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ARTICLE

A biophysical approach to delineate a northern limit to commercial forestry: the case of Quebec's boreal forest[1]

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Abstract: The boreal forest ecosystem is one of the largest frontier forests of the world, providing many ecological services to society. Boreal forests are also economically important, but forest harvesting and management become increasingly difficult when one moves from south to north in boreal environments. An approach was thus developed to assess the suitability of land units for timber production in a sustainable forest management (SFM) context in the northern boreal forest of Quebec (Canada). This area includes all of Quebec's spruce – feather moss bioclimatic domain (closed forest), as well as the southern portion of the spruce–lichen bioclimatic domain (open woodland). Four criteria specific to the biophysical aspects of SFM were evaluated in 1114 land districts: physical environment, timber production capacity, forest vulnerability to fire (e.g., probability that it reaches maturity), and conservation of biodiversity. Indicators and acceptability cutoff values were determined for each selected criterion, and a sequential analysis was developed to evaluate if a land district has the potential to be sustainably managed. This analytical process led to the classification of land districts into three categories: slightly sensitive (SFM possible); moderately sensitive (SFM possible under certain conditions); and highly sensitive (SFM not possible). The results show that 354 land districts were highly sensitive, 62 due to physical constraints (7.5% of the area), 130 due to insufficient potential productivity (15.4% of the area), 92 due to insufficient potential productivity to account for the fire risk (13.8% of the area), and 70 due to an insufficient proportion of tall and dense forest habitats (7.7% of the area — biodiversity criterion). This work provides scientific background to proposing a northern limit for forest management activities in Quebec. The developed approach could be useful in other jurisdictions to address similar issues.

Key words: northern limit of timber allocation, sustainable forest management, biophyscical conditions, boreal forest, black spruce forest.

Résumé : La forêt boréale est l'une des plus grandes forêts naturelles du monde et fournit de nombreux services écologiques à la société. La forêt boréale est également économiquement importante, mais la récolte du bois et son aménagement deviennent de plus en plus difficiles à mesure que l'on progresse du sud vers le nord. Une approche a donc été développée pour évaluer l'adéquation de districts écologiques pour la production de bois dans un contexte d'aménagement durable des forêts (ADF) dans la forêt boréale du nord de la province de Québec (Canada). Cette région inclut l'entièreté du domaine de la pessière noire à mousses (forêt fermée) ainsi que la portion sud de la pessière noire à lichens (forêt ouverte). Quatre critères spécifiques aux aspects biophysiques de l'ADF ont été évalués dans 1114 districts écologiques : l'environnement physique, la capacité de production de bois, la vulnérabilité de la forêt au feu (e.g., la probabilité qu'elle arrive à maturité) et la conservation de la biodiversité. Des indicateurs et des valeurs seuils ont été déterminés pour chaque critère et une analyse séquentielle a été développée pour évaluer si un district a le potentiel d'être aménagé de manière durable. Ce processus analytique a permis la classification de ces districts en trois catégories, soit légèrement sensibles (ADF possible), modérément sensibles (ADF possible sous certaines conditions) et fortement sensibles (ADF impossible). Les résultats montrent que 354 districts sont très sensibles, 62 du fait de contraintes physiques (7.5 % de la superficie), 130 du fait d'une productivité insuffisante (15.4 % de la superficie), 92 du fait d'une productivité potentielle insuffisante pour permettre de tenir compte du risque de feu (13.8 % de la superficie) et 70 du fait d'une insuffisance de peuplements denses et hauts (7.7 % de la superficie — critère de la biodiversité). Ce travail fournit une assise scientifique pour proposer une limite nordique des activités d'aménagement forestier au Québec. L'approche proposée pourrait être utile à d'autres juridictions pour aborder des questions similaires.

Mots-clés : limite nordique des forêts attribuables, aménagement forestier durable, conditions biophysiques, forêt boréale, forêt d'épinette noire.

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Introduction

The boreal forest ecosystem is one of the largest frontier forests of the world (Potapov et al. 2008). On a global scale, this ecosystem provides several key provisioning and regulating services such as water regulation, water purification, and carbon sequestration (Bryant et al. 1997; Brandt et al. 2013). At a continental or national level, boreal forests provide migratory bird breeding habitat and timber and nontimber forest products, as well as subsistence value for aboriginal communities, among several other provisioning or cultural services (Burton et al. 2010). Boreal forests also contain the largest tracts of primary forests in the world (Mackey et al. 2014). Boreal forests are economically important, with Canada's boreal forest supporting the largest wood products industry in the world (Burton et al. 2010).

Forest harvesting and management become increasingly difficult when one moves from south to north in boreal environments. Distances to processing mills increase, road infrastructures are usually nonexistent, and harvestable stands are interspersed with an increasing amount of nonforested environments and operational constraints (e.g., steep terrain, bogs, lakes, and rivers) as one progresses to the north (Beaudoin et al. 2014). Forest stands found in these environments generally have low commercial values because the stands are open and composed of relatively short, small-diameter trees.

In 2000, the Temperate and Boreal Forest Resources Assessment (United Nations Economic Commission for Europe (UNECE) 2000) distinguished the availability of forests (land having a tree cover greater than 10%) for harvest based on factors such as conservational value and operational constraints. Important proportions of Russian and Canadian forests were considered not available for wood supply because of their remoteness. However, remoteness is a changing condition (e.g., Nordberg et al. 2013; Powers et al. 2013), so other factors such as commitments regarding sustainable forest management (Gillis et al. 2005), conservation planning (Powers et al. 2013), and protection of remaining intact primary forests (Potapov et al. 2008; Mackey et al. 2014) must be considered before allocating land to the timber harvesting land base.

Apart from accessibility, forests are usually removed from a timber production area because of low productivity (e.g., 1.24 $m^3 \cdot ha^{-1} \cdot year^{-1}$ in the United States (Hicke et al. 2007) and 1 $m^3 \cdot ha^{-1} \cdot year^{-1}$ in Norway and Sweden (Elbakidze et al. 2013)) or difficult operational terrain (e.g., steep slopes) or for protection of wildlife habitat or preservation of rare ecosystems or water resources (United Nations Economic Commission for Europe (UNECE) 2000). In northern environments, stand regeneration is also more difficult for many reasons, including harsh climatic conditions, low seed production (Sirois 2000), strong interactions with ericoid shrubs (Mallik 2003; Thiffault and Jobidon 2006), and high fire severities (Jayen et al. 2006). Forest operations may also enhance the problem of regeneration failures and, over the long term, result in a progressive scarcity of closed-canopy forests (Payette and Delwaide 2003). Major investments such as intensive site preparation and planting may thus be required to regenerate harvested stands (Madec et al. 2012). These problems may be sufficiently important to prevent sustainable harvesting activities (e.g., Heikkinen et al. 2002). Furthermore, high natural burn rates (Payette 1992), poor access, and limited fire control activities (Chabot et al. 2009) increase the probability that stands will burn before they reach maturity (Raulier et al. 2013*a*). Thus, the addition of anthropogenic disturbances in an environment where closed forests are already scarce and fragmented by natural disturbances and other abiotic factors may have negative impacts on the maintenance of the forests' associated biodiversity. For instance, cumulative anthropic disturbances negatively affect boreal caribou populations (*Rangifer tarandus caribou* L., an ecotype of the woodland caribou subspecies that is closely associated with the boreal forest), officially listed as threatened in Canada (Environment Canada 2011; Festa-Bianchet et al. 2011).

For all of these reasons, this research wanted to address the following general question with Quebec's boreal forest as a case study: Can any given northern boreal forest be submitted to sustainable forest management practices considering its specific biophysical conditions?

For this purpose, we adopted four operational criteria that relate to the Montréal Process criteria of sustainable forest management (www.montrealprocess.org). They are specific to the biophysical aspect of sustainable forest management: constraints of the physical environment, forest productive capacity, forest vulnerability to fire risk, and conservation of biodiversity. The physical environment and forest productivity criteria express mainly degrees of direct constraints to management operations linked to the maintenance of productive capacity of forest ecosystems. The criterion specific to fire expresses an indirect constraint on management operations related to the probability of not finding standing timber at harvest time due to forest fires. The biodiversity criterion is intended to ensure the presence of a minimum of dense forest and wildlife habitat before planning any type of management. It also considers fragmentation of such habitats, as well as specific requirements of the boreal caribou, a sensitive species that is present throughout the region. Although important, other criteria of the Montréal Process, namely those concerning global cycles or those specific to social and economic aspects or governance, were not directly addressed but would be considered in any future land-use planning.

