principal effet, le retrait du couvert forestier dont les effets perdurent jusqu'à reformation du couvert par la nouvelle cohorte d'arbres (Keenan & Kimmins 1993).

Dans le cadre de l'aménagement écosystémique, les coupes devraient s'inspirer du régime de perturbations naturelles (Hunter 1999; Gauthier et al. 2008). Les coupes totales, auxquelles appartiennent les CPRS, ont d'abord été présentées à tort comme appropriées pour simuler le passage d'un feu (Gauthier et al. 2008; Kuuluvainen 2009) en raison du retrait brutal du couvert, mais leurs effets sur le plan écologique s'avèrent différents à maints égards (Voir McRae et al. (2001)). C'est le cas, notamment, pour la durée de la révolution qui s'avère réduite par rapport à l'intervalle moyen de retour des feux, estimé à 150 ans dans la pessière à mousses de l'Ouest (et à 450 ans dans la sapinière à bouleau blanc de l'Est) (Boucher et al. 2011), ce qui modifie la répartition par classe d'âge à l'échelle du paysage et fait en sorte de réduire la proportion de forêts appartenant aux classes d'âge plus vieilles (McRae et al. 2001; Bergeron & Fenton 2012). De plus, les feux n'affectent pas nécessairement toutes les surfaces laissant amplement la place à une différentiation structurale résultant de la mortalité par pied d'arbre, à l'origine de la formation de peuplements irréguliers qui occupaient une part importante du paysage naturel (Bergeron & Fenton 2012). Aussi, les feux laissent davantage de legs du peuplement précédent (i.e. arbres vivants et moribonds, abondance de chicots et débris ligneux incluant des pièces de forte dimension) par rapport à la coupe (McRae et al. 2001). Sur le plan de la composition, le feu peut donner naissance aussi bien à des peuplements de feuillus intolérants qu'à des peuplements composés d'épinette noire et/ou de pin gris (Bergeron & Fenton 2012), dépendamment de l'intensité du feu et de la station. Dans le cas de la CPRS, bien que l'espacement des sentiers empruntés par la machinerie permettent généralement d'assurer la protection de la régénération résineuse présente entre ces ceux-ci, les espèces pionnières sont néanmoins favorisées dans les sentiers et les coefficients de distribution généraux suscitent des questionnements relatifs aux rendements futurs (Harvey & Brais 2002). La composition du sous-bois s'avère aussi différente selon le type de perturbation d'origine (Bergeron & Fenton 2012). En général, les modifications de composition combinées aux révolutions plus courtes peuvent empêcher le retour aux conditions prévalant avant la récolte (McRae et al. 2001). D'ailleurs, on ignore quels seront les effets à plus long terme, de la répétition du scénario de coupe totale sur une même surface dans la pessière. Les feux ont aussi un effet important sur le sol et le cycle des éléments nutritifs (McRae et al. 2001; Gauthier et al. 2008). En modifiant les lits de germination, les feux peuvent permettre d'éviter une accumulation de la matière organique susceptible de conduire à la paludification des sols, parfois observée sur certaines stations de la pessière à la suite de la coupe (Gauthier et al. 2008). Finalement, le réseau routier développé pour la récolte provoque une fragmentation à l'échelle du paysage et facilite l'accès par les humains (McRae et al. 2001).

Dans le cas de la sapinière, les feux surviennent moins souvent (Boucher et al. 2011) et le régime de perturbations naturelles est plutôt dominé par les épidémies de tordeuse de bourgeon de l'épinette (TBE) (Boucher & Grondin 2012). La CPRS est considérée comme une pratique sylvicole pouvant être assimilée aux effets d'épidémies de TBE sévères (Déry et al. 2000), mais la coupe ne génère pas nécessairement des peuplements étagés, ni l'abondance de chicots caractéristiques des stades post-tordeuse (Bergeron et al. 1999; Desponts et al. 2002; Côté et al. 2009). Étant donné que les épidémies surviennent à environ tous les 30 ans et qu'elles ne sont pas toujours sévères (Blais 1983; Simard 2003), elles sont souvent à l'origine de peuplements soumis à une dynamique de mortalité par trouées, conduisant au développement d'une structure irrégulière (Boucher & Grondin 2012). Il en résulte une mosaïque fine et hétérogène de peuplements de classes d'âge diverses (Leblanc & Bélanger 2000). Les coupes partielles représentent des moyens permettant d'assurer le maintien d'attributs de vieilles forêts tout en autorisant une certaine récolte (Thorpe & Thomas 2007). Ce type d'intervention convient aux forêts régies par une dynamique de peuplements par mortalité partielle ou par trouées (Raymond et al. 2000; Raymond et al. 2009), à l'instar des sapinières. Une proportion de coupes partielles serait également pertinente en pessière pour émuler le développement de peuplements multi-cohortes (Bergeron et al. 1999). Lorsque le prélèvement n'est pas trop élevé (<40-50% de la surface terrière), ce type d'intervention peut permettre de maintenir les conditions d'avant la récolte et d'assurer le recrutement de bois mort (Fenton et al. 2013). Toutefois, la réalisation de coupes partielles s'avère toujours limitée pour des raisons de rentabilité et de faisabilité opérationnelle (Fenton et al. 2013). Les niveaux de coupes partielles planifiés sont faibles (moins de 6% des coupes prévues dans les 3 UAF de la région de Chibougamau (BFEC)), ils ne sont pas toujours réalisés en entier, et les modalités prévues ne sont pas favorables à une accélération de la succession (prélèvement compris entre 40 et 50% et priorité de prélèvement accordée aux résineux). L'application de scénarios de coupes partielles requiert la disponibilité de routes permanentes, ce qui pérennise la fragmentation du paysage.

Les plantations représentent un outil sylvicole reconnu pour assurer un approvisionnement en matière ligneuse, grâce à un rendement élevé, considéré comme étant généralement supérieur à celui des forêts régénérées naturellement (BFEC 2013). Les rendements escomptés en forêt boréale comportent toutefois un niveau d'incertitude élevé, étant donné qu'aucune plantation n'a atteint la maturité à ce jour dans la pessière et que les mesures réalisées pour la validation des courbes de rendement comportent un certain biais étant donné qu'elles n'ont pas été distribuées aléatoirement mais plutôt localisées de manière à éviter les grandes trouées improductives et les secteurs dominés ou éventuellement dominés par la végétation concurrente (Prégent &

Végiard 2000). De façon générale, la plantation représente un scénario sylvicole causant davantage d'impacts négatifs sur une superficie donnée par rapport à une régénération naturelle obtenue par CPRS, en raison de l'effet cumulatif des différentes interventions (i.e. récolte, préparation de terrain, plantation, contrôle de la végétation compétitrice, éclaircies) (Ross-Davis & Frego 2002). Au Québec, les plantations suscitent des inquiétudes, notamment au regard de la structure des paysages, la composition végétale, la structure interne des peuplements, la résistance aux facteurs biotiques et abiotiques et la résilience des forêts, la qualité de l'eau et de l'habitat aquatique, ainsi que la fertilité et la productivité des stations (Groupe d'experts sur la sylviculture intensive de plantations 2013). Les plantations représentent généralement un habitat moins diversifié que la forêt naturelle en raison de leur structure équienne, de leur composition généralement monospécifique, impliquant parfois l'utilisation d'espèces exotiques, et de l'application de courtes révolutions (Carnus et al. 2006). Les plantations d'espèces exotiques sont particulièrement problématiques, les espèces utilisées n'étant pas adaptées aux conditions locales (p.ex. : mauvaise adaptation à la sécheresse, au gel, au sol, et/ou d'une faible résistance aux insectes et maladies). De plus, les espèces exotiques à croissance rapide peuvent présenter un risque de remplacer graduellement les espèces indigènes, à la faveur de leur potentiel naturel invasif (Carnus et al. 2006). À l'échelle du paysage, le niveau cumulatif de plantations peut présenter des risques de modification profonde de la structure, de la composition et des processus dynamiques auxquels les espèces locales ne sont pas adaptées (Carnus et al. 2006) et l'utilisation d'espèces exotiques peut conduire à la formation de type forestiers artificiels (Hartley 2002). Les perturbations associées à la préparation de terrain et aux traitements subséquents de contrôle de la végétation compétitrice sont susceptibles d'exacerber les écarts par rapport à la composition naturelle en empêchant les espèces indigènes de perdurer (Hartley 2002). Or, la quantité et les caractéristiques de la végétation de sous-bois ont une influence prépondérante sur la biodiversité à l'échelle du peuplement, puisque de nombreuses espèces se nourrissent du feuillage des plantes de sous-bois et que les arbustes fournissent couvert d'abri et sites de nidification pour plusieurs (Hayes et al. 2005). Toutefois, le contrôle de la végétation compétitrice par des moyens mécaniques, à l'instar de ce qui est pratiqué au Québec, fait en sorte que la diversité d'espèces végétales est similaire à celle observée en forêt naturelle (Jobidon et al. 2004). L'utilisation de courtes révolutions, la monoculture et le contrôle de la végétation concurrente réalisées dans le cadre de l'aménagement intensif réduisent l'hétérogénéité horizontale et verticale et limitent le recrutement de bois mort ce qui produit une simplification de la structure (Hayes et al. 2005), alors qu'une hétérogénéité importante fournit des ressources plus variées et une plus large gamme de niches disponibles ce qui favorise la biodiversité (Hayes et al. 2005). De plus, la sélection génétique opérée pour la production de plants utilisés en plantation peut altérer la diversité génétique (Carnus et al. 2006). Par contre, les plantations représentent aussi des solutions aux échecs de régénération résultant de perturbations en rafales (Girard et al. 2008), ou pour lutter contre la raréfaction des certaines espèces, à condition de tenir compte de leur statut (i.e. espèce dominante ou compagne) dans les forêts naturelles (Hartley 2002).

La protection représente une composante importante des stratégies d'aménagement forestier visant à prévenir ou limiter les pertes de biodiversité (Redford & Richter 1999; Paillet et al. 2010; Noss et al. 2012; Gray et al. 2016; Dudley et al. 2018). La biodiversité locale est généralement plus élevée dans les aires protégées qu'à l'extérieur de celles-ci, ce qui souligne leur importance pour la conservation des espèces (Gray et al. 2016). Toutefois, il n'existe pas de consensus sur la proportion de paysages naturels qui devrait faire l'objet de conservation (Brooks et al. 2006) et la question de savoir combien de conservation serait nécessaire représente un sujet de recherche et de débats (Tear et al. 2005; Wilhere 2008). Certains auteurs mentionnent un niveau de protection atteignant 60% serait nécessaire au maintien de la biodiversité en forêt boréale (Framstad et al. 2002 dans Michelsen (2008). Cependant, pour y parvenir avec un niveau moins élevé, les objectifs de maintien de la biodiversité devraient tenir compte des effets combinés de la protection stricte et de la foresterie durable (Michelsen 2008). Le niveau de protection permettant d'assurer la viabilité des assemblages d'espèces se situerait quant à lui, au-delà de 50% (Solomon et al. 2003). D'ailleurs, récemment, nombre de scientifiques spécialistes en conservation militent en faveur d'un niveau de protection cible de 50% (Noss et al. 2012; Dudley et al. 2018). En assumant que l'identification des aires à protéger fasse l'objet d'un plan de conservation qui prend en compte les aspects relatifs à la représentativité et la fragmentation, la superficie en protection devient alors un facteur clé (Michelsen et al. 2014). Dans ce contexte, il apparaissait intéressant de considérer les résultats d'une évaluation de la naturalité qui tiendrait compte du gradient de protection. L'évaluation de la naturalité présentée au chapitre 5, se penche sur l'effet du gradient de protection parallèlement à la distinction sur le plan sylvicole, entre la régénération naturelle obtenue par CPRS et la régénération par plantations d'espèces indigènes dégagées mécaniquement.

Concernant les effets de l'aménagement forestier sur la biodiversité, une méta-analyse réalisée à l'échelle paneuropéenne (Paillet et al. 2010), montre que la richesse en espèces est légèrement plus élevée dans les forêts non-aménagées par rapport aux forêts aménagées à travers l'Europe, mais les réponses à l'aménagement diffèrent entre les groupes d'espèces; les espèces dépendantes de la continuité du couvert forestier, du bois mort et des gros arbres (i. e. bryophytes, lichens, champignons, insectes saproxyliques et carabidés) étant affectées négativement par l'aménagement, contrairement aux plantes vasculaires qui sont plutôt favorisées (Paillet et al. 2010). D'ailleurs, la corrélation entre la diversité des plantes vasculaires et la diversité en espèces des autres groupes taxonomiques est généralement faible (Coelho & Michelsen 2014). Selon Paillet & Bergès (2010) : « la différence de richesse spécifique entre forêts exploitées et non exploitées s'accroît au profit des forêts non-exploitées le long d'un gradient de naturalité ». Ceci étant dit, un effort coordonné de suivi de la biodiversité serait nécessaire pour mieux caractériser les effets des différents types d'aménagement (Paillet et al. 2010). Les premiers effets d'une utilisation susceptible d'avoir des impacts négatifs à long terme, se traduisent par une augmentation à court terme de la richesse en espèces (Coelho & Michelsen 2014), comme l'indique les données de richesse en espèces de la base de données PREDICTS qui affichent une richesse en espèces plus élevée pour les forêts primaires utilisées et les forêts secondaires matures par rapport aux forêts primaires peu ou pas utilisées (Newbold et al. 2015). Cette situation résulte des actions qui favorisent les espèces végétales héliophiles (Boch et al. 2013), et n'est évidemment pas le reflet d'une réduction des impacts sur la qualité des écosystèmes. Cependant, les stades de développement plus jeunes afficheraient généralement une richesse en espèces moindre (Newbold et al. 2015). Si bien que, pour des productions s'étendant sur de longues périodes telle que le bois, les effets devraient être considérés sur l'ensemble du cycle de production (Lindqvist et al. 2016). Une démarche fondée sur l'écologie appliquée à un territoire faisant l'objet d'aménagement forestier englobera l'ensemble du cycle de production, tandis que les données de biodiversité doivent être associées aux différents stades de développement, puis faire l'objet d'une moyenne de façon à couvrir l'ensemble du cycle (Lindqvist et al. 2016). De plus, l'évaluation d'un scénario d'aménagement doit également tenir compte de la structure d'âge (i.e. distribution de la superficie occupée par classe d'âge) et la distribution résultante des différents stades de développement pour l'ensemble du territoire (Kuuluvainen 2009), découlant de l'application progressive du scénario réalisée dans le cadre d'une production soutenue. Cet aspect étant particulièrement important pour s'assurer de la présence de vieilles forêts qui présentent une biodiversité caractéristique (Kuuluvainen 2009) alors qu'elles sont généralement convoitées pour l'exploitation. Conséquemment, la richesse en espèces sur l'ensemble du territoire aménagé de manière soutenue permettrait d'éviter d'interpréter cette augmentation ponctuelle comme une amélioration de la situation. Ceci étant dit, il est toutefois reconnu que les effets de l'aménagement intensif de plantations sur la biodiversité se font surtout sentir au niveau des populations des espèces présentes, plutôt que sur la composition des communautés d'espèces présentes (i.e. le nombre d'espèces) (Hayes et al. 2005).

1.6 Modèles non-linéaires et effets de seuil

Étant donné la présence d'effets non-linéaires de type exponentiel ou logarithmique qui interviennent dans les différents modèles, il convient d'apporter quelques précisions concernant l'effet de seuil, afin d'alimenter la discussion. L'effet de seuil réfère à un effet observé sur une variable dépendante survenant uniquement à partir d'un moment où une variable associée atteint une valeur critique correspondant au seuil.

En écologie, un seuil écologique correspond à un niveau au-delà duquel on assiste à un changement brutal de régime au sein de l'écosystème conduisant à un nouvel état d'équilibre (Scheffer & Carpenter 2003). Ce changement relativement rapide d'une condition écologique à une autre survient à l'approche du seuil écologique, ou point de bascule, à partir duquel un petit changement dans un élément moteur du système produit une importante réponse (Huggett 2005; Groffman et al. 2006; Selkoe et al. 2015). Des seuils écologiques existent à tous les plans d'organisation (populations, espèces, écosystèmes, processus et fonctions et leurs interactions) (Selkoe et al. 2015). Le modèle conceptuel pour la prise en compte de seuils critiques en aménagement prévoit l'application du principe de précaution en fixant l'objectif d'aménagement au-dessus du niveau critique correspondant au seuil écologique; la différence entre les deux correspondant à une provision de précaution (precautionary buffer) (Figure 1.5) (Selkoe et al. 2015).

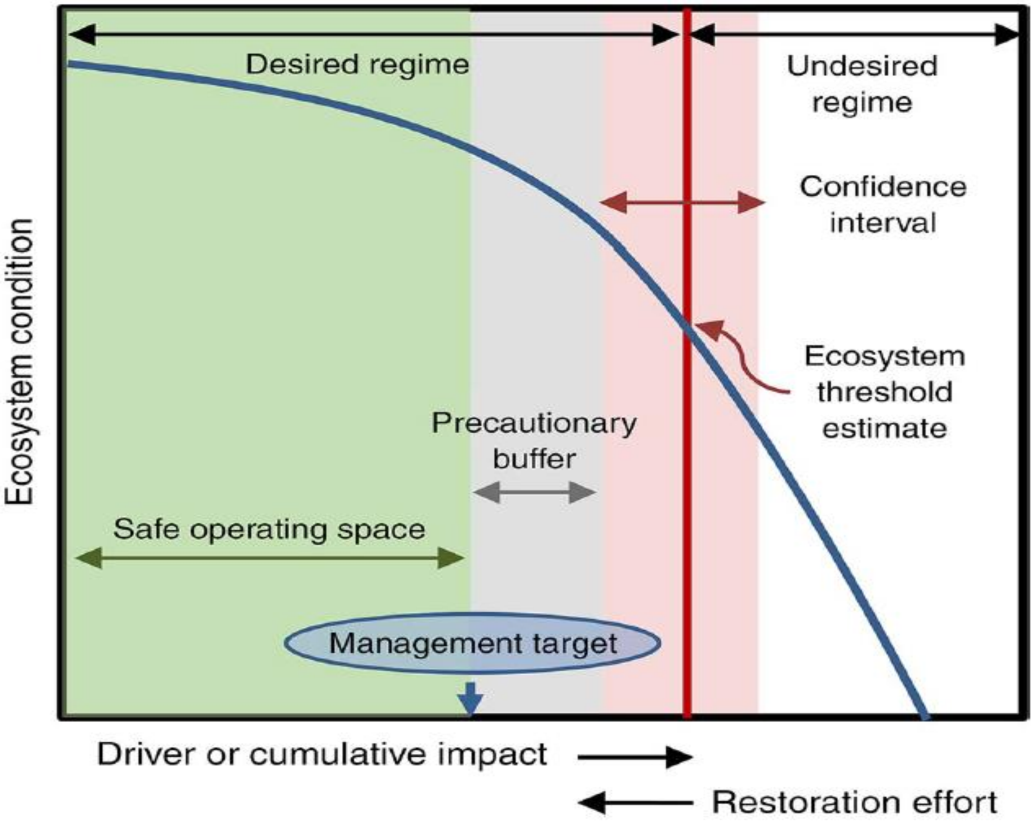


Figure 1.5 : Modèle conceptuel de la prise en compte d'un seuil critique pour déterminer le niveau correspondant à l'objectif d'aménagement (tiré de Selkoe et al. (2015)).

L'ACV n'est pas utilisée pour évaluer le changement d'état des écosystèmes ou de la biodiversité, mais plutôt l'impact environnemental relatif de systèmes de production anthropogéniques, en assumant une croissance linéaire par rapport à la quantité produite (Souza et al. 2015). Or, la biodiversité peut répondre de manière non linéaire à la pression exercée par l'utilisation des terres, ce qui soulève la question du seuil à partir duquel le système commence à répondre selon un patron non-linéaire (Koellner et al. 2013). Cette situation remet également en question la prémisse d'un accroissement linéaire des impacts écologiques avec les quantités produites, prémisse déjà remise en cause par Souza et al. (2015) qui s'interrogeaient sur le réalisme d'un cadre conceptuel procédant à une linéarisation des processus écosystémiques. Selon Souza et al. (2015), le modèle de calcul d'impact utilisé en ACV ne reflète pas l'effet cumulatif des pratiques sur les écosystèmes, alors que si l'utilisation des terres s'étend sur une longue durée et de grandes superficies, les impacts pourraient franchir un seuil écologique conduisant à un changement d'état de l'écosystème impliquant un impact permanent (différence entre Q_{his} et Q_{pnv} dans la Figure 1.4) plus important (Souza et al. 2015). De plus, considérant le délai de réponse et le fait que la destruction actuelle d'habitats peut être à l'origine d'une extinction d'espèces survenant plusieurs générations après la fragmentation de l'habitat (phénomène appelé « extinction debt » en anglais (Tilman et al. 1994)), l'évaluation de l'impact potentiel basée sur des données actuelles de biodiversité peut susciter des interrogations. L'ACV calcule des impacts potentiels; il ne s'agit pas de fournir une description fidèle de la dynamique de la biodiversité sur le terrain, comme le donnerait des données empiriques de suivi temporel. Étant donné le fort niveau d'imprécision, il apparaît extrêmement hasardeux de prédire une perte potentielle d'espèces. Selon Souza et al. (2015), il conviendrait plutôt d'identifier une mesure précise qui fasse consensus.

Il s'avère par ailleurs que les différents modèles proposés pour la prise en compte de la biodiversité dans les ACV ne sont généralement pas linéaires. À titre indicatif, Farmery et al. (2017) pour leur étude en milieu marin, mentionnent qu'il existe plusieurs options pour la distribution des intervalles entre chaque classe de naturalité : linéaire, exponentielle ou encore sigmoïde. Lindqvist et al. (2016) calculent le potentiel de biodiversité à l'aide d'une fonction exponentielle pour chaque paramètre, puis en font la moyenne arithmétique. Rossi et al. (2018) ont utilisé différentes courbes associant le niveau d'altération au potentiel de biodiversité pour chacun des paramètres, toutes non linéaires et plus ou moins exponentielles, puis ont calculé un indice global en multipliant les quatre cotes évaluées. Turner et al. (2019) ont effectué une pondération non-linéaire de leurs résultats. Enfin, la SAR reliant le nombre d'espèces à la superficie occupée par un type d'utilisation des terres, correspond à une relation de type $S = cA^z$ où « S » correspond au nombre d'espèces, « A » à la superficie occupée, et « c » et « z » correspondent à des paramètres dont la détermination est à préciser pour chaque contexte à l'étude. Par exemple, Schryver et al. (2010) mentionnent que « c » correspond au facteur de richesse en espèces et « z » au facteur d'accumulation d'espèces; Chaudhary et al. (2015) considèrent que « c » correspond à un paramètre dépendant du groupe taxonomique et de la région considérée et que « z » réfère au régime et à l'échelle d'échantillonnage; Teixeira (2014) précise que le « z » est conventionnellement interprété comme étant la pente de la SAR et correspond à une constante variant entre 0.1 et 0.35 dépendamment du taxon, de l'échelle et du type d'utilisation des terres. Le PDF est proportionnel à la fraction de superficie affectée à un type d'utilisation donné à la puissance « z ».

Chapitre 2. Objectifs

2.1 Problématique

Malgré la multitude de méthodes proposées au cours des 20 dernières années pour mesurer l'impact sur la qualité des écosystèmes dans les ACV (Winter et al. 2017), les évaluation d'impacts (EICV) de produits ou procédés n'intègrent que rarement l'évaluation des impacts sur la biodiversité (Maier et al. 2019). Cette situation n'est probablement pas étrangère au fait que les résultats d'ACV présentés ne conduisent pas toujours à des conclusions cohérentes avec les connaissances en matière de biodiversité et d'aménagement forestier (Turner et al. 2019; Gaudreault et al. 2020), pour ce qui concerne le matériau bois. Or, l'application du modèle ACV, qui se veut une simplification par rapport à un modèle plus complexe qui refléterait exactement la dynamique de la biodiversité, devrait conduire au même classement relatif des produits et processus (Teixeira 2014) et ainsi fournir des résultats de modélisation qui seraient en harmonie avec les décisions politiques et les plans stratégiques existants, tel que désiré par les utilisateurs (Teixeira et al. 2016).

2.2 Objectifs

L'objectif général de la recherche consiste à caractériser les impacts sur la qualité des écosystèmes de l'utilisation des terres associée aux pratiques d'aménagement forestier en forêt boréale, qui représente 36% du territoire québécois (MRNF 2008), et à explorer les aspects méthodologiques qui permettraient de tenir compte de l'intensité d'aménagement (et du degré d'artificialisation) dans les analyses de cycle de vie (ACV). De façon plus spécifique, la recherche vise à : 1) développer un système d'évaluation basé sur le concept de naturalité qui permette une appréciation adéquate, nuancée et bidirectionnelle (i.e. qui peut évaluer aussi bien la dégradation que l'amélioration) des impacts des systèmes forestiers et des diverses pratiques de la foresterie sur la qualité des écosystèmes en forêt boréale et tester ce système dans la pessière à mousses (MFFP 2020), 2) adapter le système d'évaluation à la sapinière à bouleau blanc (MFFP 2020) et tester la capacité du système à procéder à des évaluations bidirectionnelles, ainsi qu'à 3) présenter un exemple d'intégration du système d'évaluation de la naturalité qui tient compte de diverses stratégies d'aménagement combinant scénarios sylvicoles et gradient du niveau de protection, pour le calcul d'un score d'impact destiné à l'ACV pour le bois d'œuvre résineux (et, par extension, tous ses autres usages). Pour répondre aux différents objectifs, diverses applications du système d'évaluation de la naturalité ont été développées : naturalité actuelle et sa projection dans le temps (chapitre 3), naturalité de scénarios d'aménagement avec accent sur la sylviculture (chapitre 4) et naturalité de scénarios d'aménagement avec accent sur la protection dans la perspective d'aider à déterminer des objectifs de protection (chapitre 5).

2.3 Articulation méthodologique des trois articles de la thèse

La démarche empruntée dans le cadre de cette thèse est illustrée à la Figure 2.1. Le modèle conceptuel élaboré pour l'évaluation de la naturalité dans la forêt boréale, développé dans le premier article présenté au chapitre 3, considère cinq caractéristiques de naturalité des forêts : le contexte à l'échelle du paysage, la composition forestière, la structure, le bois mort et le processus de régénération. Les trois premières caractéristiques sont évaluées sur la base d'indicateurs de condition, affectés de divers types de pression résultant de l'aménagement, alors que les deux derniers sont évalués sur la base de la pression exercée par les pratiques d'aménagement appliquées. La description détaillée des indicateurs et mesures est fournie à l'appendice 3 du chapitre 3. Le territoire utilisé pour l'élaboration et l'application du modèle d'évaluation de la naturalité présenté au chapitre 3 appartient au sous-domaine bioclimatique de la pessière à mousses de l'ouest (MFFP 2020). L'application s'est d'abord concentrée sur l'évaluation de la naturalité actuelle. Puis, la réflexion a fait ressortir l'importance du facteur temps et la nécessité de projeter l'évolution de la naturalité dans le temps, tout en considérant différents scénarios sylvicoles pour la production de bois et en vérifiant l'effet de la protection. De plus, des scénarios hypothétiques ont été élaborés afin d'observer le comportement du modèle dans la portion très altérée. L'application présentée au deuxième article, faisant l'objet du chapitre 4, comporte l'adaptation du modèle d'évaluation de la naturalité au contexte de la sapinière à bouleau blanc de l'est (MFFP 2020) et propose une méthode pour l'évaluation de scénarios d'aménagement combinant protection et sylviculture. L'exercice réalisé a permis d'examiner l'aptitude du modèle d'évaluation de la naturalité à classer différents scénarios d'aménagement selon un gradient d'altération unique, en considérant un mélange diversement dosé de trois scénarios sylvicoles (régénération par coupe avec protection de la régénération et des sols, régénération par plantation d'espèces indigènes dégagées mécaniquement et régénération par coupe progressive à couvert permanent) et deux niveaux de protection, puis de vérifier comment le système peut être utilisé pour une évaluation bi-directionnelle permettant non seulement d'estimer la détérioration, mais aussi l'amélioration de la qualité des écosystèmes associée à l'application de stratégies de restauration ou de mesures de mitigation. L'application du modèle présentée dans le troisième article, faisant l'objet du chapitre 5, examine l'effet du gradient de proportion de territoire mis en protection, conjugué à l'application de trois scénarios sylvicoles distincts (régénération par coupe avec protection de la régénération et des sols (CPRS), régénération par plantation d'espèces indigènes dégagées mécaniquement, et un mélange comportant 60% de CPRS et 40% de plantation) dans la pessière à mousses de l'ouest, dans la perspective d'explorer les besoins en protection dépendamment de l'intensité de l'aménagement forestier associée à la sylviculture pour la production de bois, en se basant sur la naturalité. Ce chapitre présente également l'intégration au modèle d'ACV des résultats de l'évaluation de la naturalité associés à l'application de trois scénarios sylvicoles distincts en fonction d'un gradient de protection, afin d'observer le comportement du modèle ACV et de vérifier la pertinence de son utilisation dans une perspective d'aide à la prise de décision relative à l'intensité de l'utilisation des terres associé au scénario d'aménagement forestier. Pour l'ACV, l'impact sur la qualité des écosystèmes se mesure en perte potentielle d'espèces (PDF). Une courbe provisoire reliant la naturalité au PDF a été élaborée. Le score d'impact ACV a ensuite été calculé en multipliant le PDF par la superficie requise pour produire 1 m^3 de bois.

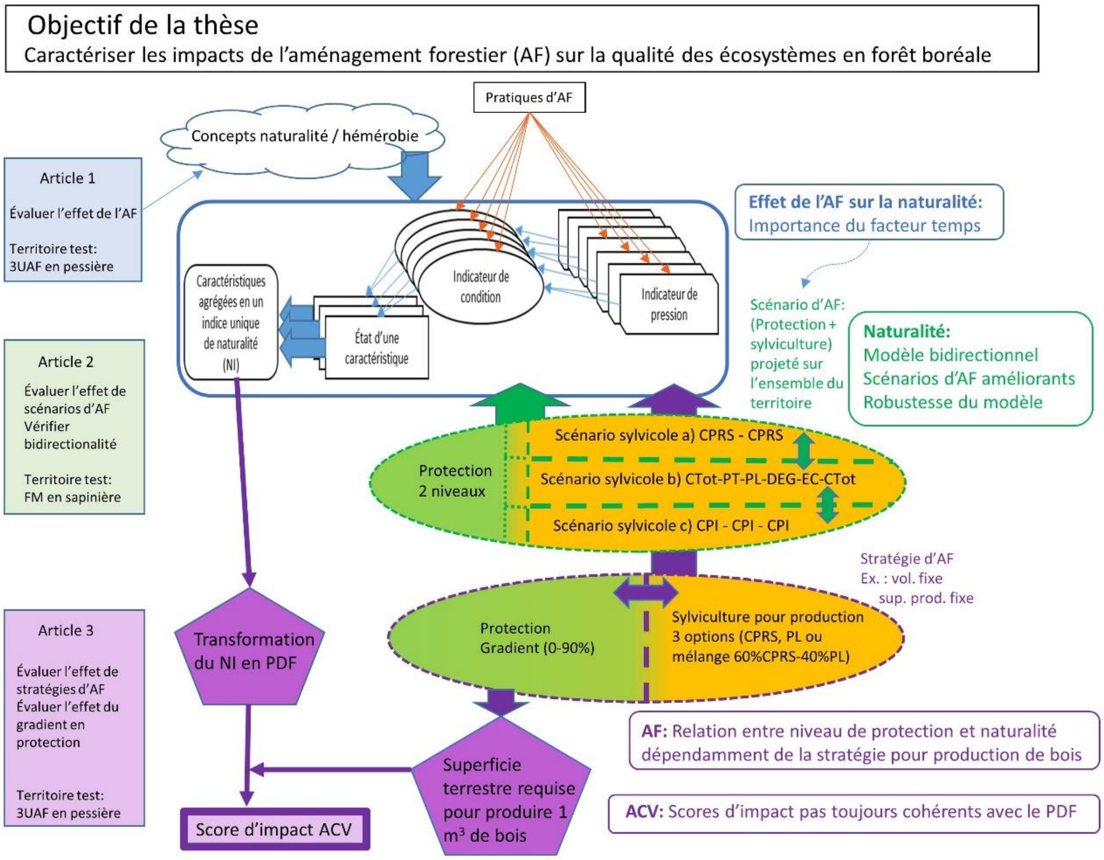


Figure 2.1 : Démarche méthodologique de la thèse. AF. Aménagement forestier; UAF : Unité d'aménagement forestier; CPRS : coupe avec protection de la régénération et des sols; CTot : Coupe totale; PT : préparation de terrain; PL plantation; DEG : dégagement mécanique; EC : éclaircie commerciale; CPI : coupe progressive irrégulière; PDF : fraction d'espèces potentiellement disparues; ACV : analyse du cycle de vie.

Chapitre 3. A Conceptual Model for Forest Naturalness Assessment and Application in Quebec’s Boreal Forest

3.1 Résumé

Ce volet présente le modèle conceptuel sous-jacent à l’élaboration d’un modèle d’évaluation de l’impact de la foresterie sur la qualité des écosystèmes. Basée sur le concept de naturalité, la méthode développée à partir des données d’un territoire de la pessière à mousses, considère cinq caractéristiques de naturalité (contexte à l’échelle du paysage, composition forestière, structure, bois mort, et processus de régénération) et repose sur les données et cartes écoforestières. Les résultats montrent qu’en 2012, le territoire d’étude affichait une naturalité quasi-naturelle (indice de naturalité NI = 0.717). Diverses stratégies d’aménagement simulées sur une période de 70 ans montrent que l’indice de naturalité pourrait diminuer de 1 ou 2 classes dépendamment de la stratégie appliquée pour régénérer ces forêts et que les réductions seraient plus importantes en l’absence d’aires protégées. L’indice de naturalité permet de combiner les effets de diverses stratégies et pratiques d’aménagement forestier selon un gradient d’altération unique.

3.2 Abstract

Research Highlights: To inform eco-designers in green building conception, we propose a conceptual model for the assessment of the impact of using wood on the quality of ecosystems. ***Background and Objectives:*** The proposed model allows the assessment of the quality of ecosystems at the landscape level based on the condition of the forest and the proportion of different practices to characterize precisely the forest management strategy. The evaluation provides a numerical index, which corresponds to a suitable format to inform decision-making support tools, such as life cycle analysis. ***Materials and Methods:*** Based on the concept of naturalness, the methodology considers five naturalness characteristics (landscape context, forest composition, structure, dead wood, and regeneration process) and relies on forest inventory maps and data. An area within the boreal black spruce-feathermoss ecological domain of Quebec (Canada) was used as a case study for the development of the methodology, designed to be easily exportable. ***Results:*** In 2012, the test area had a near-natural class (naturalness index NI = 0.717). Simulation of different management strategies over 70 years shows that, considering 17.9% of strict protected areas, the naturalness index would have lost one to two classes of naturalness (out of five classes), depending on the strategy applied for the regeneration ($0.206 \leq \Delta NI \leq 0.413$). Without the preservation of the protected areas, the management strategies would have further reduced the naturalness ($0.274 \leq \Delta NI \leq 0.492$). Apart from exotic species plantation, the most sensitive variables are the percentage of area in irregular, old, and closed forests at time zero and the percentage of area in closed forests, late successional species groups, and modified wetlands after 70 years. ***Conclusions:*** Despite the necessity of

further model and parameter validation, the use of the index makes it possible to combine the effects of different forestry management strategies and practices into one alteration gradient.

Keywords: Naturalness; forest management intensity; land use intensity; quality of ecosystems; boreal forest

3.3 Introduction

Quantitative tools to discriminate between different wood supplies depending on forest management and wood procurement practices are needed to inform architects and designers planning the eco-design of buildings. Using the science of applied ecology, such tools should make it possible to evaluate and compare the impact of different forestry strategies and the combination of practices on the quality of forest ecosystems.

This study aims to develop a methodology to characterize the potential impacts on ecosystem quality of different forestry management practices, in the perspective of describing the intensity of land use as driven by forestry. The methodology is based on the naturalness concept and relies on forest inventory maps and data. Our methodology allows the evaluation of combinations of practices and provides one numerical index, a suitable format for further use in decision-making support tools for eco-design and green building conception, such as life cycle analysis (LCA) (Jolliet et al. 2010). An area within the boreal black spruce ecological domain of Quebec (Canada) was used as a case study for the development of the methodology.

The specific objectives of the study are to:

1) Develop a naturalness evaluation model using the example of the boreal black spruce-feathermoss ecological bioclimatic domain of Quebec (Canada).

2) Apply the model over time on three forest management units (3 FMU) to analyze the variability of the naturalness evaluation associated with changes in forest management strategies and practices.

3) Perform a sensitivity analysis of the model to (hypothetical) high pressure levels and to identify the most sensitive variables.

The need for evaluating the quality of ecosystems in relation with their anthropic uses presents many challenges. As land use, and particularly land use change, is one of the main drivers of biodiversity loss (MEA 2005), there is a desire to express its impact on the quality of ecosystems in terms of biodiversity damage in LCA (Curran et al. 2016; Life cycle initiative 2016). The latest proposed LCA approach uses potential species loss from land use as an indicator; for forestry, it considers two land use intensities (intensive and extensive) (Life cycle initiative 2016). This proposal raises two issues: Biodiversity data and indicators' availability, and land use intensity evaluation. Concerning biodiversity, potential species loss is still proposed as the biodiversity indicator even if it does not reflect the multidimensional character of biodiversity and might lead to inappropriate conclusions (Gaudreault et al. 2016). As stated by Souza et al. (2015), the biodiversity models proposed up to now do not grasp the full reach of the phenomena involved, such as functional effects and impacts on populations. Furthermore, there are data gaps in biodiversity: Biodiversity data are often fragmentary (they do not include all taxa) and of varying quality (all biomes are not evenly studied, especially the boreal biome for which data are particularly scarce). For instance, boreal forests are underrepresented in global biodiversity databases (see GLOBIO ; PREDICTS). Concerning the intensity, forest management strategies generally include a mix of practices that have different impacts on the ecosystem, and the intensity is related to the recurrence of treatments over the same area planned in the silvicultural scenario. Because of these issues, we propose an alternative approach to evaluate ecosystem quality related to forest management, one that focuses on habitat characteristics and the concept of naturalness.

Many authors have proposed to use the concepts of naturalness and hemeroby in impact evaluation of land use (such as forestry) on the quality of ecosystems in LCA (Brentrup et al. 2002; Michelsen 2008; Fehrenbach et al. 2015; Farmery et al. 2017; Rossi et al. 2018). Naturalness is defined as "***the similarity of a current ecosystem state to its natural state***" (Winter 2012), whereas hemeroby expresses "***distance to nature***" in landscape ecology (Fehrenbach et al. 2015). The use of these concepts can provide a management guide that overcomes the challenge of data gaps in biodiversity. Even if the concepts of naturalness and hemeroby are closely related, one is not the exact inverse of the other. There is also divergence concerning the highest degree of alteration that should be included (Winter 2012). To clarify, we associate the naturalness concept with forest ecosystems, as shown in Figure 3.1; its lower class, i.e., the most altered state, corresponds to artificial forests (Angermeier 2000; Barrette et al. 2014) created by humans and showing deep modifications to the ecosystem and its species composition (Barrette et al. 2014). On the other hand, in the hemeroby scale, the alteration gradient is further developed and extended to sealed soils, and constructed, degraded, or devastated areas (Fehrenbach et al. 2015), with some authors even distinguishing dumpsites and partially built areas from sealed soils (Brentrup et al. 2002). As stated by Winter (2012), "***greater naturalness is characterized by a large number of adapted, specialized and often endangered plant and animal species***". Thus, in order to prevent or limit forest biodiversity loss due to forestry, the emphasis should be put on maintaining or restoring a high degree of naturalness. The concept of naturalness is well adapted to evaluate forestry management practices, but its application to evaluate the full alteration range of different land uses beyond forestry will require further work for proper insertion in the hemeroby concept that addresses a larger alteration gradient. Since the scope of this paper focuses on the impacts of forest management practices, the evaluation is restricted to the naturalness part of the alteration gradient.

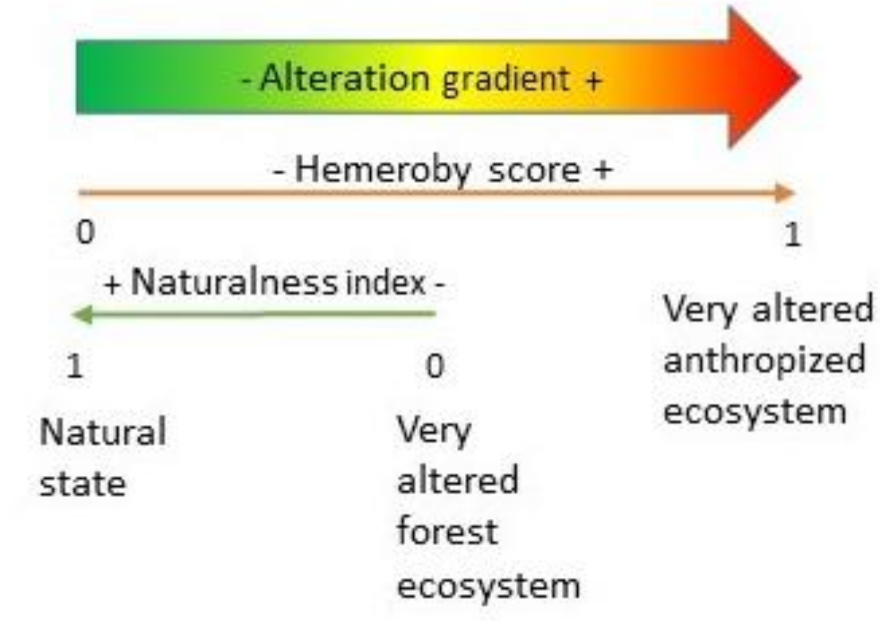


Figure 3.1 : Naturalness and hemeroby along the alteration gradient (adapted from Winter et al. (2010)).

