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Naturalness assessment performed using forestry maps to validate forest management sustainability

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ABSTRACT

One-quarter of forest areas worldwide are managed for forestry purposes. Depending upon the type of practice and intensity of management, forestry may alter forests to various degrees and raise sustainability issues. To mitigate the alteration of natural forests by forestry and to promote sustainability, ecosystem management has been implemented widely over the past quarter century. A need remains for the development of comprehensive and operational assessment approaches to validate its effectiveness. Naturalness assessment could be used to validate effectiveness of ecosystem management since this concept relates to the degree to which a natural state has been altered. We developed an approach that integrates stand- and landscape- scale traits of naturalness into a single comprehensive assessment that can be performed using only forestry maps. To illustrate our approach, we assessed naturalness in four managed forest landscapes (2184 km^2), representing a management gradient of increasing intensity from passive restoration to plantation forestry. We defined four naturalness classes, i.e., natural, semi-natural, altered and artificial. Assessment was performed in two steps. At step one, we attributed a class to each managed stand by comparing its current composition with natural stand compositions of its potential natural vegetation. At the landscape scale, certain developmental stages or forest types could be in excess in managed forest landscapes compared with natural forest landscapes. At step two, we transferred numbers of stages or types in excess from the natural class to more altered classes. We demonstrated that naturalness decreased as management intensity increased. Passive restoration and extensive management generated a landscape where semi-natural forests predominated in mixtures with a lower abundance of natural forests. Intensive management generated a largely semi-natural forest landscape. Plantation forestry generated a landscape where semi-natural and altered forests predominated. In conclusion, it should now be possible to validate the effectiveness of different practices and intensity of ecosystem management in promoting sustainability, by performing our assessment approach periodically following every update of forestry maps. Our approach could also allow for more comprehensive assessment of forest management strategies developed to mitigate global change by putting into better perspective their potential effects upon forest alteration of various forestry practices that have been implemented to sequester carbon.

1. Introduction

One-quarter of forest areas worldwide are managed for forestry purposes (FAO, 2015; Köhl et al., 2015). Depending upon the type of practice and intensity of management, forestry may alter forests to various degrees and raise sustainability issues (Lindenmayer et al., 2012; Stanturf et al., 2014; Köhl et al., 2015). To mitigate the alteration of natural forests by forestry and to promote sustainability, ecosystem management has been implemented widely over the past quarter century (Grumbine, 1994; Fischer et al., 2006; Mori, 2011). This management paradigm presumes that biodiversity and ecosystem functions will be maintained and, hence, sustainability will be achieved by reducing gaps in the variability of key forest attributes (e.g., species composition, stand structure, dead wood, landscape age structure) between managed and natural forests (Gauthier et al., 2009; Urli et al., 2017). Yet, even if ecosystem management has already been widely implemented, there is still a need for the development of comprehensive and operational assessment approaches that validate its

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effectiveness in reducing gaps between managed and natural forests (Lexer and Seidl, 2009; Stanturf et al., 2014; Mori et al., 2017).

Assessment of “naturalness” could be used to validate the effectiveness of ecosystem management, given that this concept relates to the degree to which a natural state has been altered (Winter, 2012). Naturalness can be represented in the form of an ecological gradient varying from a reference state that is deemed natural to a state that is deemed artificial (Colak et al., 2003; Winter, 2012), which could help us evaluate the gaps between managed and natural forests that ecosystem management strives to reduce (Barrette et al., 2014b). Several approaches have been proposed to assess naturalness, but the advantages and disadvantages of these approaches are still debated (Colak et al., 2003; Rüdisser et al., 2012; Winter, 2012; Côté et al., 2019). Two improvements could be made to pre-existing assessment approaches to obtain a more comprehensive and operational assessment of naturalness that would validate the effectiveness of ecosystem management. First, to be more comprehensive, independent assessments of the various traits of naturalness at both stand and landscape scales could be integrated into a single assessment (Winter, 2012). Usual traits of naturalness (e.g., species composition, stand structure, dead wood, landscape age structure) are key forest attributes, which are essential for maintaining biodiversity and ecosystem functions of natural forests (Colak et al., 2003; Winter, 2012; Barrette et al., 2014b). Second, to be more operational, the assessment approach should be developed for ease of use in actual forest planning and, thus, should employ forestry maps while not requiring additional data collection (Kneeshaw et al., 2000).

