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Issues and solutions for intensive plantation silviculture in a context of ecosystem management

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ABSTRACT

Forest plantations are recognized as a silvicultural tool for ensuring a timber supply that meets public expectations regarding sustainable forest management. However, they are also part of the silvicultural scenario that shows the greatest potential for the artificialization of natural forests. From a firsthand perspective, intensive plantation silviculture objectives may appear antagonistic to those of ecosystem management. Here we describe the process through which we defined and documented plantation issues, then propose potential solutions to allow the integration of intensive plantation silviculture into ecosystem management. We identify issues related to the scale, localization and spatial arrangement of plantations, the key attributes and resilience of natural forests, social acceptability, and the productivity and profitability of plantations. We also propose potential solutions likely to help manage plantations within a context of ecosystem management. These include modulating silvicultural treatments to enhance the naturalness of plantations, conducting treatments to obtain expected production rates, and ensuring that plantations are deployed across the landscape in a manner that integrates stakeholder concerns and considers the naturalness of the forest matrix.

Keywords: intensive silviculture, plantation, yield, ecosystem management, naturalness, spatial arrangement, biodiversity

RÉSUMÉ

Les plantations forestières représentent un outil sylvicole reconnu pour assurer un approvisionnement en matière ligneuse qui répond aux attentes de la société envers l'aménagement durable des forêts. Toutefois, elles font aussi partie du scénario sylvicole qui a le plus grand potentiel d'artificialisation de la forêt naturelle. Les objectifs de la sylviculture intensive de plantations peuvent alors paraître, de prime abord, en contradiction avec ceux de l'aménagement écosystémique. Nous décrivons le processus par lequel nous avons défini et documenté des enjeux associés aux plantations et proposé des pistes de solutions pour que la sylviculture intensive de plantations puisse s'intégrer à l'aménagement écosystémique. Nous avons identifié des enjeux relatifs à l'ampleur, à la localisation et à l'agencement spatial des plantations, aux attributs clés et à la résilience de la forêt naturelle, à l'acceptabilité sociale, ainsi qu'à la productivité et à la rentabilité des plantations. Nous avons également proposé des pistes de solutions qui permettraient de réaliser les plantations dans un contexte d'aménagement écosystémique, telles que la modulation des traitements sylvicoles pour augmenter la naturalité des plantations, la réalisation des traitements de manière à obtenir la production attendue, ainsi qu'un déploiement dans le paysage qui intègre les préoccupations des parties prenantes et qui considère la naturalité de la matrice forestière.

Mots clés : sylviculture intensive, plantation forestière, rendement, aménagement écosystémique, naturalité, agencement spatial, biodiversité

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Introduction

Forest plantations are recognized as a silvicultural tool for ensuring a timber supply that meets public expectations in terms of sustainable forest management (Park and Wilson 2007, Brockerhoff *et al.* 2008). Forest plantation yields can be very high and exceed those of naturally regenerated forests (Prégent *et al.* 2010, Paquette and Messier 2010, Thiffault *et al.* 2013). Because of their significant productivity, forest plantations will increasingly serve to meet timber supply needs. According to the Food and Agriculture Organization of the United Nations (FAO 2006), plantations could meet up to 75% of the world's supply by 2050. Plantations can also help to restore biodiversity, particularly through the plantation of rare species, rehabilitation of poorly regenerated sites and afforestation of deforested lands (Stephens and Wagner 2007, Brockerhoff *et al.* 2008, Paquette and Messier 2010). However, plantations are also part of the silvicultural scenario that shows the greatest potential for the artificialization of natural forests (Park and Wilson 2007, Brockerhoff *et al.* 2008). What emerges is an issue of social acceptability (Howe *et al.* 2005, Dare *et al.* 2011) that even elicits the concerns of environmental certification organizations (Forest Stewardship Council 2009, Klooster 2010).