The use of an index to evaluate the departure from the natural state along the alteration gradient avoids the problem of multiple classification of naturalness encountered in the literature (Machado 2004) and allows inclusion of realistic forest management strategies, which involve a mix of different practices. Naturalness evaluation based on habitat characteristics is possible with actual data, and the future evolution of characteristics can be predicted. However, impacts on biodiversity are more challenging to assess considering the need of biodiversity indicators that encompass multidimensional characteristics of the biodiversity concept (Gaudreault et al. 2016) and the uncertainty related to the timelag existing between habitat destruction and species extinction or extirpation (Angelstam et al. 2004).

Forest naturalness can be defined and evaluated using three interdependent approaches based on structure (i.e., spatial arrangement of the various components of the ecosystem (Angelstam et al. 2013)), composition, and processes (Brümelis et al. 2011). Generally, naturalness assessment results from the comparison between the actual condition and a reference state (McRoberts et al. 2012) using either historical inventory data, prior to commercial forest exploitation, or modelling studies of forest dynamics evaluating the range of natural variability (Landres et al. 1999). Where historic data are not available, the reference state, which corresponds to the most natural state, can be associated with a position along the alteration gradient (Winter et al. 2010). Many methods have been proposed to assess naturalness (Winter 2012), which is coherent with the fact that the choice of variables for naturalness studies must be adapted to regional conditions and knowledge (Winter et al. 2010).

The method developed here uses condition and pressure indicators. Indicators correspond to specific "elements of the forest system (e.g., species, processes and habitats) that correlate with many other unmeasured elements of the system" (Hagan & Whitman 2006). Condition or state indicators describe the current status or condition of a characteristic; pressure indicators represent the level of a pressure that affects the condition of a characteristic (i.e., an action that is causing the condition to degrade or improve) (Hagan & Whitman 2006). Thus, condition indicators are related to the concept of naturalness (i.e., the similarity of a current ecosystem state to its natural state), whereas pressure indicators are rather related to the hemeroby concept (i.e., distance to nature). However, pressure indicators can still be used to evaluate naturalness considering their effects on the condition of a characteristic.

We developed our conceptual model for naturalness assessment at the landscape level in a way that it could be easily adapted to other contexts and available data. Our method explores the application of non-linear relationships to integrate the notion of ecological thresholds in the naturalness assessment; habitat thresholds correspond to points or zones at which relatively rapid changes occur from one ecological condition to another (Huggett 2005). We also propose an original method for handling condition and pressure indicators in the index calculation.

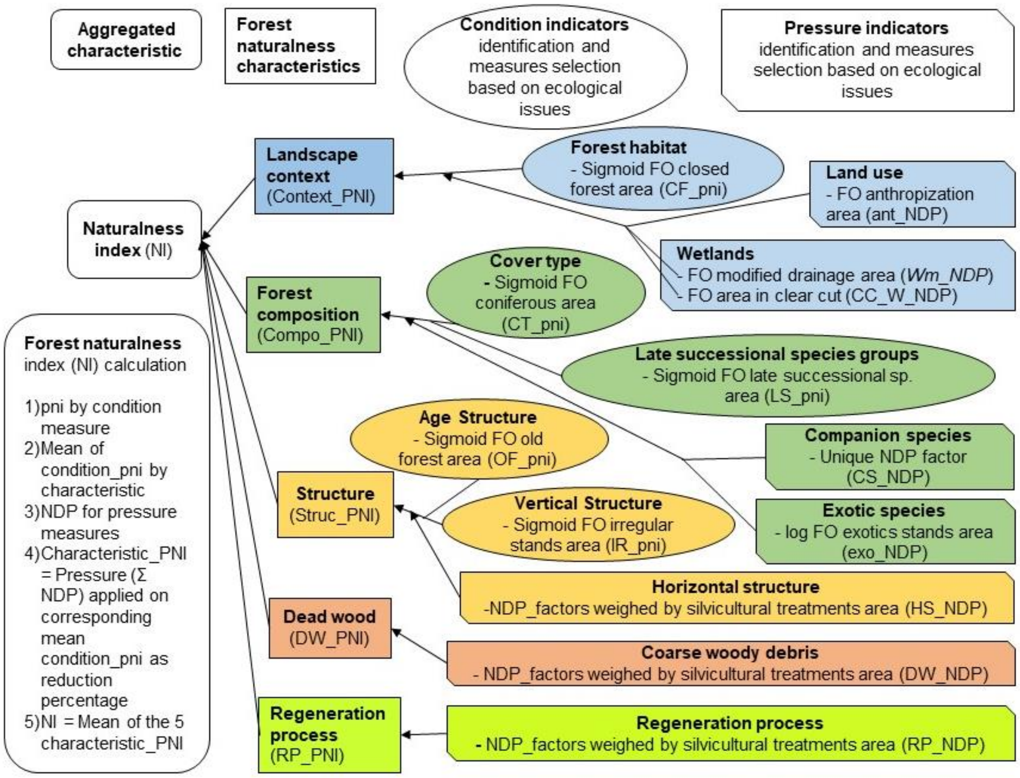
3.4 Materials and Methods

3.4.1 Conceptual Model

Designing a model to feed decision support systems relying on science-based evidence requires condensing and summarizing original information from studies and reviews in a form accessible to decision-makers (Dicks et al. 2014). This challenging exercise involves a choice of critical criteria relevant to the decision; in this case, assessing the impact of forest management practices on ecosystem quality.

The model we propose determines an aggregated naturalness index (NI) based on five forest naturalness characteristics: 1) Landscape context, 2) composition, 3) structure, 4) dead wood (DW), and 5) regeneration process (RP). The landscape context characteristic refers to forest habitat at the landscape level; composition corresponds to tree species composition; structure considers age structure as well as physical vertical and horizontal structure; dead wood focuses on coarse woody debris; finally, the regeneration process characteristic refers to the forest renewal mode (see Appendix 3.A for more details about indicators and measures for each characteristic).

The conceptual model developed for naturalness assessment in the black spruce and feathermoss domain of Quebec's boreal forest is presented in Figure 3.2.



Forest naturalness index (NI) calculation

1) pni by condition measure
2) Mean of condition_pni by characteristic
3) NDP for pressure measures
4) Characteristic_PNI = Pressure (Σ NDP) applied on corresponding mean condition_pni as reduction percentage
5) NI = Mean of the 5 characteristic_PNI

Figure 3.2 : A naturalness evaluation conceptual model for the black spruce and feathermoss boreal forest. PNI: Partial naturalness index for naturalness characteristic; pni: partial naturalness index for condition indicator; NDP: Naturalness degradation potential; FO: Function of.

For each naturalness characteristic, the selection of condition indicators was based on ecological issues relevant to this region (Jetté et al. 2013). Corresponding measures for each indicator (Table 3.1) were identified from available ecoforest maps and from relevant modelling studies.

Table 3.1: Naturalness characteristics, indicators and measures.

Naturalness Characteristic	**Condition Indicator(s)**	**Condition Measure(s)**	**Pressure Indicator(s)**	**Pressure Measure(s)**
Landscape context (Context_PNI [1])	Forest habitat (closed forest) (CF_pni)	% of terrestrial area of forest >40 years old (CF)	Land use (ant_NDP)	% of terrestrial area with anthropization (ant)
			Wetlands (Wm_NDP)	% of modified wetlands (Wm)
			(W_CC_NDP)	% of humid area in clear cut (W_CC)
Forest composition (Compo_PNI)	Cover type (CT_pni)	% of forest area with coniferous cover type (CT)	Companion species (CS_NDP)	Recognized companion species diminution (CS)
	Late successional species (LS_pni)	% of forest area in late successional species groups (LS)	Exotic species (exo_NDP)	% of forest area of exotic species stands (exo)
Structure (Struc_PNI)	Age structure (OF_pni)	% of forest area of old forests (>100 years old) (OF)	Horizontal structure (HS_NDP)	HS NDP_factor by silvicultural treatment weighed by % of forest area
	Vertical structure (IR_pni)	% of forest area of irregular forests (IR)		
Dead wood (DW_PNI)			Coarse woody debris (DW_NDP)	DW NDP_factor by silvicultural treatment weighed by % of forest area
Regeneration process (RP_PNI)			Regeneration process (RP_NDP)	RP NDP_factor by silvicultural treatment weighed by % of forest area

[1] PNI: Partial naturalness index for naturalness characteristic; pni: Partial naturalness index for condition indicator; NDP: Naturalness degradation potential.

First, the measures of condition are used to evaluate partial naturalness indexes (PNI/pni) using a sigmoidal curve (Figure 3.3a). Measures of pressure are then used to evaluate naturalness degradation potentials (NDP), using either linear or logarithmic curves (Figure 3.3b,c) or territory specific NDP factors related to practices weighed by the percentage of area as described in the section test area. Then, for each naturalness characteristic, i, the partial naturalness index ($\text{Characteristic\_PNI}_i$) is calculated as follows (see Table 3.2 for the calculation details of each characteristic):

$$\text{Characteristic\_PNI}_i = \left(\frac{1}{n}\sum_{j=1}^{n}\text{Condition\_pni}_j\right) \times \left(1 - \sum_{k=1}^{m}\text{NDP}_k\right) \quad (1)$$

where PNI/pni = partial naturalness index; NDP = naturalness degradation potential; n = number of condition indicators, j, for each characteristic, i (up to two); m: number of NDP, k, for each characteristic, i.

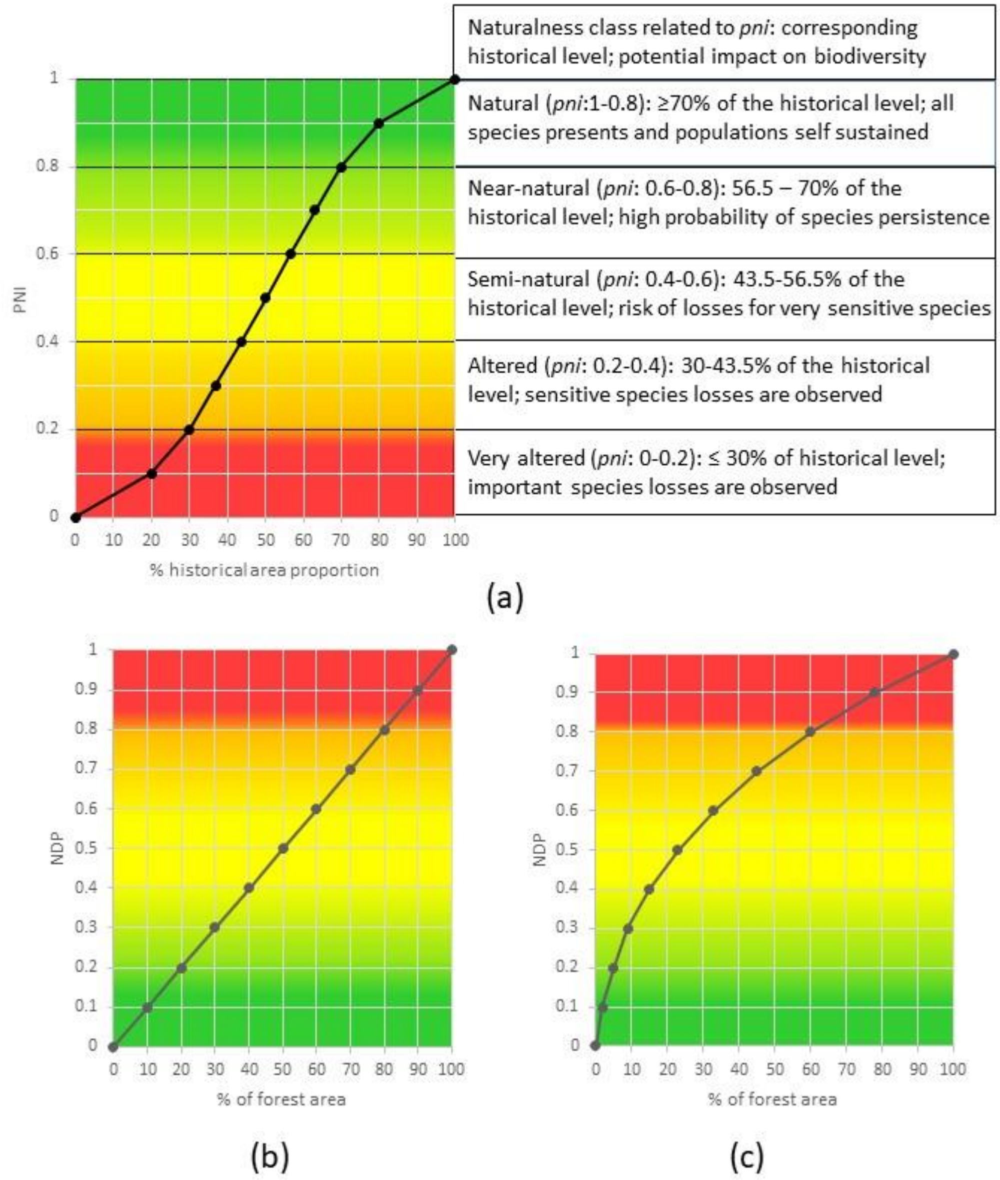


Figure 3.3: Generic curves used for modelling. (a) Sigmoid curve for the partial naturalness index of condition indicators. (b) Linear curve for naturalness degradation potential evaluation for pressure indicators proportional to the area. (c) Logarithmic curve for naturalness degradation potential evaluation for high potential impact pressure indicators.

Table 3.2: Characteristic_PNI equations for each naturalness characteristic.

Naturalness Characteristic	**Characteristic_PNI [1] Equation**
Landscape context	***Context_PNI = CF_pni × (1 − (ant_NDP + Wm_NDP + W_CC_NDP))***
Forest Composition	***Compo_PNI = ((CT_pni+LS_pni)/2) × (1 − (exo_NDP + CS_NDP))***
Structure	***Struc_PNI = ((OF_pni + IR_pni)/2) × (1 − HS_NDP)***
Dead wood	***DW_PNI = 1 − DW_NDP***
Regeneration process	***RP_PNI = 1 − RP_NDP***

[1] PNI/pni: partial naturalness index; NDP: naturalness degradation potential; see Table 3.1 for variables definitions.

The naturalness index and the partial naturalness indexes of both levels (characteristic and condition) range from 1 (natural) to 0 (very altered). To ease the interpretation and the discussion, we divided this range in five equal classes with an associated colour code: Natural (dark green): 1–0.8; near natural (light green): 0.799–0.6; semi-natural (yellow): 0.599–0.4; altered (orange): 0.399–0.2; very altered (red): 0.199–0 (see Figure 3.3a).

The evaluation of a condition indicator is based on a comparison with historical values. For each condition indicator, a partial naturalness index (condition_pni) is evaluated using a sigmoid curve relating the measure, corresponding to the actual proportion of the historical area percentage (or at a given time in the future, for forecasting scenarios) to the pni (Figure 3.3a). The sigmoid curve is considered a good representation of the type of relationship existing between the amount of habitat and species' response (Zuckerberg & Porter 2010) and reflects the presence of thresholds. In our approach, habitat thresholds were used to determine changes between naturalness classes in order to put in relation the degree of ecosystem alteration and its potential effect on biodiversity. Many authors reported an important reduction in biodiversity when the amount of habitat is below 30% of the historical level (Huggett 2005; Rompré et al. 2010; Estavillo et al. 2013); hence, the upper limit of the "very altered" class was set at 30% of the historical level. As naturalness classes correspond to equal divisions of the alteration gradient, the sigmoid curve was centered at 50% of the historical level. Therefore, on the opposite side of the gradient, the lower limit of the "natural" class was set at 70% of the historical level for each condition indicator; the lower and upper limits for the "semi-natural" class were therefore set at 43.5% and 56.5% of the historical level. This range corresponds roughly to the range of the mean thresholds (absence, colonization, extinction, and persistence) for the amount of habitat of 44% to 61% of historical levels observed for breeding birds by Zuckerberg & Porter (2010). The upper limit of the "altered" class is slightly above the threshold of 40% of the historical level values observed for the persistence of some specialized species (Rompré et al. 2010). Therefore, we can consider that the probability of persistence of a species is generally high in the "near-natural" class; it then declines in the "semi-natural" class as some very specialized species might be affected. Sensitive species will be lost in the "altered" class and many species will be lost in the "very altered" class (Figure 3.3a). PNIs and exo_NDP was evaluated by linear interpolation between curve points (see supplementary material Table S1: PNIs and exo_NDP determination).

Measures of pressures are used to evaluate a naturalness degradation potential (NDP) (Brentrup et al. 2002). In the model, the total naturalness degradation (ΣNDP) for each naturalness characteristic was applied as a relative reduction (expressed in the percent of naturalness degradation) of the corresponding mean of condition_pni (Formula 1). Higher values of NDP represent a higher potential of naturalness degradation, corresponding to the red class.

There are four possible approaches to determine an NDP. The first one considers a unique degradation factor for the whole area. The second considers that NDP is proportional to the area under pressure using a linear relationship (Figure 3.3b). The third approach relates to potentially high impact interventions, and considers that NDP is evaluated using a logarithmic curve (Figure 3.3c). A practice is considered to have a high potential impact when a small proportion of impacted area can have detrimental effects over a wider area. For example, if the proportion of exotic species stands reaches 60%, this corresponds to a very high potential of naturalness degradation resulting from the modification of the forest matrix. The fourth approach for NDP evaluation is used for variables that cannot be measured or derived from a forest cartography or inventory (i.e., horizontal structure (HS), dead wood (DW), and regeneration process (RP)). For each of these variables, the pressure level associated with silvicultural treatments was rated to reflect the effect of the disturbance intensity on the variable considered, using degradation factors based either on data (for dead wood) or on expert opinion. Expert opinion is often used in decision support systems applied to environmental management either to compensate for the lack of data or to interpret scientific results in order to provide guidelines based on science (Dicks et al. 2014). The evaluation of NDP factors related to the fourth evaluation approach (see examples in Tables 3.3, 3.4, and 3.5) could be further developed using participatory methods, such as the Delphi survey (Eycott et al. 2011), involving a team of professionals. For dead wood and regeneration process, to overcome the absence of condition measures, the NDP is applied on the value corresponding to the natural state (condition_pni = 1); therefore, in these cases: Characteristic_PNI = 1 − NDP.

Table 3.3: Naturalness degradation potentials (NDPs) for long lived companion species.

Long Lived Companion Species Status	**NDP_Factors**
Recognized species in diminution	0.2
Recognized extirpated species (theoretical)	0.6

Table 3.4: Naturalness degradation potential (NDP) for horizontal structure (HS) by silvicultural treatments in Quebec's boreal forest.

Practice	**NDP_Factors**	**% Forest_Area**	**NDPx**
Plantation—thinning	1	0.47%	0.0047
Plantation	0.9	4.62%	0.0416
Thinning (natural), strip cutting	0.8	0.46%	0.0037
Precommercial thinning (natural), release	0.75	1.68%	0.0126
Salvage logging	0.6	0.07%	0.0004
Careful logging (CL) and clear cut	0.35	13.93%	0.0488
CLASS, variable retention cut (2% vol)	0.3	0.00%	0.0000
Partial cutting	0.2	0.12%	0.0002
Undisturbed or natural disturbances	0	78.65%	0.0000
Actual HS_NDP			0.1120

Note: NDP_factors: naturalness degradation potential factors related to practices; % for_area: percentage of forested area (in 2012); NDPx: Portion of the naturalness degradation potential for the xth practice; CLASS: careful logging around small merchantable stems.

Table 3.5: Naturalness degradation potential (NDP) for dead wood (DW) by silvicultural treatments in Quebec's boreal forest.

Practice	**NDP_Factors**	**% Forest_Area**	**NDPx**
Biomass harvesting	1	0.00%	0.0000
Thinnings (in natural or plantation)	0.95	2.15%	0.0205
Plantation—no thinnings	0.85	4.62%	0.0392
Partial cut	0.75	0.58%	0.0044
Salvage logging	0.7	0.07%	0.0005
Careful logging (CL)	0.65	13.93%	0.0906
Variable retention cut (2% vol)	0.6	0.00%	0.0000
Undisturbed or natural disturbances	0	78.65%	0.0000
DW_NDP			0.1551
Actual ***DW_PNI***			0.8449

Note: NDP_factors: naturalness degradation potential factors related to practices; % for_area: percentage of forested area (in 2012); NDPx: Portion of the naturalness degradation potential for the xth practice.

The naturalness index (NI) calculation then results from the arithmetic mean of the five PNI by characteristic. For the assessment of a given forest management strategy, the calculation should cover a complete harvest cycle (i.e., forest rotation), simultaneously considering the effects over time of the harvest on condition indicators and of silvicultural treatments on pressure measures.

The generic procedure for naturalness assessment (and the corresponding files used for the 3 FMU) is as follows:

1. Define the territory for which the analysis will be performed and anticipate aggregation of results if the studied area covers multiple data sources.
2. Identify ecological issues for the studied area based on literature and/or stakeholder consultations.
3. Pinpoint potential measures available for reference and actual data of the condition and pressure based on literature, forest inventories, and maps.
4. For each naturalness characteristic, identify condition indicators and corresponding measures which can to be used to assess ecological issues.
5. For each condition indicator, find a reference value using either historical studies or old forest inventories and maps (for the 3 FMU: SIFORT1 maps (forest information system by tessellation) and Bouchard et al. (2015) for OF).
6. For each condition indicator, evaluate actual measures using the latest forest inventory map (for the 3 FMU: SIFORT4 maps).
7. For each condition indicator, set pni curves for the studied area (by changing the reference values for each condition indicator in Table S1) and enter the actual measure to calculate the corresponding pni (by changing the measured values for each condition indicator in Table S1).
8. For pressure measures, identify the appropriate approach for NDP evaluation related to each naturalness characteristic. Identify curves, set factors based on studies or expert opinion, and get the measures of the area by practice from forest inventory maps (for the 3 FMU: Ecoforest 4 maps, CS_NDP in Table 3.3, exo_NDP curve in Table S1, and NDP tables (factors and area) for HS, DW, and RP in Table S1).
9. Calculate the PNI for each naturalness characteristic using Equation (1) (for the 3 FMU: Formulas by characteristic are detailed in Table 3.2).

10. Calculate the NI, which corresponds to the arithmetic mean of the five characteristic_PNI.

3.4.2. Test Area

The proposed approach for naturalness assessment was applied to a public forest territory formed by three forest management units (FMU) located in the western black spruce feathermoss bioclimatic sub-domain, near the locality of Chibougamau in Northern Quebec region (Figure 3.4). These 3 FMU (no 2663, 2665, and 2666) cover a total area of 1,305,200 ha, which is larger than the home range of the boreal caribou, an umbrella species for the boreal forest (Bichet et al. 2016). Historical data were taken from the first Quebec forest inventory, corresponding to the 1965 to 1974 period, using Quebec's SIFORT system (tessellation of provincial forest inventory maps), from which the 6% of harvested areas and other anthropic disturbances were removed. Current data, corresponding to the 2011 to 2013 period, were taken from the fourth inventory program. The territory used for the analysis covers the whole area included in the perimeter of the FMU (without cutting tessell in SIFORT maps), including the surrounding strict protected areas (IUCN categories I to III) associated with these units. The percentage of forested area over the territory of analysis was calculated for measures of forest condition (CT, LS, OF, and IR) and the percentage of terrestrial area over the territory of analysis for context measures (CF, W_CC, Wm, ANT) was obtained from SIFORT maps (SIFORT1 for "reference" measures, except OF, and SIFORT4 for "actual" measures). Percentages of forested area by origin considering silvicultural treatments in the portion admissible for wood production necessary for weighing NDP_factors were measured with the ecoforest map, which provides polygonal data that are more precise. Each measure was then used to evaluate corresponding pnis or NDPs using curves and tables set for the territory.

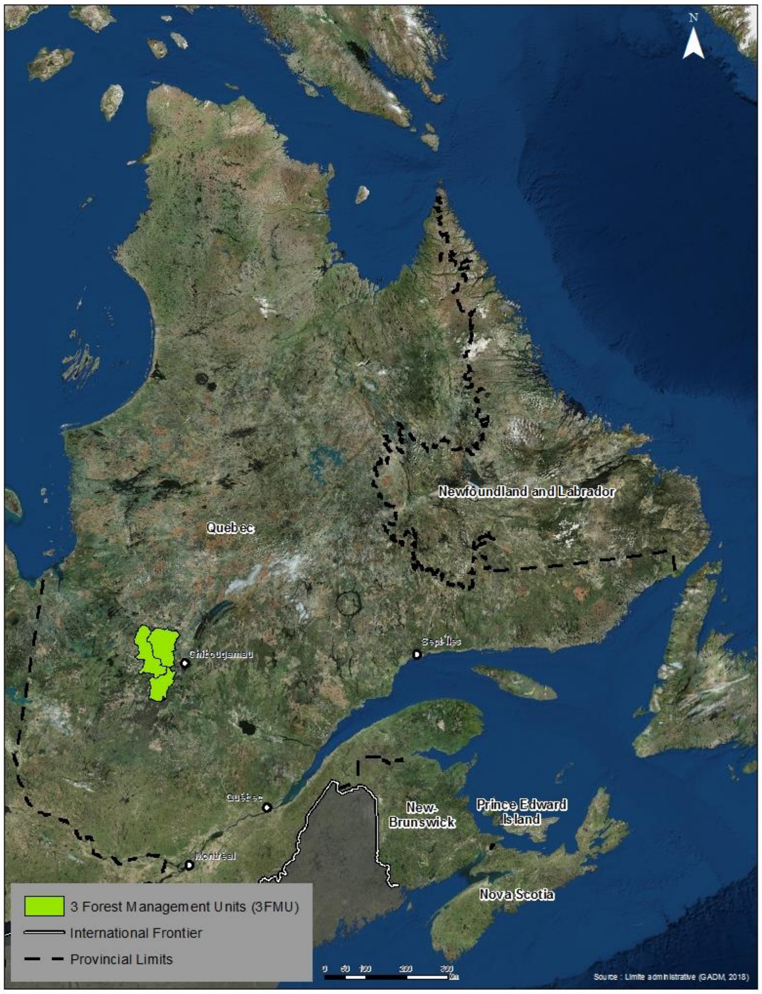
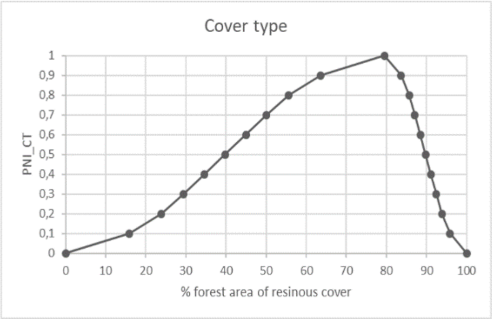


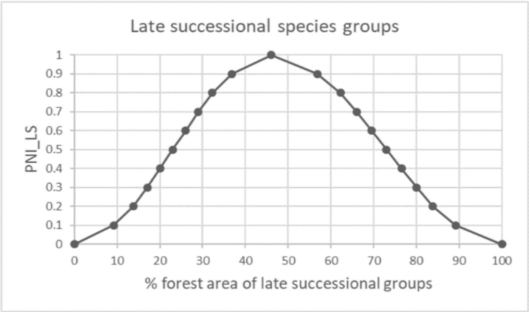
Figure 3.4: Test area localization.

The curves elaborated for pni and NDP evaluation specifically for the 3 FMU are presented in Figure 3.5 and the NDP factors used in Tables 3.3, 3.4, 3.5 and 3.6. Model adaptation to other territories will require calibration of the curves (Figure 3.5) using appropriate historical/reference values. In our study, all historical values were based on forest inventory data, except for the proportion of forest land covered by old forests (>100 years old), which was based on the modelling study of (Bouchard et al. 2015). For landscape context evaluation, the NDP related to clearcut on wetlands was arbitrarily set at 50% of the percentage of wetland area affected by clearcut, as this disturbance was considered less damaging than the drainage of wetlands (NDP_W_CC = 50% × % of wetland area with clearcut). To allow for proper evaluation of extreme scenarios, a two-sided curve was developed for cover type and late successional species groups in order to consider the loss of dominant characteristics on one side, and loss of secondary characteristics on the other. As the reduction of long-lived companion species cannot be measured precisely using inventory data, a reduction factor of 0.2, corresponding to a decrease of one naturalness class, was applied as NDP when diminution was recognized by forest managers; a factor of 0.6 was also tested to evaluate the effect of an hypothetical species extirpation. Improvement of that measure might be possible in the future with more detailed forest composition characterisation performed in more recent forest inventories in Quebec. As dead wood data are not currently available from Quebec's forest inventory, the evaluation was derived from pressure measures resulting from silvicultural treatments, by applying NDP factors weighed by the proportion of forest area by treatments. These factors were estimated based on dead wood data for coarse woody debris measured after a range of silvicultural treatments (careful clearcut logging, plantation, precommercial thinning, biomass harvesting) compared with naturally disturbed forests at the Montmorency Research Forest (Thiffault et al. 2014; Senez-Gagnon et al. 2018).



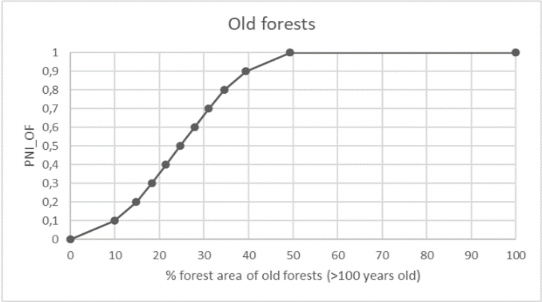
Historical proportion: 79.5% of coniferous cover
Actual proportion: 72.7%
CT_pni = 0.957

(**a**)



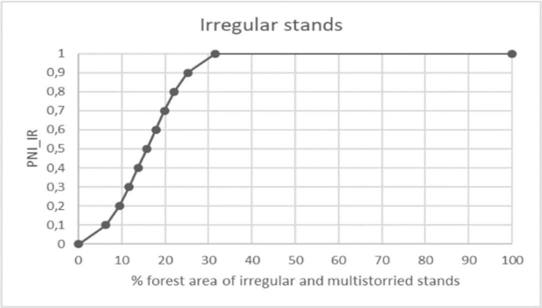
Historical proportion: 46.0% of late successional
Actual proportion: 41.0%
LS_pni = 0.946

(**b**)



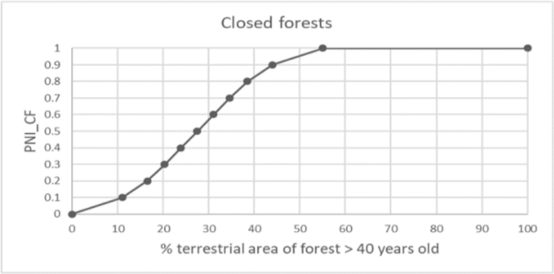
Historical proportion: 49.3% of old forests
Actual proportion: 21.5%
CF_pni = 0.402

(**c**)



Historical proportion: 31.5% of irregular stands
Actual proportion: 7.0%
IR_pni = 0.121

(**d**)



Historical proportion: 55.5% of closed forests
Actual proportion: 46.1%
CF_pni = 0.919

(**e**)

Figure 3.5: Pni determination curves used for condition indicators' evaluation for three forest management units (3FMU) in the boreal black spruce-feathermoss bioclimatic domain: (a) Coniferous cover type; (b) late successional species groups; (c) old forests; (d) irregular stands; (e) closed forests.

Table 3.6: Naturalness degradation potential (NDP) for regeneration process (RP) by silvicultural treatments in Quebec's boreal forest.

Practice	NDP_Factors	% Forest_Area	NDPx
Exotic plantations, afforestation	1	0.00%	0.0000
Plantation	0.9	5.08%	0.0458
Seeding	0.7	0.25%	0.0017
In-fill planting	0.6	0.50%	0.0030
Salvage logging	0.55	0.07%	0.0004
Clearcut and final cut	0.5	9.86%	0.0493
Commercial thinning (natural)	0.45	0.02%	0.0001
Careful logging (CL)	0.4	5.10%	0.0204
Partial cut	0.3	0.56%	0.0017
Undisturbed or natural disturbances	0	78.55%	0.0000
RP_NDP			0.1224
Actual ***RP_PNI***			0.8776

Note: NDP_factors: naturalness degradation potential factors related to practices; %for_area: percentage of forested area (in 2012); NDPx: Portion of the naturalness degradation potential for the xth practice.

3.4.3. Description of Tests

Data from 2012 were used to assess the actual naturalness of the 3 FMU. Two series of tests were then performed: 1) Scenario tests on the 3 FMU over time, using three base management scenarios to analyse the sensitivity of the evaluation system to changes in forest management strategies and practices; and 2) hypothetical tests to verify the sensitivity of the model to high pressure levels.

Base management scenarios were: 1) Regeneration through careful clearcut logging on 100% of the harvested area (CL); 2) regeneration through careful clearcut logging on 50% of the harvested area, combined with plantation with thinning on the remaining 50% (CL-PL); and 3) regeneration through plantation on 100% of the harvested area (PL). Careful clearcut logging corresponds to the cut with regeneration and soil protection (CPRS) required by law for clearcut operations in Quebec (Harvey & Brais 2002). For each scenario, the possibility of biomass harvest (bh) over the whole harvested area was also considered (Thiffault et al. 2014). For the plantation, indigenous (PL) or exotic species (PLexo), with a rotation of 70 years for the entire planted portion, were tested. Within the 3 FMU, 17.9% of the forested area have a "strict protected area" status. In order to evaluate its effect on naturalness, the same set of scenarios was applied on the 3 FMU hypothesizing the absence of protected areas. In that case, 95.7% of the forest area would be available for harvest compared to a proportion of 77.8% for the scenario with protected areas. The hypothesis used for the evaluation of naturalness over time for the 3MU are listed in Appendix 3.B. The spreadsheets used for simulation of the 3 FMU through time are provided as supplementary materials (Table S2: Area by age class evolution by a 10 year period and Table S3: Composition and irregular evaluation over time) and the procedure for evaluation over time is detailed in Appendix 3.C.

A sensitivity analysis was performed on the 3 FMU CL-PL scenarios (including protected areas), in order to identify the most sensitive variables of the model at time 0, 30, and 70 (corresponding to actual, mid-rotation, and end-rotation): A variation of ±5% was tested independently for each input variable (percentage of area or NPD factor for CS). Scenario results used for this test have been adjusted for exotics, anthropized, and modified wetlands by setting these reference values at 5% to test the influence of a ±5% variation.

Other analyses were carried out to verify the impact of specific assumptions. The effect of the hypothesis used for forest composition after careful logging or plantation was estimated by replacing the COMPO_PNI value at T_{70} by the actual value (COMPO_PNI at T_0). A fire cycle of 245 years was used for natural disturbance inclusion in the aging simulation, based on a study located East of the study area (Boucher et al. 2017b). To verify the effect of that factor on the proportions of closed and old forests, the naturalness at T_{70} was evaluated by setting the fire cycle at 150 years, i.e., the average value for the Western Black spruce-feathermoss domain (Boucher et al. 2011).

An exploratory analysis was also performed to check the model's behaviour after the first rotation. The model was applied for the PL, CL-PL, and CL scenarios with and without strict protected areas beyond the first rotation, up to T_{150}, keeping the same hypothesis for composition after CL and PL (as the composition after the second cutting cycle is still not known for these forests).

For the hypothetical extreme tests, eight scenarios were considered (Table 3.7) with an increasing percentage of exotic species from 0% to 100% of the forest area (0%, 7%, 15%, 30%, 50%, 80%, and 100%). For example, scenario 1 considers 80% of plantation (PL) and 20% of careful logging (CL) along with the use of herbicide in plantations, leading to a coniferous cover of 85% and a proportion of late successional species groups equal to 85% (minus the percentage of exotic species), with a maximal LS value set to 30%. Scenario 2 is similar to scenario 1, but without drainage of wetlands. The hypotheses used for extremes scenarios are listed in Appendix 3.D.

Table 3.7: Extreme scenarios' descriptions.

Practice or Variable [1]	**Sce1**	**Sce2**	**Sce3**	**Sce4**	**Sce5**	**Sce6**	**Sce7**	**Sce8**
Scenario	**80PL**	**80PL-0DR**	**80PL-0DR-noBH**	**10PC**	**10PC-0DR-noBH**	**100Herb.**	**0Herb.**	**100PL**
%PL	80	80	80	80	80	80	80	100
%CL	20	20	20	10	10	20	20	0
%PC	0	0	0	10	10	0	0	0
Herb.	In PL	In PL	In PL	In PL	In PL	All	No	All
%DR	50	0	0	50	0	50	50	50
%CT	85	85	85	85	85	100	60	100
%LS	85-PLexo; ≤30	id	Id	id	id	85-PLexo; ≤50	15	100-PLexo; ≤30
CS	R	R	R	R	R	R	R	D
%OF	0	0	0	15	15	0	0	0
%IR	0	0	0	10	10	0	0	0
BH	Y	Y	N	Y	N	Y	Y	Y

[1] Sce1: Scenario #1 and so on; PL: plantation; CL: careful logging; PC: partial cutting; DR: drained; CT coniferous cover type; LS: late successional species groups; CS: long lived companion species; R: rarefied; D: disappeared; OF: old forests; IR: irregular stands; BH: biomass harvest; PLexo: plantation of exotic species; Herb.: use of herbicides; id: idem as preceding.

3.5. Results

Model results for the 3 FMU give a naturalness index (NI) of 0.717 for the year 2012, which corresponds to the near-natural class (Table 3.8). This naturalness level is explained by the logging of 22.3% of the area, and the rarefaction of some long-lived companion species. The main alteration is related to structure, resulting from the reduction of irregular stands (from 31.5% in the 1970s to less than 7% in 2012) and the loss of old forests (from 49.3% to 21.5% during the same period) relative to the historical state. Detailed results are provided as supplementary materials: Table S3 for 3FMU scenarios with protected areas; Table S4 for 3FMU scenarios without protected areas; Table S5 for extremes scenarios.

Table 3.8: Actual (2012) results for the three forest management units.

Characteristic	PNI	Naturalness Class
Landscape context	0.870	Natural
Composition	0.761	Near-natural
Structure	0.232	Altered
Dead wood	0.845	Natural
Regeneration process	0.877	Natural
Naturalness index (NI)	0.717	Near-natural

3.5.1. Naturalness of Forest Management Scenarios Over Time

3.5.1.1. Naturalness Evolution of the Test Area

Results of the naturalness assessment of the 3 FMU over time are given in Table 3.9 and illustrated in Figure 3.6.

Table 3.9: Results of the 3 FMU scenarios over time.