In eastern Canada, forested Crown lands (public lands) of the Province of Quebec (261 533 km^2) must be managed according to an ecosystem management paradigm (Sustainable Forest Development Act, CQLR c A-18.1). For its implementation, government officers had determined objectives and targets for multiple ecological issues that were derived from gap analysis of key attributes between managed and natural forests (Jetté et al., 2013). These multiple objectives and targets tend to offer only a fragmented picture of the degree to which forestry practices alter natural forests. There is a need for a more integrated approach (Winter, 2012). In fact, the effectiveness of ecosystem management in reducing gaps between managed and natural forests has yet to be validated (MFFP, 2018a). Therefore, we took advantage of the forest management context of eastern Canada to develop an approach that integrates stand- and landscape-scale traits of naturalness into a single comprehensive assessment that can be performed using only forestry maps. To illustrate our approach, we assessed the naturalness of four managed forest landscapes, which represented a management gradient of increasing intensity from passive restoration to plantation forestry.

2. Materials and methods

2.1. Study area

The four managed forest landscapes (2 184 km^2) are located within the boreal region of eastern Canada (Fig. 1; Grondin et al., 2007). Mean annual temperature is 2 °C, mean annual precipitation is 1100 mm, and mean annual number of frost-free days is 110 (Grondin et al., 2007). The main natural disturbances include insect outbreaks (e.g., eastern spruce budworm [*Choristoneura fumiferana*]), windthrows and, to a lesser extent, fire (Boucher and Grondin, 2012; Boucher et al., 2014). The main tree species that are naturally found in this region are balsam fir (*Abies balsamea*), paper or white birch (*Betula papyrifera*) and yellow birch (*Betula alleghaniensis*). These species are found in mixtures with varying densities of companion species, such as black spruce (*Picea mariana*), white spruce (*Picea glauca*), red spruce (*Picea rubens*), jack pine (*Pinus banksiana*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis)*, eastern white cedar (*Thuja occidentalis*), eastern larch or tamarack (*Larix laricina*), sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), balsam poplar (*Populus balsamifera*) and trembling aspen (*Populus tremuloides*).

The four managed forest landscapes represented a management gradient of increasing intensity. Their limits were determined by the provincial government, for administrative and management purposes. Industrial forestry began in the late 19th century in all four managed forest landscapes (Boucher and Grondin, 2012; Boucher et al., 2014). Industrial forestry was characterized by extensive forest management, relied upon natural regeneration for the post-logged stands, focused upon attaining a minimum species composition, and strived to maintain a given landscape age structure to acquire sustained yield (Bell et al., 2006; Gravel and Meunier, 2013). Managed forest landscape 1 (664 km^2) was subjected to passive restoration following the creation of a national park (Parc national de la Jacques-Cartier) in 1981 (i.e., 37 years) for conservation and recreation purposes, which precludes any forest management. Managed forest landscape 2 (332 km^2) was subjected to ecosystem management planning following the application of the Sustainable Forest Development Act in 2008 (i.e., 10 years). Managed forest landscape 3 (66 km^2) was subjected to ecosystem management planning after it became the model teaching and research forest of Laval University in 1964 (i.e., 54 years). Over the years, the numerous initiatives that were tested operationally on a relatively small territory have had the effect of intensifying management of managed forest landscape 3. Managed forest landscape 4 (1122 km^2) was also subjected to ecosystem management planning for the past 10 years. In 1980, the managed forest landscape 4 also was subjected to an extensive planting program to reforest large areas and produce more wood through intensive forest management after massive infestations of spruce budworm (Bell et al., 2006; Gravel and Meunier, 2013; Barrette et al., 2014b). Plantations of native species (i.e., black spruce and white spruce) occupied 30% of the forest area of managed forest landscape 4, while plantations of an exotic species, Norway spruce (*Picea abies*), occupied 3% of the forest area (MFFP, 2018b).

2.2. Data

We used the most current forestry stand maps that had been created by the Province of Quebec (MFFP, 2018b). These maps are produced and updated every ten years to ensure that all aspects of sustainable forest management (e.g., biodiversity conservation, determination of annual allowable cut, economically viable forestry operations) can be taken into account by managers during forest management planning processes. These maps were produced through photo-interpretation of aerial photographs that were taken at a scale of 1:15 000, with field control points for ground truthing. Species identification is performed by the use of aerial photographs projected onto 3D screens (equivalent pixel size of 30 × 30 cm on the ground), using textural, shape and characteristic colour criteria for each species and with the support of 3D viewing software, Summit Evolution (DAT/EM Systems International, 2012). From these maps, we obtained data on stand- and landscape-scale traits that were relevant to naturalness assessments, i.e., species composition, stand structure, dead wood, landscape age structure and composition (Colak et al., 2003; Chirici et al., 2011; Winter, 2012; Barrette et al., 2014b).