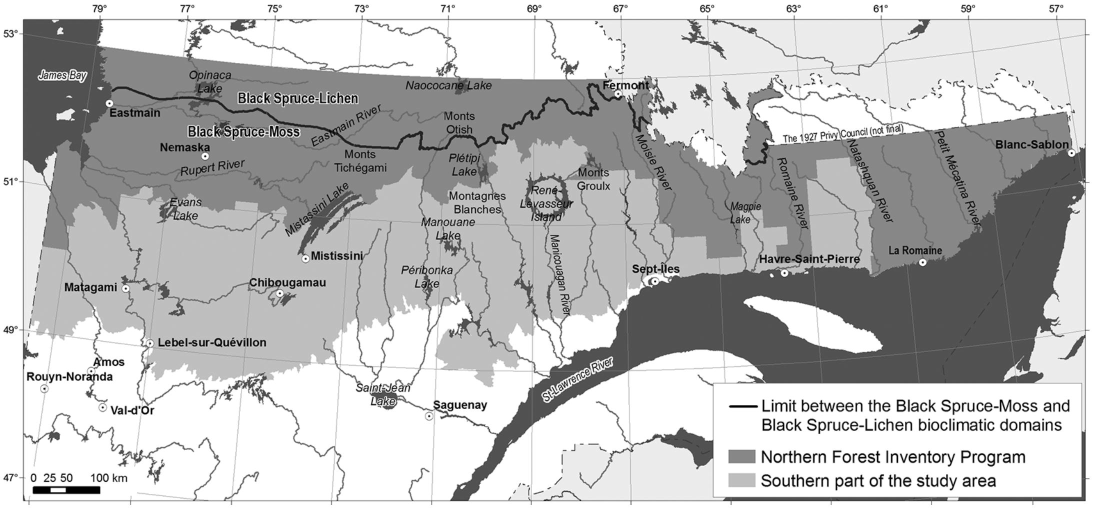
To our knowledge, no other such assessment based on ecological data has been undertaken elsewhere to determine a limit to commercial timber production. The general objective of this paper is to present such an approach developed to assess the suitability of land districts to sustainable timber production on the basis of these four selected criteria. Land districts correspond to "areas of land characterized by a distinctive pattern of relief, geology, geomorphology, and regional vegetation" (Jurdant et al. 1977). Indicators and acceptability cutoff values were determined for each selected criterion, and a sequential analysis was developed to evaluate if a land district has the potential to be sustainably managed. This method could eventually be adapted and used in other jurisdictions to address similar issues.

Study area

The study area extends from James Bay to Labrador (79°30′W to 57°W) and is located within latitudes 51°N to 53°N, encompassing an area of 242 000 km^2 (Fig. 1). It covers the northern portion of the spruce–moss bioclimatic domain and the southern portion of the spruce–lichen domain (Robitaille and Saucier 1998). To better understand the transition in the suitability for forest management existing from south to north, the analyses included data from the southern portion of the spruce–moss domain (240 000 km^2), which is well documented by the current forest inventory (total study area of 482 000 km^2). Almost all of the land in the study area is state owned. There are 17 municipalities, the three largest being Chibougamau, Havre-Saint-Pierre, and Fermont, and 37 000 permanent residents (for more details on the study area, see Lord and Robitaille 2013).

The study area is located on the Canadian Shield. Lakes and rivers cover 12% of the area, with two major watersheds: the James Bay watershed in the west, and the Saint Lawrence River watershed in the east. In the western portion, topography is relatively flat and elevations are relatively low. In the north-central part, the elevation is higher (500 to 700 m), with gentle relief. Toward the southeast, the relief becomes rather rugged and is highly dissected by broad north–south valleys. Further east, there are successive transverse valleys that become narrow and deep (elevations range from 0 to 1000 m). In the lower north shore region of the Saint

Fig. 1. Location of the areas sampled during the northern ecoforest inventory program (NFIP). (Reproduced with permission of the Ministère des Forêts, de la Faune et des Parcs du Québec.)



Lawrence River, average elevation and magnitude of relief decrease gradually, with the coast becoming more and more jagged and dotted with a multitude of islands. Glacial deposits (mostly till) and organic deposits are the most abundant types of surficial deposits. Thick till is more frequent in areas of gentle relief, whereas thin till is in areas of hills and high hills. Organic deposits cover vast areas near James Bay and at the mouths of the major rivers in the eastern part of the study area.

Forest (tree canopy density > 10%) occupies 77% of the terrestrial area. Coniferous forests are dominant (91% of the forest area) and are mostly mature stands, while mixed and hardwood forests are mostly represented by transitional stands originating from disturbances. Black spruce (*Picea mariana* (Mill.) B.S.P.) is the dominant species. Balsam fir (*Abies balsamea* (L.) Mill.) is only abundant in the eastern part of the study area, where most stands consist of a mixture of black spruce and fir. White birch (*Betula papyrifera* Marsh.) is more abundant in the southern part and is often mixed with conifers. Jack pine (*Pinus banksiana* Lamb.) occurs mainly in the western part where it can form pure stands. Areas affected by recent natural and anthropogenic disturbances (aged 0 to 40 years) accounted for 16% of the study area in 2009. Timber harvesting is concentrated in the southwestern portion of the study area. In general, the extent of recently burned areas increases from east to west and from south to north. Recent burns are omnipresent in the northwest and extensive between Lac Mistassini and the Manicouagan Reservoir. North of the reservoir, burns are numerous but smaller in area. Stands affected by recent windthrow or severe insect outbreaks cover a very small proportion (<0.5%) of the study area.

Climatic information was calculated with BioSIM 9 (Régnière and Saint-Amant 2008), which interpolates climatic information from the nearest meteorological stations (for the period 1971–2000). Using the centroids of ecoforest polygons, average values of climatic variables for each land district (~2700 polygons per land district) were calculated (see Lord 2013). Mean annual temperatures calculated in this manner range from −4.9 to 1.6 °C. Along the Saint Lawrence River shore, average temperatures are above 0 °C but decline rapidly toward the north and also with elevation. Total growing degree-days (GDD; annual cumulative total of daily average temperatures above 5 °C) range from 620 to 1380, on average (Fig. 2*a*). The lowest values of total GDD (<700) are observed on the peaks of the Otish and Groulx mountains and on the plateaus at the northern boundary of the study area. In contrast, the continental component of climate in the west seems to positively influence GDD. The highest values, about 1400 GDD, are observed in the south, close to the Pipmuacan Reservoir. Total annual precipitation (range from 650 to 1150 mm·year^{-1}) increases gradually from west to east and, to a lesser extent, from north to south (Fig. 2*b*).