Box 1. Natural Forests

Natural forests have not undergone any major transformations resulting from extensive industrial operations. They are also called "preindustrial forests". Their description is not static, but considers their "variability", i.e., their fluctuations over time under the influence of natural processes (e.g., natural disturbances, mortality and regeneration). This description is drawn from observations in unmanaged forests and historical studies covering vast spatial and temporal areas. To facilitate the operational management of this concept, judgement of experts is used to develop simplified descriptions of natural forests. Expert judgement will have to evolve, particularly following significant changes in natural processes due to global changes (climate change, pollution, invasive species, migration of some species, changes in stand composition, and present or anticipated exotic insects and diseases). Although imperfect, the concept of natural forests currently represents the best reference to integrate concerns on maintaining biodiversity and forest management by focusing on reducing the gap between managed and natural forests.

In Quebec, the new forest regime aims to implement forest ecosystem management (CQLR, C. A-18.1, Article 1) to reduce gaps between managed and natural forests (Jetté *et al.* 2008; Box 1). In other respects, this new regime also promotes the intensification of timber production, particularly through plantations (Box 2). Hence, from a firsthand perspective, the objectives of intensive plantation silviculture may appear antagonistic to ecosystem management objectives. Some approaches, like "TRIAD" (Messier *et al.* 2009), recommend functional zoning within which a certain proportion of the land is allocated primarily to timber production and includes a smaller proportion allocated to intensive silviculture. Thereafter, conservation efforts can focus on other areas dedicated to extensive management and strict conservation.

However, ecosystem management applies to the entire territory, with or without functional zoning. In this context, measures to mitigate the impact of intensive plantation silviculture on biodiversity must be considered. In addition, intensive plantation silviculture should be integrated into a planning process that serves to properly address ecological issues at the appropriate scale. One promising avenue worth considering is to define a space for solutions that offers opportunities to create wealth from plantations concurrent with environmental and social values. The exercise would be part of a process aimed at safeguarding a certain "social license to operate" for forest plantations. Indeed, the corporate world now recognizes that companies cannot operate efficiently and free of social risks unless their operations obtain overall community approval and they maintain social acceptability throughout their operations (Gunningham *et al.* 2004, Prno and Slocombe 2012). Social license to operate is particularly critical to forestry in the public domain, which needs to gain and maintain public trust in the long term in

Box 2. Plantations in Quebec's Public Forests

1882: First mention of the word "plantation" in a forestry act.

1908: Beginning of plant production by the forestry department. Reforestation objectives were relatively limited, because the type of logging (manual, during winter) at the time ensured the protection of natural regeneration. Reforestation primarily served to rehabilitate burnt areas near communities.

1950–1960: Beginning of mechanization and summer logging—the protection of natural regeneration is no longer ensured.

1980: Implementation of an ambitious plantation program of 300 million plants per year to reforest large areas, where natural regeneration failed to ensure the overall renewal of forests. With the expansion of reforested areas, the use of chemical herbicides raised public concern. Reforestation objectives and expected yields were not achieved, chiefly because of poor maintenance of reforested lands.

1986: Implementation of a new forest regime focusing forest renewal on natural regeneration through the protection of advance regeneration.

1993: Adoption of the Forest Protection Strategy to ensure forest renewal, better protect forest resources, foster harmonious use of forest resources and eliminate spraying of insecticides and chemical herbicides; stabilization of reforestation levels, ranging today between 130 million and 140 million plants per year (Boulay 2013). Plantations have since become a complement to natural regeneration.

2013: Implementation of a new forest regime promoting the intensification of timber production, particularly through plantations, as part of a general ecosystem management framework for the entire public domain covering 84% of Quebec's productive forests.

order to safeguard public fund investment programs (Howe *et al.* 2005, Dare 2011, Dare *et al.* 2011).