To analyze species composition and landscape composition, we used data on stand composition (i.e., up to 7 species in 10% classes of stand basal area), stand area (ha), forest type (i.e., coniferous, mixed, hardwood) and potential natural vegetation of each stand. Potential natural vegetation is a land classification unit that is determined by climate, superficial deposits, soil texture, slope, drainage and understory indicator species, and which predicts potential species composition of stands in late successional stages (Grondin et al., 2013; MRN, 2013; Robitaille et al., 2015; Prach et al., 2016).

To analyze stand structure, dead wood and landscape age structure, we used data on stand age class (20-year age classes) and stand area (ha). Stand age classes were grouped into four developmental stages of

Fig. 1. Location of the four managed forest landscapes representing a management gradient of increasing intensity (i.e., 1. Passive restoration < 2. Extensive management < 3. Intensive management < 4. Plantation forestry).

age ranges coherent with the longevity of trees in the boreal region of eastern Canada (i.e., regeneration, 0–20 years; young, 21–40 years; mature, 41–80 years; old, > 80 years). Developmental stages are proxies for stand structure and dead wood and, therefore, provide only indirect information regarding these two traits. Nevertheless, stand structure generally becomes more complex, with amounts of large dead wood typically increasing in older stages (Oliver and Larson, 1996; Sturtevant et al., 1997; Gauthier et al., 2009; Urli et al., 2017).

2.3. Data analysis

We defined four classes subdividing the naturalness gradient, i.e., natural, semi-natural, altered and artificial. The assessment was then performed in two steps. At step one, we attributed a class to each managed stand by comparing its current composition with natural stand compositions of its potential natural vegetation. At the landscape scale, certain developmental stages or forest types could be in excess in the managed forest landscapes compared with natural forest landscapes. At step two, we transferred numbers of stages or types in excess from the natural class to the more altered classes.

2.3.1. Step 1. Stand scale assessment

We attributed a naturalness class to each managed stand according to five criteria (Table 1). With the first criterion, we assessed whether the managed stands were natural by comparing their current composition with natural compositions of their potential natural vegetation. Natural stand compositions were determined with conceptual successional dynamics models that were developed for each of the four main natural potential vegetation types that are found in eastern Canada, i.e., balsam fir-paper birch forests (Fig. 2), balsam fir-yellow birch forests, sugar maple-yellow birch forests and black spruce forests. Development of these conceptual models is based upon a synthesis of available knowledge regarding successional dynamics occurring in eastern Canada (Bergeron, 2000; McCarthy, 2001; MRN, 2013; Grondin et al., 2013; Maleki et al., 2020). In order to allow the development of comprehensive models, we reduced model complexity by grouping species according to their capacity to dominate stand cover (i.e., dominant or companion species), shade tolerance (i.e., tolerant or intolerant species) and type (i.e., conifer or hardwood species). Species groups were dominant tolerant conifers (DTCo), dominant tolerant hardwoods (DTHa), dominant intolerant hardwoods and conifers (DIHaCo), and companion tolerant hardwoods and conifers (CTHaCo). Types were not distinguished for DIHaCo or for CTHaCo because their regeneration strategies following natural disturbances were similar (McCarthy, 2001; MRN, 2013; Maleki et al., 2020). The models were driven by five natural processes (i.e., regeneration, growth, self-thinning, senescence and natural disturbances) within four developmental stages (i.e., regeneration, young, mature, old) and four successional stages (i.e., early, transition, stabilization and equilibrium). In the early successional stage of the most frequent potential natural vegetation (Fig. 2), DIHaCo are the only species present. In the transition successional stage, DTCo appear and can come to dominate stand composition. In the stabilization successional stage, CTHaCo can appear, but they remain subdominant while they are more abundant than DIHaCo in the equilibrium successional stage.

With the second criterion, we decreased naturalness of managed stands when species groups were missing from their current composition for it to correspond to a natural stand composition of their potential natural vegetation. With the third criterion, we lowered naturalness of managed stands when the order of species groups for their current composition did not correspond to a natural stand composition of their potential natural vegetation.

With the fourth criterion, we decreased naturalness of managed stands when indigenous tree species other than those occurring naturally according to the potential natural vegetation were present. With the fifth criterion, we lowered naturalness of stands when exotic tree species occurred. For the application of criteria 4 and 5, we used a stand basal area threshold of 50%, because this threshold determines when a species that comes to dominate the composition of a stand sufficiently to change its designation (MFFP, 2018b). A single criterion was sufficient to assess naturalness and multiple criteria did not have a cumulative effect on the assessment.