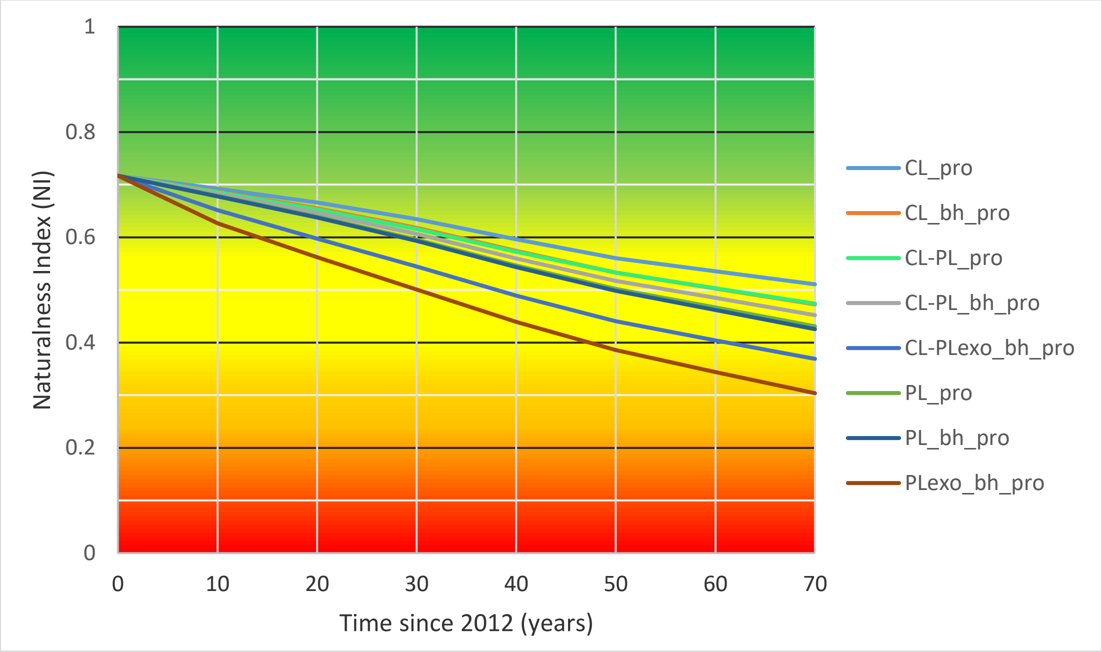
Scenarios [1] with 17.9% protected areas

Time since 2012	% logged pro	CL pro	CL-PL pro	PL pro	CL_bh pro	CL-PL_bh pro	PL_bh pro	CL-PLexo_bh pro	PLexo_bh pro
0	22.31	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717
10	30.09	0.692	0.685	0.679	0.678	0.682	0.687	0.651	0.626
20	37.86	0.666	0.653	0.639	0.638	0.647	0.655	0.598	0.562
30	45.64	0.634	0.616	0.596	0.593	0.606	0.618	0.545	0.501
40	53.42	0.596	0.573	0.546	0.543	0.560	0.574	0.489	0.439
50	61.11	0.560	0.533	0.502	0.498	0.517	0.533	0.441	0.386
60	68.97	0.535	0.503	0.467	0.462	0.485	0.503	0.404	0.344
70	76.75	0.511	0.474	0.431	0.426	0.452	0.473	0.369	0.304

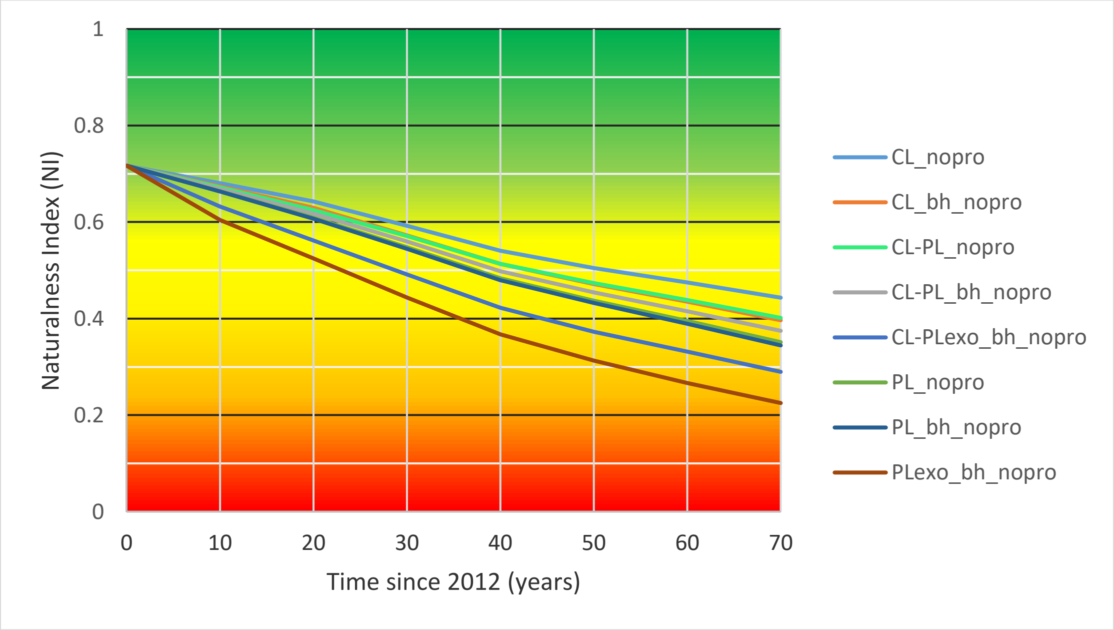
Scenarios without protected areas

Time since 2012	% logged nopro	CL nopro	CL-PL nopro	PL nopro	CL_bh nopro	CL-PL_bh nopro	PL_bh nopro	CL-PLexo_bh nopro	PLexo_bh nopro
0	22.31	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717
10	31.88	0.680	0.672	0.664	0.663	0.668	0.674	0.632	0.604
20	41.44	0.643	0.625	0.609	0.607	0.617	0.629	0.562	0.524
30	51.01	0.593	0.571	0.548	0.545	0.560	0.573	0.491	0.444
40	60.57	0.540	0.514	0.483	0.479	0.498	0.514	0.422	0.368
50	70.14	0.505	0.473	0.437	0.432	0.454	0.471	0.373	0.313
60	79.71	0.475	0.438	0.395	0.389	0.415	0.435	0.332	0.267
70	89.27	0.443	0.402	0.351	0.344	0.375	0.397	0.290	0.225

[1] % logged: cumulative % of forest area regenerated through cutting; CL: 100% Careful logging; CL-PL: 50% careful logging with 50% plantation; PL: 100% plantation; PLexo: plantation of exotic species; bh: biomass harvest; pro: with 17.9% in protected areas; nopro: without protected areas.



(**a**)



(**b**)

Figure 3.6: Results for the 3 FMU over time: (a) With protected areas; (b) without protected areas. Scenario description: CL: 100% careful logging, CL-PL: 50% careful logging and 50% plantation of indigenous species, CL-PLexo: 50% careful logging and 50% plantation of exotic species, PL: 100% plantation of indigenous species, PLexo: 100% plantation of exotic species, bh: with biomass harvest, pro: with strict protected areas, nopro: without strict protected areas.

Practicing careful logging only (CL) for the next 70 years on the 3 FMU, taking into account 17.9% of protected areas, would lead to a loss of one naturalness class relative to the current state. With 50% of careful logging and 50% of plantation of indigenous species (CL-PL), which corresponds roughly to the scenario currently applied, the study area would become semi-natural around 2045 and remain in this class for the rest of the period, while it would be from 2040 with 100% plantation of indigenous species (PL) (Figure 3.6a). In general, for a given ratio of protected areas, the naturalness declines with the proportion of plantation, and more sharply if exotic species are used. After 70 years (which roughly approaches the time required to complete the first cutting cycle), all scenarios that include protected areas would lead the studied 3 FMU to be classified as semi-natural except for those using exotic species, which would lead to an altered state. However, without protected areas (Figure 3.6b), only two scenarios would lead to a semi-natural class: CL or CL-PL, all the others would be in the altered class ($0.4 > NI > 0.2$), and the scenario considering 100% of plantation in exotic species over 70 years would be close to the very altered class. After 70 years, the scenario without protected areas corresponds to a rejuvenation of almost 90% of the territory.

After the first cutting cycle, the age structure of the forest would be closer to normalization in the harvested area (i.e., each age class would be more evenly represented among forest stands), and the pressures would cover the whole production area, so the naturalness would stop its decline. Therefore, if ratios per practice and pressures are maintained, and assuming that stand composition following the harvest of the secondary forest would remain unchanged, values for naturalness would tend to stabilize (NI_{150}, given on an indicative basis in Tables S3 and S4: with protection: PL = 0.381, CL-PL = 0.444, CL = 0.495; without protection: PL = 0.282, CL-PL = 0.351, CL = 0.406).

With the hypothesis used, forest rejuvenation through 100% careful logging (CL) produces a reduction of the naturalness index over time that is less important (ΔNI_{70}: pro = –0.206; nopro = –0.274) than regeneration through plantation with indigenous species only (PL) (ΔNI_{70}: pro = –0.286; nopro = –0.366). Use of exotic species combined with biomass harvest (PLexo_bh) (ΔNI_{70}: pro = –0.413; nopro = –0.492) would produce around twice as much alteration as natural regeneration through logging itself.

Among the tests performed, it is the application of a forest management regime over the first cutting cycle that has the most important effect on the naturalness index (mean ΔNI_{70}: pro = –0.287; nopro = –0.364). Compared with natural regeneration through CL, the regeneration mode has an important effect when exotic species are used (ΔNI_{70}: pro = –0.207; nopro = –0.218), but a lesser impact when indigenous species are planted over the whole area (ΔNI_{70}: PLpro = –0.08; PLnopro = –0.092; CL-PLpro = –0.037; CL-PLnopro = –0.042). Protection of 17.9% of the forest area has a noticeable effect in limiting the loss of naturalness in the 3FMU (mean ΔNI_{70} = 0.077).

Biomass harvesting would cause a reduction of the naturalness index of 0.038 and 0.047 after 70 years (Table 3.9) for the 100% careful logging scenarios with and without protected areas, respectively. This practice has a lesser effect in scenarios with higher levels of plantation: The NI reduction would be 0.005 and 0.007 for the 100% plantation scenario (Table 3.9) with and without protected areas, respectively, since it is assumed that site preparation prior to plantation would impact the dead wood. With the hypothesis used, the biomass harvest over the entire area would have as much impact on the naturalness as planting indigenous species over 50% of the harvested area. A better evaluation of the effect of the biomass harvest should include small woody debris for DW_NDP factors' evaluation.

When comparing scenarios with and without 17.9% of strict protected areas (Table 3.9), after 70 years from 2012, the model determines that the CL-PL scenario with protected areas leads to a higher level of naturalness than the scenario with 100% CL without protected areas (NI_{70}: 0.474 vs 0.443). The same observation is applied for 100% plantation (PL) with protected areas, which performs better than the CL-PL scenario without protected areas (NI_{70}: 0.431 vs 0.402). CL only without protection performs slightly better than PL only with protected areas (NI_{70}: 0.443 vs 0.431). The CL-PLexo (plantation of exotic species over 50%) with biomass harvest and protected areas has a higher naturalness than PL of indigenous species over 100% without biomass harvest, but no protected areas (NI_{70}: 0.369 vs 0.351). It is important to underline the fact that with protected areas, after 70 years, 77% of the forest area will have been rejuvenated after harvesting, as opposed to 89% for the scenario without protected areas. With protected areas, after 70 years of regeneration through CL, a reduction corresponding to one naturalness class is observed (NI_0 = 0.717; NI_{70} CL = 0.511 for a NI loss of 0.206). With plantation of exotic species and biomass harvest, the difference represents more than two classes (NI_0 = 0.717; NI_{70} PLexo_bh = 0.304 for an NI loss of 0.413 over 70 years). Without strict protected areas, losses are more important as a larger area is available for cutting.

3.5.1.2. Sensitive Variables and Exploratory Analysis

The results of the sensitivity analysis performed on the 3FMU for the scenario, CL-PL, with strict protected areas for current, 30 year, and 70 year periods are provided in Figure 3.7. Due to the use of non-linear models, a uniform variation of input parameters (5%) can have a non-linear effect on the results, depending on the curve slope around the parameter value. Therefore, the sensitivity of results can also vary over time (Figure 3.7). Results proved to be most sensitive to the proportion of forest area covered by exotic species. However, exotic species have never been used in the area under study. Beside the exotics, the most sensitive variables are the percentage of area in irregular (IR), old (OF), and closed forests (CF) at T_0; percentage of area in closed (CF), old (OF), and irregular (IR) forests at T_{30}; and percentage of area of closed forests (CF), late successional species groups (LS), and modified wetlands (Wm) at T_{70}.

As LS is among the most sensitive variables after 70 years, the hypothesis applied for composition after CL or PL might have an important impact on the resulting naturalness index. Assuming no effect on composition (by replacing the COMPO_PNI estimated with the actual value), the NI_{70} would be higher (ΔNI_{70}: PLpro: 0.037; PLnopro: 0.046; CL-PLpro: 0.040 CL-PLnopro: 0.051; CLpro: 0.05; CLnopro: 0.064), in the same range as planting indigenous species over 50% of the harvested area. Therefore, a better assessment of forest composition through time as influenced by silvicultural treatments would be important to improve the reliability of results.

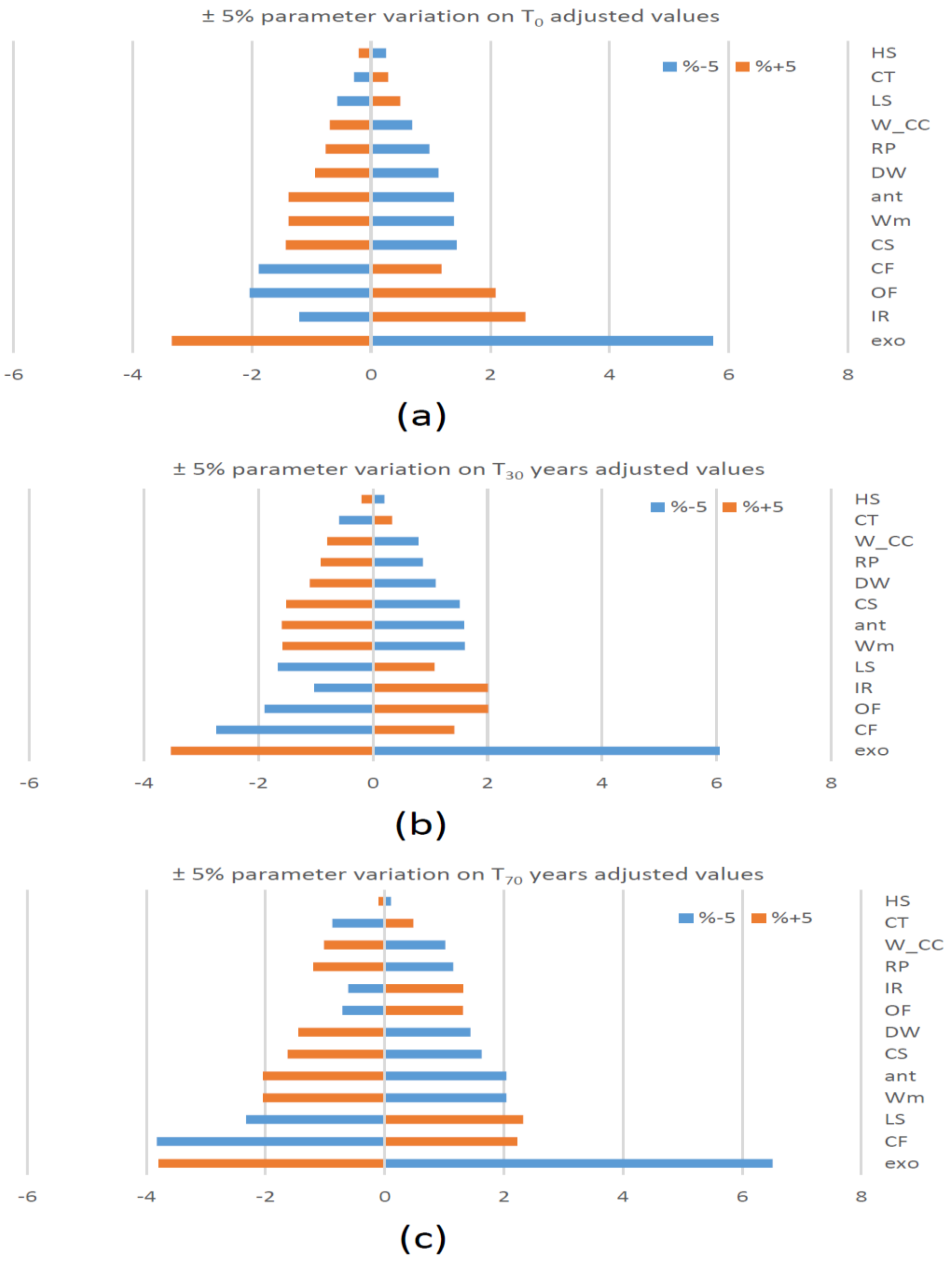


Figure 3.7: Results of the sensitivity analysis[1] testing a variation of 5% of the adjusted parameter value: (a) Adjusted values at T0; (b) adjusted values at T30; (c) adjusted values at T70; HS: Horizontal structure, CT: coniferous cover type, LS: late successional species groups, W_CC: clear cut on wetland, RP: regeneration process, DW: dead wood, ant: anthropized land; WM: modified wetland, CS: companion species, CF: closed forest, OF: old forest, IR: irregular stands, exo: exotic species.

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[1] The x axis corresponds to the percentage of variation of the result value (NI)

Considering that a fire cycle of 150 instead of 245 years induces a reduction of the NI_{70} of 0.026 (±0.001) in the scenarios with protected areas and a reduction of 0.030 in the scenarios without protected areas, the model therefore seems relatively robust to the hypothesis used for the fire cycle.

The weight of 0.5 given to estimate the effect on the naturalness of clearcuts on wetlands has a very limited effect considering that clearcuts only affect 7.8% of the wetlands. Hypothesizing 100% instead of 50% would have reduced the resulting NI_{70} by 0.0059, which is marginal.

The results suggest that the model structure, which applies pressure as a reduction of the condition, produces a degradation of the naturalness over the first cutting cycle. The exploratory analysis reveals that beyond that point, results tend to stabilize (see results at T_{150} in Table 3.10): The strategy is applied over the whole managed territory and therefore the composition after regeneration treatment related to age (here younger and older than 20 years old) becomes constant. The age structure is gradually normalized over the managed area, but continues to evolve with stand aging in the excluded (protected) areas. Applying our hypothesis, we observe a slight reduction of the naturalness between T_{70} and T_{150} in all scenarios.

Table 3.10: Results of the 3 FMU scenarios at T150.

Protection	**CL**	**CL-PL**	**PL**	**CL_bh**	**CL-PL_bh**	**PL_bh**	**CL-PLexo_bh**	**PLexo_bh**
Pro	0.495	0.444	0.381	0.441	0.412	0.374	0.328	0.260
Nopro	0.406	0.351	0.282	0.339	0.313	0.272	0.231	0.164

CL: 100% Careful logging; CL-PL: 50% careful logging with 50% plantation; PL: 100% plantation; PLexo: plantation of exotic species; bh: biomass harvest; pro: with 17.9% in protected areas; nopro: without protected areas.

3.5.2. Naturalness of High Pressure Management Scenarios

Extreme scenarios lead to a naturalness index corresponding to altered and very altered classes (Table 3.11, Figure 3.8). Higher levels of alteration are associated with an important use of exotic species combined with the loss of companion species. Absence of drainage and, to a lesser extent, application of measures leading to the presence of old forests and irregular stands make it possible to sustain a higher level of naturalness. Scenarios including a homogenous coniferous cover type (scenarios 6 and 8) and a scenario corresponding to a degraded composition with low coniferous cover and late successional representation (scenario 7) lead to a very altered class even without using exotic species. For less extreme combinations, the naturalness class is altered if no exotic species are used, and very altered if a small proportion of exotics is present.

Table 3.11: Extreme scenarios' results. See also Table 3.7 for a detailed scenario description.

Variable [1]	**Sce1**	**Sce2**	**Sce3**	**Sce4**	**Sce5**	**Sce6**	**Sce7**	**Sce8**
%exotics	**80PL**	**80PL-0DR**	**80PL-0DR-noBH**	**10PC**	**10PC-0DR-noBH**	**100Herb.**	**0Herb.**	**100PL**
0	0.215	0.247	0.269	0,231	0.292	0.167	0.177	0.085
7	0.174	0.206	0.228	0,191	0.251	0.141	0.148	0.065
15	0.149	0.181	0.203	0.165	0.226	0.125	0.130	0.053
30	0.120	0.152	0.173	0.136	0.197	0.106	0.109	0.050
50	0.090	0.122	0.144	0.106	0.167	0.085	0.087	0.046
80	0.074	0.106	0.128	0.090	0.151	0.074	0.074	0.040
100								0.036

[1] SceX: Scenario number, PL: plantation; PC: partial cutting; DR: drained; BH: biomass harvest; Herb.: use of herbicides; Sce1: 80%PL 20%CL Herb. In PL 50%DR CT = 85% LS = (85% – PLexo) ≤ 30 CS = rarefied OF = 0% IR = 0% BH; Sce2: Sce1 without DR; Sce3: Sce1 without DR nor BH; Sce4: Sce1, but 10CL and 10PC so OF = 15% and IR = 10%; Sce5: Sce4 without DR nor BH; Sce6: Sce1, but 100%Herb so CT = 100% and LS = (85% – PLexo) ≤ 50; Sce7: Sce1 without Herb in PL so CT = 60% and LS = 15%; Sce8: 100%PL 100%Herb. 50%DR CT = 100% LS = (100% – PLexo) ≤ 30 CS = disappeared OF = 0% IR = 0% BH.

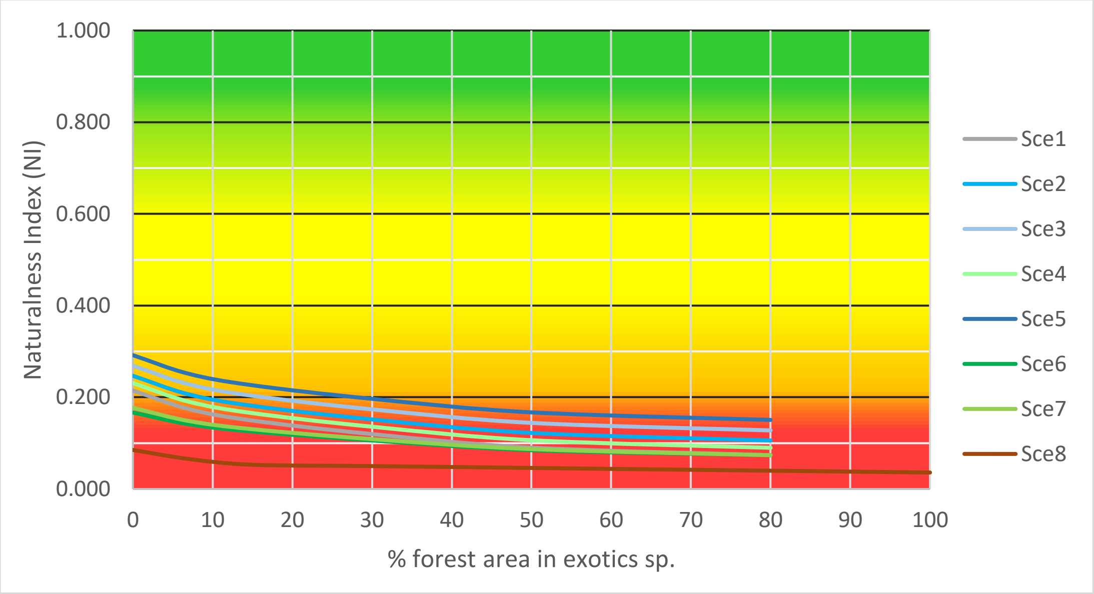

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Figure 3.8: Results for the eight extreme scenarios. See also Table 3.7 for detailed scenario descriptions. Sce1: 80%PL 20%CL Herb. In PL 50%DR CT = 85% LS = (85% − PLexo) ≤ 30 CS = rarefied OF = 0% IR = 0% BH; Sce2: Sce1 without DR; Sce3: Sce1 without DR nor BH; Sce4: Sce1, but 10CL and 10PC so OF = 15% and IR = 10%; Sce5: Sce4 without DR nor BH; Sce6: Sce1, but 100%Herb so CT = 100% and LS = (85% − PLexo) ≤ 50; Sce7: Sce1 without Herb in PL so CT = 60% and LS = 15%; Sce8: 100%PL 100%Herb. 50%DR CT = 100% LS = (100% − PLexo) ≤ 30 CS = disappeared OF = 0% IR = 0% BH.

3.6. Discussion

Decision support systems depend upon summaries and systematic reviews available at the time of their conception and are therefore subject to improvements as new information becomes accessible (Dicks et al. 2014). Nevertheless, the conceptual model developed in this study provides a basic frame for naturalness assessment, although indicators, measures, and curves might be revised when better information and data become available.

3.6.1. Conceptual Model

Evaluating the intensity of silvicultural management makes it possible to quantify land-use intensity in forests. Gossner et al. (2014) showed that biodiversity can be related with land use measures, such as naturalness based on trees species composition, dead wood, and other structural characteristics, or stand management intensity based on tree species, stand age, and aboveground living and dead woody biomass. Therefore, a methodology combining the condition evaluation of composition and structure, and pressure measures resulting from silvicultural practices represents a good proxy for the evaluation of the effects of forestry on biodiversity resulting from a combination of various practices. Further research is needed to verify to which extent the utilization of condition measures can detect improvements of naturalness resulting from restoration or enhanced ecological management strategies. The inclusion of pressure measures can adequately reflect the effects of mitigation measures, although the model should be further validated. Our results suggest that the presence of strict protected areas in a forest landscape compensates, to some extent, for the impacts of intensive management (Messier et al. 2009).

The model developed in this paper was shown to be sensitive enough to characterize the naturalness of different forestry management systems and therefore discriminate between different wood supplies from a variety of forest management practices. The results demonstrate that the proposed naturalness assessment model can be useful to evaluate the land use intensity of forestry practices at a finer level than existing approaches to inform decision-making in life cycle assessment. For instance, global guidance for life cycle impact assessments (Life cycle initiative 2016) currently considers only two levels of intensity for forestry: Intensive and extensive forestry. For their part, Chaudhary & Brooks (2018) proposed to divide secondary vegetation in four classes: Plantations, clearcut, selective logging, and reduced impact logging. In contrast, our approach makes it possible to take into account the condition of the forest as well as the proportion of different practices to more precisely characterize the forest management strategy and its impacts on ecosystem quality.

The application of pressure as a reduction of the condition contributes to an important reduction of the naturalness resulting from the progression of the first cutting cycle over the area. Such an important reduction of the quality observed as a result of the initial land use transformation process is coherent with the conceptual model proposed by LCA developers for ecosystem quality evolution related to land use (Milà i Canals et al. 2007). However, tests over time highlight some specificities of forestry land use reflected by the model. Contrary to most land uses, the first cutting cycle of a forest land corresponds to a progressive transformation from the natural state to a naturalness level related to the forest management strategy applied. In Quebec's boreal forests, this initial transformation may take up to 100 years. During the subsequent rotations, the naturalness index tends to stabilize as a result of the normalization of the forest, supposing that sustainable management is used. However, our model indicates a trend toward a slow erosion of the ecosystem quality over time during the sustainable production phase. If the land use ever stops and constraints are relaxed (although future land use changes are more likely to progress toward land uses of higher hemeroby), the naturalness should progressively improve as condition indicators will gradually recover with the aging of the forest. However, we do not know if condition indicators will ever come back to the natural state after relaxation. Nevertheless, some pressures will remain (ex: Drained wetlands or other anthropic features, like permanent roads, energy transportation lines, etc.), so theoretically the ecosystem should never recover completely.

Given the model's sensitivity to age related variables, a better integration of plantations would be necessary to improve the results. It would be interesting to explore the application of the naturalness assessment model using data from sustainable harvest calculation systems to reflect the effect of forest management strategy implementation considering simultaneously shorter rotation for plantations, application of the modelled composition and growth, simulation of harvest spatially applied to the admissible area, and a different handling method of natural disturbances (BFEC).

The natural assessment model developed in our study was designed to be easily adapted to other regions using the conceptual model. All five naturalness characteristics should be considered, indicators should be reviewed to include all regionally important ecological issues, and measures should be identified among available data. Curves for condition indicators would then have to be calibrated using the specific historical values of the studied region and NDP factors should be adjusted to reflect regional practices' effects.

Our model could also be integrated in LCA models and used to inform building and construction eco-designers beyond the outcomes of this specific case study. To do so, further work still needs to be done to generate regionalized results across Canadian FMUs and ecosystems. Depending on the availability of historical data, naturalness assessment could be performed for ecological domains or sub-domains (ex. Western black spruce feathermoss sub-domain); aggregated results could be calculated by region or country to allow for the assessment of harvested wood products in a broader context, where the exact provenance of the wood is not known.

3.6.2. Naturalness Assessment Application to the 3 FMU

The results of the case study inform us that wood coming from the 3 FMU has less negative impacts on the quality of ecosystems if the management strategy relies on natural regeneration through careful logging instead of plantation, especially if exotics are involved. It is still possible to limit the potential loss of specialized species resulting from sustainable forest management provided that the proportion of strict protected areas is sufficient to mitigate the degradation of the condition indicators.

The following observations raise questions that should be further addressed in LCA. The actual naturalness of the 3 FMU is near-natural as a result of a rejuvenation through the harvest of 22.3% of the forest area, including plantation of indigenous species over 5% of the forest area. The difference between management scenarios results from the cumulative effects of practices over time, mainly those inducing rejuvenation, the model being sensitive to age-related variables (OF and CF). Given that the naturalness index tends to stabilize after the completion of the first cutting cycle, the naturalness assessment of a forest management strategy requires an evaluation over the whole cutting cycle. This corresponds also to the potential impact of the forest regime. However, actual naturalness could be used if the objective is to characterize the naturalness of the forest from which the wood is currently procured. The actual naturalness is the result of the practices applied up to now. It does not necessarily correspond to the level resulting from sustainable management, which is more consistent with the evaluation over a whole cutting cycle. In a territory including forests that have never been harvested, such as the 3 FMU, actual naturalness gives an optimistic portrait and does not correspond to the potential impact of the present activities.

Some important limitations of the use of the model in Quebec's boreal forest need to be stressed. The model could not be used to evaluate the naturalness index in the test area beyond the first cutting cycle, as no data was available to describe the future evolution of the composition of secondary forests in that area. Pni and NDP evaluation curves and factors should be validated according to expert opinion.

The uncertainty of the results increases over time; the evolution of forest composition in older secondary forests (>40 years) in this ecological domain has yet to be verified. The future evolution of the natural disturbance regime under a changing climate is also unknown. Therefore, its effects on age structure are unknown as well as the proportion of future regeneration failures, which affects the closed forest coverage. Nevertheless, the importance of the proportion of old forests and irregular stands, and eventually closed forests, is coherent with present concerns related to age structure when attempting to apply ecosystem-based management (Jetté et al. 2013).

3.7. Conclusions

Despite the necessity of further model and parameter validation, the model developed in this paper makes it possible to assess along a single alteration gradient the impact on ecosystem quality of different forestry management systems, simultaneously considering the condition of the forest and the mix of forestry practices involved. Therefore, the model is sensitive enough to differentiate between forest management strategies. The capacity of the model to reach a very altered class was tested with hypothetical high pressure levels associated with the use of exotic species. Tests over time showed that the results are coherent with the conceptual model proposed by LCA developers for ecosystem quality evolution related to land use and highlight some specificities of the forest land use related to forestry. For instance, the initial land use transformation caused by forestry is gradual and the resulting level of naturalness depends upon the management strategy.

The results of this research work set the basis to inform building and construction designers on the potential impact on ecosystem alteration associated to harvested wood products at the landscape level as a function of forest management strategy, considering the condition of the forest and the nature of the adopted forestry practices. The naturalness index will have to be assessed at a regional level and scaled for the wood productivity and eventually aggregated at an upper geographical level in order to be used in life cycle impact assessment methodologies. Whether the naturalness index could be used as a mid-point indicator or is related to the damage category is still an open question and depends on biodiversity data that are available to generate the correlation.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/4/325/s1 , Table S1: Pni and exo_NDP determination, Table S2: Area by age class evolution by 10 years period, Table S3: Composition and irregular evaluation over time, Table S4: Detailed results over time for the 3FMU with protected areas, Table S5: Detailed results over time for the 3FMU without protected areas, Table S6: Detailed results for the hypothetical extreme scenarios, Data files: Maps: SIFORT1_3MU, SIFORT4_3MU and Ecoforest4_3MU.

Author Contributions: Conceptualization, S.C. and L.B.; methodology, S.C. and L.B.; validation, S.C.; formal analysis, S.C.; investigation, S.C.; resources, R.B.; data curation, S.C. and É.T. for dead wood.; writing—original draft preparation, S.C.; writing—review and editing, S.C., L.B., M.M., R.B. and É.T.; visualization, S.C.; supervision, R.B., L.B. and M.M.; project administration, R.B. and M.M.; funding acquisition, M.M.

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Appendix 3.A. Naturalness Characteristics, Indicators and Measures

The five naturalness characteristics selected for the naturalness assessment corresponds to 1) landscape context, 2) forest composition, 3) structure, 4) dead wood and 5) regeneration process. Grouping indicator evaluation under naturalness characteristics limit the number of indicators and can facilitate the adaptation of the method to other regions according to available measures and regional ecological issues. Tree species and forest structure are among the most studied traits of naturalness (Winter 2012). Compared with others naturalness assessments (Winter 2012), the naturalness characteristic "Landscape context" has been added to take into account the proportion of forest habitat at the landscape level. Dead wood was distinguished from the structure because forestry practices can have distinct or even opposite effects (ex: biomass harvest impact dead wood directly; partial cut can promote irregular structure but can reduce dead wood amount if harvest reduces mortality). Similarly, old forests and irregular stands are evaluated distinctly because stands over 90 years old are not necessarily irregular. Very old forests generally exhibit irregular vertical structure and important amount of dead wood, but this is not the case for 100 years old stands. The use of three different indicators for old forests (>100 years old), irregular stands and dead wood allows considering the effects of mitigation measures.

This section provides information about indicators and measures used for the naturalness assessment, and the calculation for each characteristic.

Appendix 3.A.1. Landscape Context

Landscape context refers to the amount of forest habitat at the landscape level. This characteristic considers closed forest (CF) habitat (density ≥ 25%) over 40 years old as a condition indicator (Table 3.1), measured using the percentage of terrestrial area of forest stands (Boucher et al. 2017b). This measure evaluates the extent of conditions suitable for forest dependent species, such as certain birds or litter invertebrates (Angelstam et al. 2004), or for species needing large undisturbed areas such as the woodland caribou (Environnement Canada 2011). The measure is sensitive to overabundance of young stands resulting from disturbances and/or regeneration failure following disturbance (Payette et al. 2000). Habitat loss has a greater effect on biodiversity than habitat fragmentation (Fahrig 1997) to some extent; the latter becomes more important when the amount of habitat represents a low proportion of the landscape, below a critical habitat threshold of 30% (Rompré et al. 2010), at which point many species are lost. Therefore, if the proportion of forested area is equal or below 30%, the inclusion of fragmentation in landscape context evaluation should be considered. However, the model should not be applied if the proportion of anthropized land reaches 70%: such a situation would extend outside of the proposed naturalness gradient.

The pressure on landscape context considers both land use change, identified as one of the main drivers of biodiversity loss by the Millennium Ecosystem Assessment (MEA 2005), and alteration of wetlands, recognized as an important habitat to protect in the latest Quebec's regulation (LRQ No132 2017). The pressure measures are evaluated as the percentage of terrestrial area in anthropic land use, the percentage of wetlands with an anthropically modified condition (ex: drainage or transmission line) and the percentage of wetlands with clearcut. The resulting context_PNI (Table 3.2) could have a negative value when pressures are severe enough, reflecting an extension of the naturalness gradient into the hemeroby gradient. However, in our model, negative values were set to zero.

Appendix 3.A.2. Tree Species Composition

Tree species composition considers two condition indicators: the cover type (CT) (coniferous, deciduous or mixed) which characterizes the forest matrix, and the late successional species groups (LS). Both indicators are measured using percentage of forested area (Table 3.1). The distribution of forest cover type represents a basic forest characteristic used for forest ecosystem management (Gauthier et al. 2008); it represents an indicator of ecosystem diversity that is essential for biodiversity according to Quebec's forest sustainable management criteria and indicators (MFFP 2018). The cover type distribution depends on successional status related to the major natural disturbance regime, i.e., fire in Quebec's boreal forest (Bergeron et al. 2001). The percentage of forested area of the dominant forest cover type, namely coniferous for Northeastern America (Boucher et al. 2011), is used as the indicator. This measure allows the detection of a shift toward mixed or deciduous cover types related to forest exploitation, a phenomenon observed in Quebec's boreal forests (Laquerre et al. 2009). In other parts of the world, as in southern Finland, forest management practices such as the use of herbicides reduce the non-dominant cover types (i.e., hardwood and mixed), diminishing tree species diversity (Vanha-Majamaa et al. 2007). The alteration of natural tree species composition of forest stands results primarily from forest management and past land use, which increase the abundance of stands in their early successional stages (Bončina et al. 2017). In Quebec's boreal forests, early successional stages include intolerant hardwood species such as trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). In the northernmost areas of the boreal forest, the late successional species groups correspond to pure black spruce or old black spruce/balsam fir stands (Rheault et al. 2009). The increase in extent and frequency of disturbances can lead to a reduction of the abundance of late successional species groups in the landscape. Elsewhere, as in eastern Finland for example, forest management activities can reduce the occurrence of stands in their earlier stages of succession (Uotila et al. 2002).

The pressure measure on forest composition considers exotic species stands (exo), and the decrease of the abundance of long-lived companion species (CS). Even if exotic species are absent from the test area, this indicator has been included to allow model adaptation to other regions and perform the test to high levels of pressure. The NDP from exotic stands is evaluated using the logarithmic curve (Figure 3.3c). The use of exotic species is considered to have a high potential impact because of the associated risks of genetic pollution or hybridization with indigenous species (Meirmans et al. 2010), species naturalization or even invasion (Carnus et al. 2006), and alteration of natural disturbance regime resulting from interaction with disturbance agents such as insects (Branco et al. 2015). Higher risks associated with this factor justifies the use of the logarithmic curve. The rarefaction of late successional companion species resulting from forest management activities represents another issue related to forest composition. In Quebec's boreal forests it is the case for eastern white cedar (*Thuya occidentalis*) and white spruce (*Picea glauca*) (Jetté et al. 2013). Theoretically, high pressure values for both measures applied on the mean condition indicator could yield negative values; to avoid inconsistencies, the minimal value for compo_PNI is set to 0 when the calculation leads to negative values.

Appendix 3.A.3. Structure

In general, natural stands tend to be structurally heterogeneous, both vertically and horizontally. Structural complexity may determine habitat availability and may thus influence diversity of plant, animal and microbial communities (Ferris & Humphrey 1999). Relevant measures of forest structure include canopy cover, vertical structure and size or age distribution of trees (Newton & Kapos 2002). The following condition indicators were retained for structure: age structure and vertical structure (Table 3.1). Horizontal structure was evaluated using a pressure indicator resulting from silvicultural treatments.

Forest age structure corresponds to the relative abundance of stands belonging to different development stages or age classes (Bouchard et al. 2015). In natural forests, the age structure is the result of natural disturbances regimes, mainly driven by fire in Quebec's boreal forest (Gauthier et al. 2008). Disturbance regime modelling of Quebec's boreal forest show that the median proportion of old forests (>100 years old) varies from 49 to 77% (Boucher et al. 2011). The proportion of forests older than 100 years has never been under 30% in the natural boreal forest (Bergeron & Fenton 2012). Old forests represent a critical habitat for maintaining biodiversity due to the presence of bigger older trees, internal structural complexity and high abundance of dead wood including large pieces, which are important characteristics for many specialized species (Franklin et al. 1981). In the crownland managed forest of Quebec, almost 1% of the productive forests is harvested annually (BFEC), reducing the proportion of the old forests (Bergeron et al. 2002). Therefore, the measure used for the condition indicator relates to old forests (OF) and corresponds to the percentage of forest area comprising stands over 100 years old. Vertical structure is measured with the percentage of forest area covered by irregular stands (IR). With age, old forests progressively develop an irregular vertical structure (associated with cohort replacement and gap dynamics due to the death of old trees) along with the presence of old high trees and an abundance of dead wood (Harper et al. 2005; Rheault et al. 2009). This structural complexity produces habitat diversification and favors biodiversity, especially among vascular plants, terrestrial mosses, liverworts and lichens (Bergeron & Fenton 2012). We used two different condition indicators for structure: old forests and irregular stands. 100 years old forests do not necessarily have an irregular structure and the proportion of multi-storied and irregular stands was more important before the onset of the commercial exploitation of the forest. Cohort based management had been proposed to answer this issue and the inclusion of the irregular stands as an indicator allows to consider stands from second and third cohorts (Bergeron et al. 2002).

Horizontal structure refers to spatial distribution of stems. Plantation and thinning homogenize the horizontal structure by regularising spatial stem distribution and density (Barrette et al. 2014). This results in a lower variation within the stand, and therefore a lower variety of microhabitats, suitable for a narrower array of species. Horizontal structure is evaluated through pressure measures resulting from silvicultural treatments using percentage of forest area by treatments multiplied by corresponding NDP factors. The resulting NDP is then applied as a reduction percentage on the mean of the age and vertical structure pni's (Table 3.2).

Appendix 3.A.4. Dead wood

About one fifth of all forest species are dependent on decaying wood (Uotila et al. 2002). The relationship between dead wood (DW) and species diversity is higher in boreal forests than in temperate forests (Lassauce et al. 2011). Decaying wood plays a substantial role in many ecological processes (Siitonen et al. 2000): it affects carbon storage, energy flow and nutrient cycles, contributes to the water-holding capacity of the soil, sustains ectomycorrhizal formation and activity and offers a substrate for seedlings establishment. Decaying wood hosts a large number of epixylic bryophytes and lichens, polypores and other decomposer fungi and invertebrates. Coarse woody debris are particularly impacted by wood harvesting (Siitonen et al. 2000). As no dead wood data is available from forest inventory, the PNI evaluation uses pressure related to human intervention associated with specific silvicultural treatments (PNI = 1 − NDP) (Table 3.5), considering their respective effects on coarse woody debris, weighed by the percentage of forest area affected by each treatment.

Appendix 3.A.5. Regeneration Process

Regeneration process (RP) refers to a chain of events necessary to ensure the renewal of the forest and focusses on the method of arrival or persistence of a species on a site during or after disturbance (Hicks 1998). Regeneration process considers the regeneration mode in fire dependent ecosystems as a benchmark for natural state (RP_PNI = 1) and, as for dead wood, applies NDP factors associated with silvicultural treatments, weighed by the proportion of forest area subject to each treatment. The determination of NDP factors (based on expert opinion) compares silvicultural treatments with fire effects considering: seedling provenance (natural or artificial) and their genetic variability; adaptation of regeneration to fire; regeneration density; protection/destruction of natural advance regeneration; seed tree abundance; effects on forest floor that can be either positive (when necessary to control paludification on sensitive sites) or negative.

Appendix 3.B. Hypothesis Used for the 3MU Naturalness over Time Evaluation

- Logging of 1% of the forest area per year corresponding to the forest area included in the area subject to sustainable allowable cut estimation. The harvest was applied on the oldest age class available. Scenarios were applied on 10-years time-steps for a total length of 70 years, corresponding roughly to the first cutting cycle, as 22.5% of the forest area has already been harvested once in 2012;

- A rate of 0.408% per year (Boucher et al. 2017b) of rejuvenation from natural disturbances was applied by distributing the rejuvenation proportionally to the area of age classes ≥ 30 years old;

- For aging, 2 matrix of area by age classes has been used: rejuvenation from natural disturbances only, and natural disturbances plus harvest (over 1% of the admissible area applied on the oldest age class available at each period). Then the resulting matrix has been weighed according to the percentage of excluded area from the production forest depending on the scenario: 22.2% for the scenarios with protected areas, and 4.3% without protected areas;

- Anthropic land use, drainage modification and unproductive area were held constant;

- No modification of forest composition resulting from natural disturbance was included. Composition after logging was based on composition observed on the forest map, distinguishing forest under and over 20 years old: forest under 20 years old: CL: CT = 6.5% coniferous, %LS = 1.1%; PL: CT = 42.8% coniferous, %LS = 0.4%; Forest over 20 years old: CL: CT = 48.1% coniferous, %LS = 13.1%; PL: CT = 86.6% coniferous, %LS = 9.7%.