This issue has yet to be addressed in Quebec, and the literature only provides partial answers. Therefore, we looked into how intensive plantation silviculture can be put into practice in a context of ecosystem management. Our objectives were to identify ecological, economic and social issues related to plantations and propose solutions to harmonize intensive plantation silviculture with economic, environmental and social values characterizing sustainable forest management. Although our study was conducted in Quebec, we believe that it will be of interest to foresters working in other jurisdictions.

Founding Principles and Premises

The following principles and premises guided our thinking process:

- Ecosystem management, as defined under Quebec's *Sustainable Forest Development Act* (CQLR, c. A-18.1, Article 1), applies to all the forests in Quebec (Ministère des Ressources naturelles et de la Faune 2009). Responses to ecological issues must be found at the appropriate scale for the forest matrix to remain functional for the species that thrive in such an environment.
- With a capacity to generate high timber yields, intensive plantation silviculture is meant to play a vital role in a timber production strategy. When carried out under certain circumstances within functional zoning, intensive plantation silviculture can actually concentrate timber production on part of a given territory to free land areas for conservation purposes.
- In the presence of known risks, preventive, mitigation and corrective measures must be implemented, primarily at the source (prevention principle).
- A science-based approach (Szaro and Peterson 2004) was used to ensure rigour during research analyses and discussions, particularly by integrating and referring to the latest scientific knowledge supported by a comprehensive literature review.

Methods

Group of experts and issue-and-solution-based approach

To address the complex issues associated with the implementation of intensive plantation silviculture within an ecosystem management context, the Ministère des Forêts, de la Faune et des Parcs turned to a group of experts as an instrument of governance (*Groupe d'experts sur la sylviculture intensive de plantations* 2013). The various and apparently contradictory aspects of this complex issue were addressed by sharing and reviewing experiences and scientific knowledge during a thinking and discussion process to identify consensus-based avenues for fact-based solutions (Geneletti 2007). By sharing their individual expertise, experts from fields from which the complex issues emerged conducted a thoroughly scientific analysis to build a broad consensus and foster sound, legitimate decision making (Oliver 2002, Roy *et al.* 2010).

Our group, bringing together government and university researchers and forest managers, looked into plantations defined as forest stands developed essentially by planting seedlings or rooted cuttings with an objective to rehabilitate or enhance timber production. We examined the complete sequence of treatments involved in the silvicultural scenario (including harvesting prior to plantation establishment) representing a potential for the artificialization of natural forests. However, we limited our study to forests of the public domain, managed under Quebec's forest regime.

As part of a plantation diagnostic process (Fig. 1), we used an issue-and-solution-based approach (Desmarais 2006, Comité scientifique sur les enjeux de biodiversité 2010, Grenon *et al.* 2010, Roy *et al.* 2010). With this problem-solving process (Brooks *et al.* 2006, Dennison 2008, Wilshusen and Wallace 2009), the apparently contradictory aspects of the development of plantations within a context of ecosystem management were addressed through perceived issues. The approach served to define ecological issues based on gaps observed between natural and managed forests. By definition, an issue can be something to be gained or lost.