2.3.2. Step 2. Landscape scale assessment

At the landscape scale, certain developmental stages or forest types could be in excess in the managed forest landscapes compared with natural forest landscapes. For example, even if young paper birch stands were deemed to be natural at the stand scale, they could be

Table 1
Definitions of naturalness classes and assessment criteria at the stand scale.

Naturalness classes	Definitions	Assessment criteria at the stand scale
Natural	Forest with state of naturalness traits within the range of natural variability. Usual traits of naturalness (e.g., species composition, stand structure, dead wood, landscape age structure) are key attributes, which are essential for maintaining biodiversity and ecosystem functions of natural forests	- Current composition corresponds to a natural composition of the stand's potential natural vegetation (criterion 1).
Semi-natural	Forest that still possess most of the naturalness traits. States of traits that are still present are moderately altered and depart from the range of natural variability.	- One species group is missing from current composition for it to correspond to a natural composition of the stand's potential natural vegetation (criterion 2). - The order of species groups of current composition does not correspond to a natural composition of the stand's potential natural vegetation (criterion 3). - Indigenous species other than those occurring naturally according to the stand's potential natural vegetation (IN) compose < 50% of stand basal area (criterion 4).
Altered	Forest that only possess a few naturalness traits. States of traits that are still present are heavily altered and are far from the range of natural variability.	- More than one species group is missing from current composition for it to correspond to a natural composition of the stand's potential natural vegetation (criterion 2). - The order of the species groups for current composition does not correspond to a natural composition of any potential natural vegetation (criterion 3). - IN compose ≥50% of stand basal area (criterion 4). - Exotic species compose < 50% of stand basal area (criterion 5).
Artificial	Forest with an assemblage of species that have not co-occurred naturally.	- Exotic species compose ≥50% of stand basal area (criterion 5).