Appendix 3.C. Naturalness Assessment over Time Procedure

1. Starting from actual area distribution by age classes, simulation by time step of aging, natural disturbances effects and rejuvenation from cutting (For the 3FMU: Table S2), to calculate OF and CF for each period;

2. Find hypothesis for composition indicators after silvicultural treatments included in the forest management strategy (For the 3FMU: CT and LS after CL and PL, under and over 20 years old, were compiled from ecoforest maps), calculate CT, LS and IR resulting from practices application for each period (For the 3FMU: Table S3);

3. For each condition indicator, transform the percentage of area computed by period in pni (For the 3FMU: Using Table S1);

4. Considering the proportion gradually rejuvenated as a result of practices application, evaluation of NDP (For the 3FMU: Using NDP appropriate grid or curve for the scenario from Table S1), to calculate exo_NDP, HS_NDP, DW_NDP and RP_NDP;

5. Complete NDP evaluation using hypothesis about their evolution for other pressure measures (For the 3FMU: CS, Wm, W_CC and ANT assumed to be constant);

6. Calculate NI by time step for each scenario (For the 3FMU: Tables S4 and S5).

Appendix 3.D. Hypothesis Used for Extremes Scenarios

- These scenarios use a rotation period of 65 years;
- The proportions of unproductive and anthropic lands correspond to those from the 3 FMU;
- No old forests nor irregular stands are considered except when partial cuts are used;
- Recognized reduction of companion species is included.
- Drainage of wetlands is set to 50% when applied.
- No excluded area is considered.

Chapitre 4. Naturalness Assessment of Forest Management Scenarios in *Abies balsamea-Betula papyrifera* Forests

4.1 Résumé

Ce volet présente une application du modèle d'évaluation de la naturalité pour l'évaluation de scénarios d'aménagement forestier, adaptée à la sapinière à bouleau à papier. Des scénarios d'aménagement fictifs, comportant des mélanges de pratiques selon des proportions différentes ont été évalués. La sensibilité des données utilisées comme référence préindustrielle a été évaluée en comparant les résultats obtenus en utilisant des données provenant de deux sources différentes. Les variables les plus sensibles du modèle sont le processus de régénération, le bois mort, les forêts fermées et le type de couvert. Le modèle permet une évaluation bidirectionnelle par rapport à la situation actuelle. Les scénarios avec protection rehaussée comportant de la coupe progressive irrégulière dans la portion productive peuvent jouer un rôle important dans l'amélioration de la qualité des écosystèmes. À l'inverse, les scénarios prévoyant une courte révolution (50 ans) pourraient conduire à une dégradation plus importante de la qualité des écosystèmes.

4.2 Abstract

Research Highlights: This research provides an application of a model assessing the naturalness of the forest ecosystem to demonstrate its capacity to assess either the deterioration or the rehabilitation of the ecosystem through different forest management scenarios. ***Background and Objectives:*** The model allows the assessment of the quality of ecosystems at the landscape level based on the condition of the forest and the proportion of different forest management practices to precisely characterize a given strategy. The present work aims to: 1) verify the capacity of the Naturalness Assessment Model to perform bi-directional assessments, allowing not only the evaluation of the deterioration of naturalness characteristics, but also its improvement related to enhanced ecological management or restoration strategies; 2) identify forest management strategies prone to improving ecosystem quality; 3) analyze the model's capacity to summarize the effect of different practices along a single alteration gradient. ***Materials and Methods:*** The Naturalness Assessment Model was adapted to the *Abies balsamea–Betula papyrifera* forest of Quebec (Canada), and a naturalness assessment of two sectors with different historical management strategies was performed. Fictive forest management scenarios were evaluated using different mixes of forestry practices. The sensitivity of the reference data set used for the naturalness assessment has been evaluated by comparing the results using data from old management plans with those based on Quebec's reference state registry. ***Results:*** The model makes it possible to identify forest management strategies capable of improving ecosystem quality compared to the current situation. The model's most sensitive variables are regeneration process, dead wood, closed forest and cover type. ***Conclusions:*** In the *Abies balsamea–Betula papyrifera* forest, scenarios with enhanced protection and inclusion of irregular shelterwood cuttings could play an important role in improving ecosystem quality. Conversely, scenarios with short rotation (50 years) could lead to further degradation of the ecosystem quality.

Keywords: naturalness; forest management intensity; land use intensity; quality of ecosystems; boreal forest

4.3 Introduction

Green building conception relies on quantitative tools to evaluate the environmental impact of different building materials. For wood products, the environmental impacts include the effects of forest management strategies and practices on ecosystem quality.

A conceptual model for naturalness assessment in boreal forests has been recently proposed for the assessment of the impact of wood harvesting on the quality of ecosystems (Côté et al. 2019). This model has been developed from the perspective of being used in life cycle assessment (LCA). LCA, by default, uses biodiversity damage (Curran et al. 2016; Life cycle initiative 2016) to evaluate the quality of ecosystem. However, biodiversity based on species count alone does not reflect the multidimensional character of biodiversity, which includes multiple levels of organization: genetic, species, populations, community and ecosystem (Curran et al. 2016), and might lead to inappropriate conclusions (Souza et al. 2015; Gaudreault et al. 2016). The model generally used in LCA to establish the relationship between land use and biodiversity (i.e., the species–area relationship (SAR)) presents many limitations, and is not appropriate when the habitat modification does not result in species losses (Souza et al. 2015). On the other hand, studies investigating the effects of land use on biodiversity often contrast intensive vs extensive uses (Gossner et al. 2014). For forestry, such a simplistic approach does not allow for the consideration of the full diversity of practices, each implying a different pressure on the environment (Gabel et al. 2016; Chaudhary & Brooks 2018; Jolliet et al. 2018). To overcome these issues, we developed an alternative approach, based on the naturalness concept (Winter 2012), which focuses on habitat characteristics, and allows the evaluation of various forest management practices along a single bi-directional alteration gradient (Côté et al. 2019), i.e., forest ecosystem degradation or restoration, related to given forest management strategies. Generally, models proposed up to now in LCA do not account for a possible improvement of habitat condition related to enhanced ecological management strategies and restoration efforts (Souza et al. 2015; Life cycle initiative 2016), despite the fact that these are seen as crucial actions to enhance ecosystem functioning and halt the decline of biodiversity (Kouki et al. 2012; Hekkala 2015).

Many authors have proposed the use of the concepts of naturalness and hemeroby in impact evaluation of land use (such as forestry) on the quality of ecosystems in LCA (Brentrup et al. 2002; Michelsen 2008; Fehrenbach et al. 2015; Farmery et al. 2017; Rossi et al. 2018). Naturalness is defined as "*the similarity of a current* *ecosystem state to its natural state*" (Winter 2012), whereas hemeroby expresses "*distance to nature*" in landscape ecology (Fehrenbach et al. 2015). The use of these concepts can provide a management guide that overcomes the challenge of data gaps in biodiversity (Côté et al. 2019). However, the use of subjective hemeroby or naturalness classes has been criticized (Curran et al. 2016). The model developed here for boreal forest provides a single numerical index, a suitable approach for use in LCA (Côté et al. 2019).

In order to evaluate forest management scenarios, the assessment should go beyond the gradual transformation related to the progressive implementation of the scenario through time (Côté et al. 2019), and be placed in the context of its continuous application over the whole productive area.

The aim of this study was to test the bi-directional capacity of the recently proposed model for the assessment of the impact of wood harvesting on the quality of ecosystems (Côté et al. 2019), to evaluate the performance of distinct enhanced ecological management strategies, including restoration efforts, at the landscape level. For this purpose, we used two adjacent territories located in the boreal eastern *Abies balsamea–Betula papyrifera* ecological bioclimatic domain of Quebec (Canada) with different histories of forest management. The specific objectives of the study were to:

Determine the naturalness of different mix of forest management practices to evaluate the bi-directional capacity of the model to assess both ecosystem degradation and restoration;

Identify forest management strategies prone to improving ecosystem quality based on a naturalness evaluation;

Analyze the model's capacity to summarize the effect of different practices along a single alteration gradient.

4.4 Materials and Methods

The impact on ecosystem quality of forest management scenarios involving a mix of different proportions of forestry practices is evaluated using the Naturalness Assessment Model initially developed for the *Picea mariana*–feathermoss ecological domain of Quebec (Côté et al. 2019). This model uses indicators of condition and pressure to calculate a unique index of naturalness resulting from the combination of management strategies including conservation, and different silvicultural treatments (e.g., careful logging, plantation of indigenous species and partial cutting) (see Côté et al., 2019 for the full description of the naturalness assessment method). For the purpose of this study, the model was adapted to the context of the boreal eastern *Abies balsamea–Betula papyrifera* ecological bioclimatic domain of Quebec (see Appendix 4.A for details related to model's adaptation).

4.4.1. Test Area

The territory of the Montmorency Experimental Forest, located north of Quebec City and included in the *Abies balsamea–Betula papyrifera* domain, was used as a test area (see Appendix 4.A for localization and historical information). This experimental research station is divided in two sectors, designated as FM-A and FM-B, according their different histories. FM-A has been subject to continuous small-scale commercial harvest since the mid-sixties, while FM-B has been subject to a second wave of large-scale commercial harvest between 1985 and 2008, before being incorporated into the Montmorency Experimental Forest.

4.4.2. Naturalness Assessment

For the *Abies balsamea–Betula papyrifera* domain, the five naturalness characteristics of the model were evaluated using the same indicators and variables used for the *Picea mariana*–feathermoss domain of the Quebec's boreal forest (Côté et al. 2019) (Table 4.1), except for composition where merchant volume proportion of *Picea* spp. was used as a surrogate to obviate the lack of composition data for late successional species (see Appendix 4.A for details). The evaluation is realized in two steps: partial naturalness index for condition indicators (condition_pni: pni in lower case) and naturalness degradation potentials (NDP) are first evaluated. To do so, we use respectively curves, relating measures (percentage of area or volume) to condition_pni, and tables relating percentage of forest area by practices to NDP factors, shown in Appendix 4.A. Then, the partial naturalness for each naturalness characteristic (characteristic_PNI: PNI in capital letters) is calculated using corresponding formula as per Table 4.1. The final result corresponds to the naturalness index (NI) obtained from the arithmetic mean of the five characteristic_PNI. To ease results interpretation the continuous gradients (partial or global naturalness indexes) can be split in classes of 0.2 (0.0–0.2: very altered; 0.2–0.4: altered; 0.4–0.6: semi-natural; 0.6–0.8: near-natural; 0.8–1: natural).

Table 4.1: Partial naturalness index equations for each naturalness characteristic (characteristic_PNI) (source: (Côté et al. 2019)).

Naturalness Characteristic	Characteristic_PNI Equation
Landscape context	$Context\_PNI = CF\_pni \times (1-(ANT\_NDP+Wm\_NDP + W\_CC\_NDP))$
Forest Composition	$Compo\_PNI = ((CT\_pni + LS\_pni)/2) \times (1 - (exo\_NDP + CS\_NDP))$
Structure	$Struc\_PNI = ((OF\_pni + IR\_pni)/2) \times (1 - HS\_NDP)$
Dead wood	$DW\_PNI = 1 - DW\_NDP$
Regeneration process	$RP\_PNI = 1 - RP\_NDP$

PNI: partial naturalness index for naturalness characteristics; pni: partial naturalness index for condition indicators; NDP: naturalness degradation potential; CF: closed forests; ANT: anthropization; Wm: modified wetlands; W_CC: humid area in clearcut; CT: cover type; LS: late successional species; exo: exotic species; CS: companion species; OF: old forests; IR: irregular stands; HS: horizontal structure; DW: dead wood; RP: regeneration process.

The model's adaptation to a new region requires to ensure the capture of the main ecological issues recognized for the territory under investigation, and to identify appropriate indicators, as well as variables and data sources for the evaluation. We tested two types of data sources for reference data: local historical studies (Leblanc & Bélanger 2000; Boucher & Grondin 2012; Bouliane et al. 2014) or Quebec's reference state registry (Boucher et al. 2011) (Table 4.A1). The curves used for partial naturalness index (condition_pni) evaluation were calibrated according to the reference data set used (Figures 4.A2 and 4.A3 based on reference data from studies and registry respectively), and the factors used for naturalness degradation potential (NDP) evaluation adapted (Tables 4.A2–4.A5).

4.4.3. Description of Scenarios

Scenarios correspond to different mixes of practices applied in the context of sustainable timber production. To figure out the result at the landscape level, in the current study, each practice representing a scenario component is applied on a constant basis over a given proportion of the productive area. However, this exercise is highly theoretical, considering that, in reality, each scenario is adjusted through time to maximize the wood production, rather than having each component being applied on a constant basis. Furthermore, the prevalence of spruce budworm epidemics, which affect balsam fir (*Abies balsamea*) landscapes every 30 years (MFFP 2019), is not taken into account here.

Total area is broken down as follows: total area = water area + terrestrial area; terrestrial area = non-forested area + forested area; forested area = protection area + productive area. Protection is applied as a reduction percentage over the total forested area, and practices related to wood procurement are applied over a given proportion of the productive area. The evaluation must cover the whole landscape; therefore, scenario components must encompass 100% of the productive forested area. The forested area excluded from the productive area corresponding to protection will have a natural evolution, for which historical reference data has been used, except for late successional species. The hypothesis for spruce content (LS) in protected areas was reduced to 4%, based on results from secondary forests (Côté & Bélanger 1991; Grondin & Cimon 2003; Thiffault 2019), given that protected areas are generally located in previously exploited areas, where spruce seed-trees have been harvested.

The practices considered for scenarios in the productive area were: careful clearcut logging (CL), which corresponds to the cut with regeneration and soil protection required by law for clearcut operations in Quebec (Harvey & Brais 2002), forest plantation (PL) and irregular shelterwood cutting (ISC). As a result of the abundance of natural pre-established balsam fir regeneration in these secondary balsam fir forests (Côté & Bélanger 1991; Déry et al. 2000; Bouliane et al. 2014), careful logging (CL) is the main regeneration method applied in these forests. Plantations (PL) are generally concentrated on rich sites, where natural resinous regeneration is scarce. The irregular shelterwood silvicultural system (ISC) is compatible with forests types driven by partial stand mortality and gap dynamics such as balsam fir forests, and provides a way to maintain old-growth forest attributes (Raymond et al. 2009). Two levels of protection were considered: initial protection (ip) and enhanced protection (ep). The initial protection represents 24.4% of the forested area for FM-A and 13.3% for FM-B, and corresponds to current protected areas, along with other areas excluded from forest management, due to the various regulations and constraints (e.g., riparian strips, steep slopes etc.). The enhanced protection (ep) corresponds to the initial protection, plus protected areas projects proposed for the Montmorency Forest (Bouchard et al. 2017), and represents 31.7% of the forested area for FM-A and 32.2% for FM-B.

For careful clearcut logging (CL), two different rotation lengths were tested: 50 years (CL50) and 70 years (CL70), the first one corresponding to the business-as-usual in commercial balsam fir forests, and the second one to a practice that favors establishment of natural regeneration (Thiffault 2019) and carbon sequestration (Paradis et al. 2019). Plantation with a rotation length of 60 years (PL60) has been used, based on the rotation used in the last sustainable yield calculation. The irregular shelterwood cutting (ISC) corresponds to a sequence of partial cuts organized in space and time to insure the permanency of the forest cover (Raymond et al. 2009); this practice was simulated as harvests of 33% of the volume every 30 years. Data used to evaluate practices effects come from secondary forests.

Scenario elaboration began with the evaluation of each of the three components with two variants of CL, over the entire productive area separately, in order to evaluate the maximal theoretical effect of each practice. These scenarios were first evaluated with the current level of protection and then with the enhanced protection level. For the scenarios involving practices mixes, the first assessment considered only the enhanced protection level. Each mix involving CL has been evaluated two times: one with CL50 and one with CL70. Proportion of CL tested varied between 90% and 50% of the productive area (by multiple of 10), between 0 and 40% for PL and between 0 and 50% for ISC, and a test considering 50% PL and 50% ISC has also been included (Table 4.2).

Table 4.2: Description of management scenarios evaluated[2].

	Productive Area Proportions by Scenario Component		
Scenario#	**ISC**	**PL60**	**CL**
1	0	1	0
2	0	1	0
3	0	0	1
4	0	0	1
5	0	0.1	0.9
6	0	0.2	0.8
7	0	0.3	0.7
8	0	0.4	0.6
9	0.1	0.1	0.8
10	0.2	0.1	0.7
11	0.1	0.2	0.7
12	0.1	0.3	0.6
13	0.2	0.2	0.6
14	0.3	0.1	0.6
15	0.1	0	0.9
16	0.2	0	0.8
17	0.3	0	0.7
18	0.4	0	0.6
19	0.5	0	0.5
20	0.5	0.5	0
21	1	0	0
22	1	0	0

Scenario #: scenario number; ISC: irregular shelterwood cutting; PL60: plantation with 60 years revolution; CL: careful logging.

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[2] Deux périodes de révolution ont été considérées pour CL (50 et 70 ans). La correspondance entre le numéro séquentiel du scénario et le SCE# est fournie dans le fichier de matériel supplémentaire, onglet scenario_nb_description

4.4.4. Hypotheses

The hypotheses used for each scenario component are presented in Table 4.3.

Table 4.3: Hypotheses used for each scenario component.

Scenario Component	**Cover Type (CT: % Prod Area of Coniferous Cover Type)**	**Late Successional Species (LS: % Merchantable Volume in *Picea* spp.)**	**Closed Forests (CF: % Productive Area of Forests > 40 Years Old)**	**Old Forests (OF: % Productive Area of Forests > 80 Years Old)**	**Irregular Stands (IR: % Productive Area of Irregular Stands)**
CL50 [1]		1	20	0	0
FM-A	77.49				
FM-B	79.79				
CL70		3.5	42.85	0	0
FM-A	81.54				
FM-B	83.84				
PL60		50	33.33	0	0
FM-A	92.38				
FM-B	94.64				
ISC		15	90	90	90
FM-A	78.02				
FM-B	80.41				
Protection					
FM-A	79.3	4	79.9	23.7	17.8
FM-B	85.7	4	76.19	57.9	40

[1] CL50: careful logging in 50 years old stands; CL70: careful logging in 70 years old stands; PL60: plantation with 60 years rotation; ISC: irregular shelterwood cutting; prod_area: productive area.

Age structure related to each scenario under sustainable production has been used to evaluate closed and old forests. For example, for a rotation of 50 years, 40% of the productive area will be in the 10 years old class, 40% in the 30 years old class and 20% in the 50 years old class, therefore, the corresponding proportion of closed forests will be 20% and 0% for old forests (>60 years old). For ISC, 10% of the area are permanent skid trails. Despite the fact that these trails will be part of the future stand, the proportion of CF, OF and IR were set to a maximum of 90% used as a security factor. The proportion of coniferous cover type for PL60 and ISC is based on eco-forest map data for the corresponding origin code in each territory. For CL50 and CL70, the proportion of coniferous cover type is based on data (number of stems) gathered in FM-A (Senez-Gagnon et al. 2018). The resulting proportion has been raised of 2.3% in FM-B, based on the differences observed in inventory data between the two territories for diverse practices, to be coherent with the coniferous aggressiveness in that territory. The proportion of spruce (*Picea* spp.) for each practice was estimated using different studies in the Montmorency Forest (Raymond et al. 2000; Urli et al. 2017; MFFP 2019). Clearcuts on wetlands and anthropization levels were set to current values, and kept constant in all scenarios. For pni's evaluation, the proportion of the productive area was adjusted to represent the proportion of forest area for CT, LS, OF and IR, and the proportion of terrestrial area for CF.

4.4.5. Sensitivity Analysis

To identify the most sensitive variables of the current naturalness assessment, a sensitivity analysis was performed by varying pni for condition indicators and NDP by ±10%. The same analysis was also performed for each scenario component, using the 100% scenario with enhanced protection, in order to identify the most sensitive variables related to each component.

As naturalness condition indicators are assessed against historical values considered to be representative of the pre-industrial condition, the sensitivity to the choice of reference data set has been evaluated by comparing results obtained when using two different reference data sets (Table 4.A1). The first assessment was performed using values drawn from different studies and old management plans around the territory of Montmorency Forest (Leblanc & Bélanger 2000; Boucher & Grondin 2012; Bouliane et al. 2014). A second assessment was performed on scenarios initially assessed using values from the reference state Quebec's registry (Boucher et al. 2011), resulting from simulations of the vegetation dynamics considering only natural disturbance regimes. The scenario ranking resulting from the use of the two reference data sets was statistically compared using the Kendall rank correlation coefficient. The statistical test was performed with "R" 3.6.1 (R Core Team 2019).

Multiple assessments of the same set of scenarios was then performed to analyze the effect of different combinations of management parameters, such as the proportion of protected areas, plantation rotation lengths and the proportion of *Picea* spp. in plantations.

4.5 Results

Detailed results of each scenarios evaluation, including those performed for sensitivity analysis, are presented as supplementary material where the different assessments (ass) are as follows:

- ass_1: initial scenarios assessment with enhanced level of protection (ep);
- ass_2: scenarios with enhanced level of protection using registry's reference data set;

- ass_3: scenarios with the initial level of protection (initial protection: ip);
- ass_4: scenarios with PL50 and enhanced level of protection;
- ass_5: scenarios with PL50 and initial level of protection;
- ass_6: scenarios with PL50 and enhanced level of protection and 90% of spruce at maturity in plantations;
- ass_7: scenarios with enhanced protection and alternate set of NDP factors.

4.5.1. Naturalness Index for the Current State of the Forest of the Experimental Forest

The naturalness assessment results for the current state of the forest in FM-A and FM-B are presented in Figure 4.1, showing intermediary results for condition indicators (pni), results for each naturalness characteristics (PNI) and the resulting naturalness index (NI), which corresponds to the arithmetic mean of the five Characteristic_PNI. Results show a naturalness index (NI) of 0.5294 for FM-A and 0.4691 for FM-B. Both territories scored in the semi-natural class (NI: 0.4-0.6), despite their different histories. However, FM-B showed a lower naturalness compared to FM-A, mainly related to a poor structural diversity associated with an important deficit of old forests combined with a lack of irregular stands (Figure 4.1). The structure is altered in FM-A (PNI_Struc= 0.3332) and very altered in FM-B (PNI_Struc= 0.1931). The alteration of structure in FM-A results from the very low ratio of old forests compared with the historical values; whereas, in FM-B, it is both the low ratio of old forests and the lack of irregular stands.

The landscape context of FM-B is also characterized by an important deficit of closed forests where it reaches the altered level. According to the map information, in FM-A less than 10% of the harvested area was in 50 years old stands, whereas in FM-B this proportion reaches 50%. Precommercial thinning covered 9.2% of the forest area in FM-A compared to 23.4% in FM-B, plantation 6.8% in FM-A and 8.8% in FM-B, and partial cuttings, excluding commercial thinning, 5.5% in FM-A and 1.4% in FM-B.

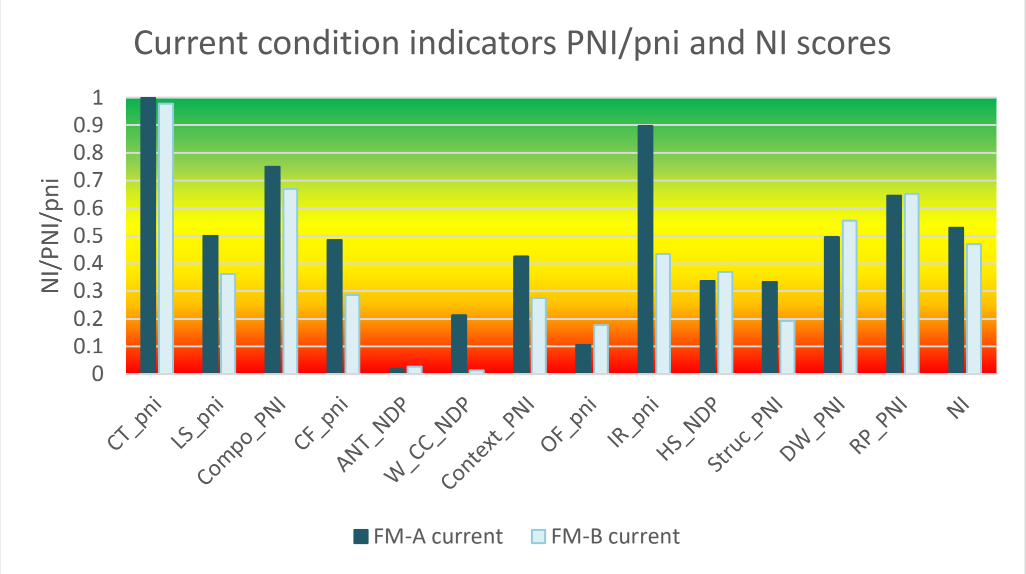
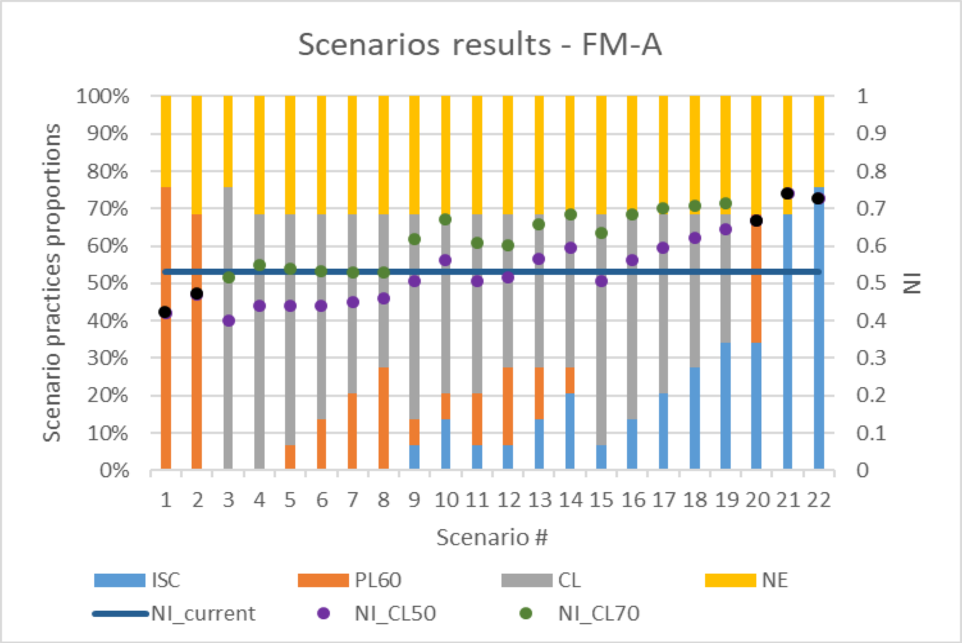


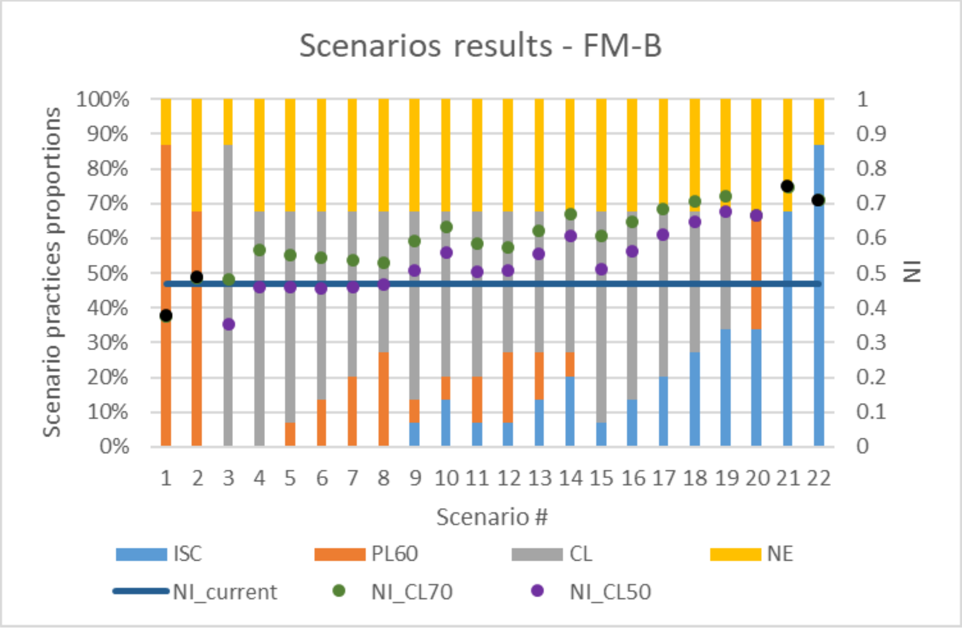
Figure 4.1: Results for condition indicators and naturalness for FM-A and FM-B. PNI: partial naturalness index for naturalness characteristics; pni: partial naturalness index for condition indicators (intermediary results); CT: cover type; LS: Picea spp. corresponding to late successional species; Compo: composition; CF: closed forests; Context: landscape context; OF: old forests; IR: irregular stands; Struc: structure; DW: dead wood; RP: regeneration process; NI: naturalness index.

4.5.2. Naturalness of Different Forest Management Scenarios

Scenarios results of the initial assessment are presented in Figure 4.2 (detailed results in supplementary material, file results, page ass_1). Compared with results based on the current state of the forest, some scenarios lead to a lower naturalness index and others to a higher level, indicating the model's capacity to detect not only alteration of the ecosystem quality, but also its improvement.



(**a**)



(**b**)

Figure 4.2: Naturalness assessment of forest management scenarios: (a) FM-A; (b) FM-B. For each scenario, practices mixes are illustrated using the stacked histogram: ISC: Irregular shelterwood cutting; PL60: plantation with 60 years revolution; CL: careful logging; NE: natural evolution (protection); Resulting naturalness index (NI) is indicated with the dots: NI_CL70 (green): naturalness index for CL applied in 70 years old stands; NI_CL50 (purple): naturalness index for CL applied in 50 years old stands; naturalness index for practices other than CL (black); the horizontal solid line shows the current naturalness index (2018) with the initial level of protection.

Scenarios featuring the application of only one practice on 100% (of the productive area) were tested to evaluate their respective extreme theoretical effects on the naturalness assessment resulting from the model. Each of these were evaluated twice: once with the current level of protection (initial protection: ip), and once with the inclusion of the protection projects (enhanced protection: ep). These 100% theoretical scenarios are shown as benchmarks in every test performed to see the maximal theoretical effect related with each scenario component, considering the two levels of protection. Figure 4.2 shows that enhanced protection impact differs among the scenario components. The positive impact related to protection enhancement is more important when applied concurrently with PL60 than with CL50, CL70 and finally ISC.

The PL60 scenario (Sce#1) produces a degradation of the naturalness in both territories. With the inclusion of protection projects (Sce#2), the 100% PL60 scenario still scores lower than current results for FM-A, but slightly better for FM-B. The 100% CL50 scenario is worse than the 100% PL60 scenario, because of the shorter rotation period and a lower amount of spruce. The 100% ISC scenario (Sce#21 and Sce#22) would have the potential to improve naturalness at the quasi-natural level. The quasi-natural level could also be reached in FM-A, with CL70 combined with at least 30% of ISC and enhanced protection (Figure 4.2a), and in FM-B with CL70 and enhanced protection with at least 40% ISC (Figure 4.2b). The 100% CL70 scenario has a NI near to the current level, for the same level of protection. Protection projects represent a greater proportion in FM-B, so the resulting naturalness improvement related to the inclusion of these projects is more important.

The current naturalness in FM-A shows an impact level analog to the 100% CL70 scenario with initial protection, or CL70 with enhanced protection and some plantation. The current level in FM-B presents an impact closer to the 100% CL70 scenario with initial protection, or CL50 with enhanced protection scenarios with some plantation. Considering the intervention mixes, ISC has the potential to compensate at least for a part of the degradation related to forest rejuvenation resulting from careful logging or plantation.

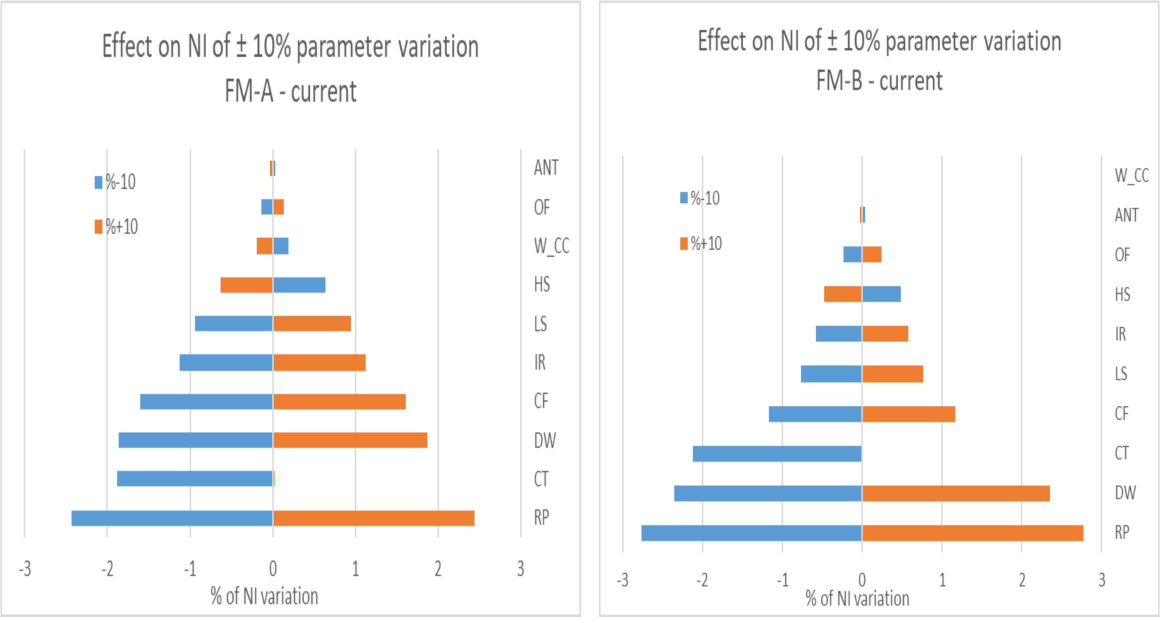
The ISC's potential to improve the overall naturalness is more important when the proportion of ISC is smaller than the historical proportion of irregular stands (FM-A: 17.9%; FM-B: 40%). Above this level, naturalness improvement resulting from a higher level of ISC is less important, as seen in FM-A's CL70 results, where the difference of NI between 40% and 50% of ISC is smaller than the difference between 10% and 20% of ISC. Results suggest that ISC can compensate to some extent for the alteration caused by CL50.

With the hypotheses used, plantations under 60 years rotation, with 50% of the volume in spruce at maturity, could produce an improvement of the naturalness when combined with CL50, mainly related to rotation length.

4.5.3. Sensitivity Analysis

4.5.3.1. Test of a Variation of 10% of the Parameter Values

The results of the sensitivity analysis performed on current pni and NDP values for the two territories are provided in Figure 4.3. Due to the use of non-linear models, a uniform variation of input parameters (10%) can have a non-linear effect on the results, depending on the curve slope around the parameter value (Côté et al. 2019).



(**a**) (**b**)

Figure 4.3: Results of the sensitivity analysis testing a variation of 10% of the parameter value on the current assessment: CF: closed forests; ANT: anthropization; W_CC: humid area in clearcut; CT: cover type; LS: late successional species; OF: old forests; IR: irregular stands; HS: horizontal structure; DW: dead wood; RP: regeneration process. (a) FM-A, (b) FM-B.

The most sensitive variables for the naturalness assessment of the current state of the forest are the regeneration process (RP), the cover type (CT), the dead wood (DW) and the closed forest (CF) for both territories; however, dead wood is more sensitive than cover type in FM-B.

The results of the sensitivity analysis performed on the scenarios in which a single component is applied over 100% of the productive area are shown in the Supplementary Material (page sensitivity analysis). As seen from these figures, the most sensitive variables for scenarios involving cuttings (CL, ISC) correspond, in varying order, to the regeneration process, the dead wood, the cover type and the closed forests, whereas the plantation influences mainly closed forest, cover type, late successional companion species and the regeneration process.

4.5.3.2. Test of an Alternative Reference Data Set

Using the registry's reference data set (Boucher et al. 2011), the naturalness of the two territories are closer (FM-A: NIr = 0.4683; FM-B: NIr = 0.4349) (Figure 4.4) and are both lying in the semi-natural range. The main disparities between the two data sets values are for OF and IR (Table 4.A1) especially for FM-A, leading to a much lower PNI_Struc with the registry's values. The difference related to coniferous cover type between the two data set is not reflected in the model, because of the use of topped curve for CT above the historical value.

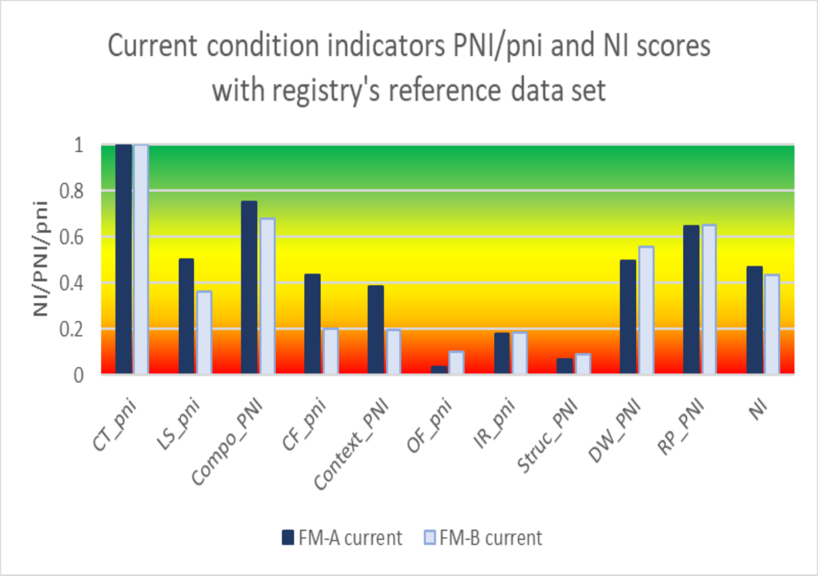


Figure 4.4: Results for condition indicators and naturalness index (NI) for FM-A and FM-B using registry's reference state data set (Boucher et al. 2011).

Scenario results using registry's data as alternative reference data set are presented in Supplementary Material (page ass_2 and Figure S2). The use of the registry's data set places the current assessment for FM-A to a level below CL70 scenarios with some PL60, with initial protection, as well as enhanced protection. We observe the same trends seen with the use of studies as the reference data set: improvement related to use of some ISC, and a slight degradation related to the use of PL60 combined with CL70, but no deterioration (even a slight improvement) with an additional use of PL60 when combined with CL50. However, the reference data set used might affect the identification of the potentially improving or deteriorating scenarios when compared with the current result.

The scenarios were sorted in descending order of NI results using local studies (Leblanc & Bélanger 2000; Boucher & Grondin 2012; Bouliane et al. 2014) as the reference data set versus the registry's reference data (Boucher et al. 2011) (Table 4.4). The ranking of scenarios is not the same, depending on the reference data set used, but the four best-scoring scenarios are the same (the 100% ISC with both level of protection, and at least 40% ISC combined with CL70 with enhanced protection), as well as the two worst-scoring scenarios (CL50 and PL60 with initial protection). The remaining 34 scenarios score in the semi-natural class ($0.4 \leq NI < 0.6$). Among these, CL70 with at least 20% ISC and enhanced protection score in the upper part of the class, while CL50 with PL60 and enhanced protection are in the lower part. Among scenario components, the addition of ISC has the biggest positive impact on naturalness, while the addition of PL60 has a negative impact, but is less important when compared to the importance of the positive impact of the ISC.

The use of registry reference data set induces a negative bias compared with the use of the studies reference data set (FM-A: -0.0591; FM-B: -0.0522), as the naturalness index is generally lower when registry's data are used. This bias is not constant as a result of the use of nonlinear relationships in the model. Nevertheless, the general trends related to the positive effects of ISC and the relatively limited negative effects of mechanically released plantations, including 50% of spruce at maturity, are observed in the ranking arising from both data sets. The ordinal association between the two rankings, as measured with Kendall rank correlation computed with the base cor function in R, showed a coefficient of 90.5% for FM-A and 95.9% in FM-B. Therefore, the model's aptitude at classifying different scenarios along a single alteration gradient is robust, in regard to the reference data set used. However, assessing improvement or degradation against the current value might be affected by the reference data set used.

Table 4.4: Scenario ranking resulting from the use of the two reference data sets for FM-A and FM-B, sorted in descending order of their naturalness index.