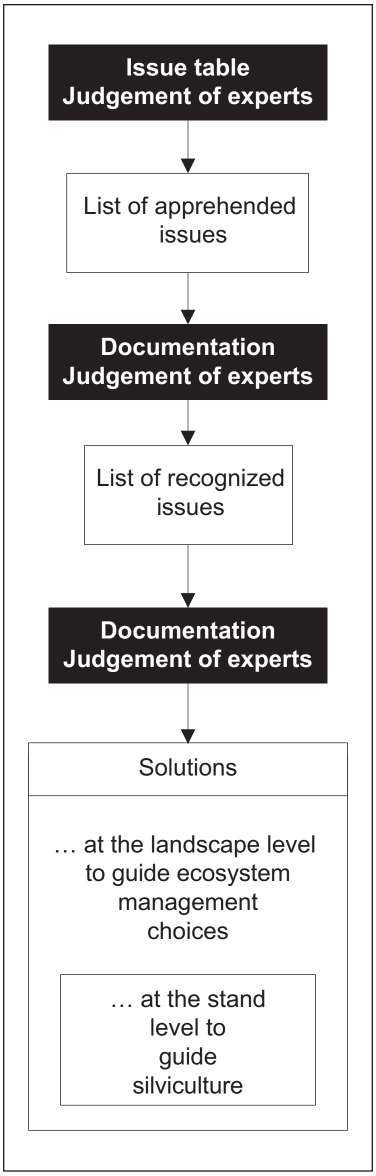


Fig. 1. Plantation diagnostic process within an ecosystem management context.

We prepared a list of issues apprehended to maintain biodiversity, ecological processes and socio-economic values within a context of plantation silviculture intensification. These issues were documented to assess their importance and identify applicable solutions in relevant literature. The issues deemed real on the basis of scientific literature and a case study (see below) were then integrated and grouped under functional groups to develop comprehensive solutions meant to be applied at the stand and landscape levels.

Solutions for stands were detailed based on the various stages of the plantation scenario, including harvesting, site preparation, planting, intermediate treatments (release, cleaning, precommercial thinning, commercial thinning) and final harvest.

Assessment of naturalness to manage forest alteration

To develop solutions, we adapted the concept of naturalness (Colak *et al.* 2003, Winter *et al.* 2010, St-Hilaire 2011, Rüdisser *et al.* 2012, Winter 2012). This concept can be represented in the form of an ecological gradient varying from a state deemed natural to a state deemed artificial. The measure of naturalness serves to assess the ecological "distance" from reference conditions observed in natural forests. This concept can be integrated directly into the paradigm of ecosystem management since its evaluation allows quantifying gaps between managed and natural forests. To facilitate the application of the concept to forest management, the naturalness gradient is generally subdivided into classes useful to assess and manage the alteration of managed forests (Colak *et al.* 2003). Although naturalness is measured quantitatively, the opinion of experts is needed to determine the limits of the gradient classes. We selected five classes to develop solutions: *natural*, *near-natural*, *semi-natural*, *altered* and *artificial* (Table 1). We adapted the definitions and elements of measure to assess the naturalness of forest stands according to two key attributes of the natural forest that influence ecosystem functions and resilience: stand composition and structure.

To address solutions at the landscape level, we assigned a class of naturalness to the stands of four distinct landscapes where plantations are found in different land proportions and are scattered based on two aggregation scenarios and two dispersion scenarios. A semi-quantitative approach was used to assess the naturalness of stands and produce the four naturalness maps, an approach deemed sufficient to contribute to our objectives in order to identify landscape-level solutions, applicable and easy to operate at a large scale. Data unavailable at the time would have been required for the quantitative assessment of naturalness. Our semi-quantitative assessment was based on the information available in Table 1, ecoforest mapping data and our expert judgements, considering current empirical knowledge on natural forests (e.g., Boucher *et al.* 2009) of the region under study (see following section). The naturalness maps were produced by adding stand assessments from a case study (see following section). To facilitate the spatial interpretation of the maps, a neighbourhood analysis was conducted using the Spatial Analyst extension of the ArcMap 9 software (ESRI, ArcGis version 9/ArcMap, Redlands, CA). It resulted in the spatial smoothing of the degree of naturalness. From the image produced, we conducted a visual evaluation of the naturalness environment of the forest matrix based on the predominant naturalness class.