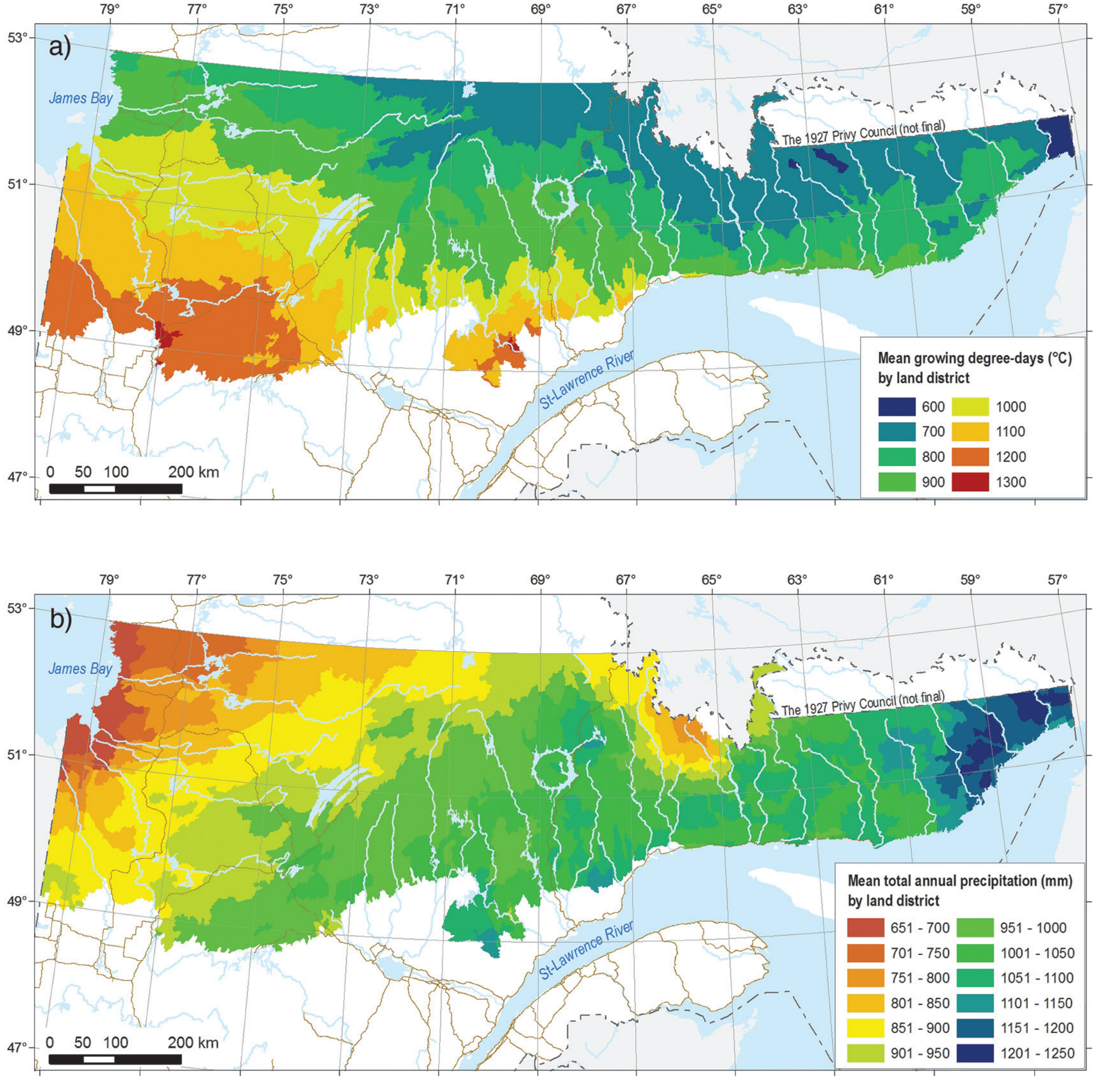
Data

For the southern portion of the study area, data came from recent forest maps (scale of 1:20 000, Ministère des Ressources naturelles et de la Faune (MRNF) 2009), maps of land districts (scale of 1:250 000), regional landscape units and ecological regions (1:1 250 000), and thousands of sample plots (MRNF 2006*a*, 2006*b*). Forest maps provided information on surficial deposits, drainage, and forest stand characteristics (canopy height, canopy density, age class, and species composition). Sample plots provided information on physical (soils, stoniness), dendrometric (diameter, age, tree height), and ecological (indicator plants, ecological types) characteristics. For the northern portion, a northern forest inventory program (NFIP) was carried out over a period of 5 years, from 2005 to 2009. For any portion of the study area, this consisted of a first year of forest mapping, followed by a second year of data collection from sample plots. Below, we briefly review the main steps undertaken by the team during the NFIP (see Robitaille et al. (2013) and Saucier (2013) for more details).

1. Forest map of the northern forest inventory program (NFIP)

For the northern portion of the study area, aerial photographs at a scale of 1:40 000 were interpreted to map the surficial deposits and moisture regimes. Landsat satellite images (spatial resolution of 30 m on the ground) were used to interpret and map the vegetation in three steps: (*i*) polygons were created by segmenting images in homogeneous areas using eCognition software (Definiens Inc. 2002); (*ii*) polygons were classified automatically into vegetation types, also with the eCognition tools calibrated with thousands of field checks; and (*iii*) the contours of polygons were manually edited and vegetation types that could not be automatically classified were manually edited (Leboeuf et al. 2012). The resulting map provided information on surficial deposits, moisture regime, slope, stands (density, height, development stage, undergrowth, species composition), and occurrence of recent natural disturbances (fire, windthrow, and insect outbreaks) at a resolution of 8 or 16 ha. Considering that the NFIP forest map was created from satellite images, a ground-truthing approach was developed based on georeferenced video taken during an airplane overflight. A random sample of 1000 polygons was drawn from all overflown polygons of the study area and classified by an independent photo-interpreter. Kappa tests (Landis and Koch 1977; Sim and Wright

Fig. 2. (*a*) Growing degree-days (°C) by land district and (*b*) total annual precipitation (mm) by land district. Growing degree-days correspond to the annual cumulative total of daily average temperatures above the 5 °C threshold. (Reproduced with permission of the Ministère des Forêts, de la Faune et des Parcs du Québec.)



2005) that measure the agreement between the map's classes and the photointerpreter's classes (see Table 1) confirm that, overall, the forest map gives an accurate and unbiased picture of the forested landscapes of the study area (see Robitaille et al. 2013).

2. Mapping of land districts and regional landscape units

A land district is defined as "an area of land characterized by a distinctive pattern of relief, geology, geomorphology, and regional vegetation" (Jurdant et al. 1977). A regional landscape unit is defined as "an area characterized by a recurrent arrangement of the principal permanent ecological factors and vegetation" (Robitaille and Saucier 1998). The regional landscape unit is a grouping of land districts that are similar in terms of type of relief, elevation, surficial deposits, and plant species distributions. The study area includes 1114 land districts (average size is 433 km²) and 76 regional landscape units (average size is 6341 km²).

3. Sample plots and sampling design

Stands similar with respect to forest types and surficial deposits were regrouped into classes that were assigned a number of plots proportional to their terrestrial area. The four main forest categories used for stratification purposes were regenerating forests (10–30 years) and hardwood-dominated, mixed, and coniferous-

Table 1. Results of the ground-truthing of the forest map using the kappa coefficient (κ)[a].

	κ	Agreement	Overall accuracy index (%)[b]
Canopy type	0.46	Average	91.2
Undergrowth vegetation	0.49	Average	78.3
Development stage	0.36	Acceptable	71.8
Field code[c]	0.90	Almost perfect	92.8
Original disturbance	0.96	Almost perfect	99.6
Individual cover classes	0.12	Poor	32.8
Combined cover classes[d]	0.35	Acceptable	67.0

[a]Kappa coefficient, adapted from Landis and Koch (1977): $\kappa < 0$, no agreement; κ between 0 and 0.19, poor agreement; κ between 0.20 and 0.39, acceptable agreement; κ between 0.40 and 0.59, average agreement; κ between 0.60 and 0.79, substantial agreement; κ between 0.80 and 1.00, almost perfect agreement.

[b]The overall accuracy index is added for information purposes.

[c]Forested or unforested.

[d]Stands with density cover >80%, between 61% to 80%, and between 41% to 60% were combined (>40%); stands with density cover between 26% to 40% and between 11% to 25% were combined (≤40%).

Table 2. Biophysical criteria, indicators and qualifying and sensitivity cutoff values for sustainable forest management.

Biophysical criterion	Indicator	Qualifying cutoff value	Sensitivity cutoff value
Physical environment	Proportion of features that impose few constraints on forest operations or for supporting a forest cover in a district	20% of terrestrial area consists of features that impose few constraints or 40% if mountain-type relief	40% of terrestrial area consists of features that impose few constraints regardless of type of relief
Productivity	Proportion of potentially productive stands in a district	20% of terrestrial area potentially exceeds the double productivity cutoff (50 $m^3 \cdot ha^{-1}$ and 70 $dm^3 \cdot stem^{-1}$)	
Fire risk	Proportion of potentially productive stands in a district, considering the fire risk	20% of terrestrial area has a greater than 33% probability of reaching the double productivity cutoff, considering the fire risk	20% of terrestrial area has a greater than 66% probability of reaching the double productivity cutoff, considering the fire risk
Biodiversity			
Coarse filter	Proportion of tall and dense forest habitats in a district	20% of terrestrial area consists of tall and dense forest habitats	
Coarse filter	Degree of fragmentation of tall and dense forest habitats in a district		20% of terrestrial area consists of tall and dense forest habitats over more than 80% of the 15 km^2 subunits of a district
Fine filter (specific to woodland caribou)	Proportion of undisturbed habitat in a district		65% of terrestrial area consists of undisturbed habitat at the regional landscape unit scale

Note: Qualifying cutoff values discriminate districts that are highly sensitive for forest management from those that are suitable for forest management. Sensitivity cutoff values discriminate districts that are moderately sensitive from those that are slightly sensitive for forest management activities.

dominated stands older than 30 years. The main surficial deposits were deep tills, shallow tills, fluvio-glacial deposits, and glacio-lacustrine deposits. In all, 37 classes were used in the sampling design (see Saucier 2013). Within each class, plot location was assigned randomly.