Scenario Sequential nb	Scenario Description [1]	Rank FM-A Studies	Rank FM-A Registry	Rank FM-B Studies	Rank FM-B Registry
22	100ISC_ep	1	1	1	1
23	100ISC_ip	2	2	3	2
20	50CL70_50ISC_ep	3	3	2	3
19	60CL70_40ISC_ep	4	4	4	4
18	70CL70_30ISC_ep	5	7	5	7
15	60CL70_10PL60_30ISC_ep	6	8	7	8
17	80CL70_20ISC_ep	7	9	10	10
11	70CL70_10PL60_20ISC_ep	8	11	11	11
21	50PL60_50ISC_ep	9	5	8	5
14	60CL70_20PL60_20ISC_ep	10	12	12	12
40	50CL50_50ISC_ep	11	6	6	6
16	90CL70_10ISC_ep	12	13	14	13
39	60CL50_40ISC_ep	13	10	9	9
10	80CL70_10PL60_10ISC_ep	14	14	16	16
12	70CL70_20PL60_10ISC_ep	15	15	17	17
13	60CL70_30PL60_10ISC_ep	16	16	18	19
38	70CL50_30ISC_ep	17	19	13	14
35	60CL50_10PL60_30ISC_ep	18	17	15	15
34	60CL50_20PL60_20ISC_ep	19	25	22	25
37	80CL50_20ISC_ep	20	26	20	22
31	70CL50_10PL60_20ISC_ep	21	27	21	24
5	100CL70_ep	22	18	19	18
6	90CL70_10PL60_ep	23	20	23	20
7	80CL70_20PL60_ep	24	21	24	21
8	70CL70_30PL60_ep	25	22	25	23
1	Current_ip	26	28	33	33
9	60CL70_40PL60_ep	27	23	26	26
4	100CL70_ip	28	24	32	31
33	60CL50_30PL60_10ISC_ep	29	29	28	28
32	70CL50_20PL60_10ISC_ep	30	31	30	30
36	90CL50_10PL60_ep	31	32	27	27
30	80CL50_10PL60_10ISC_ep	32	33	29	29
3	100PL60_ep	33	30	31	32
29	60CL50_40PL60_ep	34	34	34	34
28	70CL50_30PL60_ep	35	35	36	36
27	80CL50_20PL60_ep	36	36	38	38
25	100CL50_ep	37	37	35	35
26	90CL50_10PL60_ep	38	38	37	37
2	100PL60_ip	39	39	39	39
24	100CL50_ip	40	40	40	40

[1] ISC: Irregular shelterwood cutting; PL60: plantation with 60 years revolution; CL50: careful logging applied in 50 years old stands; CL70: careful logging applied in 70 years old stands; ip: initial protection; ep: enhanced protection; Current: current naturalness (2018). The digits preceding component code correspond to the percentage of productive area of the component application (ex:100PL60_ep: plantation with 60 years revolution applied over 100% of the productive area with enhanced level of protection).

4.5.3.3. Naturalness of the Forest Management Scenarios Tested Using Various Hypothesis

Scenarios with initial protection

In order to see the impact related to the protection level, scenario evaluation using studies as reference data set was calculated using the current level of protection (ip) (Supplementary Material: page ass_3 and Figure S3). With 24% of the forested area in protection in FM-A, none of the scenarios, except 100% ISC (sce#22), would reach the quasi-natural level, and the scenarios considering CL50 with some PL60 would score around the limit between the altered and the semi-natural levels. The current alteration level is similar to 100% CL70, and scenarios combining with some PL60 are below to the current level even when combined with CL70. In FM-B, with 13% of the forested area in protection, the scenarios considering CL50 with some PL60 would score in the altered level, except when combined with at least 20% of ISC or, at least 10% ISC, if considering CL50 without plantation. The current alteration level in FM-B is similar to 100% CL70, or CL70 with less than 20% PL60, or CL70 with up to 30% PL60, if combined with 10% ISC, with initial protection.

Scenarios with enhanced protection and plantation with 50 years rotation

In order to see the impact related to plantation rotation length, an evaluation using studies as the reference data set was calculated using a rotation length of 50 years for plantations (PL50). This test was performed by adjusting the age structure for the planted proportion of the scenario, but keeping all others factors constant (Supplementary Material: page ass_4 and Figure S4).

The 100% PL50 with initial protection scenario would lead to a naturalness index lying in the altered class for both territories (Sce #1: FM-A: NI = 0.3871; FM-B: NI = 0.3308). Adding new protection projects (reaching a total of more than 30% of the forested area) makes it possible to attain the semi-natural class even with 100% PL50 in the productive area (Sce#2: FM-A: NI = 0.4400; FM-B: NI = 0.4511). The use of PL50 instead of PL60 reduces slightly the improvement related to the increasing use of PL, when combined with CL50. We can still observe no further degradation and even a small improvement for Scenario 8 with CL50, compared with Scenario 7 with CL50, related to the increase of spruce species at the landscape level. However, more spruce in the plantations could induce a degradation, as these species were subdominant at the landscape level.

Scenarios with initial protection and plantation with 50 years rotation

In order to see the combined impact related to the protection level and plantation rotation, scenario evaluation using studies as reference data set was calculated using the current level of protection and plantation with 50 years rotation (PL50) (Supplementary Material: page ass_5 and Figure S5). Compared with the test considering initial protection only, the use of PL50 instead of PL60 has a limited effect, but pushes more scenarios closer to the altered class in FM-B. With the initial protection and the use of PL50, some ISC is necessary to reach a level above the current naturalness.

Plantation with enhanced protection and 50 years rotation and 90% of merchantable volume in spruce at maturity

A test was performed using a proportion of spruce of 90% (instead of 50%) of the merchantable volume at maturity for PL50, in order to analyze the effect of more monospecific plantations with a short rotation (Supplementary Material: page ass_6 and Figure S6). The 100% PL50 with 90% of spruce at maturity scenarios, with initial protection, would lead to a naturalness index lying in the altered class in both territories. The addition of protection projects (reaching more than 30% of the forested area) makes it possible to attain the semi-natural class in FM-B, even with 100% PL50 in the productive area, that would produce 90% of the volume in spruce (Sce#2: FM-A: NI = 0.3998; FM-B: NI = 0.4242). An increasing use of PL50 producing 90% of the volume in spruce, combined with CL50, could improve the naturalness to some extent, until the total spruce proportion of the scenario reaches its historical level. However, above this level, an increase of spruce proportion could lead to a noticeable deterioration, as shown with the 100% PL50 with 90% of spruce (Sce #1 and 2).

Scenarios with enhanced protection and a variant of NDP factors

The regeneration process and dead wood were among the most sensitive variables for the assessment of the current forest and for the evaluation of scenario components related to harvest (CL, ISC). In order to see the influence of NDP factors, an alternate set of factors, inducing more difference between CL70 and CL50 and ISC, was tested by lowering the three NDP factors (i.e., HS, DW and RP) for CL50 of 0.1, and the NDP factor for partial cutting of 0.1 for HS and RP. Inducing a more important degradation of RP, DW and HS for CL50, and of HS and RP for partial cuttings, results in a slightly higher NI for the assessment of the current forest (FM-A: 0.5550; FM-B: 0.4756). The difference is marginally more important for FM-A, as this territory has less CL50 than FM-B. As expected, this enhances the performance of CL70 scenarios compared to CL50 scenarios, allowing more scenarios to reach the quasi-natural level. On the other hand, the distinction between scenarios that improve naturalness vs. those that degrade it remains the same (Supplementary Material: page ass_7 and Figure S7).

4.6. Discussion

Scenario evaluation suggests that some combinations of practices could produce an improvement of the naturalness index, compared to the state of the current forest, confirming the model’s capacity of performing bi-directional assessment to satisfy the need of assessing restoration efforts.

4.6.1. Naturalness Assessment of FM-A And FM-B’s Current Forest

Current results in FM-A and FM-B lead to a naturalness index lying between 0.4 and 0.6, corresponding to the semi-natural class. These results consider the current level of protection (ip: FM-A: 23.8%; FM-B: 12.7% of the terrestrial area or 24.4% and 13.3% of the forested area). The difference induced by the distinct forest management strategies applied over the last 50 years is a priori small; it is, however, not surprising, considering that the forest management strategies in both territories were prioritizing the liquidation of old forests using principally single aged management. The lower naturalness observed in FM-B is mainly related to the low level of closed forests (only 27% of the forest area is over 40 years old in FM-B), and a lack of structural diversity (the low level of old forests in FM-B being worsened by the scarcity of irregular stands). However, the contrast between the two territories is limited by the use of the same hypothesis for IR and LS. As the forest rejuvenation was applied more uniformly and over a short period in FM-B, compared with FM-A, a better characterization of the landscape context, taking into account the size of the stands by age-class, could be necessary to include that issue and improve the comparison.

4.6.2. Naturalness Evolution through Time

Results from the Naturalness Assessment Model can be applied to the conceptual time frame of the evolution of land quality with land use intervention generally applied in LCA (Milà i Canals et al. 2007) (Figure 4.5), considering that the reference state (Qref) corresponds to the natural state (NI=1). The reference time considered in this study refers to the pre-industrial state, characterized by the spruce budworm epidemics prevailing every 30–40 years in the balsam fir forests (Morin et al. 2008). The first cutting cycle (from t_0 to t_1) corresponds to the transformation phase causing the initial decrease in ecosystem quality, which is progressive in forestry, as shown with the assessment performed in the three Forest Management Units in the *Picea mariana*–feathermoss domain (Côté et al. 2019). For a given management strategy, the subsequent rotations (from t_1 to t_2) cause further degradation, but this is relatively less important than the impact resulting from the initial transformation (Côté et al. 2019). For FM-A and FM-B, as no data was available for t_1, the same level of naturalness after the first cutting cycle has been assumed. FM-B shows a current naturalness index lower than FM-A, which can be related to the forest management regime applied up to now. Evolution during the sustainable management phase depends upon the forest management scenario applied, and can be further degraded or improved, depending on the forest management strategy, as schematized. A full rotation is necessary to reach the naturalness level evaluated for a given scenario (prior to that, the evaluation would include a part of the previous forest management strategy). Therefore, in order to compare different scenarios, the scenario evaluation must be performed as if the scenario would have been applied over the entire productive area, covering a whole cutting cycle. The conceptual framework for the evolution of ecosystem quality (Milà i Canals et al. 2007) considers an hypothetical relaxation of the land use (at t_2), and a progressive return to a level corresponding to the potential natural vegetation (Q_{PNV}). The level of quality after relax (Q_{PNV}) depends not only on natural vegetation dynamics, but could also be affected by the permanent impact related to practices applied in the past (for example, the introduction of exotic species, disappeared species, forest drainage, etc.). When the land has been used for an extended period of time ($t_2 >>> t_1$), the natural reference could not be appropriate, the PNV represents an alternative (Milà i Canals et al. 2014). Our evaluation uses historic pre-industrial data as reference, data from secondary forest to quantify the impact of the silvicultural treatments, and to adjust data for protection to reflect their localization in previously harvested sectors by lowering the proportion of *Picea* spp. However, scenario assessments do not consider future changes resulting from other causes, such as pollution, natural disturbance regime modification related to climate change or other modification of pressures.

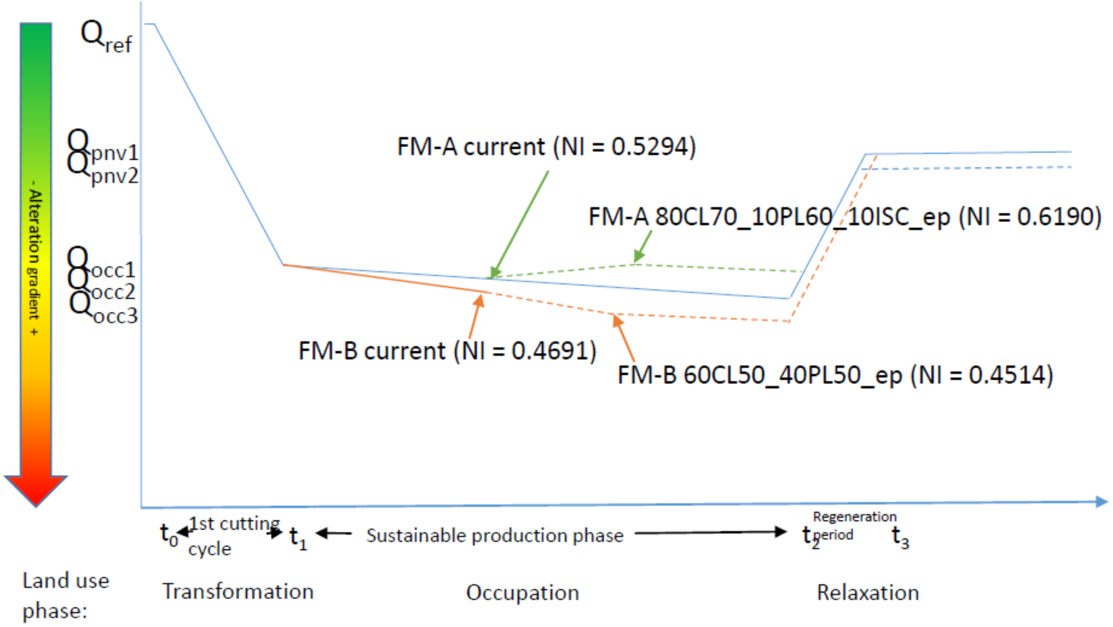


Figure 4.5: Ecosystem quality evolution thru time. Qref: Quality at the reference state (natural); Q_{PNV} : Quality of the Potential Natural Vegetation that have been regenerated after land use; $Q_{PNV}1$: with low permanent impacts; $Q_{PNV}2$: with higher permanent impact; Qocc: Quality during occupation phase; Qocc1: for the scenario with the lower impact; Qocc2: for the mid-impact scenario; Qocc3: for the lower impact scenario; FM-A 80CL70_10PL60_10ISC_ep: scenario for FM-A figuring 80% of the productive area in clearcut careful logging on a rotation of 70 years, plus 10% in plantation on a 60 years rotation and 10% subject to irregular shelterwood cutting, with the enhanced level of protection; FM-B 60CL50_40PL50_ep: scenario for FM-B figuring 60% of the productive area in clearcut careful logging on a rotation of 50 years, and 40% in plantation on a 50 years rotation, with the enhanced level of protection; NI : Naturalness index.

4.6.3. Scenario Comparison

The model is used to express the impact level on the environment along a single alteration gradient. Though the choice of the reference data set used to parametrize the curves for condition_pni evaluation might influence the fine ranking of the forestry management practices, in the studied case, the scenarios that could improve naturalness were identified with a good level of confidence.

Among the practices considered, with the hypotheses used, the enhancement of protection combined with the use of ISC provided the best naturalness index scores. Conversely, practices involving short rotation (50 years) lead to the lowest scores. The scenarios are generally leading to the semi-natural range. Reaching of the quasi-natural level is associated with the use of irregular shelterwood cutting (ISC); a proportion close to 100% would be necessary with the initial level of protection. With an enhanced level of protection, the quasi-natural level could be attained when combining CL70 without plantations with at least 30% ISC in FM-A, and at least 40% ISC in FM-B.

On the opposite side of the alteration gradient, with the current level of protection of 13.3% of the forested area in FM-B, the scenario considering clearcuts with a rotation of 50 years (CL50), with or without plantation, would produce an altered level, indicating a potential loss of species, according to the model (Côté et al. 2019). In FM-A, with a current level of protection of 24.4% of the forested area, the CL50 scenario with up to 10% PL60 would produce an altered level; scenarios with CL50 combined with more PL60 would also score close to the altered level. The results show the important role of protection in mitigating forest management effects, from the perspective of limiting the negative effects on biodiversity.

According to our results, most forest regimes involving a combination of practices (excluding the use of exotic species) applied on a sustainable basis, combined with a significant level of protection (around 30%), would lead to the semi-natural class. However, in FM-B, with a lower naturalness index (NI = 0.4713) compared with FM-A (NI = 0.5294), the threatened boreal caribou has declining populations, though the decline causes are manifold, and result from interacting factors (Leblond et al. 2016; MFFP 2019). However, in FM-B, where precommercial thinnings were performed over 23.4% of the forested area, the habitat quality of the snowshoe hare, a keystone species in this boreal forest, has been affected; however, effects on populations dynamic depend on multiple factors and are subject to time lag (Kawaguchi & Desrochers 2018).

Our results underline the need for the development of more comprehensive biodiversity indicators that can capture other effects than species loss. The impact on biodiversity of different forest regimes including an important proportion of protection (30%) is related to the impact on species assemblage and populations, rather than to species loss, with the latter being restricted to very specialized and sensitive species. In this respect, a study based on time series showed that changes in assemblage composition has been widespread over the last 40 years, but there was no impact on the number of species (Dornelas et al. 2014). In the *Abies balsamea–Betula papyrifera* forest of low and high altitude, the assemblage of bird species evolves with the vegetation succession (Morin et al. 2008). In FM-B, old growth and senescent forests, which are waning, harbor specialized communities of invascular species (Milà i Canals et al. 2014). In fact, biodiversity issues recognized for the area are mainly related to species associated with old growth and senescent forests or some of their particular features (e.g., dead wood) (MFFP 2019). This situation raises the issue of the appropriate biodiversity indicators in LCA, for land uses have a low impact where biodiversity erosion is slow, and do not necessarily result in species loss, in comparison with other land uses causing a drastic change of habitat and observable loss of species richness. The model could thus be used to refine the ecosystem quality assessment in a more comprehensive way than the use of the five naturalness classes.

A test on the scenarios confirms the model's capacity of performing bi-directional assessment to satisfy the need of assessing restoration efforts. However, the effects on biodiversity of enhanced forest management strategies and restoration depend not only on the restored presence of essential habitat features, but also the duration of prior intensive management application (Kouki et al. 2012). This poses another challenge associated with the use of biodiversity as an indicator of ecosystem quality, as proposed for LCA (Jolliet et al. 2018).

Despite over 20 years of research on how to include man-made impacts on biodiversity in LCA, no comprehensive biodiversity impact assessment has been performed so far (Winter et al. 2017). In LCA, pressures on biodiversity resulting from land use can be represented as a midpoint impact category, whereas biodiversity in general corresponds to an endpoint category related to ecosystem health (Winter et al. 2017). The naturalness assessment model evaluated in this research work could be used as a midpoint level indicator to evaluate the pressure of forestry management practices on ecosystem quality. However, linking such a naturalness index with the endpoint biodiversity indicator, representing the potential loss of species as currently used in LCA, is reductive, as it fails to capture other factors influencing ecosystem health, such as species assemblages and populations. Ideally, other earlier warning biodiversity indicators, such as populations of sensitive species, should be taken into account.

4.6.4. Recommendations for Model's Improvement

As highlighted by the present exercise, here are some recommendations for further use of the model for naturalness assessment:

- Historical data should be accurate to avoid bias;

- Historical data should include an estimation of the natural variability to improve the setting of the pni's evaluation curves;
- Historical data acquisition must match the method used for current evaluation. In the case of methodology improvements—as seen with internal structure evaluation subject to recent technical evolution, or with the new method developed in Quebec's forest inventory for species group identification by 10% of basal area, which would have been appropriate to evaluate the current importance of the white spruce in the stands—the historical data should be accordingly reassessed if possible;
- Improve NDP factors evaluation as these are used to evaluate model's most sensitive variables;
- Improve the hypotheses used for projection of scenario components on a sustainable basis, considering that the model is applied over the whole landscape (not only on the most important ecological types), as some marginal types in terms of area, such as wetlands, could be important for biodiversity;
- Improve the hypotheses used for natural evolution considering that some condition indicators will probably not recover their initial status as a result of past management practices (e.g., some protected area are created in areas which have been subject to harvest in the past) and climate change;
- Explore the inclusion of variables characterizing landscape configuration and connectivity (Kuipers et al. 2019) in the landscape context.

Tests performed on *Picea* spp. proportion in plantations points to a limit of the model, when using a general indicator, such as the proportion of merchantable volume in spruce, instead of an indicator that would capture the subdominant status of the characteristic late successional companion species.

There is a certain level of uncertainty related to climate change and its potential effects on the natural disturbance regime, which we did not take into account in this study.

Naturalness evaluation should be extended to reach a scale more suitable for LCA. This could be done either by assessing other management units within the same bioclimatic domain (MFFP 2020) (which could also provide a better evaluation of the variability), or be performed at the scale of the bioclimatic sub-domain, depending on the scale of the available data.

Additional research efforts should be dedicated on expanding the assessment on ecosystem alteration levels beyond the sole forestry land use.

4.7. Conclusions

This study has applied a model assessing the impact on ecosystem quality of different forestry management practices through a naturalness index over two regions in Québec. The most sensitive variables for the current naturalness assessment correspond to the regeneration process, the cover type, the dead wood and the closed forest for both territories. The results show the capacity of the naturalness assessment model to perform bi-directional evaluation, assessing not only deterioration, but also improvement of ecosystem quality related to different enhanced ecological management strategies and restoration efforts. In the *Abies balsamea–Betula papyrifera* forest, scenarios that include irregular shelterwood combined with enhanced protection could play an important role in improving ecosystem quality, whereas scenarios applying short rotation (50 years) could lead to further deterioration. Provided that an enhanced protection level is assured, most management scenarios among those tested would produce a semi-natural environment. The model allows adequate forest management scenarios ranking within the different naturalness classes, leading to a finer characterization of the impact of forestry on ecosystem quality. However, the accuracy of historical reference data is important for a fine characterization of the impact, compared with the assessment of the current state of the forest. As most of the results lie in the semi-natural class with an enhanced level of protection, the effects on biodiversity could be mainly related to impacts on species assemblages and populations of species, but not necessarily leading to species losses. This still needs to be better studied.

4.8. Acronyms

ANT: Anthropization

ANT_NDP: Naturalness degradation potential from anthropization

CF: Close forests

CF_pni: partial naturalness for close forests

CL: careful clearcut logging

Compo: composition

Compo_PNI: Partial naturalness for composition

Context: landscape context

Context_PNI: Partial naturalness for landscape context

CS: Companion species

CS_NDP: Naturalness degradation potential related to companion species

CT: cover type

CT_pni: partial naturalness index for cover type

DW: dead wood

DW_NDP: Naturalness degradation potential related to dead wood

DW_PNI: Partial naturalness index for dead wood

ep: enhanced protection

exo: exotic species

exo_NDP: Naturalness degradation potential from exotic species

for_area: forest or forested area

HS: horizontal structure

HS_NDP: Naturalness degradation potential related to horizontal structure

ip: initial level of protection

IR: irregular stands

IR_pni: Partial naturalness index for irregular stands

ISC: irregular shelterwood cutting

LCA: Life cycle analysis

LS: Late successional characteristic species (i. e. *Picea* spp.)

LS_pni: Partial naturalness index for late sucessionnal characteristic species

NDP: Naturalness degradation potential

NE: natural evolution

NI: Naturalness Index

OF: Old forests

OF_pni: Partial naturalness index for old forests

PL: Plantation

PNI: Partial naturalness index for a given characteristic of naturalness (characteristic_PNI)

Pni: Partial naturalness index for a given condition indicator (condition_pni)

Prod_area: productive area

RP: regeneration process

RP_NDP: Naturalness degradation potential related to regeneration process

Struc: Structure

Struc_PNI: Partial naturalness index for structure

W_CC: Clearcuts on wetlands

W_CC_NDP: Naturalness degradation potential related to clearcuts on wetlands

Wm: Modified wetlands

Wm_NDP: Naturalness degradation potential related to modified wetlands.

Supplementary Materials: The following is available online at http://www.mdpi.com/1999-4907/11/5/601/s1, Results: Scenario_nb_description: scenario numbering and description; ass_1 and Figure S1: Naturalness assessment for scenarios with enhanced protection (ep) using studies for reference data set; ass_2 and Figure S2: Naturalness assessment for scenarios with enhanced protection (ep) using registry as reference data set; ass_3 and Figure S3: Naturalness assessment for scenarios with initial protection (ip) using studies for reference data set; ass_4 and Figure S4: Naturalness assessment for scenarios with enhanced protection (ep) and PL50 using studies for reference data set; ass_5 and Figure S5: Naturalness assessment for scenarios with initial protection (ip) and PL50 using studies for reference data set; ass_6 and Figure S6: Naturalness assessment for scenarios with enhanced protection (ep) and PL50 with 90% of spruce at maturity using studies for reference data set; ass_7 and Figure S7: Naturalness assessment for scenarios with enhanced protection (ep) and alternate set of NDP factors using studies for reference data set; sensitivity_analysis: results of sensitivity analysis for scenario involving 100% of each practice tested.

Author Contributions: conceptualization, S.C. and L.B.; methodology, S.C. and L.B.; validation, S.C.; formal analysis, S.C.; investigation, S.C.; resources, R.B.; data curation, S.C. and E.T. for dead wood.; writing—original draft preparation, S.C.; writing—review and editing, S.C., L.B., M.M., R.B. and E.T.; visualization, S.C.; supervision, R.B., L.B. and M.M.; project administration, R.B. and M.M.; funding acquisition, M.M. and E.T.

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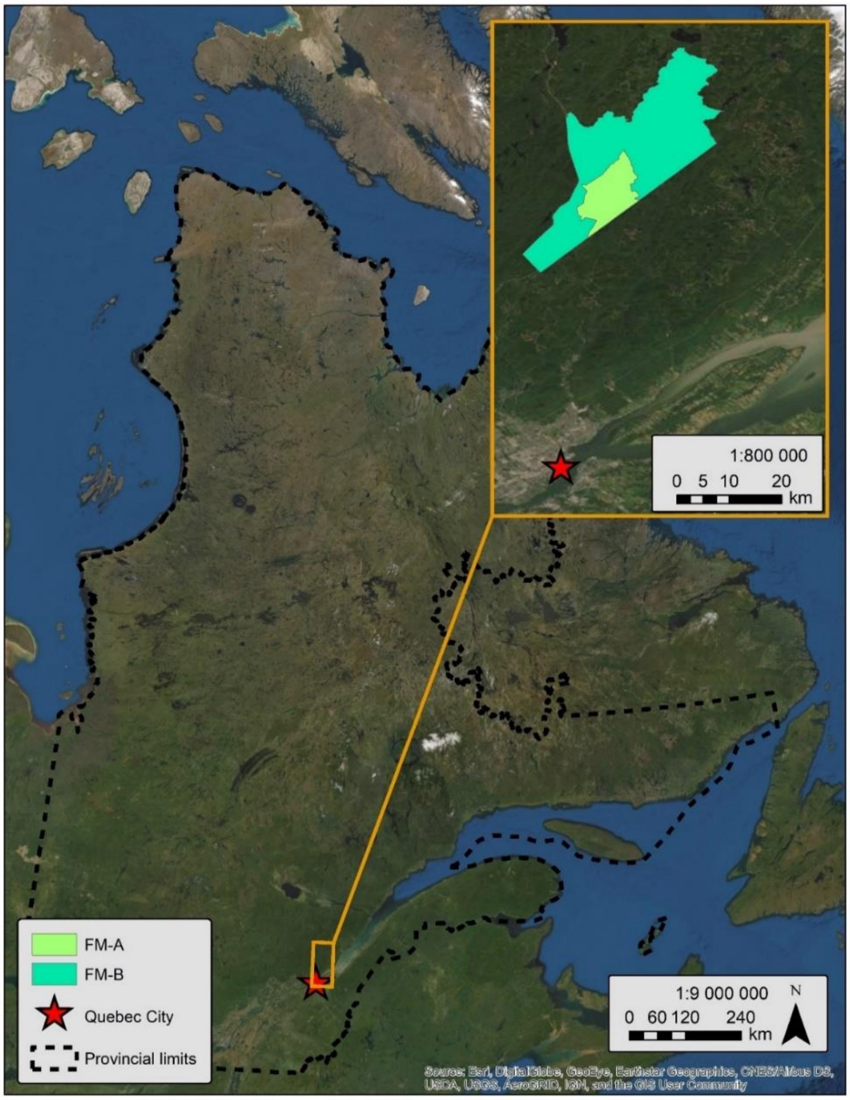
Appendix 4.A: Model adaptation to Abies balsamea–Betula papyrifera *domain*

Test Area Description and Localization

The territory of the Montmorency Experimental Forest, located north of Quebec City and included in the *Abies balsamea–Betula papyrifera* domain, was used as a test area (Figure 4.A1). Most of the current territory of the Experimental Forest was part of a forest concession allocated to the Anglo Canadian Pulp and Paper company in 1926. The territory has been subject to a first commercial harvest in the 1930s and 1940s. At the time of its creation in 1963, the experimental forest covered a total area of 66 km^2, now designated as FM-A. In 2014, an adjacent territory of 348 km^2, formally part of a public forest management unit with a forest company, has been added to the Experimental Research station and is now designated as FM-B. Therefore, between the 1960s and the beginning of 2010s, the two territories were subject to two different management scenarios. In FM-A, small-scale commercial harvest was continuous since the mid-1960s, while in FM-B, the territory has been subject to a second wave of harvest between 1985 and 2008. At the time of its creation, FM-A was poorly stocked as a result of the young age of the previously harvested stands. Therefore, the initial forest management plan for FM-A focused on the liquidation of the older stands as the harvest priority. Partial cutting was also performed on around 5.5% of the productive area in FM-A and 1.4% in FM-B. Plantations cover 6.8% and 8.8% of the productive area of FM-A and FM-B, respectively. Precommercial thinning has been performed over 9.2% of the productive area for FM-A compared to 23.4% for FM-B. At the time of its inclusion to the experimental station, most of FM-B had been recently harvested; parts of the remaining old forests were saved for protection.

The territory is subject to regular outbreaks of spruce budworm. Past management activities raised the following ecological issues in both territories: decrease of old forests, especially in FM-A, and overabundance of young forests, particularly in FM-B. Prior to the first harvest, stands were characterized by the presence of several old and large white spruce trees. The decrease of spruce in these stands resulting from the first commercial harvest has been described in an experimental design installed on the territory in the 1950s (Hatcher 1960). The remeasurement of some of these plots in the mid 1980s confirmed the scarcity of spruce among the pre-established regeneration of the second-growth forest; spruce regeneration was found only where adult individuals were present, related to residual small trees left at the time of harvest (Thiffault 2019). It also indicated a high risk of broadleaf invasion after clearcutting on the most fertile sites, as a result of the low abundance of coniferous seedlings combined with their small size (Déry et al. 2000; Thiffault 2019).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.A1: Montmorency Forest localization.

Model adaptation to balsam fir-white birch domain

For the *Abies balsamea*–*Betula papyrifera* domain, the five naturalness characteristics of the model were evaluated using the same indicators and variables used for the *Picea mariana*–feathermoss domain of the Quebec's boreal forest (Côté et al. 2019), except for composition (Table 4.1). In this case, the decreasing late successional species (LS) are the spruce species. In *Abies balsamea*–*Betula papyrifera* domain, black spruce (*Picea mariana*) can be dominant on humid stations, but white spruce is a companion species, and has not been quantified at the stand level in the historical data. The percentage of merchantable volume of spruce species for late successional characteristic species was used to assess its presence. However, this measure does not allow controlling for the companion status of the white spruce. As no other companion trees species presents signs of reduction and exotic species were never used in Montmorency Forest, the corresponding values for naturalness degradation potential from exotic species (exo_NDP) and naturalness degradation potential related to companion species diminution (CS_NDP) are set to 0. We kept these variables in the Forest Composition formula (Table 4.1), despite their null effect for the time being, making provision for future assessment.

Determining condition indicator curves

Assessing naturalness requires definition of a reference state of the condition indicators, i.e., the natural undisturbed habitat (Winter 2012). For Quebec's context, the model application requires pre-industrial data, which can be found in local studies or in the Quebec's reference state registry (Boucher et al. 2011). We tested both sources of reference data in order to analyze the sensitivity to the historical data set. Model adaptation involves resetting the curves used for partial naturalness index of condition indicators, corresponding to variables related to "pni" in lower cases in the Table 4.1 equations, using historical values considered valid for the territory. For the original evaluation, reference data used for naturalness assessment were drawn from studies performed in the vicinity of Montmorency Forest (Leblanc & Bélanger 2000; Boucher & Grondin 2012; Bouliane et al. 2014) (lines –s in Table 4.A1). However, in cases where historical information is not available, studies based on forest dynamic simulation, such as Quebec's reference state registry (Boucher et al. 2011), can be used as an alternate source of historical data. The registry provides reference values for cover types, irregular stands, closed and old forests by homogenous vegetation regions. For the evaluation based on the registry, values for our two sectors were obtained by weighing by the area proportion in each vegetation unit and were used to reset the condition_pni curves accordingly. Compared with the reference data set from studies, the data set from the registry shows, for both territories, less of the coniferous cover type (below current coverage), but a more important coverage of closed forests, old forests and irregular stands (lines –r in Table 4.A1). The spruce proportion was not evaluated in the registry data set; therefore, the same proportion used for the initial assessment was applied for the test using registry's data.

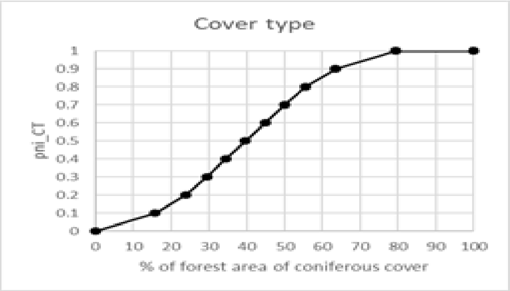
Data used for current naturalness evaluation were taken from the 2018 version of the Quebec eco-forest map (MFFP 2018), except for *Picea* spp. volume proportion (Urli et al. 2017).

Table 4.A1: Historical values from studies (s) in Forest Montmorency vicinity or reference state registry (r) used as reference data, and current values from 2018 eco-forest map.

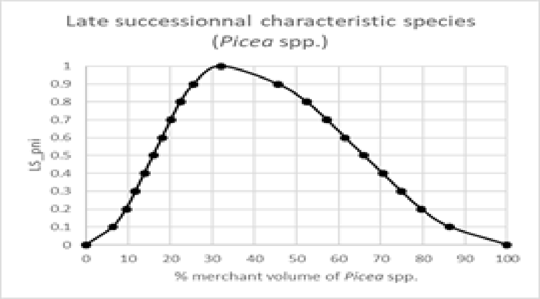
Territory	**Cover Type** (CT: % Forest Area of Coniferous Cover Type)	**Late Successional Species** (LS: % Merchantable Volume in *Picea* spp.)	**Closed Forests** (CF: % Terrestrial Area of Forests > 40 Years old)	**Old Forests** (OF: % Forest Area of Forests > 80 Years Old)	**Irregular Stands** (IR: % Forest Area of Irregular Stands)
FM-A – historical-s	79.3 [1]	32 [2]	79.9 [1]	23.7 [1]	17.8 [1]
FM-A – historical-r	63.2	32 [2]	85.5	71.0	51.1
FM-A – current	79.1 [3]	16 [4]	39.1 [3]	4.9 [3]	14.2 [3]
FM-B – historical-s	85.7 [5]	39 [2]	76.19 [1]	57.9 [6]	40 [7]
FM-B – historical-r	77.8	39 [2]	90.5	81.1	64.4
FM-B – current	81.9 [3]	16	27.4 [3]	16.1 [3]	18.3 [3]

FM-A: Montmorency Forest sector a; FM-B: Montmorency Forest sector b;[1] (Leblanc & Bélanger 2000); [2] (Bouliane et al. 2014); [3] Eco-forest map; [4] (Urli et al. 2017); [5] Anglo's data in (Leblanc & Bélanger 2000); [6] (Boucher & Grondin 2012); [7] Donnacona's data in (Leblanc & Bélanger 2000).

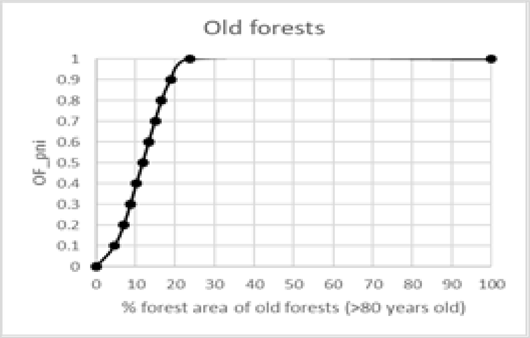
Curves used for the evaluation of partial naturalness index of condition indicators evaluation using local studies for reference data are presented in Figure 4.A2 for FM-A and Figure 4.A3 for FM-B. The curves were topped to one for irregular stands (IR), old forests (OF) and coniferous cover type (CT) for the following reasons. Descending curve past the historical value has not been used for IR, because of the evolving evaluation of stands with irregular structure related to improvements of technological identification capacities. For OF, the natural variability is important, as a result of spruce budworm epidemics, and the proportion used as the historical value is based on aerial photography taken around 20 years after an epidemic (Leblanc & Bélanger 2000); the ratio used as the historical value is therefore conservative and values over that ratio are considered natural. The cover type in the Forest Montmorency area was mainly coniferous, and the presence of deciduous cover was related to previous fires and showed an important variability (Leblanc & Bélanger 2000). As the proportion of coniferous cover observed in the ancient forest could reach 97.8% (Leblanc & Bélanger 2000), the curve used for pni_CT evaluation was also topped to one. This could theoretically hinder a diagnosis of broadleaf species decrease; however, as no such issue has been identified for that area and no hypothesis used for scenario evaluation goes beyond this proportion, an adjustment for the curve end was not considered necessary. Nevertheless, this situation indicates that it could be appropriate to set both ends of the natural class, considering the natural variability range instead of using a proportion of a unique value. For late successional species (LS), we used the percentage of merchantable volume of spruce species, and descending the curve past the historical value was applied (Figure 4.A2b and 4.A3b), as too much spruce in the landscape would be outside of the natural range of variability.



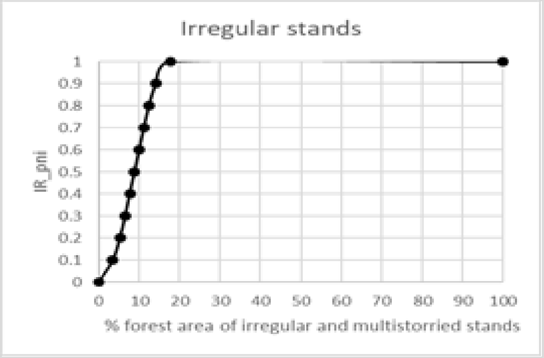
Historical proportion: 79.3% of coniferous cover
Current proportion: 79.1%
CT_pni = 0.998
(**a**)



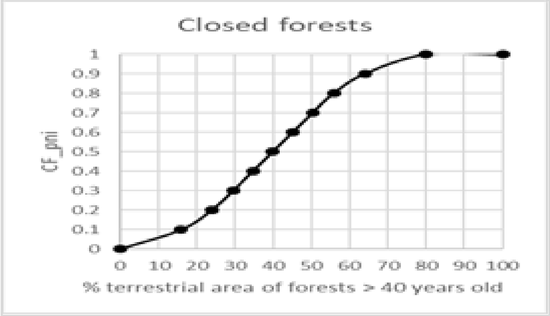
Historical proportion: 32% of *Picea* spp.
Current proportion: 16%
LS_pni = 0.500
(**b**)



Historical proportion: 23.7% of old forests
Current proportion: 4.9%
CF_pni = 0.106
(**c**)

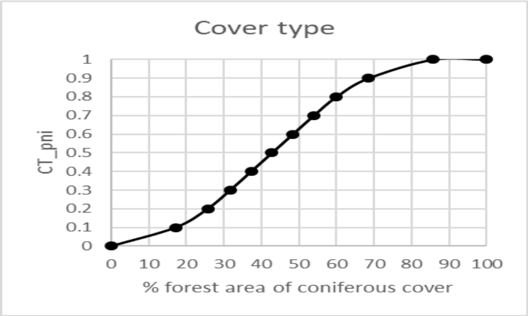


Historical proportion: 17.8% of irregular stands
Current proportion: 14.2%
IR_pni = 0.897
(**d**)

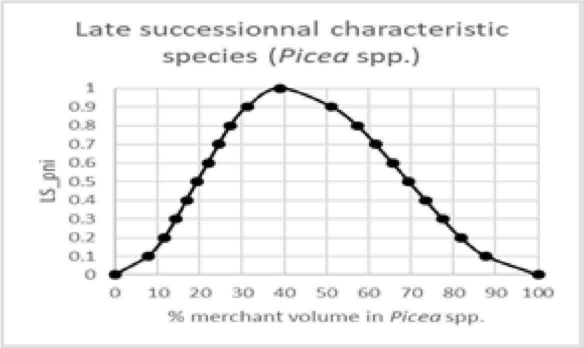


Historical proportion: 79.9% of closed forests
Current proportion: 39.1%
CF_pni = 0.484
(**e**)

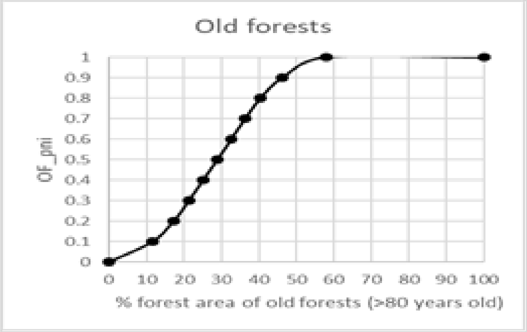
Figure 4.A2: Curves determining the potential naturalness index to evaluate the condition indicators (condition_pni) for FM-A using local studies for reference data: (a) coniferous cover type; (b) late successional characteristic species; (c) old forests; (d) irregular stands; (e) closed forests.