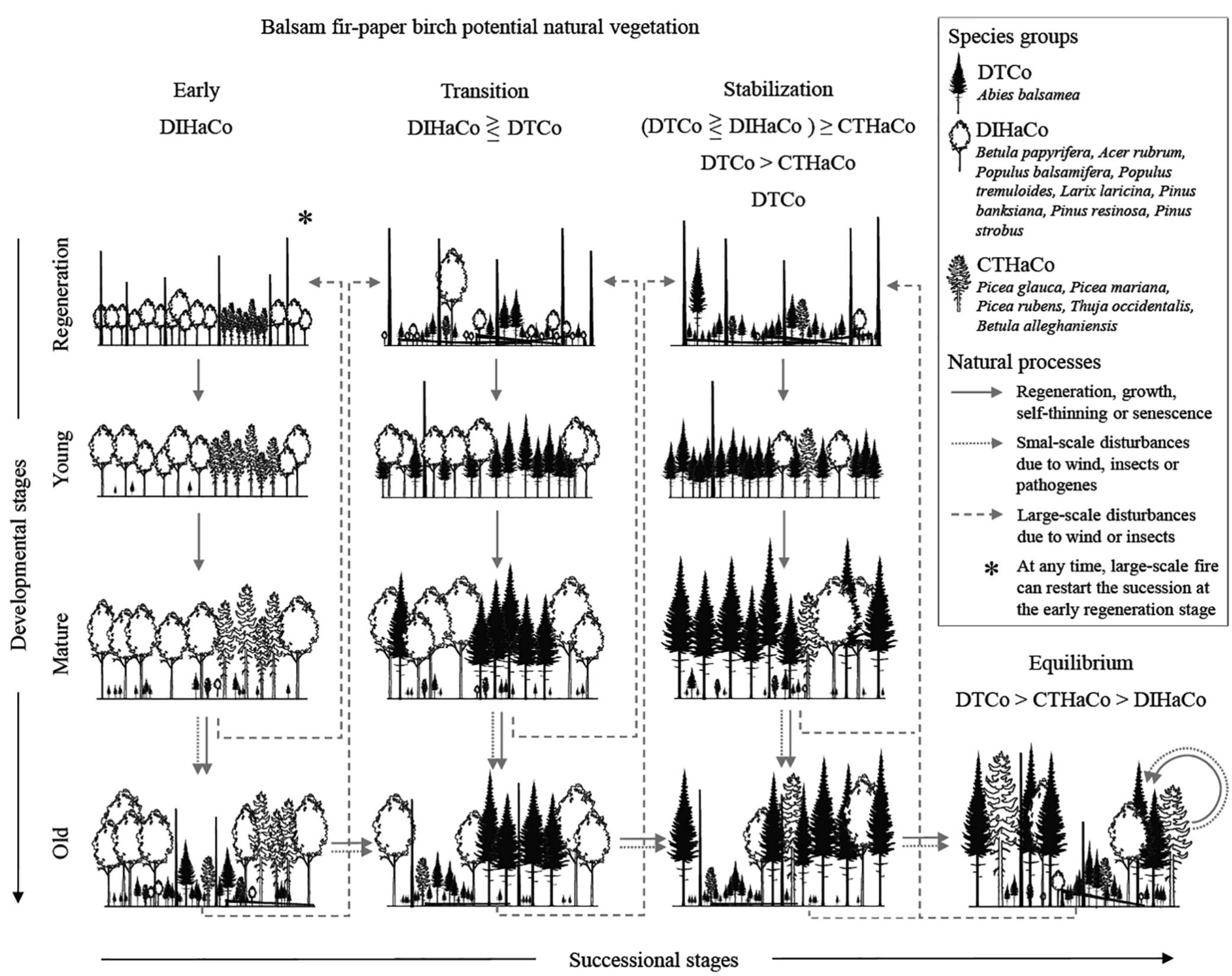

Fig. 2. Illustration of the conceptual successional dynamics model of the most frequent potential natural vegetation. DIHaCo: Dominant Intolerant Hardwoods and Conifers; DTCo: Dominant Tolerant Conifers; CTHaCo: Companion Tolerant Hardwoods and Conifers.

Table 2
Illustration of the landscape scale assessment, i.e. step 2. At this step, we transferred the excess numbers of stages or types from the natural class to the more altered classes according to two scenarios. In the following example, young hardwood stands covers 36% of the managed forest landscape of which 20% are in the natural class. In scenario 1, the excess number of young hardwood stands (i.e., 15%) ≤ while in scenario 2, the excess number of young hardwood stands (i.e., 25%) > than the number of young hardwood stands in the natural class (i.e., 20%).

Stage	Type	Naturalness class	Proportion of forest area (%)		
			Stand scale	Landscape scale	
				Scenario 1 e.g., excess of 15%	Scenario 2 e.g., excess of 25%
Young	Hardwood	Natural	20	20–15 = 5	20–25 = −5 (i.e., 0)
		Semi-natural	10	10 + 15 = 25	(10 + 20) − (25–20) = 25
		Altered	5	5	5 + (25–20) = 10
		Artificial	1	1	1

considered in excess at the landscape scale. Landscape age structure and composition are fundamental traits of naturalness (Winter, 2012) and paramount issues of sustainable forest management (Gauthier et al., 2009; Mori, 2011; Köhl et al., 2015). Hence, at step 2, we transferred the numbers of stages or types in excess from the natural class to the more altered classes. To determine excess numbers, we subtracted the relative abundances of stages and types in the natural forest landscapes from relative abundances of stages and types in the four managed forest landscapes. Proportions of forest area in each stage and type in managed forest landscapes were calculated from data of the stand map (MFFP, 2018b), while proportions of forest area in each stage and type in the natural forest landscapes were retrieved from natural variability studies covering our study area (Boucher et al., 2011; Bouchard et al., 2015). These studies were based upon a synthesis of available knowledge regarding the effects of landscape scale natural disturbances (e.g., insect outbreaks and fire regimes) on the composition and age structure of the natural forest landscape.

We transferred excess numbers according to two scenarios (Table 2). In Scenario 1, if the excess number was lower than or equal to the number of natural stands in the stage or type in excess, we implemented a straightforward transfer of the excess number from the natural class to the semi-natural class. In Scenario 2, if the excess number was higher than the number of natural stands in the stage or type in excess, we also transferred the residual excess from the semi-natural class to the altered class. Since stands are in a developmental stage at the same time that they are in a forest type, transfers were performed in a single operation, prioritizing the attribute with the largest excess number.

3. Results

3.1. Step 1. Stand scale assessment

Naturalness at the stand scale decreased as management intensity increased (Fig. 3). In fact, the proportion of forest area in the lower classes of naturalness generally increased as management intensity increased. Natural stands covered about 75% of managed forest landscapes 1, 2 and 3, while natural stands covered 51% of landscape 4. Semi-natural stands covered 28%, 17%, 17% and 36% of landscapes 1, 2, 3, and 4, respectively. Altered stands covered less than 1%, 3%, 6% and 9% of landscapes 1, 2, 3 and 4, respectively. Artificial stands covered 3% of landscape 4, but they were absent from the other landscapes.