Dendrometric plots (707 plots) were established in areas that were dominated by forests older than 30 years, while postfire plots (168 plots) were established in areas that had been affected by fires 10 to 30 years before sampling, for a total of 875 plots. Both types of plots were similar with respect to the information collected on the physical environment such as topography, pedological, and geomorphological information. In both types of plots, mature trees (diameter at breast height (dbh) > 9 cm) were sampled in one 400 m^2 circular plot, and saplings (dbh between 1.1 and 9.0 cm) were sampled in one 40 m^2 circular microplot placed in the middle of the 400 m^2 plot. Dendrometric and postfire plots differed mainly with respect to the sampling of the seedling layer (height > 15 cm; dbh ≤ 1.0 cm), with 10 seedling microplots in the postfire plots compared with five microplots in each of the dendrometric plots. In addition, discs were collected from up to seven trees and three saplings in dendrometric plots for stem analysis. Disks were dried and sanded, and two series of ring-width measurements were acquired per cross section to characterize tree growth (more details provided in Girardin et al. 2012).

Suitability indicators, analysis, and integration process

Suitability indicators were determined for each selected criterion (see Table 2) and evaluated at the scale of land districts. Land districts were used here to assess the potential for sustainable timber production based on biophysical criteria, although forest management units (usually encompassing several districts) are usually used in the forest management planning process.

For three of the four indicators, we determined a "qualifying cutoff value" and a "sensitivity cutoff value" (Table 2). A qualifying cutoff value was used to discriminate districts where constraints or risks are too great to allow for sustainable timber production ("highly sensitive districts", in red in Table 3 and Fig. 4) from those that could be suitable for forest management. Within those that could be managed, a sensitivity cutoff value was used to discriminate the districts that were "moderately sensitive" (in yellow in Table 3) from those that were "slightly sensitive" (in green in Table 3) to forest management activities. The detailed methodologies used for determining indicators and cutoff values are presented in companion papers: Robitaille et al. (2015; physical environment), Gauthier et al. (2015; productivity and fire), and Imbeau et al. (2015; biodiversity). They are briefly described below.

Physical environment indicator and cutoff values

Surficial deposits and relief are the foundations of ecosystem components; they determine the spatial distribution and growth of vegetation, as well as the nature of some human activities. The chosen physical environment indicator is the proportion of a land district occupied by features that impose constraints for (*i*) forest operations or (*ii*) supporting a forest cover. These features are hydromorphic organic deposits, dead-ice moraines, washed till, glacial block fields, scree and active wind deposits, and slopes steeper than 40% (Robitaille et al. 2015).

A land district was considered suitable for management (meeting the qualifying cutoff value) when more than 20% of its terrestrial area consists of features that impose few constraints on forest operations or for supporting a forest cover. However, if a land district had an average slope greater than 30% or an average elevation change of 120 $m \cdot km^{-1}$ at the district scale (mountain-type relief; Robitaille et al. 2015), this qualifying cutoff value was raised to 40% because analysis of previously managed area showed that potentially manageable small patches embedded in a rugged landscape were avoided by forest activities. The sensitivity cutoff value was set at 40% of the terrestrial area with features that impose few constraints on forest operations or for supporting a forest cover (Table 2). Because no other studies on this subject had been conducted before in Quebec, these cutoff values were selected based on the opinion of a group of experts with different backgrounds (geomorphology, ecological classification, forestry), including people with experience in operational forest planning in boreal forest environments.

Table 3. Types and subtypes of districts resulting from the sequential analysis.

Type and subtype of district	Number of districts
1. Highly sensitive districts	
1.1. Very significant environment constraints	62 districts: A (23%); A, B, and C (6%); A, B, C, and D (68%); A and D (3%)
1.2. Insufficient productive capacity	120 districts: B and C (47%); B, C, and D (53%)
1.3. Insufficient productive capacity to face fire risk	92 districts: C (28%); C and D (72%)
1.4. Insufficient tall and dense forest habitats	70 districts: D (100%)
2. Moderately sensitive districts	
2.1. Major physical environment constraints	31 districts: A (32%); A and D (68%)
2.2. High impact of recurrent natural disturbances by fire	89 districts: C (30%); C and D (5%); C, D, and D2 (4%); C and D1 (27%); C, D1, and D2 (22%); C and D2 (11%)
2.3. Insufficient tall and dense forest habitats because of a single year of fire	5 districts: D (100%)
2.4. Fragmented tall and dense forest habitats	57 districts: D (100%)
2.5. Districts with too great a proportion of disturbed habitats to conserve woodland caribou	No districts
3. Slightly sensitive districts	
3.1. A few factors of concern for sustainable forest management	49 districts
3.2. Little risk for sustainable forest management	529 districts

Note: Number of districts in each subtype is also indicated. A, physical environment; B, productivity; C, fire risk; D, biodiversity.

Productivity indicator and cutoff values

The indicator of forest productivity is the proportion of a land district with potentially productive stands. Potential productivity is defined as the productive capacity of the site, whether or not there are currently trees. It is based on the premise that a closed forest stand will always develop and is estimated using physical characteristics of a site (climate, surficial deposit, drainage).

Stand suitability for timber production was assessed with a double cutoff: a harvesting value defined at the stand level (a merchantable volume (>9 cm) greater than 50 $m^3 \cdot ha^{-1}$) and a harvesting value defined at the tree level (an average merchantable volume greater than 70 $dm^3 \cdot stem^{-1}$). These cutoff values were derived from an empirical examination of harvesting patterns in the managed forest of northern Quebec between 1995 and 2005 (Raulier et al. 2013*b*).

Three steps were required to estimate values of stand merchantable volume and stem volume for each stand. In the first step, yield tables adapted from Pothier and Savard (1998) were used to estimate site index (SI) and relative density index at 100 years (RDI_{100}) for each sample plot. These yield tables were recalibrated with sample plots from the present study. In the second step, SI and RDI_{100} were estimated for each stand with a nonparametric method of imputation of stand productivity (*k*-nearest neighbor) based on values observed in the plots located in the stand neighborhood within a multidimensional space defined by mapping and climatic attributes. In the third step, yield tables were used to identify stands that cannot reach the double productivity cutoff and to exclude them from the timber productive area of each land district. Uncertainty in the estimation of the timber productive area per land district was accounted for with a bootstrapping procedure.

To distinguish between productive and unproductive districts, the qualifying cutoff value was set at 20% of the terrestrial area that potentially exceeds the double productivity cutoff (potentially productive district). Such a cutoff value is used to maintain an appropriate representation and spatial distribution of typical ecosystems able to sustain the hydrological functions (Pouliot et al. 2010). The sensitivity of the results to the choice of 20% as the cutoff value is provided in Gauthier et al. (2015).

Fire vulnerability indicator and cutoff values

In areas with high burn rates such as northern Quebec, it is increasingly recognized that the burn rate must be taken into account to avoid carrying out a harvest that would be unsustainable (Savage et al. 2010) when combined with fires. The fire vulnerability indicator assesses the proportion of a land district with potentially productive stands that is likely to reach the double productivity cutoff given the burn rate to which they are exposed over time. The time period during which stands are exposed to fire risk was calculated to estimate the probability that stands reach minimum harvest age.