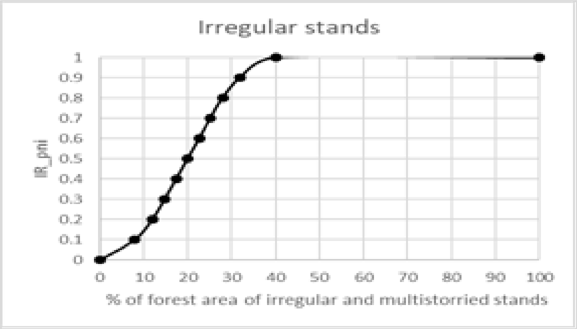
Historical proportion: 85.7% of coniferous cover
Current proportion: 81.9%
CT_pni = 1
(**a**)



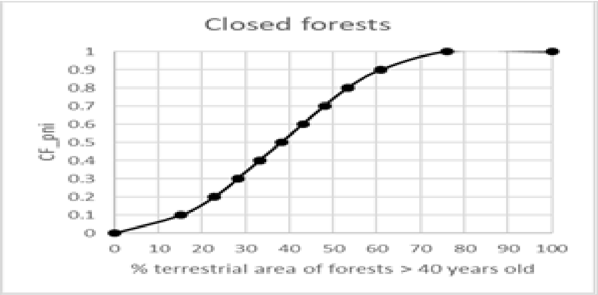
Historical proportion: 39% of *Picea* spp.
Current proportion: 16%
LS_pni = 0.362
(**b**)



Historical proportion: 57.9% of old forests
Current proportion: 16.1%
CF_pni = 0.178
(**c**)



Historical proportion: 40.0% of irregular stands
Current proportion: 18.3%
IR_pni = 0.435
(**d**)



Historical proportion: 76.2% of closed forests
Current proportion: 27.4%
CF_pni = 0.285
(**e**)

Figure 4.A3: Curves determining the potential naturalness index to evaluate the condition indicators (condition_pni) for FM-B using local studies for reference data: (a) coniferous cover type; (b) late successional characteristic species; (c) old forests; (d) irregular stands; (e) closed forests.

Determining the naturalness degradation potentials

The evaluation of naturalness degradation potentials (NDP) was adapted by resetting the NDP factors related to practices. NDP calculation for horizontal structure, dead wood and regeneration process are presented in Tables 4.A2–4.A4, respectively, for each territory. For careful logging effects, a distinction has been made between a CL performed in a 50-year-old stand (CL50) and a 70-year-old stand (CL70). Stands resulting from logging performed in 50-year-old stands were identified using an overlay of the eco-forest map and the SIFORT1 map, a tessellation of provincial forest inventory maps for the first measure, considering clear-cuts or careful logging performed between 1981 and 2002, located in sectors having a development stage designed as "young" at the time of the first forest inventory.

The others NDP factors evaluated based on current values and kept constant for all scenarios are showed in Table 4.A5.

Table 4.A2: Naturalness degradation potential for horizontal structure (HS_NDP) by silvicultural treatment in Montmorency Forest.

Territory:		**FM-A**		**FM-B**	
Practice	**NDP Factors**	**% Forest_Area**	**NDPx**	**% Forest_Area**	**NDPx**
Plantation - thinning	1	2.50%	0.0250	5.58%	0.0558
Plantation	0.9	4.32%	0.0388	3.21%	0.0289
Thinning (natural), strip cutting	0.8	1.45%	0.0116	0.17%	0.0014
Precom. thinning (natural), release	0.75	9.24%	0.0693	23.40%	0.1755
CL50	0.5	7.01%	0.0351	13.28%	0.0664
CL70	0.3	48.34%	0.1451	13.17%	0.0395
Partial cutting	0.2	5.48%	0.0110	1.38%	0.0028
Undisturbed or natural disturbances	0	21.64%	0.0000	39.80%	0.0000
Current HS_NDP			**0.3359**		**0.3702**

Note: NDP_factors: naturalness degradation potential factors related to practices; %for_area: percentage of forested area; NDPx: portion of the naturalness degradation potential for the xth practice; CL50: careful logging (CL) and clearcut of 50-year-old stands; CL70: careful logging (CL) and clearcut of 70-year-old stands.

Table 4.A3: Naturalness degradation potential for dead wood (DW_NDP) by silvicultural treatment in Montmorency Forest.

Territory:		**FM-A**		**FM-B**	
Practice	**NDP Factors**	**% Forest_Area**	**NDPx**	**% Forest_Area**	**NDPx**
Biomass harvesting	1	0.00%	0.0000	0	0.0000
Plantation + thinnings	0.95	2.50%	0.0237	5.58%	0.0530
Plantation – no thinnings	0.85	5.76%	0.0490	3.39%	0.0288
Partial cutting and precom. thinnings	0.8	14.72%	0.1178	24.78%	0.1983
CL50	0.7	7.01%	0.0491	13.28%	0.0930
CL70	0.55	48.35%	0.2660	13.17%	0.0725
Undisturbed or natural disturbances	0	21.64%	0.0000	39.80%	0.0000
DW_NDP			**0.5056**		**0.4454**
Current *DW_PNI*			**0.4944**		**0.5546**

Note: NDP_factors: naturalness degradation potential factors related to practices; %for_area: percentage of forested area; NDPx: portion of the naturalness degradation potential for the xth practice; CL50: careful logging (CL) and clearcut of 50 years old stands; CL70: careful logging (CL) and clearcut of 70-year-old stands.

Table 4.A4: Naturalness degradation potential for regeneration process (RP_NDP) by silvicultural treatment in Montmorency Forest.

Territory:		**FM-A**		**FM-B**	
Practice	**NDP Factors**	**% Forest_Area**	**NDPx**	**% Forest_Area**	**NDPx**
Exotic plantations, afforestation	1	0.00%	0.0000	0.00%	0.0000
Plantation	0.9	6.82%	0.0613	8.79%	0.0791
Seeding	0.7	2.78%	0.0195	0.00%	0.0000
Precommercial thinning	0.65	9.24%	0.0601	23.40%	0.1521
In-fill planting	0.6	2.48%	0.0149	0.00%	0.0000
CL50	0.5	4.53%	0.0226	13.28%	0.0664
Commercial thinning (natural)	0.4	1.45%	0.0058	0.17%	0.0007
CL70	0.35	45.58%	0.1595	13.17%	0.0461
Partial cut	0.2	5.48%	0.0110	1.38%	0.0028
Undisturbed or natural disturbances	0	21.64%	0.0000	39.80%	0.0000
RP_NDP			**0.3547**		**0.3472**
Current *RP_PNI*			**0.6453**		**0.6528**

Note: NDP_factors: naturalness degradation potential factors related to practices; %for_area: percentage of forested area; NDPx: portion of the naturalness degradation potential for the xth practice; CL50: careful logging (CL) and clearcut of 50-year-old stands; CL70: careful logging (CL) and clearcut of 70-year-old stands.

Table 4.A5: Naturalness degradation potential for companion species (CS_NDP), exotic species (exo_NDP), wetlands with clear cuts (W_CC_NDP) and anthropization (ANT_NDP) in Montmorency Forest.

Territory:	**FM-A**		**FM-B**	
Item	**% Area [1]**	**NDPx**	**% Area [1]**	**NDPx**
Companion species	0.00%	0.0000	0.00%	0.0000
Exotic species	0.00%	0.0000	0.00%	0.0000
Wetlands with clear cuts	42.37%	0.2118	2.66%	0.0133
Anthropization	1.72%	0.0172	2.68%	0.0268

[1] % of forested area for companion species and exotic species; % of terrestrial area for wetlands with clear cuts and anthropization.

Chapitre 5. Using naturalness for assessing the impact of forestry and protection on the quality of ecosystems in Life Cycle Assessment.

5.1 Résumé

Ce volet présente une évaluation des impacts de la foresterie sur la qualité des écosystèmes basé sur l'évaluation de la naturalité, considérant un gradient de protection appliqué concomitamment à trois scénarios sylvicoles pour la production de bois. L'indice de naturalité permet d'évaluer les besoins en protection en tenant compte du type d'aménagement appliqué pour la production de bois. Les résultats indiquent qu'il serait préférable pour l'environnement d'intensifier la production sur une proportion limitée du territoire tout en assurant une protection stricte sur la portion résiduelle, par rapport à un aménagement extensif appliqué sur la vaste majorité du territoire. Une courbe provisoire reliant l'indice de naturalité à la fraction d'espèces potentiellement disparue (PDF) est proposée. Les scores d'impact ACV en PDF pour produire 1m^3 de bois peuvent être cohérents avec ceux de naturalité, mais l'incertitude est élevée et la fenêtre permettant l'obtention de résultats cohérents est étroite.

5.2 Abstract

A novel approach is proposed to evaluate the impact of forestry on ecosystem quality in life cycle assessment (LCA) combining a naturalness assessment model with a species richness relationship. The approach is applied to a case study evaluating different forest management strategies involving concomitantly silvicultural scenarios (plantation only, careful logging only or the current mix of both) combined with an increasing share of protected area for wood production in the Québec black spruce forest. The naturalness index is useful to compare forest management scenarios and can help evaluate conservation needs considering the type of management foreseen for wood production. The results indicate that it is preferable to intensify forest management over a small proportion of the forest territory while ensuring strict protection over the remaining portion, compared to extensive forest management over most of the forested area. To explore naturalness introduction in LCA, a provisory curve relating the naturalness index (NI) with the potential disappeared fraction of species (PDF) was developed using species richness data from the literature. LCA impact scores in PDF for producing 1 m^3 of wood might lead to consistent results with the naturalness index but the uncertainty is high while the window leading to consistent results is narrow.

Keywords: life cycle assessment; ecosystem quality; naturalness; biodiversity; potential disappeared fraction of species (PDF); forest management intensity; forestry; protected area; protection target.

5.3 Introduction

Green building relies on quantitative tools such as life cycle analysis (LCA) to evaluate the environmental impact of alternative design choices, among them the supply of different building materials (Zabalza Bribián et al. 2011; Fouquet et al. 2015; Heeren et al. 2015; Anand & Amor 2017; Lessard et al. 2018), to support environmentally sound choices in the context of decision making based on scientific evidence (Souza et al. 2015). For harvested wood products, the impact on the ecosystem quality is influenced by forest management strategies, silvicultural practices and management intensity (Newbold et al. 2015; Barrette et al. 2020). Impact assessment of anthropic activities on ecosystem quality in LCA has been a subject of research for more than 20 years (Winter et al. 2017; Turner et al. 2019). According to LCA framework, the impact corresponds to the marginal change in ecosystem quality related to a given use of the land during a certain period of time (considered here on an annual basis), multiplied by the area required to produce the functional unit (Koellner et al. 2013), corresponding here to 1m^3 of wood used in building structure. These impacts are assumed to grow linearly with the quantity produced (Souza et al. 2015), whereas land use intensity should be related to impact using non-linear functions (Teixeira et al. 2016).

Anthropic activities and especially habitat change related to land use and land use change has caused losses of biodiversity and contributed to an unprecedented rate of species extinction (MEA 2005). Impact on ecosystem quality is expressed as the effects on biodiversity in the context of life cycle analysis (LCA) (Milà i Canals et al. 2007; Koellner et al. 2013; Verones et al. 2017). The Convention on Biological Diversity (CBD) states that "Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part, this includes diversity within species, between species and of ecosystems" (CBD 2006). Methods proposed for assessing biodiversity in LCA focus either on the species or ecosystem level, or both (Maier et al. 2019). Among the multitude of approaches experimented for ecosystem quality assessment, some propose the use of hemeroby classes as biodiversity indicator (Brentrup et al. 2002; Fehrenbach et al. 2015; Curran et al. 2016). Others use either biodiversity indicators (de Baan et al. 2013a; Chaudhary et al. 2016), or parametric functions relating the area used to diversity data based on a predefined mechanistic relationship describing an observed process (e.g. SAR: species area relationship) (Schryver et al. 2010; de Baan et al. 2013b).Some used models based on experts' judgement to assess biodiversity globally (e.g. variety of genes, species and ecosystems) (Lindner et al. 2014; Winter et al. 2018; Turner et al. 2019). Biodiversity losses in LCA is are expressed in potentially disappeared fraction of species (PDF) (Verones et al. 2017) as loss of species richness is generally the prevalent indicator used because of limited data availability (Curran et al. 2016; Teixeira et al. 2016). The use of species richness as a biodiversity indicator can lead to ambiguous conclusions, because an increase does not necessarily mean an enhanced biodiversity value, as some rare forest interior species are being replaced by more generalist and common species (Chaudhary et al. 2016). However, a reduction in species richness can safely be interpreted as a negative impact (Chaudhary et al. 2016). Despite the incompleteness of adopting species richness as the sole indicator (Teixeira et al. 2016; Winter et al. 2018), it still represents an appropriate starting point to model potential impacts on biodiversity in LCA models of impacts on biodiversity.

The approach actually proposed by the UNEP-SETAC initiative recommends the use of the SARc (species-area relationship for countryside) to evaluate the potential impacts of land use on biodiversity associated with species loss at the global scale. Chaudhary & Brooks (2018) proposed corresponding characterization factors for five land use and three land use intensities, providing results for five taxa. However, this approach is limited by its coverage of the management intensity (three classes only: minimal, light or intense) and the use of the species-area relationship (SAR) which relates the impact with the area of a given land use by adjusting the parameter of a power function (Gaudreault et al. 2020). Their results reflect the fact that species groups are differently affected by forest management, hence site specific assessments are still needed to characterize the effect on species at a local scale (Chaudhary et al. 2016; Gaudreault et al. 2020). Multiple species groups do not necessarily ease the interpretation of the results in the context of LCA, by raising questions about possible trade-offs (Gaudreault et al. 2020). Species based evaluation rely on data availability, which are limited for boreal forests (Alkemade et al. 2009; Newbold et al. 2016). Furthermore, biodiversity is subject to delayed responses (Brooks et al. 1999; Hanski 2005), while some practices are recognized to have negative effects even if the impact on biodiversity has not yet been quantified. These considerations explain why we favor focusing on the ecosystems themselves to evaluate the effects of forest management strategies considering different silvicultural scenarios. A forest management strategy corresponds to a plan of action or a policy designed to insure a major aim, here defined as sustainable timber production. Forest management strategy corresponds to a land-use decision. Silvicultural scenarios include forest regeneration methods such as plantation or careful logging. Silvicultural scenarios along with protection design are used in forest management strategies.

Though several methods have been proposed over time to measure impact on ecosystem quality in LCA (de Baan et al. 2013a; de Baan et al. 2013b; Chaudhary & Brooks 2018), these are still rarely used in Life Cycle Impact Assessment (LCIA) of products and processes (Maier et al. 2019). Improvements could be possible with a better consideration of specific impacts associated with the type of land-use and related management parameters and a better assessment of the land-use intensity (Maier et al. 2019). For forestry, different management strategies can be adopted (Hunter 1999), such as high-yield plantation silviculture, extensive forestry, multiple-use management or ecological forestry.

Setting aside areas for strict protection represents an important component of forest management strategies to prevent or limit biodiversity losses (Hunter 1999; Paillet et al. 2010; Gray et al. 2016; Dudley et al. 2018). Therefore, it would be of interest to analyze concomitantly the effects of a protection gradient with different silvicultural scenarios to assist forest management strategy elaboration and verify the possibility of including it in LCIA to support decision-making (Maier et al. 2019). Such a use of LCA results related to ecosystem quality is still restricted up to now, as LCA impact evaluation does not always lead to conclusions aligned with the ecosystem quality assessed. For example, Turner et al. (2019) found an LCA impact score lower for a forest management system based on pine plantations to produce softwood, compared with a native forestry system relying on partial cuttings, though the former was recognized as the one having the most negative impact on ecosystem quality. Another case using a SAR based approach, obtained results which were not always aligned with the existing scientific knowledge on biodiversity and forest management (Gaudreault et al. 2020). This situation is problematic as it can lead to inaccurate conclusions about management practices (Costanza 2020; Gaudreault et al. 2020).As stated by Michelsen et al. (2014), "*when different approaches give rise for different recommendations, the usefulness for decision-making will be questioned*". Therefore, it is important to examine the passage from an assessment of the impact on the ecosystem quality over a given territory to the LCA impact evaluation, which is calculating the impact per area required to produce one functional unit (i.e. 1 m^3 of wood for building structure).

We propose an approach to evaluate the potential impacts of forest management intensity on ecosystems based on the concept of naturalness. A naturalness assessment model has been designed for this purpose for boreal forests (Côté et al. 2019). Many authors have proposed to use the concepts of naturalness and hemeroby to evaluate impacts of land use, such as forestry, on the quality of ecosystems in LCA (Brentrup et al. 2002; Michelsen 2008; Fehrenbach et al. 2015; Farmery et al. 2017; Rossi et al. 2018). Naturalness is defined as "***the similarity of a current ecosystem state to its natural state***" (Winter 2012), whereas hemeroby expresses "***distance to nature***" in landscape ecology (Fehrenbach et al. 2015). The use of these concepts provides indexes to be used as guiding principles for forest management overcoming the challenge of gaps in obtaining empirical data on biodiversity. Côté et al. (2019)'s naturalness assessment model relies on forest inventory maps and data to compare the anticipated outcome of different forest management strategies including protection over a given territory (Côté et al. 2020).

This study aims at exploring the integration of the naturalness assessment results in a characterization model to evaluate ecosystem quality impacts of different forest management scenarios within the Life Cycle Analysis (LCA) framework, in order to verify its relevance for forest management decision-making. The specific objectives are to:

1) Establish the relationship between naturalness and species richness and expand the model developed by Côté et al. (2019) to express results in potential disappeared fraction of species (PDF);

2) Evaluate the effects on naturalness and PDF of increasing the share of protected area combined with different silvicultural scenarios and compare different forest management strategies in the Québec boreal forest;

3) Provide an example of LCA impact score calculation based on a naturalness assessment transformed in PDF to evaluate impacts on the quality of ecosystem of harvested wood products supplied from different forestry management practices in the LCA context.

5.4 Materials and Methods

5.4.1 Description of the Test Area and Forest Management Scenarios

5.4.1.1 Test Area

The test area is the same that has been used in Côté et al. (2019) and corresponds to a public forest formed by three forest management units (FMU) located in the western black spruce feathermoss bioclimatic sub-domain, near the locality of Chibougamau in Northern Quebec region (Appendix 5.A: Figure 5.A1).

The area arrangement considered for the 3FMU is presented in Figure 5.1. The share of protected area was applied on the available forested area (forested minus excluded), and practices related to wood procurement were applied over a given proportion of the productive area. Silvicultural scenario components must encompass 100% of the productive forested area. The excluded forested area (BFEC 2017) and the protected area were ascribed a natural evolution based on historical reference data (Appendix 5.A: Table 5.A1).

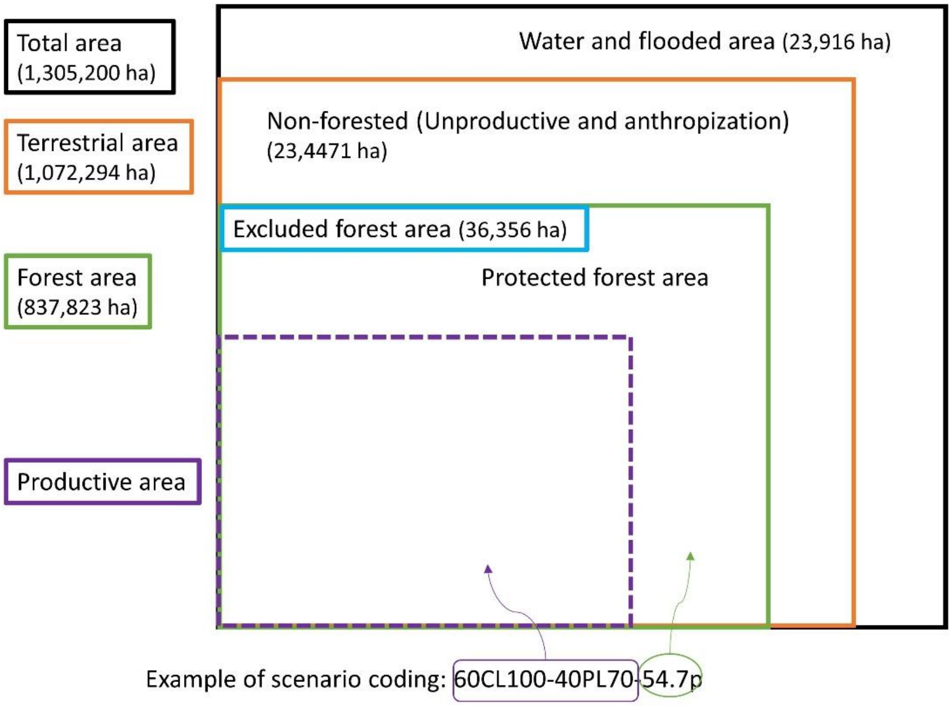


Figure 5.1: Typology of the territory: silvicultural components of the scenario are applied over the productive area and protection corresponds to the portion of forest area not excluded, nor used for wood production. Specified areas are those from the test area: FMU no 2663, 2665 and 2666 (BFEC 2017; MFFP 2018). Scenario coding: 60CL100-40PL70-54.7p: 60% of the productive area in careful logging with a rotation of 100 years, with 40% of the productive area in plantation on a rotation of 70 years, combined with 54.7% of the forest area in strict protection © Sylvie Côté, Laval University, 2021.

5.4.1.2 Management Scenarios and Strategies Tested

Three components were involved in the tested forest management strict protection, careful logging and plantation. Strict protection was defined as protected areas belonging to IUCN category I, II, or III (Dudley 2008). The practices considered for silvicultural scenarios applied in the productive area were careful clearcut logging (CL), which corresponds to clearcut with the protection of pre-established regeneration and soil as required by law for clearcut operations in Quebec (Harvey & Brais 2002) and forest plantation of indigenous species mechanically released (PL). To determine results at the landscape level, each silvicultural scenario, corresponding to the sequence of silvicultural interventions over time, were applied on a constant basis over a given proportion of the productive area. However, this exercise is highly theoretical, considering that in reality the different scenarios are adjusted through time. The impact of future fires was not taken into account here. Ecological effects of careful clearcut logging and plantations are detailed in Appendix 5.A.2

Three silvicultural scenarios were considered: (1) CL only: 100% in careful logging on a 100-year rotation (coded 100CL100); (2) Current Mix: 60% CL on a 100-year rotation combined with 40% PL on a 70-year rotation (coded 60CL100-40PL70); (3) PL only: 100% plantation on a 70-year rotation (coded 100PL70). The two 100% scenarios evaluate the maximal theoretical effect of each practice. Forest management scenario coding (Figure 5.1) details the percentage of productive area of each silvicultural component (CL or PL) specifying the related rotation length (PL70: plantation with a 70 year rotation) completed by the percentage of protected forest area (e.g., 17.9p: 17.9% of the forest area in strict protection).

A forest strategy corresponds to a plan of action or a policy designed to ensure a major aim, here defined as sustainable timber production. Two different forest management strategies were considered: 1) variable wood production over a fixed productive area, and 2) fixed wood production over a variable productive area completed with strict protection. The first strategy implies that each silvicultural scenario was applied over the current productive area, considering the current proportion in protection (17.9% of the forest area) and varying wood production. The second forest management strategy, considers intensifying wood production to increase area available for conservation but aims to produce the same volume from each of the three tested silvicultural scenarios. The area available for protection was computed as follows: forested area minus excluded area minus productive area necessary to produce the expected volume (Figure 5.1).

The effect of the level of protection was evaluated by the reassessment of the three silvicultural scenarios with an increasing proportion of forest area in protection, from 0% up to 90%, by steps of 5%. We used the proportion of forest area to control forest protection objectives so to not take into account unproductive areas that occupy a significant proportion of the territory (18% of the terrestrial area). We assumed that conservation plans consider ecosystem irreplaceability and vulnerability (Brooks et al. 2006).

5.4.2 Naturalness assessment

The impact of forest management scenarios involving several forestry practices on ecosystem quality was evaluated using the Naturalness Assessment Model developed for the *Picea mariana*–feathermoss ecological domain of Quebec (Côté et al. 2019). The naturalness assessment of forest management scenarios considered that the scenarios were being applied over the whole territory, as described in Côté et al. (2020).

The Côté et al. (2019) model evaluates five naturalness characteristics: landscape context, forest composition, structure, dead wood and regeneration process (Table 5.1). The model uses indicators of condition (closed forests for context; cover type and late successional species groups for composition; old forests and irregular stands for structure), which are assessed against historical values, and pressures indicators resulting from practices (anthropization, modified wetlands, clearcuts on wetlands, exotic species, companion species, horizontal structure, dead wood and regeneration process). The evaluation is realized in two steps (see Appendix 5.A for details). First, a partial naturalness index for each condition indicator (condition_pni: pni in lower case) is determined as a function of empirical curves relating measures (percentage of area) to condition_pni (Figure 5.A2) and naturalness degradation potentials (NDP) are evaluated through tables relating percentage of forest area by practices to NDP factors (Appendix 5.A: Tables 5.A2 and 5.A3). Second, the partial naturalness for each naturalness characteristic (characteristic_PNI: PNI in capital letters) is calculated using the corresponding equation as per Table 5.1. The final result, the naturalness index (NI), is obtained from the arithmetic mean of the five characteristic_PNI. For the full description of the method see Côté et al. (2019).

Table 5.1: Partial Naturalness Index equations for each naturalness characteristic (Characteristic_PNI) and naturalness index equation (source: (Côté et al. 2019)).

Naturalness Characteristic	**Characteristic_PNI Equation**
Landscape context	*Context_PNI = CF_pni × (1-(ant_NDP+Wm_NDP+W_CC_NDP))*
Forest Composition	*Compo_PNI = ((CT_pni+LS_pni)/2) × (1-(exo_NDP+CS_NDP))*
Structure	*Struc_PNI = ((OF_pni+IR_pni)/2) × (1-HS_NDP)*
Dead wood	*DW_PNI = 1-DW_NDP*
Regeneration process	*RP_PNI = 1-RP_NDP*
Naturalness index equation	NI = *1/5* × (*Context_PNI* + *Compo_PNI* + *Struc_PNI* + *DW_PNI* + *RP_PNI)*

PNI: partial naturalness index for each characteristic; pni: partial naturalness index for condition indicators; NDP: naturalness degradation potential; CF: closed forests; ant: anthropization; Wm: modified wetlands; W_CC: humid area in clearcut; CT: cover type; LS: late successional species; exo: exotic species; CS: companion species; OF: old forests; IR: irregular stands; HS: horizontal structure; DW: dead wood; RP: regeneration process; NI: naturalness index.

5.4.2.1 Expanding Naturalness to Species Richness Assessment

In LCA, it is proposed to express the impact of land use on ecosystem quality by the potential disappeared fraction of species (PDF) (Verones et al. 2017). The naturalness assessment model used in this study was expanded to estimate the anticipated effects on species richness, using global data. To do so, the five naturalness classes (by NI interval of 0.2) based on the conceptual model defined in Côté et al. (2019) were related to species richness data as per Figure 5.2, using data associated with land use characteristics corresponding to the pressure level (i.e.: primary vegetation – minimal, light or intense use; secondary vegetation – young, intermediate or mature – minimal or light/intense use; plantation forest – minimal, light or intense). Data were taken from PREDICTS data base (Hudson et al. 2017) and built on land use characteristics corresponding to different pressure levels based on 485 studies across the globe with available data of any taxon (Newbold et al. 2015). Species richness assessed in that study corresponds to the within-sample number of differently named taxa recorded at a given site. Values provided are expressed relatively to an un-impacted baseline (score of 100%), corresponding to complete naturalness. Species richness values from Newbold et al. (2015) were considered to be the biodiversity potential and correspond to (1-PDF). The PDF value for a given NI was computed using a linear estimation between established points of correspondence. The resulting curve (Figure 5.2) is provisional considering the global scale, the restricted representation of boreal forests in the database used and the necessity to quantify empirically the relationship between naturalness and PDF. This curve was used to calculate an impact score for LCA based on PDF derived from naturalness (NI).

The NI-PDF curve was given a concave shape (Figure 5.2) showing a decreasing PDF with a rising naturalness index. This corresponds to a growing negative effect (i.e., more species loss) as the pressure resulting from forest management for wood production rises, which is consistent with cumulative impacts related to multiple stressors, and effects accumulation over large areas and over time (Whitehead et al. 2017).

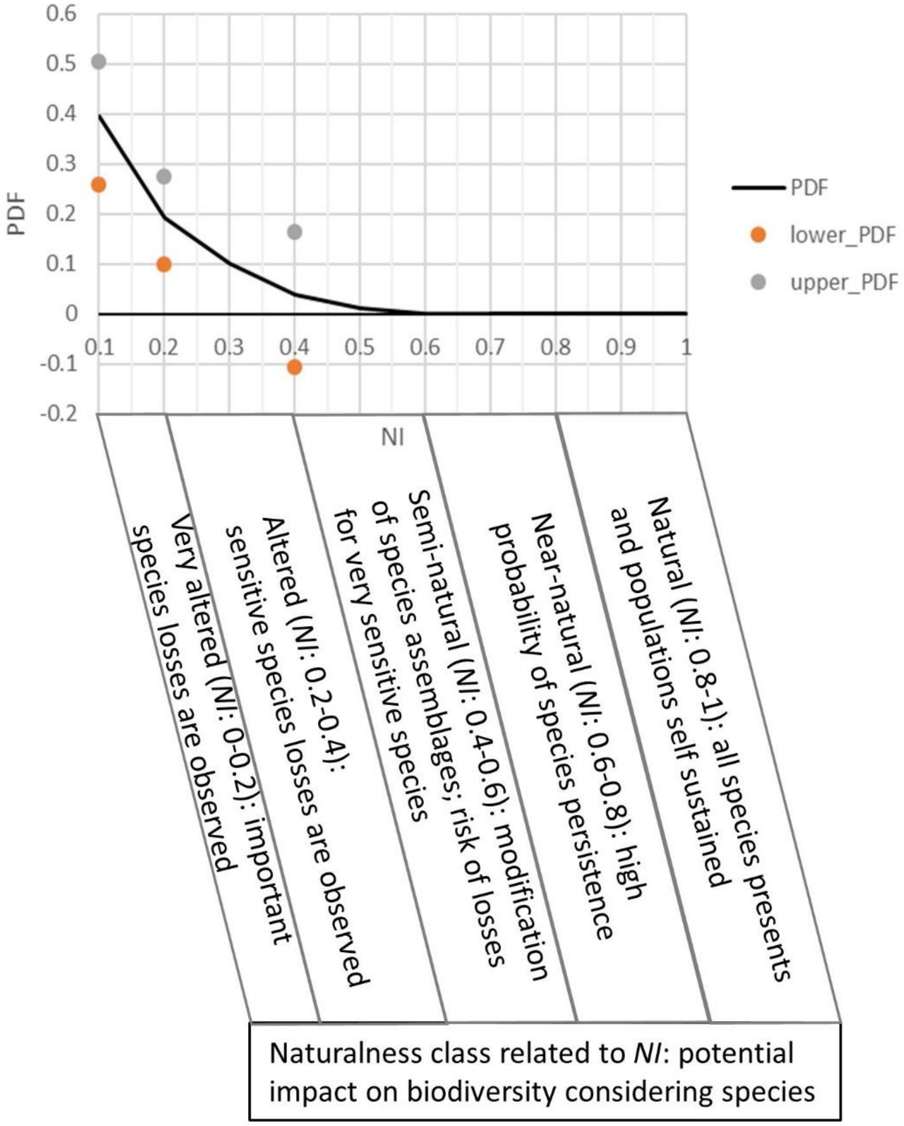


Figure 5.2: Provisional curve relating potential disappeared fraction of species (PDF) as a function of the naturalness index (NI). Lower and upper PDF corresponds to available confidence intervals limits (Newbold et al. 2015) © Sylvie Côté, Laval University, 2021.

We underline the high level of uncertainty of the NI-PDF curve resulting from the high variability of the available biodiversity data. Therefore, it should not be used as a basis for decision-making. However, we performed a sensitivity analysis of the curve setting using the mean, to explore what would be the effects of variations in corresponding values of PDF on the forest management scenarios assessment using LCA impact scores. The curve building procedure is detailed in Appendix 5.B and the alternative curve settings used for sensitivity analysis are detailed in the Appendix 5.C.

5.4.3 Life Cycle Assessment Framework of Land Use

According to the land use impact assessment framework in LCA, the impact score (IS) on ecosystem quality due to the land occupation by a given forest management was calculated as follow (Koellner et al. 2013):

$$IS = \Delta Q \times A \times T \tag{1}$$

Where ΔQ corresponds to the change in ecosystem quality, here assessed against to the natural situation, A corresponds to the area of land occupied (ha) and T the time of occupation (years). A × T typically represent the area-time of occupation related to the functional unit, e.g., the ha × years required to produce 1 m^3 of harvested wood product. ΔQ corresponds to the characterization factor and is computed by a given impact assessment methodology with its specific category indicator units.

The theoretical framework considers a sudden transformation of ecosystem quality from a land use to another (Milà i Canals et al. 2007). In reality, the initial transformation related to forestry is gradual at the scale of the whole productive area and will span over the length of the first cutting cycle (Côté et al. 2019). Land occupation for forestry scenario evaluation corresponds to the state of the ecosystem after the implementation of the production scenario over the entire productive area (Côté et al. 2020).

For our study, ΔQ was expressed as the potential disappeared fraction of species (PDF) (a dimensionless value between 0 and 1) and A × T was the terrestrial area required annually to produce 1 m^3 of wood (TAR) and corresponds to the life cycle inventory (LCI) data representing the flow for land occupation (Koellner et al. 2013). The TAR was based on yield hypothesis (see Appendix 5.A.4 for details) and the sensitivity of yield was evaluated by varying the respective scenario yields by ± 20%, for plantation and careful logging. The area needed each year for the production of 1m^3 is calculated over the terrestrial area as follows:

$$TAR = 1 \div (\textit{yield} \times \textit{productive area} \div \textit{terrestrial area}) \tag{2}$$

Where the yield related to each scenario component, expressed in (m^3/(ha productive × yr)), where yr = 1, was multiplied by the productive area to calculate the annual harvest in (m^3/yr), which was then divided by the terrestrial area of the 3FMU to calculate the annual harvest related to the total terrestrial area in (m^3/(ha terrestrial × yr)). For LCA, we need the area required for the production of 1 functional unit defined here as 1 m^3 of wood. Applying the rule of three, the inverse (1/x) of the annual harvest related to the terrestrial area corresponds to the TAR (terrestrial area required annually to produce 1 m^3 of wood) and is expressed in ((ha terrestrial × yr)/m^3), where yr = 1 and m^3 = 1.

Therefore, the LCA impact score (IS) corresponds to:

$$IS \text{ (PDF x ha\_ter x yr/m}^3\text{)} = PDF \times TAR \text{ (ha\_ter x yr/m}^3\text{)} \quad (3)$$

Where yr = 1 and m^3 = 1.

5.5 Results

5.5.1 Naturalness Assessment Results on the Test Area

Considering a fixed productive area with varying wood production, the C*L only* scenario results in the highest naturalness, followed by the *Current Mix* and the *PL only* (Table 5.2; supported by detailed results in Supplementary Material, sheet “results_current_protection”). In comparison, the *PL only* silvicultural scenario has a positive effect on composition, but negative effects for the four others naturalness characteristics. A forest management strategy aimed at producing a maximum of wood over a given productive area results in a low level of naturalness. With 17.9% of the forest area in protection, regeneration through careful logging would produce 502 100 m^3/yr, leading to a naturalness index in the lower portion of the semi-natural class (NI = 0.470). With the same protection level, regeneration with indigenous species plantations would produce more wood (1 629 025 m^3/yr), but lead to an altered naturalness state (NI = 0.301)

Considering a fixed production of wood (502 100 m^3/yr), it would be possible to produce the same amount of wood with *PL only* over 28.3% of the forest area with the remaining 71.7% of the forest area in strict protection. Such a strategy would lead to a naturalness index in the higher portion of the near-natural class (NI = 0.746). Applying the current regeneration mix (60% careful logging and 40% plantation) over 45.3% of the forest area while protecting the remaining 54.7% would lead to a naturalness index in the lower portion of the near-natural class (NI = 0.649). According to the conceptual model of the naturalness assessment model, there is a high probability of species persistence associated with the near-natural class (Figure 5.2).

Table 5.2: Naturalness assessment results for different management scenarios for two forest management strategies.

Management Strategy	**Fixed Productive Area with Varying Wood Production**			**Fixed Wood Production with Varying Productive Area**		
Management scenario	*CL only* 100CL100-17.9p)	*Current Mix* (60CL100-40-PL70-17.9p)	*PL only* (100PL70-17.9p)	*CL only* 100CL100-17.9p)	*Current Mix* (60CL100-40-PL70-54.7p)	*PL only* (100PL70-71.7p)
Annual Harvest (m^3/yr)	*502 100*	*952 870*	*1 629 025*	*502 100*	*502 100*	*502 100*
Productive area (ha)	*651 610*	*651 610*	*651 610*	*651 610*	*343 356*	*200 840*
Context_PNI	0.669	0.572	0.426	0.669	0.651	0.764
Compo_PNI	0.409	0.463	0.493	0.409	0.677	0.755
Struc_PNI	0.089	0.064	0.027	0.089	0.479	0.654
DW_PNI	0.494	0.401	0.261	0.494	0.684	0.772
RP_PNI	0.689	0.533	0.300	0.689	0.754	0.784
NI	0.470	0.407	0.301	0.470	0.649	0.746
Estimated PDF	0.012	0.035	0.099	0.012	0	0

PNI: partial naturalness index for naturalness characteristics Context: landscape context; Compo: forest composition; Struc: forest structure; DW: dead wood; RP: regeneration process; NI: naturalness index; PDF: potential disappeared fraction of species.

The naturalness assessment results expressed as a function of the level in strict protection show that the level of naturalness risies with an increase in the proportion of protected forest area (Figure 5.3; see detailed results in Supplementary Materials, sheet “NI-PDF_a”). The naturalness index of *CL only* without protection (NI = 0.414) is almost equivalent to the naturalness index resulting from *PL only* combined with 35% of the forest area in protection (NI = 0.408), or from the *Current Mix* combined with 20% of protection (NI = 0.417).

5.5.2 Transformation of NI to PDF

The transformation to PDF required for life cycle assessment has the following effects on the NI (Figure 5.3): 1) it reverses tendencies to express damages (with NI representing the state of “what is remaining”: PL only < Current Mix < CL only, while PDF represents “what is lost”:: *PL only* > *Current Mix* > *CL only*); 2) it narrows and reduces markedly the range of values (NI: 0.23-0.92; PDF: 0-0.16); 3) when increasing the protection level from 0% onwards, it reduces more rapidly the differences between silvicultural scenarios; 4) it sets all effects at 0 when above a certain level of protection.We adjusted a part of it by introducing infinitesimal values for PDF when NI lies in the near-natural class, but this does not affect the results and conclusions.

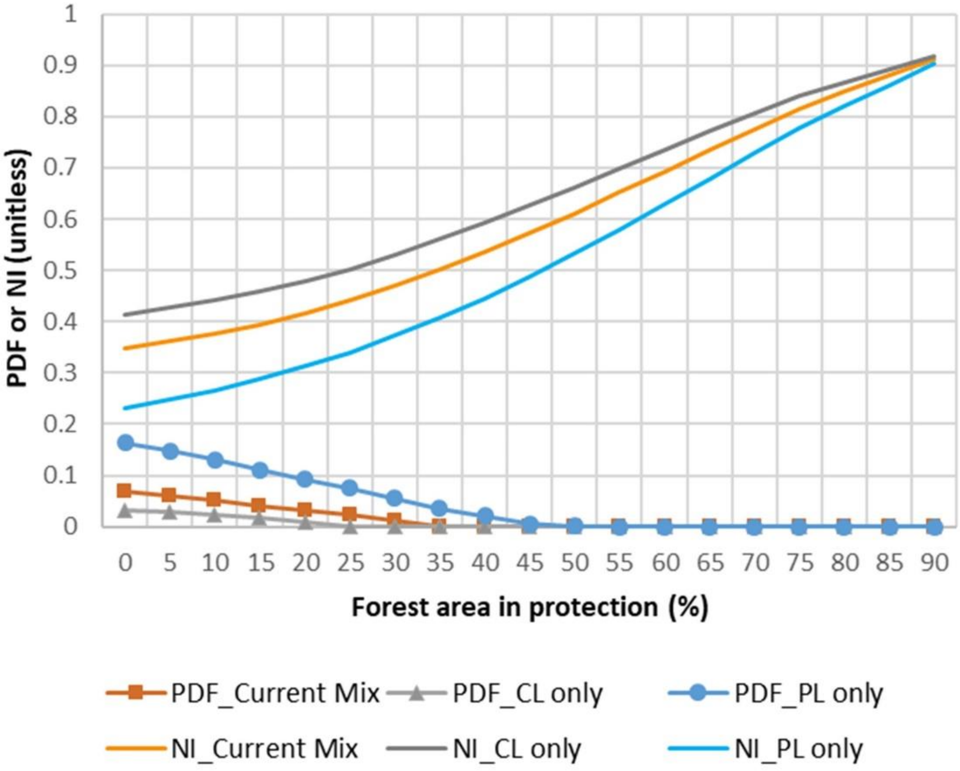


Figure 5.3: Naturalness index (NI) and potential disappeared fraction of species (PDF) as a function of the proportion of forest area in protection CL: careful logging; *PL*: plantation.

5.5.3 Life Cycle Assessment Results

Life cycle assessment results and related key input data are presented in Table 5.3 for the two forest management strategies, resulting from the combination of each of the three silvicultural scenarios assessed with the protection level required to achieve the objective of the strategy. Silvicultural scenario ranking results are summarized in Table 4 for each LCA parameter.

Table 5.3: Life cycle assessment results and related data for each scenario of the two evaluated forest management strategies.