Overall, 54% of semi-natural stands and 85% of altered stands were assessed as such because the order of species groups within the current composition did not correspond to a natural composition that reflected the stand's potential natural vegetation (criterion 3; Table 1). In semi-natural stands, groups of shade-tolerant companion species predominated. In altered stands, the cause was the predominance of white spruce, which is in the group of shade-tolerant companion species.

Forty-five percent of semi-natural stands and 13% of altered stands were designated as such because indigenous species other than those occurring naturally according to the stand's potential natural vegetation were present (criterion 4). Other indigenous species most frequently included non-commercial hardwoods, such as *Prunus pensylvanica*, *Sorbus americana*, *Salix* spp. or *Acer spicatum*.

One percent of semi-natural stands were designated as such because one species group was missing from current composition for it to correspond to a natural composition of the stand's potential natural vegetation (criterion 2). Finally, 2% of altered stands and all artificial stands were designated as such because an exotic species was present (criterion 5).

3.2. Step 2. Landscape scale assessment

Naturalness at the landscape scale also decreased as management intensity increased (Fig. 3). Once again, the proportion of forest area in the lower classes of naturalness generally increased as management intensity increased. Natural forests covered 30%, 25%, 11% and 33% of managed forest landscapes 1, 2, 3 and 4, respectively. Semi-natural forests covered 66%, 69%, 80% and 36% of landscapes 1, 2, 3 and 4, respectively. Altered forests covered 3%, 3%, 6% and 27% of landscapes 1, 2, 3 and 4, respectively. Artificial forests covered 3% of landscapes 4, but these were absent from the other landscapes.

We present transfers of developmental stages only since it was the attribute with the largest excess number (Table 3). In managed forest landscape 1, 41% of the natural forest area was transferred from the natural class to the semi-natural class and 3% of semi-natural forest area was transferred from the semi-natural class to the altered class. In landscape 2, 52% of the forest area was transferred from the natural class to the semi-natural class. In landscape 3, 63% of the forest area was transferred from the natural class to the semi-natural class. Finally, in landscape 4, 18% of the forest area was transferred from the natural class to the semi-natural class, and 18% of the forest area was transferred from the semi-natural class to the altered class.

4. Discussion

Our study is one of the first to develop an approach that integrates stand and landscape scales traits of naturalness into a single comprehensive assessment. Other studies have assessed naturalness, but most often these have been derived from the assessment of a single trait, such as coarse woody debris (Kunttu et al., 2015), stand structure (Uotila et al., 2002; Winter et al., 2010) or species composition (Wallenius et al., 2010; Bončina et al., 2017). Such non-integrated approaches can only produce partial portraits of forest alteration and, hence, the latter could not validate the overall effectiveness of ecosystem management practices (Winter, 2012). Moreover, these other studies often need additional data collection to assess naturalness of these specific traits. Conversely, our approach can be performed by using only pre-existing