The data used to calculate the fire risk came from different sources, including aerial surveys, satellite images, and archived maps. The mean annual burn rate (proportion of terrestrial area that burns annually, on average) was calculated by using a sample of randomly selected points and computing the mean percentage of points burned per year. The landscape regional unit was chosen for the calculations because the districts are too small relative to fire size. To obtain the most robust burn rate values, regional landscape units with similar burn rates were clustered, creating 10 fire risk zones. To characterize the interannual variability in burn rates (Armstrong 1999), we used bootstrap resampling methods to estimate the probability distribution of the mean annual burn rate for each zone. The time required to reach the productivity indicator (minimum harvest age) was derived from the recalibrated yield tables of Pothier and Savard (1998). For a given burn rate, the higher the minimum harvest age, the greater is the likelihood that a stand will be lost by fire. Frequency distributions for the probability of achieving minimum harvest age when the burn rate is taken into account for each land district were calculated as a function of the frequency distributions of minimum harvest ages of the district and mean annual burn rates of the corresponding fire zone (Raulier et al. 2013*b*).

Districts where more than 20% of the area has a >33% probability level of reaching minimum harvest age, taking into account fire risk, reached the qualifying cutoff value (productive and moderately vulnerable to fire). However, districts where less than 20% of the terrestrial area does not have at least a 33% probability of reaching minimum harvest age were considered too vulnerable (highly vulnerable to fire) to be subjected to any sustainable forest management practices. Districts where 20% of the area has more than a 66% probability of reaching minimum harvest age, taking into account fire risk, reached the sensitivity cutoff value (productive and slightly vulnerable to fire).

Biodiversity indicators and cutoff values

Three indicators were selected to examine the biodiversity criterion according to coarse- and fine-filter approaches. A coarse filter aims to provide forest habitats for many species, whereas a fine filter aims to protect the critical habitat needs for a particular species not accounted for with a coarse filter. This combination of applying both coarse and fine filters ensures that habitats for all species are maintained (Hunter et al. 1988).

The first coarse-filter indicator is defined as the proportion of the terrestrial area occupied by tall (height > 7 m) and dense (canopy density > 40%) forest stands in a district. In land districts located south of the 2002 limit, the study area in its current state is sometimes mostly composed of stands < 7 m tall resulting from harvesting operations. It was assumed that these stands were tall and dense before anthropogenic disturbances. This procedure was necessary to compare districts currently located on either side of the 2002 northern limit on the same basis. Many studies undertaken in this area, particularly on birds and small mammals, showed that the conservation of tall and dense habitats is of great importance for these two groups of species (Imbeau et al. 1999; Cheveau et al. 2013). There is a great variability in responses of individual species to habitat loss (Lindenmayer et al. 2005). When marked changes in the pattern of species occurrence in remnants of suitable habitat do occur, a threshold value of habitat amount of between 10% and 30% is often identified (see Swift and Hannon 2010). The qualifying cutoff value for this indicator was therefore set at 20% of the terrestrial area of a district occupied by tall and dense forest habitats (see Imbeau et al. 2015). Below this value, biological diversity associated with this type of canopy could become threatened because of a lack of good-quality habitat.

The second coarse-filter indicator is related to the degree of fragmentation of tall and dense forest habitats within each district, which is known to be detrimental for many species (Villard and Jonsson 2009). Subunits of 15 km² within a district (~24 to 60 subunits per district) have been created to study the level of habitat fragmentation. This size corresponds to the minimum area needed for maintaining seasonal home ranges of late-seral bird species most sensitive to fragmentation of tall and dense forest habitats (e.g., Boreal Owl (*Aegolius funereus* (Linnaeus, 1758); Hayward et al. 1993); American Three-toed Woodpecker (*Picoides dorsalis* (S.F. Baird, 1858); Leonard 2001); Black-backed Woodpecker (*Picoides arcticus* (Swainson, 1832); Dixon and Saab 2001)). A land district reached the sensitivity cutoff value for fragmentation when at least 80% of the 15 km² subunits reach the selected 20% cutoff value of tall and dense forest habitats.

The fine-filter indicator is the maximum amount of disturbed habitat that can be tolerated by boreal caribou. This species was selected because forest management activities have clearly been identified as a major reason for its decline (Environment Canada 2011; Festa-Bianchet et al. 2011). Disturbed habitats are defined as those that have been affected by recent fires (<40 years) or by logging (<50 years), as well as roads, railways, and power transmission lines (with a buffer effect of 500 m from these anthropogenic disturbances; Environment Canada 2011). Analyses for this indicator were conducted at the regional landscape unit scale because this species has a large range (~5000 km² in Quebec). The sensitivity cutoff value was set at 65% of terrestrial area undisturbed at the regional landscape unit scale when only natural disturbances are considered (for results including anthropic disturbances, see Imbeau et al. 2015). Below this threshold, boreal caribou herds have recruitment rates that are too low to be self-sustaining in the long term (Environment Canada 2011).

Finally, districts with insufficient tall and dense forest habitats due to a single year of fire that burned more than 40% of the district over the last 40 years have been identified. Because this situation is due to stochastic events and is temporary, these districts could eventually be sustainably managed.

Process of analyses and integration of criteria

Land districts were analyzed sequentially to determine if they have the potential to be sustainably managed. Figure 3 illustrates the logical process of this sequential analysis and types of districts resulting from the integration of the four criteria. A given district was first examined for its forest management potential with regard to its physical constraints. Then, it was examined for timber productivity alone and then by taking into account fire risk. Finally, the district was examined using biodiversity filters: coarse filters for habitat quality for a majority of species and a fine filter specific to woodland caribou. This allowed us to discriminate, sequentially, districts that were constrained by permanent features, forestry-related factors, and biodiversity.

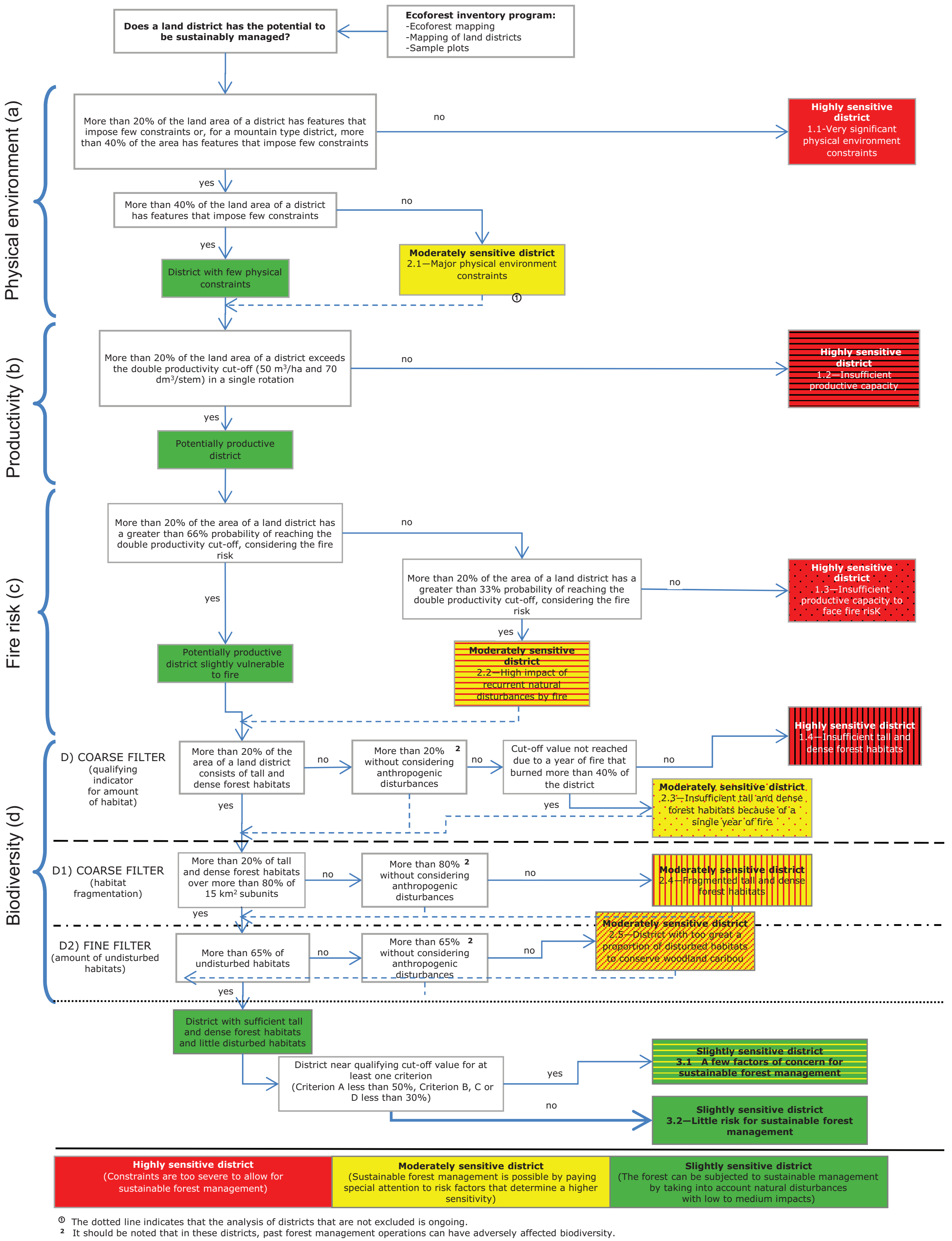
Three types of districts have been identified on the basis of the first criterion that failed to reach a qualifying cutoff value (Table 3). In highly sensitive districts (HSD), constraints or risks were too high to allow for sustainable forest management. There are four subtypes in this type of district depending on which criterion first failed to reach a qualifying cutoff value. Slightly sensitive districts (SSD) reached the qualifying and sensitivity cutoff values for all criteria. In this type of district, the forest can be subjected to sustainable management. Moderately sensitive districts (MSD) reached the qualifying cutoff values for all criteria but these districts present specific risk factors for forest management operations. This type of district is suitable for sustainable forest management if these specific risks are taken into consideration. There are five subtypes in this type of district depending on which criterion is sensitive.