Management strategy	Fixed Productive Area with Varying Wood Production			Fixed Wood Production with Varying Productive Area		
Management scenario	*CL only* 100CL100-17.9p)	*Current Mix* (60CL100-40-PL70-17.9p)	*PL only* (100PL70-17.9p)	*CL only* 100CL100-17.9p)	*Current Mix* (60CL100-40-PL70-54.7p)	*PL only* (100PL70-71.7p)
Mean productivity (m^3/ha_prod x yr)	0.77	1.462	2.5	0.77	1.462	2.5
Terrestrial area (ha_ter)	1 072 294	1 072 294	1 072 294	1 072 294	1 072 294	1 072 294
Productive area (ha_prod)	651 610	651 610	651 610	651 610	343 356	200 840
Excluded area (ha_for)	36 356	36 356	36 356	36 356	36 356	36 356
Protected area (ha_for)	149 856	149 856	149 856	149 856	458 111	600 626
Percentage protected (% ha_for)	17.9%	17.9%	17.9%	17.9%	54.7%	71.7%
Annual harvest (m^3)	502 100	952 870	1 629 025	502 100	502 100	502 100
TAR (ha_ter × yr/m^3)	2.136	1.125	0.658	2.136	2.136	2.136
Potential disappeared fraction of species (PDF)	0.012	0.035	0.099	0.012	0	0
Impact score (PDF × (ha_ter × yr)/m^3))	0.026	0.040	0.065	0.026	0	0

TAR: terrestrial area annually required to produce 1 m^3 of wood; PDF: potential disappeared fraction of species; Ha: hectares; ha_prod: productive area in hectares; ha_ter: terrestrial area in hectares; ha_for: forest area in hectares; yr: year; m^3: cubic meter of wood. Scenario coding: 60CL100-40PL70: *Current Mix*: 60% of the productive area in careful logging with a rotation of 100 years, with 40% of the productive area in plantation on a rotation of 70 years; 100CL100: *CL only*: 100% of the productive area in careful logging with a rotation of 100 years; 100PL70: *PL only*: 100% of the productive area in plantation with a rotation of 70 years.

Table 5.4. Scenario ranking results for each LCA parameter using the provisory NI-PDF curve.

Strategy/Parameter	PDF	TAR ((ha_ter × yr/m^3)	IS (PDF × (ha_ter × yr)/m^3))
Fixed productive area with varying wood production	PL > CM > CL	CL > CM > PL	PL > CM > CL
Fixed wood production with varying productive area	CL > CM = PL	CL = CM = PL	CL > CM = CL
Protection gradient	PL > CM > CL	CL > CM > PL	PL > CM > CL

NI: naturalness index; PDF: potentially disappeared fraction of species; TAR: terrestrial area annually required for the production of 1 m^3 of wood; IS: impact score; PL: *PLonly*; CM: *Current Mix*; CL: *CL only*.

For the strategy over a fixed productive area considering 17.9% of the forest area protected, the scenario ranking based on the PDF is the opposite of the TAR related ranking (Table 5.4). The strategy producing annually a fixed volume of 502 100 m^3 of wood, with the *CL only* scenario, requires 651 610 ha of productive forest, which leaves 149 856 ha available for protection corresponding to the current level of protection of 17.9% (Table 5.4). The same production of wood can be obtained with the *Current Mix* scenario combined with 54.7% of the forest area in protection or with the *PL only* scenario combined with 71.7% in protection. Therefore, producing the same volume of wood (502 100 m^3) over the same terrestrial area (1 072 294 ha) for the three management scenarios (each combining one silvicultural scenario with different percentage of area in strict protection) leads to the same value for the TAR (2.136 ha_ter × yr/m^3).

For the strategy over fixed area,,we observe that the impact scores are highly correlated to the PDF characterization factors and lead to the same ranking of management scenarios (Table 5.4), but show less difference between the scenarios compared with the PDF.(Table 5.3). For the fixed wood production strategy, it is not possible to discriminate between *Current Mix* and *PL only* based on PDF and LCA impact score results because of zero values.

The evaluation of silvicultural scenarios considering a protection gradient is illustrated in Figure 5.4. It presents the modeled relationships between the Impact scores (IS) and the potential disappeared fraction of species (PDF), the terrestrial area annually required (TAR) to produce 1 m^3 of wood and the proportion of the forest area in protection. The PDF characterization factor is illustrated along the protection level using the solid chart bars associated with the left axis. The TAR is illustrated along the protection level using the empty chart bars associated with the right axis. The impact score, which corresponds to the multiplication of the PDF with the TAR, is illustrated with the lines associated with the left axis.

The results along the protection gradient show a nonlinear relationship between the level of protection and the TAR (Figure 5.4). The shape corresponds to the inverse function of the land productivity resulting in the area required to produce 1 m^3 of wood (as per Eq. 2). The TAR results display a wide range varying between 0.53 and 9.04 ha_ter × yr/m3 for *PL only*, between 0.92 and 15.47 ha_ter × yr/m3 for the *Current Mix*, and between 1.74 up to 29.4 ha_ter × yr/m3 for *CL only* (see Supplementary Materials for detailed results). The PDF results expressed as a function of the level in protection show a decrease in the PDF as the proportion of protected forest area in protection increases (Figure 5.4). For *CL only*, the PDF results varies between 0 and 0.033, between 0 and 0.070 for the *Current Mix*, and between 0 and 0.1638 for *PL only*. The TAR and the PDF show opposite effects (Figure 4), as well as opposite scenario ranking (Table 5.4). The impact score ranking corresponds to the PDF one.

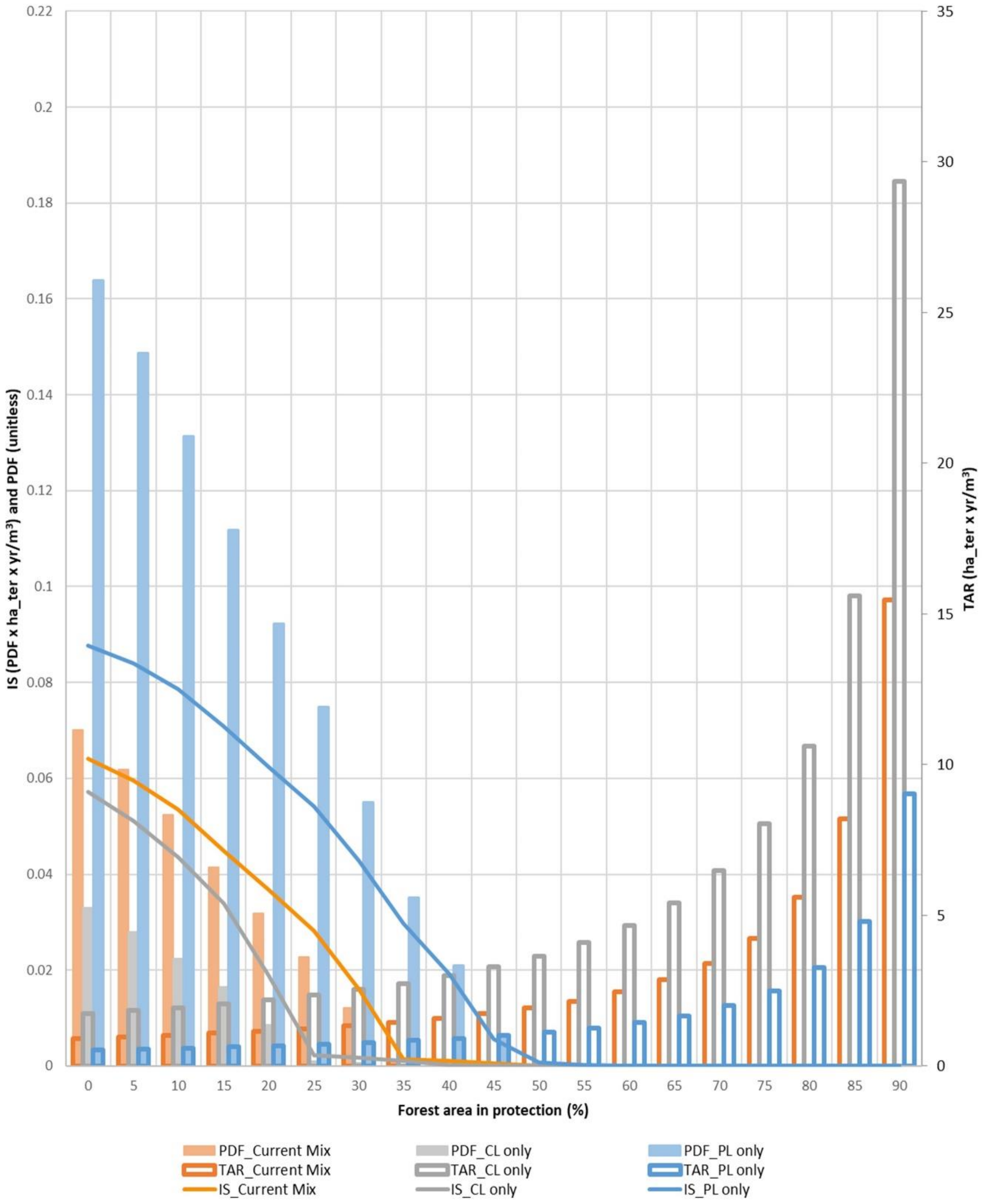


Figure 5.4: Impact score (IS) as a function of potential disappeared fraction of species (PDF), terrestrial area annually required to product 1 m³ of wood (TAR) and the proportion of the forest area in protection.

5.5.4 Sensitivity analysis

A sensitivity analysis of the values used to set up the provisional NI-PDF curve was performed by applying alternative correspondence values for PDF (indicated in red in Figures 5.5 and S1) to evaluate their effects on the resulting impact scores. The setting and detailed results for each alternative curve are included in the Supplementary Materials, the Excel file sheets correspond to the letter associated with the curve tested. The representations of these results displayed accordingly to Figure 5.4 are included in the Supplementary Materials, sheet "Figures_curves_a_to_f".

The analysis shows high sensitivity to the values used to generate the curve relating potential disappeared fraction of species (PDF) to the naturalness index (NI). A small change in correspondence values, comprised within the confidence interval of the PDF data, can affect not only the magnitude of differences between scenario impact scores (Figure 5.5b,c) but can lead to different results (Figure 5.5d,e). Based either on the naturalness index or on the PDF the scenario ranking in decreasing order of damage is *PL only* > *Current Mix* > *CL only*. This ranking is consistent with scientific knowledge on ecological impacts of silvicultural treatments. The use of the provisional curve (curve (a)) leads to impact scores displaying the same ranking. However, using the curve (d), with 0 and 5% levels of protection, the impact scores would rank *PL only* > *CL only* > *Current Mix*. Using the curve (e), the impact scores with a 0 to 20% protection level would rank *CL only* > *PL only* ≈ *Current Mix*. With more than 25% of protection, they would rank *PL only* > *Current Mix* > *CL only* (see Supplementary Materials, sheet "NI-PDF_e" for detailed results). We also observe that the use of the impact score to compare the level of protection related to a scenario would lead to different results depending on the NI-PDF curve setting. For example, the protection level where losses reach near zero values when using curves (c) and (d) is different from the level obtained with the provisional curve.

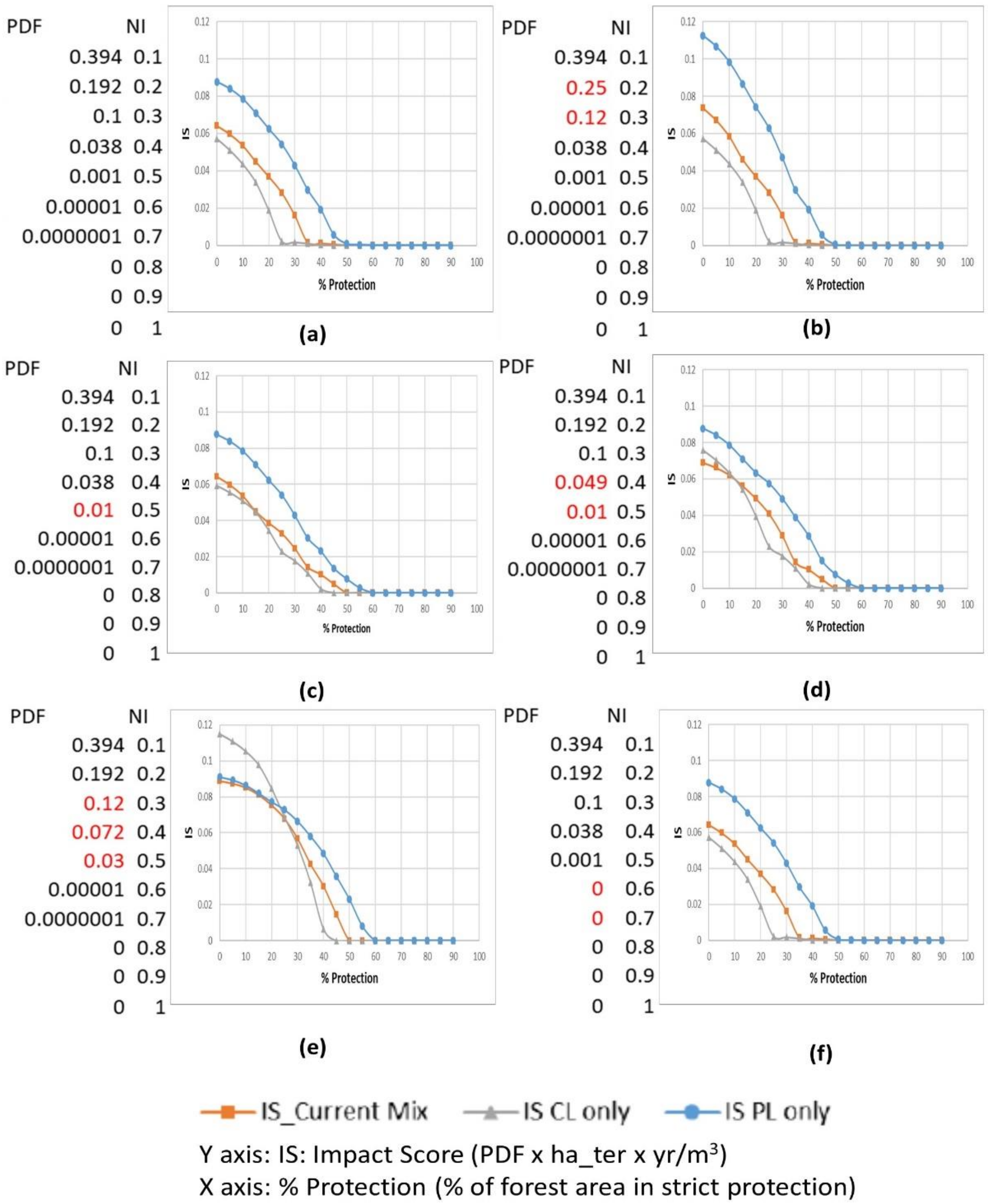
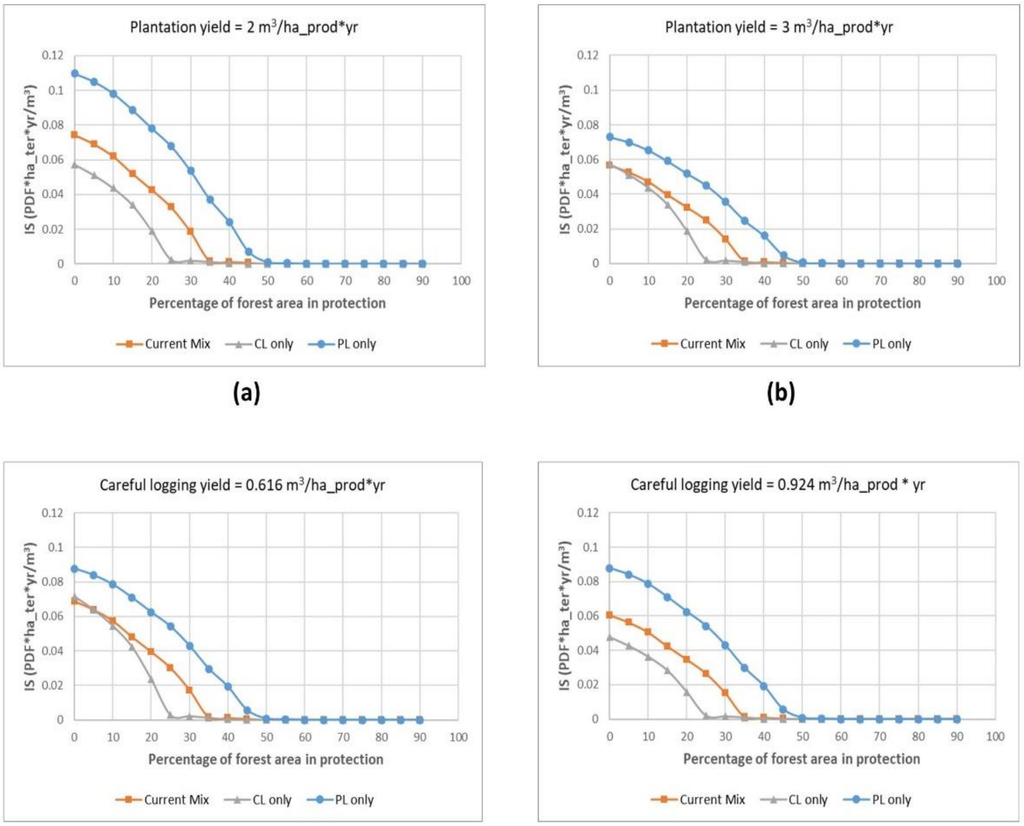


Figure 5.5: Sensitivity analysis results: impact score (IS) based on the alternative NI-PDF curves. (a) Provisional curve; (b) test of a higher PDF for the altered class; (c) test of a higher PDF for the mid semi-natural class; (d) test of a higher PDF for the semi-natural class; (e) test of a higher PDF for the semi-natural and altered classes ; (f) test of no species losses (PDF = 0) for the near-natural class.

The second parameter involved in the impact score calculation is the TAR associated to the scenario, which results from the division by the yield.

The effect on the impact scores of a variation of ± 20% of the scenarios yield for PL or CL are illustrated in Figure 5.6. Results are affected by the difference between the scenario's productivity. Larger differences between the basic scenarios can lead to questionable conclusions at low levels of protection (Figure 5.6b,c).



(a) (b)

(c) (d)

Figure 5.6: Sensitivity analysis of the impact score considering a varying yield of: (a) -20% for the plantation yield; (b) +20% for the plantation (PL) yield; (c) -20% for the careful logging yield; (d) +20% for the careful logging (CL) yield.

5.6 Discussion

5.6.1 LCA Impact Assessment

The trial use of the naturalness in LCA considering gradient of protection sheds light on the LCA model behavior. The two parameters involved in the LCA impact score calculation, the potentially disappeared fraction of species (PDF) and the terrestrial area required annually to produce 1 m^3 of wood (TAR), showed opposite non-linear effects that have to be properly put in balance in order to lead to impact score results consistent with existing scientific knowledge about the impacts of forest management. The transformation in PDF using the provisional curve provided a range of values and a distribution allowing to offset the effect of the TAR and led to impact scores correlated with the PDF rankings (i.e., *PL only* showing the greater impact followed by *Current Mix* and *CL only*). As the biodiversity data necessary to calibrate and confirm empirically the NI-PDF curve are not available for our study area, the use of the proposed NI-PDF curve could be hazardous with the current state of knowledge. The sensitivity analysis showed that the window for obtaining consistent results is narrow. There are risks of inaccurate results if data on s species richness loss do not have the mathematical characteristics allowing to compensate for the effect of the area required (TAR), itself determined by the inverse of the yield function (1/x). When the quality indicator does not vary appropriately with the variation of the TAR, it can produce misleading conclusions. This supports raised doubts about the possibility to implement the non-linear relationship between LCI data related to land use productivity (e.g., land occupied/transformed in area × year) and impact on biodiversity (e.g., potentially disappeared fraction of species locally) in LCA models that typically scale impacts up or down using simple proportionality (Teixeira et al. 2016). This also supports worries expressed by Teixeira et al. (2016) about the use of LCA biodiversity models. It highlights the need to look beyond the characterization factor and the necessity to analyze the effect on the impact score of introducing an indicator into the LCA model, in regard to the effective protection of the safeguard subject (i.e., the ecosystem quality).

Turner et al. (2019) obtained also diverging results from LCA impact scores when comparing with existing knowledge on the effects of a given type of forest management they linked this with issues related to scaling/weighing, cumulative effects and the reference benchmark. Our results confirm the relevance of scaling and weighing indices from ecological models for their inclusion into the LCA model as ecosystem quality indicator. When evaluating the environmental impact of anthropogenic production systems, LCA assumes a linear relationship between the impact and the quantity produced, which does not reflect the shape of cumulative effects (Souza et al. 2015). However, our results indicate that the mathematical framework imposed by the TAR calls for the use of an indicator reflecting somehow the cumulative effects, because it has the power to compensate for TAR's preponderance within the LCA framework. Interestingly, most biodiversity indicators or weighing approaches proposed in the land use LCA context do reflect a cumulative effect. It is the case in our study with the potentially disappeared fraction of species along the alteration gradient (Figure 5.2), as it is often found in the literature expressed through the use of some kind of exponential/logarithmic relationship between habitat degradation and species losses. It can be seen in Chaudhary et al. (2015) with the SAR; or in Rossi et al. (2018) between hemeroby level and partial biodiversity scores; or in Lindqvist et al. (2016) to express the contribution of a given parameter to a biodiversity potential function; or in Turner et al. (2019) for weighing results from expert opinions.

In the perspective of using LCA results for forest management decision-making, the present study shows difficulties for both the protection level and the silvicultural scenarios. The transformation of NI in PDF required for LCA involved values equal or near 0 for PDF in the higher portion of the protection gradient to offset the non-linear portion of the TAR. This impaired the possibility to properly consider the effects of the level of protection on the quality of ecosystems. As for the evaluation of silvicultural scenarios the transformation in PDF reduced the difference between scenarios more rapidly along the protection gradient. The sensitivity analysis showed that the LCA impact scores could not be used as comparative basis to associate the level of protection related to a given management scenario as it would correspond to an artefact of the NI-PDF curve. Moreover, the sensitivity analysis showed that the LCA impact scores were sensitive to PDF value and to the productivity, as well, and there are risks of curve inter-crossings (i.e., changing ranking of silvicultural scenarios) which produce results that are difficult to interpret.

Another point is that the use of an LCA impact score for decision making in sustainable forest management has the potential to misinform as it does not take into account the crossing of ecological thresholds. An ecological threshold corresponds to a point where a small marginal change in the quality of ecosystems can cause a large response leading to an irreversible reorganization of the ecosystem (Scheffer & Carpenter 2003; Groffman et al. 2006). LCA does not aim to evaluate the shifting state of ecosystems or biodiversity (Souza et al. 2015) and most of the time we do not know exactly which level corresponds to an ecological threshold until it has been crossed. Furthermore, for a given ecosystem, biodiversity thresholds can be numerous (Evans et al. 2017) and cannot be expressed on a functional unit basis. This situation supports the recommendation of using site-specific evaluations for decision-making about land use and management practices (Gaudreault et al. 2020).

In any case, best management practices or strategy identification must be aligned with local evaluation over a given territory, as we are managing at the scale of hundreds of thousands of hectares of forests, which are finite over the planet. It would not be environmentally sound to take a direction towards more production at the expense of the overall ecosystem quality. Site specific and/or territorial studies should be used to support decisions (Gaudreault et al. 2020) in order to prevent inaccurate conclusions about the forest management strategy and practices and their effects on landscape (Teixeira et al. 2016) The available LCA model calls for another round of critical evaluation of the underpinning of the land use aspects in LCA modelling, considering the mathematical features related to the non-linear relationships involved (Chaudhary et al. 2015). Moreover, questions still remain about the proper method to consider ecosystem quality in LCA. As recommended by Teixeira et al. (2016), LCA modelling should strive for a better coupling between results and policy decisions and existing strategic plans.

5.6.2 Consequences for Forest Management

5.6.2.1 Targeting the Level of Protection Using Naturalness.

Limitations imposed to the incorporation of naturalness assessments into the LCA model does not question the use of naturalness assessment as a tool to assist decision-making related to forest management scenarios and strategies.

The area set aside for strict protection is an important component of a forest management strategy to prevent or limit biodiversity losses (Paillet et al. 2010; Gray et al. 2016; Dudley et al. 2018). The question of how much is enough has been a source of questioning for years (Tear et al. 2005; Wilhere 2008).

With the hypothesis that strictly protected forests have the characteristics of natural forests, the increase in protection contributes to the improvement of overall naturalness, and to the decrease in the potential loss of species due to forest management at the landscape level. Protection targets could be estimated using the relation between the naturalness index and the potential impacts on biodiversity (Figure 5.2). For example, aiming a management target seeking to limit species loss (i.e., NI ≥ 0.5), the proportion in protection should be 25% of the forest area with the *CL only* scenario (Figure 5.3 and Supplementary Materials, sheet “NI-PDF_a”). It should be set at 35% with the *Current Mix* scenario (which represents twice the current level of protection for the forest management units (FMU) under study), and 50% for the *PL only* scenario. This level of protection is consistent with the level recently proposed as a “big bold conservation target” (Dudley et al. 2018). However, according to the naturalness conceptual model (Figure 5.2), if the objective is to avoid species loss, the naturalness level target should aim for the lower limit of the near-natural class (NI ≥ 0.6). Such a level is reached with 45% of protection with the *CL only* scenario, or 50% of protection with the *Current mix* scenario, or 60% of protection with the *PL only* scenario (Figure 5.3 and Supplementary Materials, sheet “NI-PDF_a”). This 60% level corresponds to the proportion of area set aside estimated by Framstad et al. 2002 in Michelsen (2008)to be necessary to maintain biodiversity within boreal forests. The current protection level for the three FMUs under study (17.9% of the study forest area) combined with the *Current Mix* of regeneration methods (60% in careful logging and 40% in plantation) is expected to lead to an ecosystem at the limit of being altered (NI = 0.407). This level is likely to produce some biodiversity losses. These losses could be limited by doubling the proportion of forest area in strict protection to reach a level of 35%.

5.6.2.2 Considering Protection in Forest Management Strategies Using Naturalness

A forest management strategy producing wood over a given productive area shows a lower naturalness level if wood is produced through plantation of indigenous species when compared with careful logging (Table 5.2). In contrast, a forest management strategy producing a given amount of wood leads to a higher naturalness if wood is produced through plantation of indigenous species with a revolution of 70 years over a small portion of the area combined with strict protection of the remaining fraction, compared with production over the whole current productive area through careful logging with a revolution of 100 years combined with the actual level of protection. Based on the naturalness assessment results, it would be better for the environment to intensify forest management over a small proportion of the forest territory while ensuring strict protection over the remaining portion, compared with an extensive forest management applied over the vast majority of the forested area. This confirms the pertinence of a zoning approach such as the “Triad strategy” (Seymour & Hunter 1992; Messier et al. 2009). Obviously, this conclusion holds true only if the area not used for wood production is permanently set aside for strict protection through an effective strict protected area system (Leverington et al. 2010), and if the enhanced production does not involve the plantation of exotic species. However, the implementation of scenarios involving increased production to compensate for protection is complicated by the necessary delay to obtain wood products from plantations and the related question of wood procurement in the meantime (Carnus et al. 2006; Ward & Erdle 2015). Such approaches require a paradigm shift in policy-making (Hartmann et al. 2010) and necessitates prompt action to ensure conservation of primary forests.

5.6.3 Future Research.

High priority should be given to studying the effects of forest management on biodiversity, especially species loss in boreal forests. This should be put in relation with research on the relationship between naturalness and biodiversity. The reliability of the NI-PDF curve set up could be improved using an updated subset of the PREDICTS database corresponding to boreal forest with the appropriate definition of land use intensity. Further empirical data should be sought to reduce uncertainty and confirm the relevance of using species richness data in the LCA model.

The use of the naturalness concept could be promoted, by adapting the model for more bioclimatic domains and performing assessment over more forest management units (FMU) and at the bioclimatic domain scale. To expand our approach to ecosystem quality evaluation in LCA, the method used for naturalness assessment of forestry should be adapted for other land uses in order to allow land-use comparisons based on the ecosystem quality. To do so, the naturalness assessment should be integrated into the whole alteration gradient (Côté et al. 2019), along with the other land uses by designing a hemeroby assessment model based on the habitat characteristics.

To improve the robustness of the LCA model, it is of outmost importance to investigate the mathematical effects of non-linear parameters in order to verify if and how issues related to scaling and non-linear effects in the LCA model could be properly addressed.

Supplementary Materials: The following are available online at www.mdpi.com/article/10.3390/su13168859/s1. SM_Sensitivity_analysis_curve.doc: Description of tested alternative curve settings., SM_Results_3FMU.xls: results_current_protection: Results with the current level of protection (17.9% of the forest area). NI-PDF_a: Detailed results for Figure 5.5a using the provisional curve of Figure 5.S1a. NI-PDF_b: Detailed results for Figure 5.5b using the curve of Figure 5.S1b. NI-PDF_c: Detailed results for Figure 5.5c using the curve of Figure 5.S1c. NI-PDF_d: Detailed results for Figure 5.5d using the curve of Figure 5.S1d. NI-PDF_e: Detailed results for Figure 5.5e using the curve of Figure 5.S1e. NI-PDF_f: Detailed results for Figure 5.5f using the curve of Figure 5.S1f. Figures_curves_a_to_f: model display format of Figure 5.4 for each NI-PDF curve tested, Yield_PL-20: Detailed results for Figure 5.6a using a plantation yield reduced of 20%. Yield_PL+20: Detailed results for Figure 5.6b using a plantation yield raised of 20%. Yield_CL-20: Detailed results for Figure 5.6c using a careful logging yield reduced of 20%. Yield_CL+20: Detailed results for Figure 5.6d using a plantation careful logging yield raised of 20%. Naturalness_assessment_ex: example of naturalness assessment of a forest management scenario (60CL100-40PL70-cp).

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Abbreviations

Acronym	**Signification**
ant	Anthropization
ant_NDP	Naturalness degradation potential from anthropization
CBD	Convention on Biological Diversity
CF	Close forests
CF_pni	Partial naturalness for close forests
CL	careful clearcut logging
Compo	Composition
Compo_PNI	Partial naturalness for composition
Context	Landscape context
Context_PNI	Partial naturalness for landscape context
CS	Companion species
CS_NDP	Naturalness degradation potential related to companion species
CT	Cover type
CT_pni	Partial naturalness index for cover type
DW	Dead wood
DW_NDP	Naturalness degradation potential related to dead wood
DW_PNI	Partial naturalness index for dead wood
cp	Current protection level
exo	Exotic species
exo_NDP	Naturalness degradation potential from exotic species
FMU	Forest management unit
Ha	Hectares
ha_for	Forest area in hectares
ha_prod	Productive area in hectares
ha_ter	Terrestrial area in hectares
HS	Horizontal structure
HS_NDP	Naturalness degradation potential related to horizontal structure
IR	Irregular stands
IR_pni	Partial naturalness index for irregular stands
IS	Impact score
IUCN	International Union for Conservation of Nature
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LS	Late successional characteristic species (i. e. Picea spp.)
LS_pni	Partial naturalness index for late successional characteristic species
m^3	Cubic meter of wood
NDP	Naturalness degradation potential
NE	Natural evolution
NI	Naturalness index
OF	Old forests
OF_pni	Partial naturalness index for old forests

PDF	Potential disappeared fraction of species
PL	Plantation
PNI	Partial naturalness index for a given characteristic of naturalness (characteristic_PNI)
Pni	Partial naturalness index for a given condition indicator (condition_pni)
Prod_area	Productive area
RP	Regeneration process
RP_NDP	Naturalness degradation potential related to regeneration process
SAR	Species–area relationship
SETAC	Society of Environmental Toxicology and Chemistry
Struc	Structure
Struc_PNI	Partial naturalness index for structure
TAR	Terrestrial area annually required to produce 1 m^3 of wood
UNEP	United Nations Environment Program-
W_CC	Clearcuts on wetlands
W_CC_NDP	Naturalness degradation potential related to clearcuts on wetlands
Wm	Modified wetlands
Wm_NDP	Naturalness degradation potential related to modified wetlands
yr	Year

Appendix 5.A: Naturalness Assessment of the 3 FMU and related data

The test area corresponds to three Forest Management Units (FMU) (nos. 2663, 2665 and 2666) covering a total area of 1,305,200 ha (BFEC). The localization of the test area is shown in Figure 5.A1. The study area is currently subject to the first cycle of harvest.

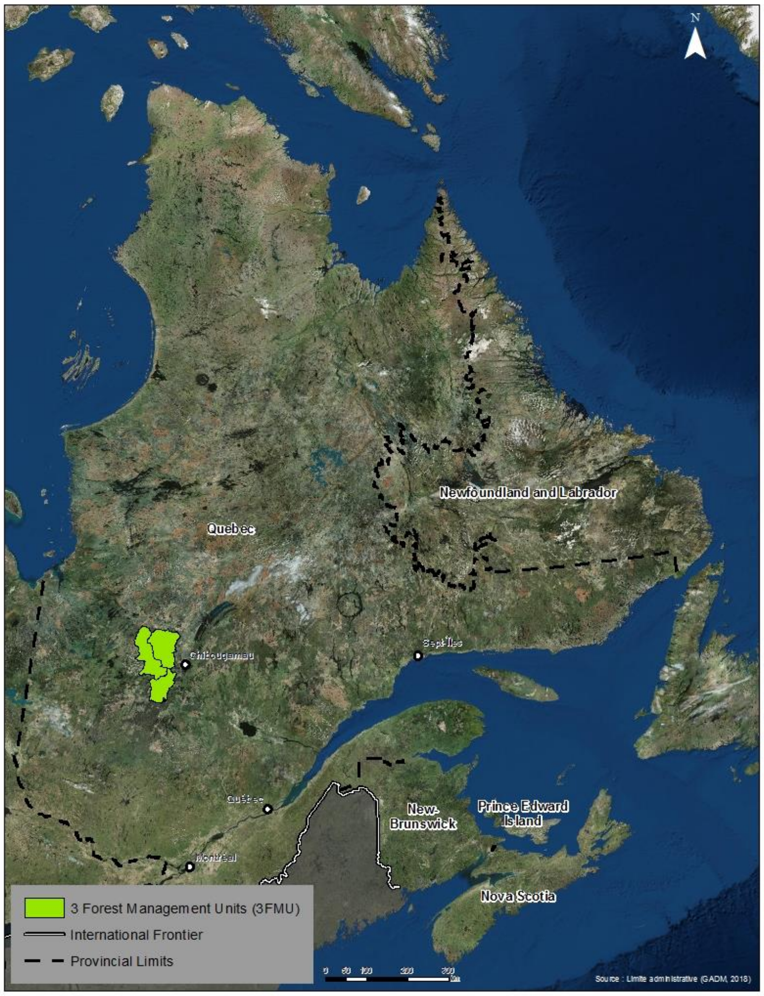


Figure 5.A1: Test area localization.

Appendix 5.A.1 Historical Data of the Test Area

Historical data are shown in Table 5.A1. Reference data for cover type (CT), late successional species groups (LS), old forests (OF) and irregular stands (IR) were taken from the first Quebec forest inventory, corresponding to the period from 1965 to 1974 period, using Quebec's SIFORT system (tessellation of provincial forest inventory maps) (MFFP 2017), from which the 6% of harvested areas and other anthropic disturbances were removed. To conform to the integral application of the forest management scenario, the reference value for CF (closed forest : >40 years old) corresponds to the (total forest area minus the forest area in old forests), spread evenly over the younger age classes (0-100), then adding the corresponding area for 0 to 40 years.

Table 5.A1: Reference values of condition indicators used for naturalness assessment.

Condition Indicator	**Value (%[1])**
Cover type (CT)	79.54
Late successional species group (LS)	46.03
Closed forest (CF)	62.29
Old forests (OF)	49.31
Irregular stands (IR)	31.54

[1] % of forest area except for CF which is based on terrestrial area.

Appendix 5.A.2 Ecological Effetcs of Careful Logging and Plantations

Careful clearcut logging represents a significant and abrupt change in habitat conditions for forest wildlife (Escobar et al. 2015). At the stand level, clearcutting induces modifications in vegetation structure and composition, microclimate and ground substrate (Keenan & Kimmins 1993; Ross-Davis & Frego 2002; Escobar et al. 2015). It also resets the vegetation succession to earlier stages (Oliver & Larson 1996). At the landscape level, even aged management (regenerated through clearcuts) modifies the age structure (distribution of age classes) of the forest by reducing the proportion of old forests to an extent related to the rotation length (Keenan & Kimmins 1993). This precludes the formation of characteristics related to old growth forests (Hayes et al. 2005), thus affecting species associated with old-growth habitat (Hartmann et al. 2010). Impacts on biodiversity are mainly influenced by the rate and the spatial pattern of harvesting and the type and intensity of subsequent management practices (Keenan & Kimmins 1993).

Plantation corresponds to an intensive form of forest management involving a suite of anthropogenic manipulations of forest regeneration including site preparation, tree planting (including sometimes genetic selection of the planted trees), and various tree-releasing and tree-thinning treatments (Ross-Davis & Frego 2002). Plantation forests support generally lower diversity compared with natural forests (Ross-Davis & Frego 2002; Stephens & Wagner 2007). Negative effects are particularly important when exotic species are used (Hunter 1999; Carnus et al. 2006; Stephens & Wagner 2007), which is not the case in the study area. Plantation of indigenous species can have positive effects by contributing to forest composition restoration for example (Paquette & Messier 2010), but still there are potentially negative effects related to modification of genetic pools, site preparation, shorter rotation, repeated thinning and homogenization of conditions (Hunter 1999; Hayes et al. 2005; Carnus et al. 2006). Cumulative effects on biodiversity of intensive forest management are likely to increase over time as a result of reduced species diversity, reduced amount of dead wood and enhanced frequency of high-disturbance over large areas (Hayes et al. 2005). By producing more wood from intensively managed areas, plantations could be used to reduce indirectly pressure on natural forests (Carnus et al. 2006; Stephens & Wagner 2007; Paquette & Messier 2010). To be efficient, such an approach requires that forest conservation objectives are permanent and guaranteed by rigorous legislation (Hayes et al. 2005; Hartmann et al. 2010), which can be obtained with the creation of strictly protected areas (Dudley 2008).

Appendix 5.A.3 Scenario Naturalness Assessment

The territory used for the analysis covers the whole area included in the perimeter of the FMU (without cutting tessell in SIFORT maps), including the surrounding strict protected areas (IUCN categories I to III) associated with these units. The percentage of forested area over the territory of analysis was calculated for measures of forest condition (CT, LS, OF, and IR) and the percentage of terrestrial area over the territory of analysis for context measures (CF, W_CC, Wm, ant).

Age structure related to each scenario under sustainable production has been used to evaluate closed and old forests. For example, for a rotation of 100 years, 10% of the productive area will be in each 10 years class (0-10 years up to 90-100 years), and for a rotation of 70 years, 14.2857% of the productive area will be in each 10 years class (from 0-10 years up to 60-70 years).

Current data, corresponding to the 2011 to 2013 period, were taken from the fourth inventory program (MFFP 2018). Clearcuts on wetlands and anthropization levels were set to current values using data from ecoforest4 map (MFFP 2018) (% of terrestrial area: W_CC = 7.88%, ant = 0.74%) and kept constant in all scenarios. Percentages of forested area by origin and by age class considering silvicultural treatments has been used to determine CT and LS under 20 years and over 20 years old, in careful logging (CL) and plantations (PL). Hypotheses used for condition indicators (CT, LS, IR and OF) are shown in Table 5.A2 (see Côté et al. (2019) for details). Values for CF (closed forests over 40 years old) are determined based on age structure resulting from scenario components application.

Table 5.A2: Hypotheses used for condition indicators (coniferous cover type (CT); late successional species groups (LS); old forests (OF); irregular stands (IR)) for each scenario component: careful logging (CL), plantation (PL) and natural evolution for protection and excluded area.

Scenario Component	**CT**	**LS**	**IR**	**OF**
Young CL (< 20 yr)	6.54	1.09		
Older CL (≥ 20 yr)	48.11	13.10	0[1]	0[1]
Young PL (< 20 yr)	42.81	0.41		
Older PL (≥ 20 yr)	86.57	9.70	0[1]	0[1]
Natural evolution	79.54	46.03	31.54	49.31

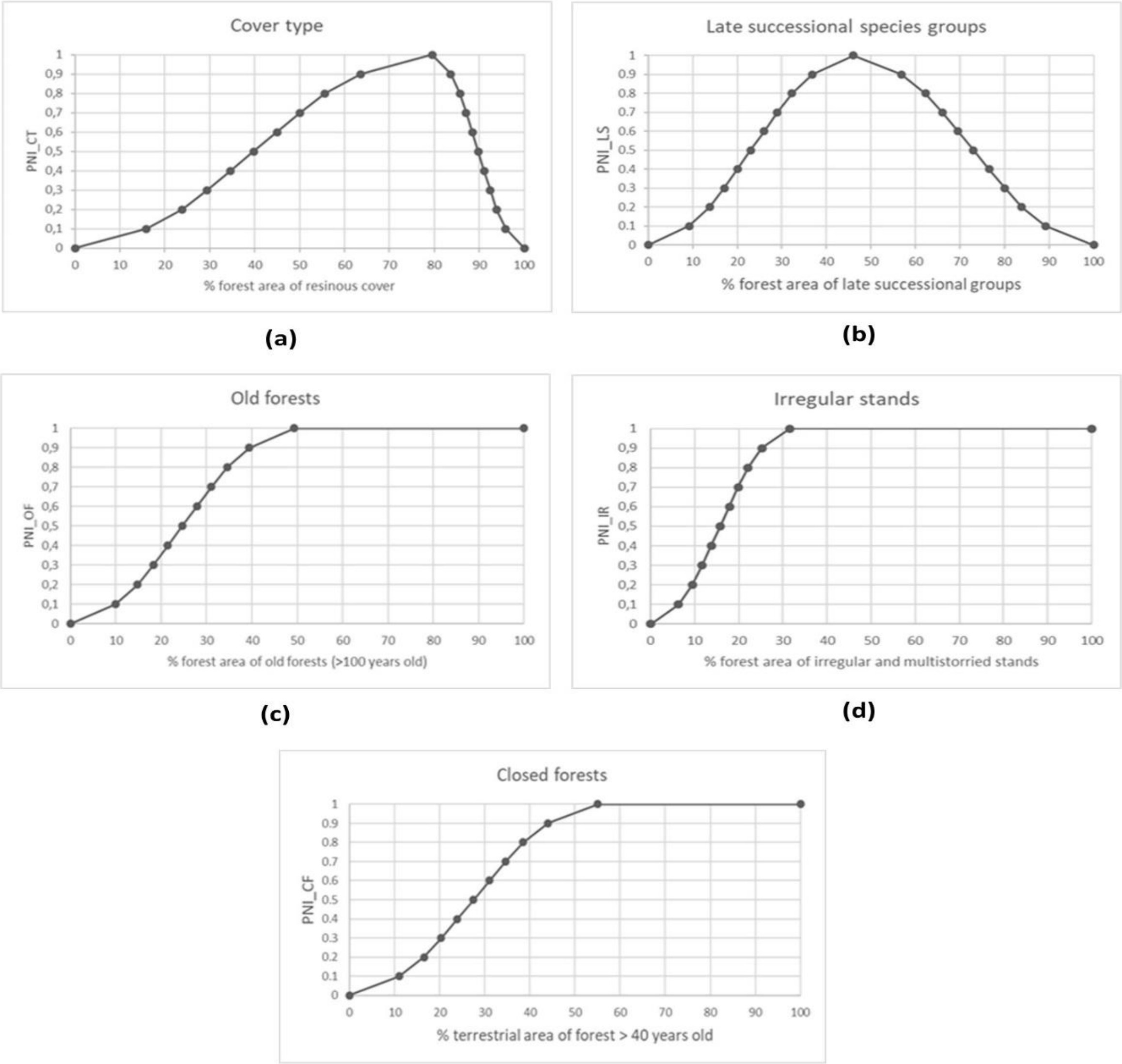
[1] value for the whole component (all age classes).