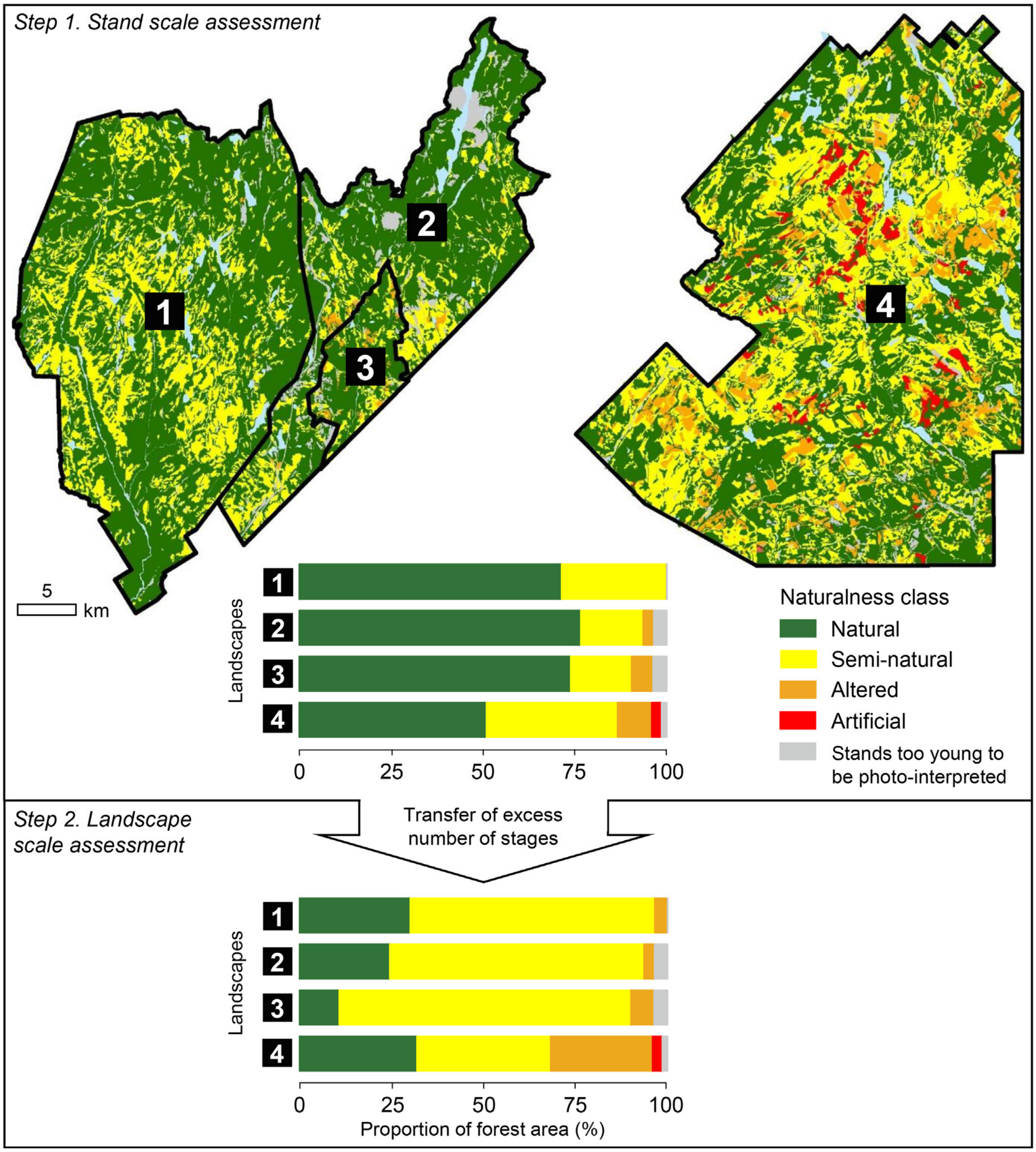

Fig. 3. Naturalness assessment of four managed forest landscapes, representing a management gradient of increasing intensity (i.e., 1. Passive restoration < 2. Extensive management < 3. Intensive management < 4. Plantation forestry).

Table 3
Excess numbers of developmental stages and forest types in the four managed forest landscapes compared with natural forest landscapes.

	Proportion of forest area (%)											
	Managed forests				Natural forests[†]				Excess numbers			
	1	2	3	4	1	2	3	4	1	2	3	4
Stages												
Regeneration	1	23	16	9	4	4	4	6	–	19	12	3
Young	34	46	40	49	15	15	15	17	19	31	25	32
Mature	35	12	36	11	10	10	10	10	25	2	26	1
Old	30	19	8	31	71	71	71	67	–	–	–	–
Types												
Coniferous	62	81	79	56	73	73	73	65	–	8	6	–
Mixed	28	15	17	29	19	19	19	30	9	–	–	–
Hardwood	10	4	4	15	8	8	8	5	2	–	–	10

[†] Retrieved from Boucher et al. (2011) and Bouchard et al. (2015).

forestry maps, which also make it possible to assess naturalness rapidly over large forest landscapes (Chirici et al., 2011).

We were able to illustrate that naturalness decreased as management intensity increased by applying our assessment approach over four large managed forest landscapes. The landscape with the lowest management intensity (landscape 1) had the highest naturalness. Passive restoration occurring over the last 37 years following 80 years of extensive management generated a landscape mixture where semi-natural forests predominated with a lower abundance of natural forests. In this landscape, the occurrence of indigenous species, other than those occurring naturally according to the potential natural vegetation, generated numerous semi-natural stands. These other indigenous species were generally non-commercial hardwoods. While such species are usually not as abundant in natural stands (Delisle-Boulianne et al., 2011; Terrail et al., 2014), their presence was probably favored by clearcutting operations that were performed prior to the creation of the national park (Jobidon, 1995). These species were less abundant in the other managed forest landscapes, possibly because they were removed by tending treatments that are no longer allowed in landscape 1 after the creation of the national park (Wiensczyk et al., 2011). Thus, passive restoration possibly reduced naturalness by letting management legacies persist. Yet, passive restoration possibly also favored naturalness by letting natural dynamics drive the landscape age structure back toward its range of natural variability (Oliver and Larson, 1996; Sturtevant et al., 1997; Gauthier et al., 2009; Mori, 2011). Effectively, the excess number of developmental stages was moderate and only a moderate proportion of natural forests was transferred from the natural class to the semi-natural class.