Application of the diagnostic process to a case study

To develop and test the diagnostic process and provide concrete foundations to our thinking process, the Lower St. Lawrence region (Quebec) was selected for the case study. This choice was based on the fact that this region features a relatively large reforested surface area (close to 123 000 ha, accounting for 12% of the public forest land area) and some large plantation concentrations due to the combination of two events: the ambitious government reforestation program of 300 million plants per year implemented in the 1980s (Box 2) and massive reforestation required after forest stands affected by the last spruce budworm (**Choristoneura fumiferana** [**Clemens**]) outbreak were recovered between 1967 and 1992 (Boucher *et al.* 2009). In addition, the region was recently the subject of controversies over plantations (Nature Québec 2008a,b), particularly owing to their scale within the landscape and the silvicultural methods used. Lastly, certain ecological issues related to softwood species plantations could become more critical since the study area is located in the mixed forest zone.

Results and Discussion

Issues

We produced a list of 39 perceived issues, later grouped under 10 comprehensive issues (Fig. 2 and Table 2). Box 3 presents the plantation fertility and productivity issue. This, combined with the issue involving the maintenance of key attributes of natural forests, were at the core of the group's entire thinking process. A detailed description of the other issues is available in our group's report (Groupe d'experts sur la sylviculture intensive de plantations 2013). Practically all the comprehensive issues were deemed real, based on scientific literature and the case study. The only issue we were unable to assess involved the repetition of the plantation scenario because of a lack of relevant scientific knowledge. Each comprehensive issue included one to 10 issues from the initial list. The comprehensive issues that included but a few issues were no less important because they apply to large spatial and temporal scales, encompass other comprehensive issues or simply cannot be overlooked. For instance, plantations must be productive and profitable, and the repetition of the plantation scenario has implications in all the other issues, while social acceptability and the maintenance of First Nation community values can become overriding concerns. Although quite real, some of these issues, such as plantation profitability and First Nation community values, were not addressed in depth due to a lack of more specific data and expertise.