Results

Figure 4 shows the result of the sequential analysis of each criterion. Districts excluded because of the importance of physical constraints on forest operations or for supporting a forest cover are characterized by extensive bogs (extreme west of the study area), by very thin soil and rugged relief (north of Sept-Îles and Havre-Saint-Pierre; Fig. 1), or by bare outcrops (lower north shore of the Saint Lawrence River) (Fig. 4*a*). These environmental constraints are also related to a low potential productivity except for the zone located between Sept-Îles and Mingan where, despite these constraints, land districts qualify based on potential productivity (Fig. 4*b*). Consequently, the physical environment in these areas is a constraint to forest operations (mountain-type relief) but does not constrain forest productivity. The main limiting factor for sustainable forest management in the study area appears to be the high probability that stands will not reach the productivity threshold because the burn rate is too high compared with their productivity (Fig. 4*b* vs. Fig. 4*c*). To the south, forests have lower burn rates, therefore a longer fire cycle, and lower minimum harvest ages, which makes them less vulnerable to fire risk. Almost 75% of the total number of districts assessed is eligible for forest management according to the biodiversity criterion (Fig. 4*d*). Biodiversity indicators show clear associations with attributes of the physical environment, fire, and the proportion of productive stands at the land district level. In the northern part of the area where fire cycles are short, there is a lower amount of tall and dense forest habitats and forests are more fragmented. Fragmentation of tall and dense forest habitats are linked either to fires or to physical constraints. Fires have a temporary effect on forest fragmentation, whereas the physical environment (bogs in the west and bare outcrops, very thin soil, and rugged relief in the east) has a more permanent effect.

The sequential analysis (Fig. 4) revealed that a total of 354 districts were considered too sensitive for forest management (HSD, 44.4% of the area): 62 due to physical constraints (7.5% of the area), 130 due to insufficient potential productivity (15.4% of the area), 92 due to insufficient potential productivity to account for the fire risk (13.8% of the area), and 70 due to insufficient proportion of tall and dense forest habitats (7.7% of the area). Most districts classified as highly sensitive for forest management occur in the northern part (except in the lower north shore of the Saint Lawrence River), while those slightly sensitive occur in the southern part.

Fig. 3. Logical process of analysis and integration of constraints of the physical environment, stand productivity, fire risk, and biodiversity criteria. (Reproduced with permission of the Ministère des Forêts, de la Faune et des Parcs du Québec.)



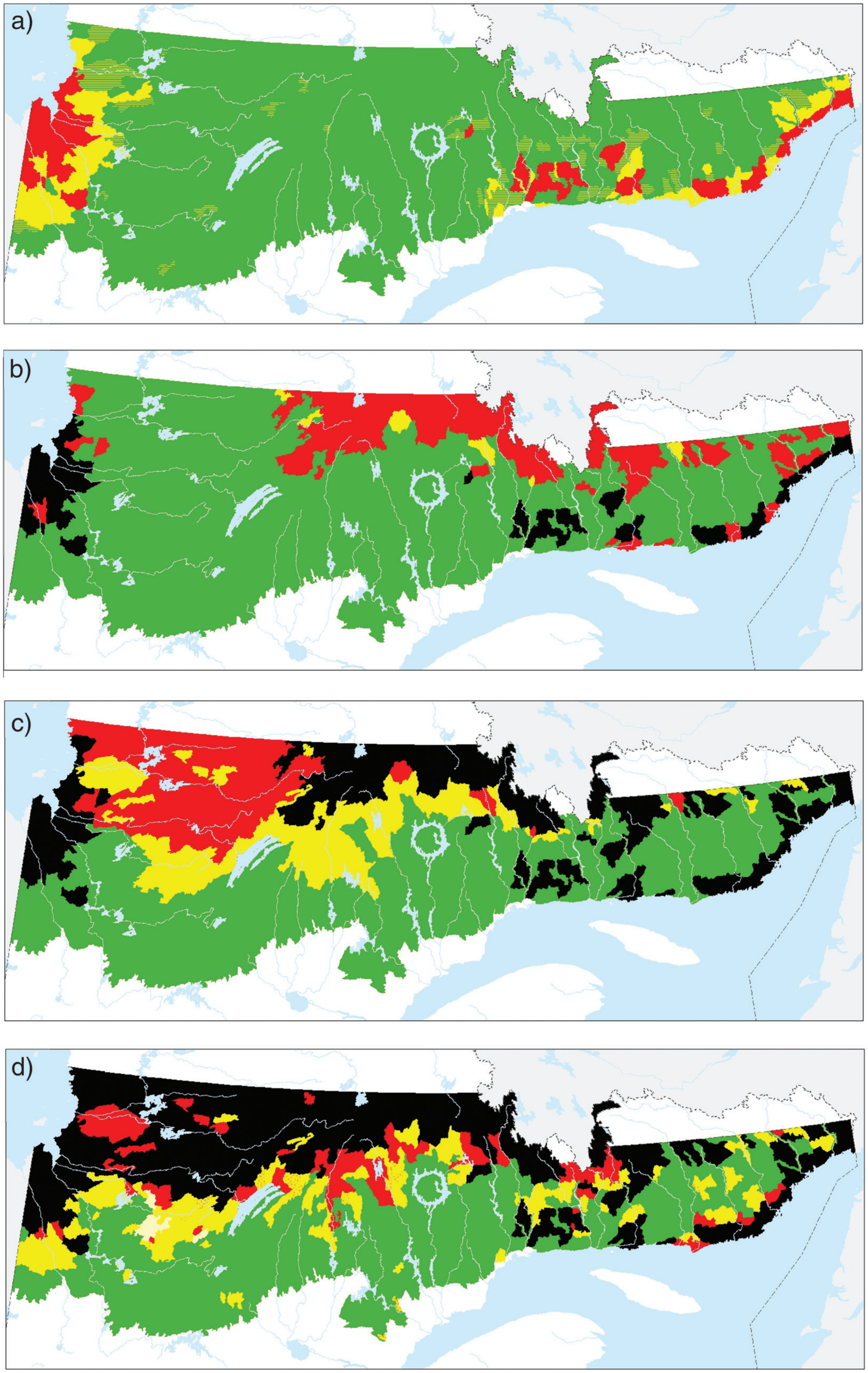
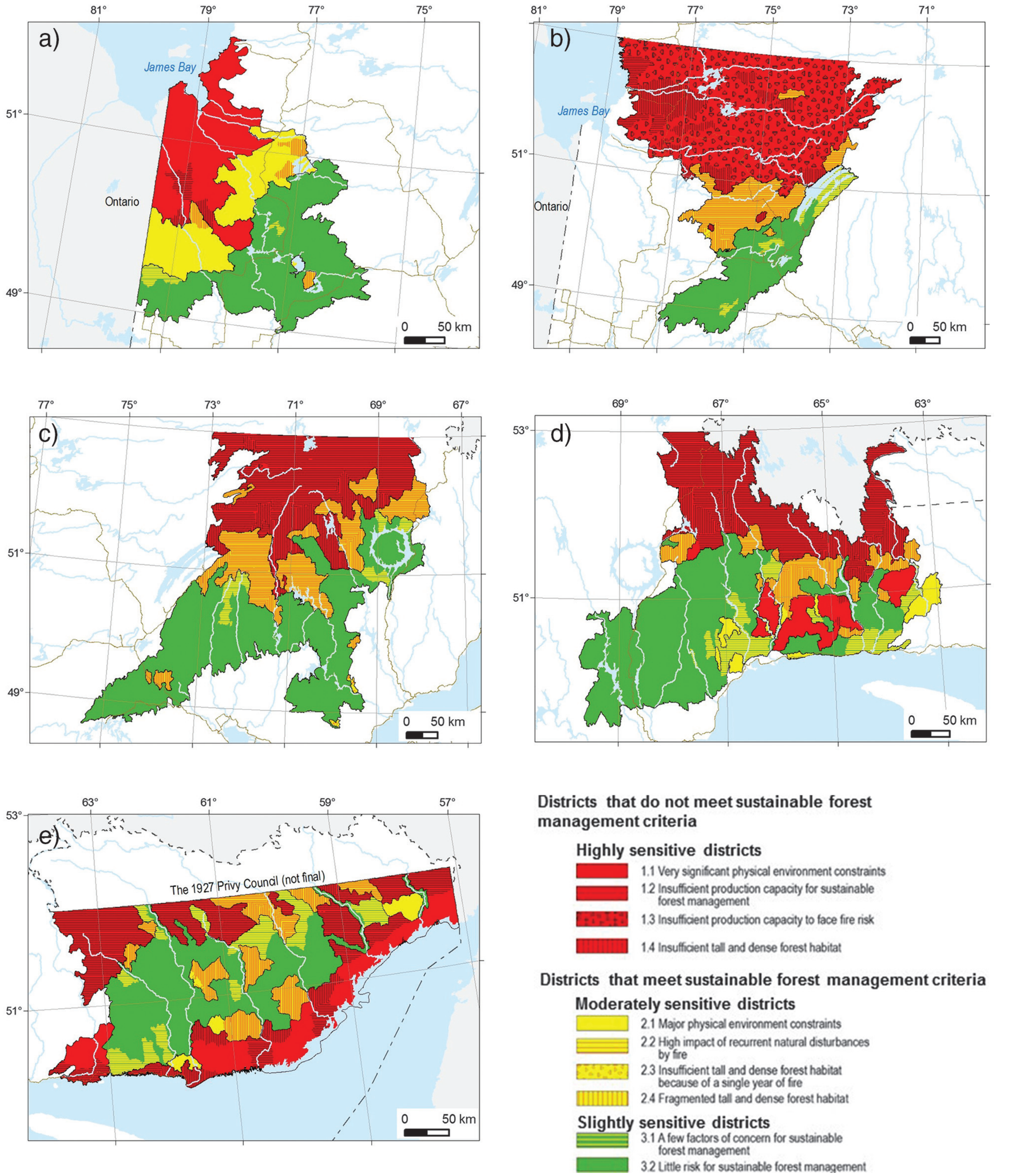