In landscape 2, extensive management that occurred over about 120 years also generated a landscape where semi-natural forests predominated in mixtures with a lower abundance of natural forests. The only noteworthy difference between this and landscape 1 was the occurrence of a few altered stands. Continued passive restoration in landscape 1 and extensive management in landscape 2 should widen the naturalness gap between the two. First, resilience should enable naturalness at the stand scale of landscape 1 to recover completely as semi-natural stands that follow natural successional pathways back to their natural composition (Barrette et al., 2019). Second, naturalness at the landscape scale should also recover completely as the landscape age structure returns toward its range of natural variability now that it is driven only by natural dynamics (Oliver and Larson, 1996; Sturtevant et al., 1997; Gauthier et al., 2009; Mori, 2011; Boucher and Grondin, 2012).

In landscape 3, intensive management that occurred over the last 60 years following 60 years of extensive management generated a largely semi-natural forest landscape. Naturalness was lower in landscape 3 than in landscape 2 because there was a greater excess of developmental stages in landscape 3; consequently, a larger proportion of natural forests was transferred from the natural class to the semi-natural class.

Finally, the landscape with the highest management intensity (landscape 4) had the lowest naturalness. Plantation forestry that was performed over the last 38 years following 80 years of extensive management generated a landscape where semi-natural and altered forests predominated. Plantation forestry is the only management practice that generated artificial forests. Most altered stands in landscape 4 and many semi-natural stands in landscapes 2 and 3 occurred because shade-tolerant companion species predominated. When such species are found within an ecological context that puts them in competition with more aggressive species (e.g., balsam fir, birch species, maple species) their response to ambient light levels and to competition, together with their regeneration strategy after natural disturbances, usually do not enable them to dominate stand compositions (Grondin et al., 2007; MRN, 2013; Barrette et al., 2014a, 2019). All of these stands most likely originated from plantations (MFFP, 2018b).

5. Forest management implications

In conclusion, it should now be possible to validate the effectiveness of different practices and intensity of ecosystem management in promoting sustainability, by performing our assessment approach periodically after every update of provincial forestry maps. Such periodical assessments could also be useful for identifying critical resilience thresholds (Miller and Bestelmeyer, 2016; Seidl et al., 2016). During intervals between management interventions, resilience should enable managed forests to recover higher levels of naturalness (Mori, 2011; Barrette et al., 2014b; Seidl et al., 2016). If naturalness does not recover during these intervals, the responses could indicate that resilience has been altered beyond a threshold (Mori et al., 2017; Barrette et al., 2019). Identifying such thresholds and their cause is paramount to ascertaining forest management sustainability, moreover so in the context of global change (Duncan et al., 2010; Bridgewater et al., 2011; Mori et al., 2017).

Worldwide naturalness assessments usually set apart natural forests from planted forests based upon management intensity (FAO, 2015; Forest Europe, UNECE and FAO, 2011; Bastrup-Birk, 2014). The fact that a forest has been managed does not necessarily mean that it has been altered significantly (Barrette et al., 2014b). Since our approach is based upon assessment of variability of key attributes, it should provide a more accurate assessment of actual forest alteration and sustainability issues. In turn, a more accurate assessment could help forest managers implement more relevant initiatives to mitigate forest alteration (Winter, 2012). It could also allow more comprehensive assessments of forest management strategies that have been developed to mitigate global change by putting into better perspective the potential impacts on forest alteration that are incurred by various forestry practices, which have been implemented to sequester carbon (Noormets et al., 2015).

Finally, concepts such has ecosystem management and naturalness will remain relevant only if natural forest references are adapted as our knowledge of the effects of global change on natural processes and ranges of natural variability evolves (Duncan et al., 2010; Bridgewater et al., 2011, Barrette et al., 2014b; Mori et al., 2017).

CRediT authorship contribution statement

Martin Barrette: Conceptualization, Methodology, Writing - original draft. **Daniel Dumais:** Methodology, Writing - review & editing. **Isabelle Auger:** Software, Writing - review & editing. **Yan Boucher:** Methodology, Writing - review & editing. **Mathieu Bouchard:** Software, Writing - review & editing. **Julie Bouliane:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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