Assessment of naturalness

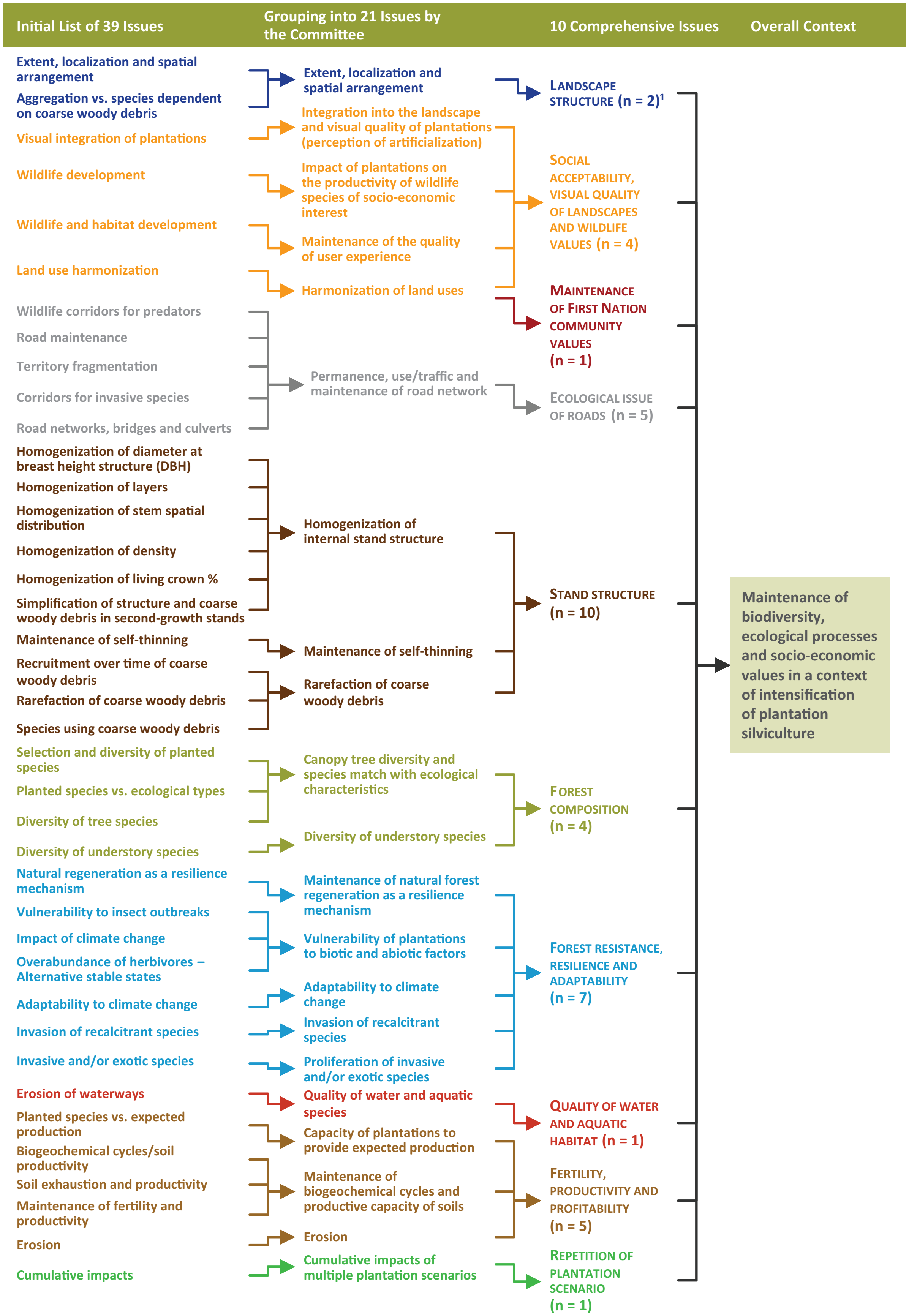
To address the solutions, we used the definitions and elements of measures of forest stand naturalness described in Table 1. With regard to plantations, we believe that the naturalness gradient is useful since it allows a shared understanding and precludes a binary approach. In other words, planting trees does not necessarily create an artificial forest stand, and even plantations excluding exotic species can lead to altered stands. In this regard, the naturalness gradient could contribute to the current discussions on the review of Forest Stewardship Council (FSC) certification standards for the purpose of developing a Canadian standard. In addition, this gradient offers the flexibility to choose among management options and allows controlling and managing the proportion of most altered stands likely to impact biodiversity. Therefore, we believe that the application of this concept will foster the social acceptability of plantations by becoming a consensus-making tool within a context of integrated land and resource management. Lastly, using naturalness degrees will facilitate good practices to achieve greater degrees of naturalness.

Naturalness is quantified using the range of variability of key attributes of the natural forest. Therefore, it does not depend directly on the intensity of the silvicultural scenario. It is thus important to distinguish the naturalness gradient from the silvicultural intensity gradient. The key attributes proposed to measure naturalness are based on structural

Table 1. Conceptual framework for the definition and measure of forest stand naturalness along the ecological gradient subdivided into five classes

	Definition		Elements of measure				
			Structure and Composition		Dynamic Regime		
Naturalness Gradient Classes	Structure and Composition	Process	Distance vs. the distribution and natural variability margins of key attributes	Probability of finding this state in the natural landscape	Energy required to maintain current state	Energy required to return to the resilience of the natural forest	Early warning signals[b] of critical transition between the resilience of a natural forest and that of a novel ecosystem
Natural	Stand in which key attributes, and the characteristics of these attributes, are representative of variability deemed natural	Functions and dynamic regimes[a] associated with the resilience of the natural forest and its alternative stable states, when applicable	n.a.	n.a.	None	None	None
Near-natural	Stand with all the key attributes of natural stands. Most attributes have been slightly altered.		The margins overlap.	Frequent state	Very low	None	Very weak
Semi-natural	Stand with all the key attributes of natural stands. Most attributes have been moderately altered.		The margins no longer overlap, but the distributions touch each other.	Potential state	Low	None	Weak
Altered	Stand without all the key attributes of natural stands. Most of the attributes present have been greatly altered.		The distributions no longer touch each other. The asymmetry of the distribution has changed.	Rare state	Great	None or low	Strong
			n.a.	Non-existing state	Continuous	None or low	Very strong
Artificial	Man-made stand. Profound modifications to the ecosystem and species, whose presence is due to humans.	Functions and dynamic regimes associated with the resilience of a novel ecosystem[c], hardly reversible in a context of forest management (i.e., > 300 years)	n.a.	Non-existing state	None due to novel ecosystem	Great due to novel ecosystem	None due to novel ecosystem