Fig. 4. Results of the analysis of each of the four criteria: (*a*) physical environment, (*b*) productivity, (*c*) fire risk, and (*d*) integration of the three indicators of biodiversity. For a given criterion, highly sensitive districts are in red, moderately sensitive districts are in yellow, and slightly sensitive districts are in green. Land districts that do not reach the qualifying cutoff values for one criterion are masked in black during analysis of subsequent criteria. (Reproduced with permission of the Ministère des Forêts, de la Faune et des Parcs du Québec.)

Fig. 5. Types and subtypes of districts according to their sensitivity to sustainable forest management. The study area was divided into five sections each showing a relatively homogeneous result: (*a*) northwestern Abitibi, (*b*) west of Lake Mistassini, (*c*) north of Saguenay – Lac-Saint-Jean, (*d*) middle north shore of the Saint Lawrence River, and (*e*) lower north shore of the Saint Lawrence River. (Reproduced with permission of the Ministère des Forêts, de la Faune et des Parcs du Québec.)



Moderately sensitive districts are found mostly between these parts. Overall, 860 districts are suitable for sustainable forest management according to our criteria, with 578 SSD (39.4% of the area) and 182 MSD (16.2% of the area). HSD are present mostly in the northern portion of the study area, whereas SSD are present mostly in its southern part; MSD are often found between these two.

Most of the land districts are above the qualifying cutoff values for each indicator: 96% for the physical environment,

Table 4. Proportion of the terrestrial area by indicators for each section and district type.

	Section														
	Northwestern Abitibi			West of Lake Mistassini			North of Saguenay-Lac-Saint-Jean			Middle north shore of the Saint-Lawrence River			Lower north shore of the Saint-Lawrence River		
Indicator	SSD	MSD	HSD	SSD	MSD	HSD	SSD	MSD	HSD	SSD	MSD	HSD	SSD	MSD	HSD
Features that impose few constraints (%)	74.9	36.1	12.7	72.2	73.9	70.7	85.8	80.0	80.7	72.1	56.6	66.9	73.6	71.2	42.2
Potentially productive stands (PPS) (%)	74.1	34.4	9.1	70.2	66.8	43.1	83.1	57.9	19.1	66.3	36.4	18.8	44.8	36.0	13.4
PPS slightly vulnerable to fire (%)	73.9	34.4	7.6	57.9	10.5	0.5	74.1	15.2	0.7	66.1	30.4	9.3	43.1	33.5	13.1
PPS highly vulnerable to fire (%)	74.1	34.4	8.8	70.2	57.1	10.0	83.1	55.3	16.5	66.3	36.4	18.8	44.8	36.0	13.4
Tall and dense forest habitats (%)	63.3	30.4	10.6	60.7	30.9	7.3	69.2	33.9	8.0	69.7	37.5	22.6	61.2	38.6	26.6
Unfragmented habitats (%)	96.5	68.9	18.2	96.9	61.6	12.1	97.6	65.8	13.1	98.0	71.6	41.0	95.4	69.6	46.4
Undisturbed habitats (%)	95.6	94.0	88.6	90.1	68.2	54.1	89.3	79.5	80.0	97.5	93.9	88.3	94.0	93.9	96.7

Note: District type: SSD, slightly sensitive; MSD, moderately sensitive; HSD, highly sensitive.

84% for the potential productivity, 76% for the vulnerability to fire, and 74% for the quantity of tall and dense forest habitats. From the 826 districts where the amount of tall and dense forest habitats was sufficient according to our criterion, about 20% are considered too fragmented. Without taking anthropogenic disturbances into account, most of the analyzed districts (88%) have a sufficient proportion of habitat undisturbed by fires to maintain populations of caribou. To better understand these results obtained at such a large scale (Fig. 4), the study area was further partitioned in five sections, from west to east, each showing a relatively homogeneous result.

Section 1: northwestern Abitibi

SSD of this section are characterized by clay deposits where productive stands are abundant (74%) (Fig. 5*a*; Table 4). In MSD, organic deposits (bogs) are dominant but clay deposits are also present. The proportion of the area occupied by productive stands decreases and the fragmentation of tall and dense forest habitats increases compared with SSD. In HSD, major constraints of the physical environments (87% of the area of HSD) are mainly related to the high proportion of bogs, which form a nearly continuous cover in the northwest. Potentially productive land, productive land with low vulnerability to fire, and tall and dense forest habitats, each considered separately, do not exceed ~10% of the area.

Section 2: west of Lake Mistassini

In this section (Fig. 5*b*; Table 4), SSD are characterized by a relief of plains and hills with thick till deposits, and productive land accounts for 70% of the area. The transition from SSD to MSD is related to the rapid increase in vulnerability to fire. In MSD, productive lands slightly vulnerable to fire occupy only 11% of the area. The vulnerability to fire leads to a decline of tall and dense forest habitats and to their fragmentation. The transition between MSD and HSD is marked by a decrease in mean annual temperature, mean annual total precipitation, and number of GDD. HSD are characterized by insufficient productivity to compensate for the burn rate (area slightly vulnerable to fire is <1%) and the lack of tall and dense forest habitats (only 7% of the area), which can be explained by the high recurrence of fires.