Table 5.A3: Natural degradation potential (NDP) factors for each scenario component: careful logging (CL), plantation (PL) and natural evolution (protection).

Scenario Component	**Horizontal Structure**	**Dead Wood**	**Regeneration Process**
CL	0.35	0.65	0.4
PL	1	0.95	0.9
Natural evolution	0	0	0

The curves elaborated for pni evaluation specifically for the three FMUs are presented in Figure 5.A2.

The naturalness assessment of the *Current Mix* scenario forecasting 60% of CL on a 100 year rotation with 40% PL on a 70 year rotation with the current level of 17.9% of the forest area in protection (60CL100-40PL70-17.9p) is provided as an example for the detailed description of the naturalness assessment method (File: SM_Results; Naturalness_assess_ex.xls).



(a)

(b)

(c)

(d)

(e)

Figure 5.A2: Partial naturalness index (pni) determination curves used for condition indicators' evaluation for three forest management units (3FMU) in the boreal black spruce-feathermoss bioclimatic domain: (a) coniferous cover type (CT); (b) late successional species groups (LS); (c) old forests (OF); (d) irregular stands (IR); (e) closed forests (CF).

Appendix 5.A.4 Scenario Yiels Hypotheses

For the protection, obviously there was no yield. For the careful logging, the yield estimation of 0.77 m^3/(ha productive × yr), was based on the sustainable harvest calculated in 2014 (BFEC 2017) (502100 m^3/yr) over the productive area (651610 ha), considering a rotation of 100 years. For the plantations, an expected yield of 2.5 m^3/(ha productive× yr) was based on tables for black spruce plantations having a station quality index of 6 (IQS = 6) with 2000 or 2500 stems/ha has been used (Pothier & Savard 1998). For the 60% careful logging with 40% plantation scenario, the yield corresponds to the weighed sum of the productivity of both scenarios (1.462 m^3/ha productive× yr).

The main source of uncertainty related to the estimation of the yield is for plantations, as no plantation has ever reached maturity in the study area and the plantation yield is more likely to be overestimated due to unaccounted mortality over the lifespan of the forest plantations (Prégent & Végiard 2000). Moreover, for the PL only scenario, the mean expected yield should be lower as plantations covering 100% of the productive area should be lower than the productivity of plantations concentrated on the best sites.

Appendix 5.B: NI-PDF Curve Setting

The points of correspondence used to build the NI-PDF curve were established as follow. According to the naturalness model's conceptual framework (Côté et al. 2019), there is no specie loss (i.e. PDF = 0) in the natural class (NI = 1-0.8), and there is a very low probability of losses (i.e. PDF ≈ 0) in the near-natural class (NI = 0.6-0.8). The PDF has been set to 0.0000001 for NI = 0.7 and to 0.00001 for NI = 0.6 to consider a risk of marginal losses of sensitive species while allowing the detection of improvements in the near-natural class. The losses of very sensitive species begin in the semi-natural class (NI = 0.4-0.6), but PDF are still limited. In another territory located in a balsam fir forest, a naturalness index around 0.5 could be put in relation with decline of few sensitive species (Côté et al. 2020). Unfortunately, these impacts have not yet been fully quantified, but they indicate that the PDF should be different from 0 when the NI reaches that level. The PDF has been set to 0.001 for NI = 0.5 and alternatives values were tested thru sensitivity analysis. The correspondence values for NI ≥ 0.5 represents expert opinions proposed by the authors and have to be validated. For the near-natural class (NI 0.6–0.8), we introduced infinitesimal values for PDF to verify the possible effects of such introduction in the model, in the perspective of opening the reflection surrounding the consideration of effects on biodiversity when there are no species losses. However, the results for that portion on the protection gradient were not adjusted accordingly in the text (results rounded to the third digit), nor used in for interpretation. The results without the introduction of the infinitesimal section for the near-natural class are provided in the sensitivity analysis (curve f)). To link PDF to NI, the age structure (area by age classes) resulting from the application of the 100% scenarios over the whole area without protection (excluded portion not considered) has been used to estimate the proportion of the area in each development stage of secondary forests used by Newbold et al. (2015) (Table 5.B). The naturalness evaluation for the scenario involving CL only without protection (100CL100-0p) results in NI = 0.414 (see Supplementary Materials, results using the provisional curve with 0% protection), which can be roughly associated with the lower bound of the semi-natural class (NI = 0.4). Gradual application of clearcuts over the entire productive area will lead to secondary forests, spread over the various development stages depending on their age (young: 0–20 years, so 20% of the area subject to CL only; intermediate: 21–70 years, so 50% of the area in CL only; mature: 71–100 years, so 30% of the area in CL only). Using the species losses ((100 species richness data) ÷ 100) from Newbold et al. (2015) for secondary forests lightly and intensively used (Table A4), weighted by the proportion in each development stage associated with their age, gives a mean of 0.038. Therefore, we associated the lower bound of the semi-natural class (NI = 0.4) with a PDF of 0.038. Losses of sensitive species are measurable in the altered class (NI = 0.2–0.4) and important losses of species can be associated with the very altered class (NI < 0.2). The naturalness evaluation for the scenario involving PL only of indigenous species without protection (100PL70-0p) gives a result of NI = 0.231 (see Supplementary Materials, results using the provisional curve with 0% protection), which can be roughly associated with the lower bound of the altered class. Therefore, we associated the lower bound of the altered class (NI = 0.2), to a PDF of 0.192 using the species richness data for plantation with minimal use from Newbold et al., 2015, considering that plantations are of native species, not fertilized nor cleared with herbicides. The PDF at NI = 0.3 has been set to 0.1 to smooth the curve. Finally, tests of extremes hypothetical scenarios involving exotic species lead to a naturalness index lying in the very altered class (Côté et al. 2019). We associated the middle of the very altered class (NI = 0.1), as no forestry use will ever create a biological desert, with the species richness data for intensively used plantation (PDF = 0.394). The last part of the curve (below NI = 0.2) has no effect in this study, since no scenario in the context of forestry modeled in this study is likely to lead to such degree of alteration. The levels used to estimate the end of the curve, for the altered and very altered levels, are consistent with the proportion of species associated with dead wood which are recognized to be sensitive to forest management. According to Klamerus-Iwan et al. (2020): “It is now estimated that 20–40% of organisms in forested ecosystems depend, during some part of their life cycle, on wounded or decaying woody material from living, weakened, or dead trees”. Species richness data for forests plantations intensively used equals 60.6 (Newbold et al. 2015) (corresponding to a loss of 39.4% of species), which is very close to the maximal loss of 40% associated with forestry (Klamerus-Iwan et al. 2020). In Finland, where intensive forestry using indigenous species is practiced, nearly 20% of all species are extinct, threated or near threated (Hanski 2000). This value is also very close to the PDF of 0.192 used to estimate the curve at NI = 0.2. Alternative correspondence values are tested in the sensitivity analysis.

Table 5.B: Species richness data by pressure level (Source: Newbold et al. (2015)).

Pressure level	**Species Richness (Mean** (Newbold et al. 2015)[1]**)**	**PDF (100 - Mean Richness) ÷ 100**
Mature secondary vegetation (light/intense use)	117.1	-0.171
Intermediate secondary vegetation (light/intense use)	90.1	0.099
Young secondary vegetation (light/intense use)	79.9	0.201
Plantation forest (minimal use)	80.8	0.192
Plantation forest (light use)	73.1	0.269
Plantation forest (intense use)	60.6	0.394

[1] Reprinted by permission from the Copyright Clearance Center: Springer Nature. Global effects of land use on local terrestrial biodiversity. (Newbold et al. 2015).

Appendix 5.C: Sensitivity analysis of the NI-PDF curve setting

The NI-PDF curve was built using meta-analysis results based on global data (Newbold et al. 2015) including only few data from boreal forests and for which pressure level or stage of development definitions raises questions about the proper data to be used for the curve setting.

The effect of the NI-PDF curve set up on the related impact score has been analyzed by applying alternative PDF values for the different portions of the curve corresponding to the naturalness classes. Alternative settings are detailed in Tables 5.C1; 5.C1a shows the provisional curve and the other letters correspond to alternative NI-PDF points of correspondence tested. Alternative curves tested are illustrated in Figure 5.C1.

Table 5.C1a: Hypothesis and data source of the provisional (a) curve.

NI	**PDF**	**Hypothesis and data source**
0.1	0.394	Plantation intense use (Newbold et al. 2015)
0.2	0.192	Plantation minimal use (Newbold et al. 2015)
0.3	0.1	Curve smoothing
0.4	0.038	20% Young; 50% Intermediate; 30% Mature; light/intense secondary forests (Newbold et al. 2015)
0.5	0.001	Curve smoothing
0.6	0.00001	theoretical low losses related to the low probabilities of species losses
0.7	0.0000001	Theoretical very low losses related to the very low probabilities of species losses
≥0.8	0	No losses

Table 5.C1b: Alternative hypothesis and data source of the (b) curve.

NI	PDF	Hypothesis and data source
0.2	0.25	50/70 Plantation minimal use; 20/70 Plantation intensive use (Newbold et al. 2015); one fourth of the forest species dependent of dead wood (Joelsson et al. 2018; Rossi et al. 2018)
0.3	0.12	Curve smoothing

Table 5.C1c: Alternative hypothesis and data source of the (c) curve.

NI	PDF	Hypothesis and data source
0.5	0.01	Curve smoothing

Table 5.C1d: Alternative hypothesis and data source of the (d) curve.

NI	PDF	Hypothesis and data source
0.4	0.049	30% Young; 40% Intermediate; 30% Mature; light/intense secondary forests (Newbold et al. 2015)
0.5	0.01	Curve smoothing

Table 5.C1e: Alternative hypothesis and data source of the (e) curve.

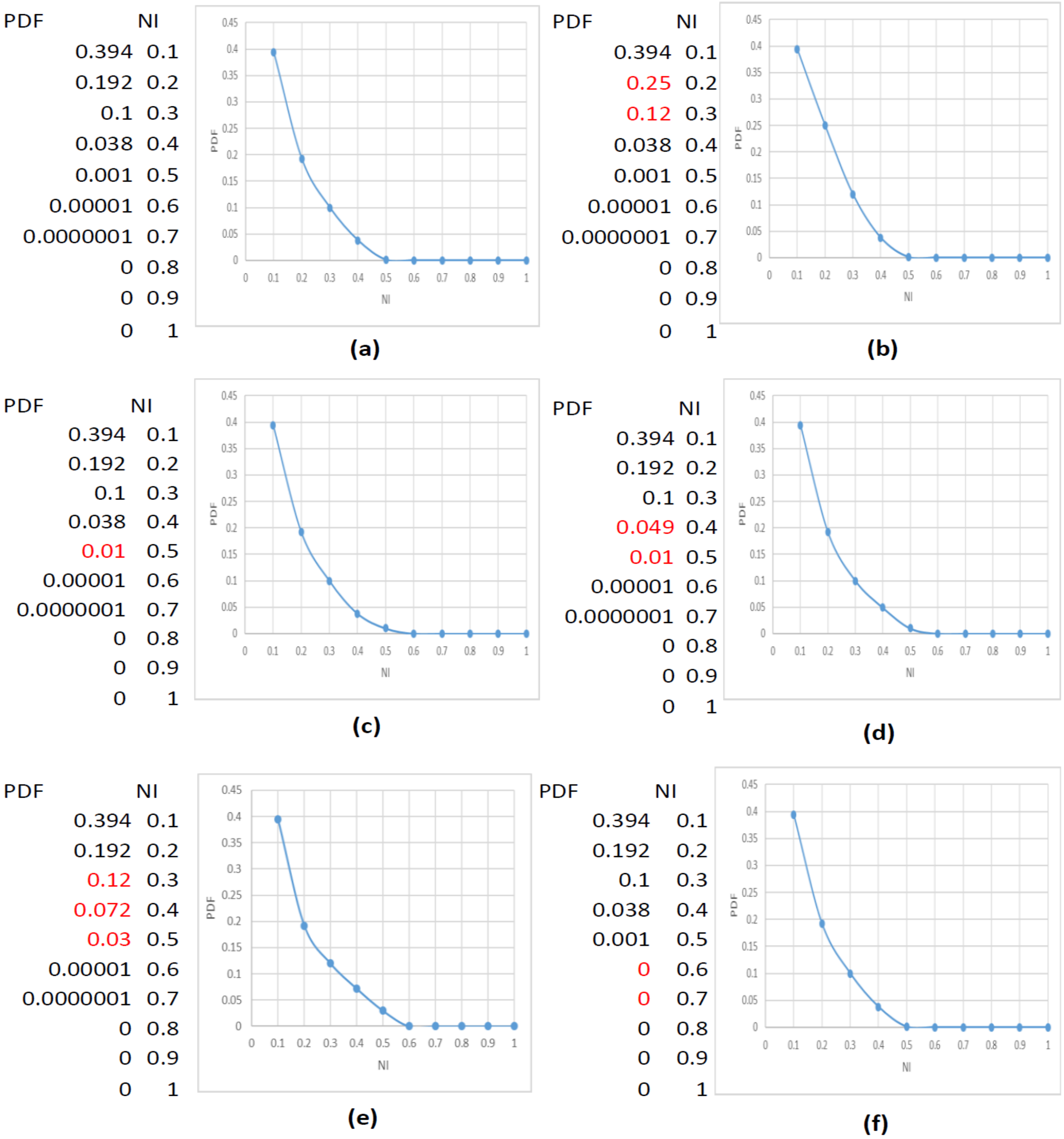
NI	PDF	Hypothesis and data source
0.3	0.12	Curve smoothing
0.4	0.0724	20% Young; 50% Intermediate; 30% Mature; minimal secondary forests (Newbold et al. 2015)
0.5	0.03	Curve smoothing

Table 5.C1f: Alternative hypothesis and data source of the (f) curve.

NI	PDF	Hypothesis and data source
0.6	0	No losses
0.7	0	No losses

With the provisional curve (Figure 5.C1a), the resulting ranking of the silvicultural scenarios based on the impact score (IS) was consistent with the scientific knowledge related to forest management showing the following impact ranking: *PL only* > *Current mix* > *CL only* and an impact decreasing with the level in strict protection. Figure 5.5b shows the results if the lower limit of the altered class would have been instead set based on a proportion of one fourth of the forest species dependent of dead wood (Joelsson et al. 2018; Rossi et al. 2018). Using Newbold's richness data for minimally used plantations over 50/70 (i.e. the proportion of plantations over 20 years old) of the planted area and data for intensively used plantations over 20/70 of the area, would lead to a PDF of 0.25 and the PDF at NI = 0.3 adjusted to 0.12 to smooth the curve (Figure 5.C1b). By increasing the range of the data, this setting would have amplified the difference between the impact scores for PL and CL in the low levels of protection (up to 30% of protection, as the NI reach 0.4 at 35% of protection). Therefore, if the species losses would be higher in the altered class (PDF up to 25% instead of 19.2% with the provisional curve) (Figure 5.5b), the impact score would allow a better discrimination between silvicultural scenarios at low levels of protection as indicated by the wider spacing between the IS curves. If the PDF in the middle of the semi-natural class would have been set to an higher level (0.01 instead of 0.001) (Figure 5.C1c), this would have put the CL results curve closer to the 60%CL-40%PL curve as it raises CL curve between 0 and 40% of protection, and the PL curve between 35 and 55% of protection (Figure 5.5c). The points related to protection levels allowing to avoid important losses are still at the same level of 25, 35 and 50% for 100CL100, 60CL100-40PL70 and 100PL70 respectively, but the levels preventing any losses would correspond to 40, 50 and 60% respectively. The Figure 5.5d shows the results if the middle of the semi-natural class would have been set to 0.01 instead of 0.001, and the lower limit of the semi-natural class would have been set to 0.05 instead of 0.04, considering a slower recovery of vegetation after clearcut by applying an alternative proportion by development stages (i.e. 30% of young, 40% of intermediary and 30% of mature lightly and intensively used secondary forests from Newbold et al. (2015)). The resulting impact score would be greater for 100CL100 than for 60CL100-40PL70 at low levels of protection, despite a higher naturalness (or a lower alteration) for the 100CL100 scenario for every level of protection (Figure 5.5d). The points where losses start lowering are still for 25, 35 and 50% in protection for 100CL100, 60CL100-40PL70 and 100PL70 respectively, but an objective of avoiding losses would use 40, 50 and 60% in protection for 100CL100, 60CL100-40PL70 and 100PL70 respectively. Figure 5.C1e shows the curve if it would have been set using higher potential species losses for the lower bound of the semi-natural class using data for minimally used secondary forests with the initial spreading over the development stages (i.e. 20% of young, 50% of intermediary and 30% of mature), and applying PDF = 0.3 for NI = 0.5 and PDF = 0.12 for NI = 0.3. This produces a curve shape closer to the linear pattern for the data scope. The resulting impact scores would indicate a higher impact of 100CL100 up to 20% of protection, and an impact of 60CL100-40PL70 equivalent to the one of 100PL70 (Figure 5.5e). Finally, the figure 5.5f shows the results if no species loss would be associated with the near-natural class. This would not have a noticeable effect on the outcome.

We see that protection level identification related to forest management could be performed with the naturalness results but not with the PDF results, as these corresponds to an artefact of the NI-PDF curve.



PDF	NI
0.394	0.1
0.192	0.2
0.1	0.3
0.038	0.4
0.001	0.5
0.00001	0.6
0.0000001	0.7
0	0.8
0	0.9
0	1

(a)

PDF	NI
0.394	0.1
0.25	0.2
0.12	0.3
0.038	0.4
0.001	0.5
0.00001	0.6
0.0000001	0.7
0	0.8
0	0.9
0	1

(b)

PDF	NI
0.394	0.1
0.192	0.2
0.1	0.3
0.038	0.4
0.01	0.5
0.00001	0.6
0.0000001	0.7
0	0.8
0	0.9
0	1

(c)

PDF	NI
0.394	0.1
0.192	0.2
0.1	0.3
0.049	0.4
0.01	0.5
0.00001	0.6
0.0000001	0.7
0	0.8
0	0.9
0	1

(d)

PDF	NI
0.394	0.1
0.192	0.2
0.12	0.3
0.072	0.4
0.03	0.5
0.00001	0.6
0.0000001	0.7
0	0.8
0	0.9
0	1

(e)

PDF	NI
0.394	0.1
0.192	0.2
0.1	0.3
0.038	0.4
0.001	0.5
0	0.6
0	0.7
0	0.8
0	0.9
0	1

(f)

Figure 5.C1: Alternative NI-PDF curves tested for sensitivity analysis, with alternative data used for curve parametrization indicated in red. (a) Provisional curve; (b) Test of an alternative setting for the altered class; (c) Test of an alternative setting for the middle of the semi-natural class; (d) Test of an alternative setting for the whole semi-natural class; (e) Test of an alternative setting considering higher losses for the data range; (f) test of a very low species losses for the near-natural class.

Conclusion

Afin de caractériser les impacts sur la qualité des écosystèmes de l'utilisation des terres associées aux pratiques d'aménagement forestier en forêt boréale, ce projet de recherche a été l'occasion de développer un modèle d'évaluation de la naturalité utilisant les données écoforestières, permettant ainsi de palier à la disponibilité limitée de données empiriques de biodiversité propres à la forêt boréale. Le modèle présenté permet de mesurer la naturalité résultant des pratiques et stratégies d'aménagement forestier selon un gradient unique pouvant être associé à l'intensité de l'utilisation des terres pour la foresterie. Diverses démarches d'évaluation ont été testées, tant dans la pessière à mousses que dans la sapinière à bouleau blanc, dans une perspective d'aide à la décision : l'évaluation de la naturalité actuelle, l'évolution de la naturalité parallèlement à l'application graduelle du scénario actuel d'aménagement et la projection de la naturalité résultant de divers scénarios fictifs d'aménagement. L'évaluation de la naturalité projetée, résultant de l'application de scénarios d'aménagement considérant différents dosages de scénarios sylvicoles sur l'ensemble du territoire, comparée à la naturalité actuelle a permis de mesurer aussi bien les dégradations que les améliorations possibles, confirmant l'aptitude du modèle d'évaluation de la naturalité à procéder à des évaluations bidirectionnelles. Une application prenant en compte un gradient de protection parallèlement à l'application de scénarios sylvicoles a permis de montrer comment le modèle d'évaluation de la naturalité développé pouvait être utilisé pour alimenter la réflexion quant à l'impact potentiel des choix pour élaborer une stratégie d'aménagement forestier concomitamment à la détermination de cibles de protection. Enfin, l'utilisation de la naturalité pour évaluer la qualité des écosystèmes résultant de différents scénarios d'aménagement forestier dans l'analyse du cycle de vie (ACV) a été l'occasion de proposer une courbe provisoire reliant la naturalité à la perte potentielle en espèces, puis de se pencher sur l'introduction des résultats en découlant dans le modèle proposé en ACV pour évaluer les impacts sur la qualité des écosystèmes de l'utilisation des terres pour la foresterie.

La naturalité utilise la référence historique, mais il est également possible de comparer l'évaluation actuelle de la naturalité à celle résultant de l'application d'un scénario d'aménagement donné afin d'en mesurer les effets éventuels de manière bidirectionnelle. L'évaluation de la naturalité actuelle fournit le résultat des stratégies et pratiques d'aménagement appliquées jusqu'au moment de l'évaluation. Dépendamment de la situation, elle peut correspondre à une évaluation ponctuelle en cours de la phase de transformation initiale (qui n'est pas radicale pour la foresterie, mais plutôt progressive), comme dans le cas des 3 unités d'aménagement forestier (UAF) du nord du Québec, ou à une évaluation ponctuelle au cours de la phase d'occupation qui inclura aussi l'effet de la transformation initiale, comme dans celui de la Forêt Montmorency. L'évaluation de scénarios d'aménagement basée sur la naturalité intègre les phases de transformation initiale et d'occupation et elle permet de mesurer directement les écarts par rapport à la situation naturelle. Une évaluation de la projection de l'application de scénarios d'aménagement sur l'ensemble du territoire, comparée à la situation actuelle permet de faire ressortir la capacité bidirectionnelle du système d'évaluation de la naturalité développé. Toutefois, le modèle d'évaluation de la naturalité ne tient pas compte d'un éventuel franchissement d'un seuil écologique qui ferait en sorte d'empêcher un retour vers l'état naturel à la suite d'une dégradation trop importante.

Les résultats de l'évaluation de la naturalité confirment que celle-ci diminue avec une intensification des pratiques d'aménagement forestier dans la portion forestière productive d'un territoire. Les évaluations réalisées tant dans la pessière à mousses de l'Ouest que dans la sapinière à bouleau blanc de l'Est ont permis de confirmer que dans la forêt boréale (pessière et sapinière), la plantation d'espèces indigènes produit des impacts négatifs plus importants que la régénération naturelle obtenue à la suite de la coupe avec protection de la régénération (CPRS). Les évaluations réalisées dans la sapinière ont montré que la régénération par coupe progressive irrégulière produisait moins d'impacts négatifs que la CPRS, et que la réduction de la révolution de 70 à 50 ans pour les scénarios avec coupe finale (i.e. CPRS et plantation) induisait des impacts négatifs supplémentaires. De plus, le modèle d'évaluation de la naturalité permet d'évaluer l'impact de stratégies d'aménagement forestier combinant simultanément des proportions variées de divers scénarios sylvicoles en territoire forestier productif et de protection stricte par rapport à l'ensemble du territoire d'analyse. Avec un niveau de protection rehaussé à 32%, il serait possible d'améliorer davantage la naturalité à la Forêt Montmorency avec l'aménagement d'une portion du territoire en coupes progressives irrégulières. Dans les 3 UAF de la région de Chibougamau, l'indice de naturalité associé à l'utilisation exclusive de la CPRS comme méthode de régénération sans aires protégées correspond au niveau qui serait obtenu avec une régénération exclusivement basée sur la plantation d'espèces indigènes avec dégagement mécanique assortie de 35% de la superficie forestière en aires-protégées strictes. Un indice de naturalité équivalent serait obtenu en combinant le mélange actuel de scénarios sylvicoles (i.e. 60% de régénération par CPRS et 40% par plantation), avec 20% de la superficie forestière en protection stricte, soit un peu plus que le niveau actuel de 17.9% de la superficie forestière. Le scénario d'aménagement actuel comportant 60% de régénération par CPRS et 40% par plantation assorti de 17.9% de la superficie forestière en protection stricte, conduit à une naturalité anticipée (une fois que le scénario sylvicole couvrirait l'ensemble de la superficie productive) s'approchant de la limite supérieure de la classe altérée (indice de naturalité, NI = 0.407) (pour laquelle on estime une perte d'espèces potentielle de l'ordre de 3.5%). Avec le scénario sylvicole actuel, si un objectif visant à limiter les pertes de biodiversité était visé (i.e. NI ≥ 0.5), le niveau de protection nécessaire serait de 35%, et si l'objectif était plutôt d'éviter toute perte ((i.e. NI ≥ 0.6), le niveau de protection nécessaire serait de 50%.

Si l'on considérait plutôt une stratégie d'aménagement visant une production donnée à partir d'un territoire, il serait possible de réduire les impacts négatifs en intensifiant la production sur une petite portion du territoire, à condition d'assurer une protection stricte sur le reste de la superficie non assujettie à la production. Toutefois, l'adoption d'une telle stratégie d'aménagement requiert un changement de mentalité des décideurs, puisqu'au

Québec on vise plutôt à maximiser le volume produit. Une stratégie visant une production déterminée devrait être envisagée rapidement pour que la conservation permette effectivement de protéger des caractéristiques associées aux forêts naturelles n'ayant jamais fait l'objet de coupe. Une telle stratégie devrait impérativement être appuyée par des mesures légales garantissant le maintien de la protection à long terme, ce qui représente un défi considérant les pressions exercées pour l'utilisation anthropique des terres. De plus, la mise en œuvre d'une telle stratégie peut être compromise si tous les bois sont alloués et qu'il n'existe pas de sources alternatives d'approvisionnement.

L'utilisation de la naturalité dans l'ACV a été testée, afin de vérifier la pertinence d'utiliser les résultats de l'ACV comme aide pour une prise de décision relative à l'aménagement forestier qui soit respectueuse de l'environnement. Pour ce faire, une courbe provisoire établissant la relation entre l'indice de naturalité (NI) et la fraction de perte potentielle d'espèces (PDF) a été construite. La prise en compte du gradient de protection a permis de faire la lumière sur les relations mathématiques impliquées dans le calcul du score d'impact selon le modèle proposé pour l'ACV dans lequel interviennent deux paramètres aux effets contraires: le facteur de caractérisation visant à évaluer la qualité de l'écosystème, correspondant ici à la fraction de perte potentielle d'espèces (PDF) sur le territoire, et la superficie requise pour la production d'une unité fonctionnelle, en l'occurrence pour la présente étude : 1 m^3 de bois d'œuvre résineux et, par extension, tous ses autres usages (p. ex : bois d'emballage).

Les résultats de l'évaluation de la naturalité montrent une augmentation de l'indice de naturalité avec une augmentation du niveau de protection, ainsi qu'une naturalité plus élevée associée à un renouvellement des forêts via la coupe avec protection de la régénération et des sols (CPRS), par rapport à un renouvellement par plantation d'espèces indigènes dégagées mécaniquement. La qualité de l'écosystème évaluée sur la base de la naturalité transformée en PDF a fourni des résultats cohérents avec les connaissances en matière d'aménagement forestier (i.e. diminution du PDF avec une augmentation du niveau de protection traduisant l'effet positif de la protection et PDF plus élevé pour les plantations que pour les CPRS, traduisant l'effet négatif de l'intensification des pratiques sur la qualité des écosystèmes). L'autre paramètre du modèle ACV, la superficie requise pour produire 1m^3 de bois, affiche quant à lui les tendances inverses, soit une augmentation de la superficie requise associée à une augmentation de la proportion en protection et davantage de superficie requise pour le scenario de CPRS par rapport à celui de plantation. Le modèle ACV s'avère fortement influencé par l'effet de la superficie requise, qui diminue avec une intensification des pratiques d'aménagement (p. ex : plantation par rapport à la CPRS, réduction de la proportion en protection). La superficie requise pour produire l'unité fonctionnelle correspond à (1 ÷ productivité). La prise en compte du gradient de protection a permis de mettre en évidence que la superficie requise affichait un patron associé à la fonction inverse (1/x), caractérisé par un changement prononcé de pente.

La transformation de l'indice de naturalité (NI) en PDF utilisant la courbe provisoire a permis de calculer un score d'impact qui reflète les tendances observées avec le PDF, avant son introduction dans le modèle de l'ACV. Toutefois, l'analyse de sensibilité de la courbe utilisée pour traduire la naturalité en PDF a montré que la fenêtre permettant l'obtention de résultats de qualité des écosystèmes susceptibles de contrebalancer l'effet non-linéaire de la superficie requise pour produire l'unité fonctionnelle est étroite et qu'il y a des risques de distorsions le long du gradient de protection, voire d'inversion de résultats, si la transformation s'ajuste mal par rapport à l'effet de la superficie requise. Les résultats mettent en évidence l'importance d'acquérir davantage de données sur l'évolution de la biodiversité en rapport avec l'aménagement forestier en forêt boréale. Ceci étant dit, une validation basée sur des données de terrain pose des défis considérant que l'ACV porte sur des impacts potentiels alors que l'aménagement forestier provoque une transformation lente et graduelle sur de très vastes superficies dont les impacts ne sont pas immédiats. Étant donné que l'ACV cherche à développer un modèle fondé sur des données empiriques de biodiversité afin d'évaluer l'effet de la production d'un produit sur la qualité des écosystèmes, rien ne garantit que le score d'impact résultant pourrait effectivement contrebalancer l'effet de la superficie requise si des données de suivi temporel de la biodiversité propres au territoire étaient disponibles.

La transformation de NI en PDF a conduit à l'obtention de résultats cohérents grâce à un effet nul pour les niveaux élevés de protection ayant permis d'annuler l'augmentation exponentielle de la superficie requise. Cependant, l'utilisation de valeurs nulles fait en sorte de limiter artificiellement le potentiel améliorant du niveau de protection à la portion inférieure du gradient de naturalité, correspondant aux faibles niveaux de protection. Pour pallier, du moins partiellement, à cette situation, un effet infinitésimal a été introduit arbitrairement pour la portion quasi-naturelle du gradient de naturalité afin d'éviter de perdre la sensibilité obtenue avec la naturalité, laquelle est nécessaire pour bien caractériser les effets de l'aménagement forestier qui ne conduisent pas nécessairement à une perte d'espèces. De plus, une accélération des pertes en progressant vers le niveau plus altéré du gradient, associé à des faibles niveaux de protection, est nécessaire pour différencier les différents scénarios d'aménagement. Toutefois, avec la transformation du NI en PDF, l'importance des différences entre les scénarios sylvicoles croissante vers les niveaux inférieurs de protection résulte plutôt d'un écrasement de ces différences en progressant le long du gradient croissant de protection. Par conséquent, il ne serait pas judicieux d'utiliser les résultats du modèle ACV pour tenter de déterminer le niveau de protection requis, étant donné que celui-ci dépendrait des valeurs utilisées pour le paramétrage de la courbe NI-PDF et représenterait de ce fait un artefact du modèle ACV. Pour ce qui est de la différenciation entre les scénarios sylvicoles permettant le classement relatif des différents scénarios, la transformation en PDF fournit de petites valeurs (comprises entre 0 et 0.16 dans les 3 UAF du nord) qui, lorsque multipliées par la superficie requise (dont l'étendue varie grosso modo entre 0.5 et 30 dans les 3 UAF du nord), sont susceptibles de fournir des scores d'impacts respectant l'ordination relative des scénarios obtenue avec la naturalité ou le PDF, lesquels reflètent les connaissances scientifiques sur la dégradation des écosystèmes en lien avec l'aménagement forestier. Par contre, si les valeurs utilisées pour la mesure de la qualité des écosystèmes n'ont pas l'étendue et la forme appropriée pour contrebalancer l'effet de la superficie requise, l'ordination des scénarios sylvicoles pourrait être différente par rapport à l'évaluation effectuée à l'échelle du territoire, ce qui pose problème dans une perspective d'aide à la prise de décision visant à protéger la qualité et l'intégrité des écosystèmes.

Quant au seuil écologique, on ignore quel est le niveau de d'altération ou de perte de richesse en espèces au-delà duquel on assisterait à un changement permanent de l'écosystème conduisant à une dégradation irrémédiable. En fait, lorsqu'il devient possible d'identifier un tel seuil pour un écosystème donné, il est déjà trop tard. Cependant, le modèle conceptuel sur lequel repose l'évaluation de la naturalité prévoit un changement notable de qualité des écosystèmes dans la classe semi-naturelle auquel serait associé une perte potentielle d'espèces grandissante. En principe, les objectifs d'aménagement devraient être fixés de manière à prévenir le franchissement du seuil écologique. Considérant notre modèle conceptuel d'évaluation de la naturalité qui prévoit une accélération de l'altération dans la classe semi-naturelle, avec des pertes d'espèces qui deviennent de plus en plus importantes, un objectif d'aménagement fixé de manière à demeurer au-dessus de la classe semi-naturelle ($NI \geq 0.6$) permettrait d'assurer l'application du principe de précaution, tandis qu'un objectif appliquant un $NI \geq 0.5$ admettrait un certain niveau d'altération impliquant potentiellement des pertes d'espèces relativement limitées. Pour ce qui est du passage à l'ACV, on peut s'interroger à savoir si l'effet de seuil nécessaire pour contrebalancer l'effet de la superficie requise sera en adéquation avec un éventuel seuil écologique de proportion d'espèces disparues calculé à partir de données empiriques et réfléchir sur les implications éventuelles d'un mauvais ajustement.

Par ailleurs, il faut également tenir compte de l'effet des hypothèses de rendement qui influencent l'étendue des données entre les différents scénarios sylvicoles, ce qui influence à son tour la force de la transformation requise pour permettre d'inverser l'ordre des scénarios et aboutir à des résultats qui soient dominés par l'effet du facteur de caractérisation correspondant au sujet à protéger, en l'occurrence la qualité des écosystèmes, et non pas par celui de la superficie requise résultant de la productivité. Les résultats de l'analyse de sensibilité montrent la nécessité d'aller plus loin que l'évaluation d'un facteur de caractérisation découlant d'une méthode quelle qu'elle soit et l'importance d'en vérifier l'effet dans le modèle ACV.

De plus amples essais, incluant davantage de type d'utilisation des terres et diverses productions, avec différentes productivités pour voir l'effet simultané des deux paramètres impliqués dans le modèle ACV, sont nécessaires pour le développement d'un ou des indicateurs de biodiversité devant être utilisés dans les ACV, car la mesure du facteur de caractérisation (ΔQ) devrait être adaptée à l'usage que l'on veut en faire compte tenu des caractéristiques des relations mathématiques en jeu. Avant d'aller plus loin dans l'utilisation des résultats de l'ACV, il serait primordial de déterminer les paramètres qui feraient en sorte de garantir que ce soit effectivement la qualité des écosystèmes qui prime lorsque ce facteur est pris en compte dans les ACV.

Les résultats de la présente recherche devraient éventuellement être intégrés à une ACV de bâtiments afin de comparer les résultats avec les autres méthodes proposées (comme par exemple, l'utilisation du système BioImpact pour évaluer la biodiversité dans son ensemble sur la base d'opinions d'experts (Penman et al. 2010; Turner et al. 2019), ou des facteurs de caractérisation globaux de de Baan et al. (2013b), ou de ceux résultant de l'utilisation de la SAR (Chaudhary et al. 2015; Chaudhary & Brooks 2018)). Cette étape devrait intégrer la prise en compte de la qualité du bois, ce qui nécessite des données permettant de caractériser la répartition par produits pour chacun des scénarios sylvicoles considérés. Il serait notamment important que les futures études se penchent sur les effets sur le plan mathématique de différentes unités fonctionnelles d'une part et sur la partition du PDF par taxons, telle que proposée par Chaudhary & Brooks (2018), d'autre part. Cette dernière suscite des questionnements quant aux résultats éventuels des scores d'impact, si les données de PDF partitionnées selon les différents taxons ne permettaient pas de contrebalancer l'effet de la superficie requise. Une avancée méthodologique visant à s'assurer que l'indicateur de qualité possède les caractéristiques mathématiques nécessaires pour contrebalancer l'effet de la superficie requise serait appropriée à cet égard. Il serait également judicieux de se pencher sur l'effet sur les scores d'impact ACV, de la prise en compte simultanée des différentes catégories d'impact, à savoir : la qualité des écosystèmes, l'épuisement des ressources naturelles, la santé humaine et les changements climatiques. Mentionnons à cet égard que l'approche méthodologique à l'échelle du paysage développée dans le cadre de la présente étude pour l'évaluation de la naturalité associée à l'application de scénarios d'aménagement pourrait éventuellement être utilisée comme base pour évaluer de manière intégrée, les effets sur les changements climatiques à l'échelle du paysage en tenant compte de la structure d'âge résultante associée à chacune des composantes des scénarios d'aménagement appliquées de manière soutenue et ainsi fournir une base commune qui permettrait d'établir des relations avec des données de bilan carbone pour différents scénarios sylvicoles.

Finalement, considérant la présence de relations non-linéaires non contrôlées, il ne serait pas judicieux, dans l'état actuel des choses, d'utiliser les résultats de l'ACV pour une prise de décision relative à l'utilisation des terres pour l'aménagement forestier en forêt boréale. De plus amples recherches sont nécessaires afin de voir si et comment il serait possible de contrôler cet aspect. Il s'avère nécessaire de se pencher sur la mathématique du modèle considérant les effets en présence pour assurer l'obtention de résultats qui permettraient de tenir compte prioritairement de l'aspect à protéger, soit la qualité des écosystèmes. En principe, la prise en compte de ce qu'il importe de protéger dans le cadre d'une évaluation de l'impact environnemental devrait permettre de limiter les dommages. Or, le modèle de l'ACV divise l'effet de la mesure de la dégradation des écosystèmes par la productivité. Si bien, qu'en l'absence d'une prise en compte adéquate de ce qu'il importe impérativement de protéger, on pourrait penser augmenter la productivité sans limites et ainsi diviser les impacts. Une évaluation considérée comme respectueuse de l'environnement, devrait permettre notamment d'identifier certaines limites : on pourrait produire davantage mais les impacts négatifs sur le sujet à protéger, soit la qualité des écosystèmes dans le cas qui nous occupe, représentent une limite que pour le moment on n'arrive pas à identifier. Pour ce faire, les résultats du modèle de l'ACV devraient respecter la hiérarchisation des impacts évalués sur le sujet à protéger pour l'ensemble du territoire considéré. À cet effet, les aspects mathématiques intervenant dans le modèle de l'ACV devraient être examinés plus en profondeur afin d'être en mesure de développer une méthode adéquate pour s'assurer que la prise en compte du sujet à protéger prime sur l'effet de la superficie requise déterminée par la productivité (i.e. s'assurer mathématiquement que l'effet de ΔQ surpasse celui de la superficie requise sur l'ensemble du gradient de protection). À défaut d'un contrôle adéquat de cet aspect, le modèle de l'ACV pourrait être utilisé pour justifier une augmentation de la production en prétendant tenir compte de la qualité des écosystèmes, alors que dans les faits, les dommages causés à l'environnement à l'échelle des territoires concernés seraient plus importants et pourraient s'avérer irrémédiables. L'utilisation des terres s'applique à des surfaces dont la quantité est finie à l'échelle de la planète. Il s'avère donc primordial que la prise de décision s'effectue à cette échelle. Ceci étant dit, il serait néanmoins judicieux de faire en sorte que les évaluations environnementales associées à un produit reflètent les impacts à l'échelle des territoires aménagés.

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