Section 3: north of Saguenay – Lac-Saint-Jean

Within this section (Fig. 5*c*; Table 4), few physical constraints are observed. In SSD, neither fire recurrence nor habitat fragmentation is problematic. In MSD, stands are more vulnerable to fire, likely because sand and gravel deposits generate dry soil over large flat areas. HSD are characterized by a low productive capacity (19% of the area), a low productive capacity to compensate for the risk of fire (area slightly vulnerable to fire <1%), an insufficient quantity of tall and dense forest habitats (8% of the area), a high degree of forest fragmentation (87% of the area), a high average elevation, and a low annual temperature.

Section 4: middle north shore of the Saint Lawrence River

Physical environments impose few constraints for SSD of this section (Fig. 5*d*; Table 4), despite relatively rugged relief and the presence of thin till. More than two-thirds of the area is productive and slightly vulnerable to fire. In MSD, constraints imposed by the physical environment such as thin soils and steep slopes are relatively important. HSD in the southern part of this section are characterized by a combination of constraints imposed by the physical environment (very thin soil, outcrops, many slopes with a gradient over 40%) that lead to a deterioration in productive capacity. On outcrops and in the northern part of this section (beyond latitude 51°30′N), the main limiting factor is the low productivity, which coincides with a low number of GDD. The secondary factor is the low proportion of tall and dense forest habitats.

Section 5: lower north shore of the Saint Lawrence River

This section (Fig. 5*e*; Table 4) is characterized by sudden transitions that occur either to the south or to the north of a central SSD area. SSD in this section are notable with respect to their low proportion of productive stands, probably because GDD is lower in this area compared with the other sections. The first portion of HSD, located in the south, is marked by major constraints of the physical environment (absence of deposits on the bedrock and abundance of very thin till). The second portion, located in the north, is marked by a low productive capacity due to a major drop in GDD (the lowest of the study area) and to the increase in average elevation.

Discussion

Using scientific information to define suitability for forest management

To our knowledge, this is the first study aiming to assess the suitability of a forest for forest management before it undergoes forest operations and management. Before assessing suitability, we developed an understanding of the biological and ecological mechanisms that influence forest productivity and biodiversity. A large amount of information was collected, both in the field and through the analysis of remote sensing data, specifically to achieve this understanding.

Even though the main drivers of productivity have been identified, including fire, soil productivity, and regeneration failures, some sources of error and uncertainty remain regarding these processes. For instance, the density of weather stations is much lower in the northern part of the study area than in the southern part; consequently, the calculation of climatic variables with models represents a source of error (Girardin et al. 2012). Another source of error comes from productivity variability between sites caused by intrasite factors not considered in this study such as stand history or population genetics (Lapointe-Garant et al. 2010). Furthermore, some stands that are potentially productive currently have a deficient postfire forest recovery caused by regeneration failure (Mansuy et al. 2012). We protected our results against these sources of errors first by using a coarse scale of analysis (land districts) and then by using a bootstrapping procedure to reduce the risk of obtaining an overestimated percentage of productive stands per district (see Gauthier et al. 2015).

Likewise, because ecological thresholds represent unacceptable levels of habitat alteration, most authors suggest that they should not be used within managed areas as management or conservation targets (Drapeau et al. 2009; Johnson 2013). In this regard, our biodiversity indicators and cutoff values provide only an effective diagnostic process for determining where sustainable forest management can and cannot be effectively implemented. As an example, conservation targets of tall and dense forests within managed areas should vary according to the natural, regional historical range of such habitats (Drapeau et al. 2009).

General trends

Factors that contribute to limiting sustainable forest management potential do not act independently but are closely intermingled. It is therefore difficult to clearly hierarchize their importance. For instance, stands located west of Lake Mistassini (Fig. 5*b*) are very vulnerable to fire because the fire cycle is short and productivity does not really compensate for the burn rate (Gauthier et al. 2015). These results confirm the importance of fire in shaping forest landscapes in this part of the boreal forest (Payette 1992). It stresses, however, how variability in fire frequency between the western and the eastern parts of the gradient (Boulanger et al. 2013) strongly influences the proportion of productive forests.

When fire is not considered, the combination of climate, dominant surficial deposit, and relief type of a land district is a good predictor of a potentially productive land district (Raulier et al. 2013*b*). Several districts supported a low (<20%) proportion of productive stands, particularly those located in the north-central portion of the study area (Figs. 5*c* and 5*d*). Their low potential productivity is explained by a generally harsher climate compared with the rest of the study area (continental climate with short growing season: average GDD < 825 and first frost before 31 August (Raulier et al. 2013*b*)).

The important effect of past natural and anthropogenic disturbances in some districts indicates that restoration measures should be considered to increase the area of tall and dense habitats and decrease their fragmentation so as to reduce impacts on woodland caribou. Indeed, when past anthropogenic disturbances are taken into account, woodland caribou habitat in the study area is considered highly disturbed at the regional landscape scale (see Imbeau et al. 2015). A recent report analyzing demographic and behavioral conditions of woodland caribou (Rudolph et al. 2012) highlights this concern.

Need for a periodical reassessment

Although physical constraints will remain relatively similar in the future, it is expected that climate change will have an impact in the studied region. Effects on forest growth remain uncertain. With climate warming, it has been predicted that black spruce growth will increase through an extension of the growing season, earlier budbreak, and shoot growth stimulation (Bronson et al. 2009; Rossi et al. 2011; Huang et al. 2013). On the other hand, the increase in moisture stress and respiration losses caused by warmer temperatures might be limiting for black spruce growth (Girardin et al. 2012). Furthermore, higher future burn rates are expected under warming climatic conditions for northern Quebec (Bergeron et al. 2010; Boulanger et al. 2013). Oris et al. (2014) reported a rapid change of fire cycle following change in climate during the Holocene for the western part of the studied area. This may induce more frequent shifts from closed-canopy black spruce forests to open lichen–spruce woodlands (Girard et al. 2009; Mansuy et al. 2012). Rapanoela et al. (2015)) showed that when fire cycles are below 200 years, fire impacts timber supply not only directly by burning stands, but also indirectly through deficient postfire forest recovery. When the fire cycle is short, the probability of finding more open-canopied and unproductive forests is thus expected to increase. Change in composition towards more productive and fire-resistant species might also be considered (Terrier et al. 2013), as well as a possible negative feedback due to lack of available burning biomass (Héon et al. 2014), but only in a longer time perspective. As climate change may potentially modify burn rates, productivity, and then availability of tall and dense habitats, the assessment of the northern limit of the commercial forest should be revised periodically to reflect future changing conditions.

Conclusions

The results of our work provide a scientific background to a policy decision that has to be made to define a new northern limit of timber allocation for the province of Quebec. To make best use of our results, we recommend that (*i*) the northern timber allocation limit be modified to currently exclude highly sensitive districts from forest management units, (*ii*) forest management strategies be implemented to reduce the sensitivity of moderately sensitive districts, (*iii*) risk factors be taken into consideration in slightly sensitive districts, especially for habitat fragmentation issues, (*iv*) within areas added to existing forest management units, detailed mapping and sampling be conducted to support allowable cut evaluation and allow forest management planning on an equivalent basis with current forest management unit, and (*v*) the sensitivity of districts be reassessed if studies reveal modifications in forest productive capacity, fire cycle, or biodiversity, particularly regarding the impact of climate change.

In addition, this study provides new information about the ecology of the northern boreal forest in Quebec. Furthermore, our work led to pooling scientific expertise, which translated into an original sequential approach that integrates several complementary disciplines. For example, validating map information obtained by interpreting satellite images required the development of a science-based approach for validation. Integrating productivity with fire risk produced a more accurate understanding of the capacity of sites to sustain a stand to maturity. Incorporating biodiversity issues into the process ensured that this level of knowledge would be available to determine sustainable forest management potential. With all of this comes a greatly enhanced understanding of the dynamics of the northern boreal forest, its diversity, and its complexity. As numerous ecological classification systems have been developed in the world to characterize the actual or potential vegetation and (or) the permanent physical environment variables, we suggest that our approach to assess the potential for land districts to be sustainably managed could be used elsewhere to address similar questions.

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