[a]Set of disturbance and regeneration dynamics shaping the ecosystem together with the feedback loops contributing to its maintenance.
[b]Increased of recovery time toward natural variability, of autocorrelation and of variance of key attributes, as well as changes in the asymmetry of the distribution of their variance (spatial or temporal; Dakos *et al* 2011).
[c]Historically absent in natural forests (*Novel ecosystems*; Bridgewater *et al*, 2011; *Future range of variability*; Duncan *et al*. 2010).



[1] The number in parentheses shows the number of issues from the initial list grouped under each comprehensive issue.

Fig. 2. Initial issues and comprehensive issues.

Table 2. Brief description of the ten comprehensive issues and summary of main related solutions

Comprehensive issue	Short description of issue	Summary of main related solutions
Landscape structure	Cumulative impacts of plantations on all the other issues at the landscape level, particularly because of their extent, location and spatial arrangement.	Identify a strategy of localization and spatial arrangement of plantation across the landscape. Limit the proportion of stands of the *altered* and *artificial* classes in the landscape. Apply good practices compatible with yield objectives to enhance the naturalness of plantations.
Social acceptability, visual quality of landscapes and wildlife values	Perception of stand and landscape artificialization associated with plantations. Impacts of plantations on the quality of wildlife habitats, density of wildlife populations and the quality of hunter experience.	Inform stakeholders and integrate their concerns during forest operations planning. Promote multi-species plantations of irregular configuration.
Maintaining First Nation community values	Impacts of plantations on First Nation activities.	Integrate First Nation concerns with regard to plantations during forest operations planning.
Stand structure	Homogenization of the vertical (e.g., diameter distribution, vegetation layers) and horizontal (e.g., spatial distribution of stems, density) structure of stands. Reduction in coarse woody debris abundance.	Promote plantations of variable density integrating long-lived species and mature natural vegetation (living and dead) and in regeneration. Modulate site preparation treatments, slash management, intermediate treatments and final cutting.
Forest composition	Impacts of plantations on the diversity of tree and understory species. Matching of species with site ecological characteristics.	Promote multi-species plantations that make the complementarity of niches possible and that integrate natural forest species and specifies that have become rare. Limit the use of exotic species.
Forest resistance, resilience and adaptability	Crossing of a resilience threshold and shift of dynamic regime toward an artificial ecosystem. Risks of hybridization, naturalization and invasion by exotic and recalcitrant understory layer species. Adaptability to climate change. Vulnerability to biotic and abiotic factors.	Promote the presence of natural forest species. Limit risks of hybridization, naturalization and invasion by exotic and recalcitrant understory species. Use the least severe possible site preparation.
Ecological issues of roads	Need for a dense, permanent road network with impacts on the flow and quality of water, fragmentation and use of the territory, and the creation of corridors for predators, hunters and invasive species.	Plan the density and durability of road networks by considering their effects on ecological processes and species, and apply the best practices.
Quality of water and aquatic habitat	Impacts of silvicultural plantation practices on the quality of water and aquatic habitat (erosion, nutrient cycles).	Limit soil and organic matter export and the leaching of nutrients.
Fertility, productivity and profitability	Capacity of plantations to provide expected production based on the selected species, intensity of site preparation, soil fertility, presence of competing vegetation and modification of scenario to consider new issues. Importance of achieving economic profitability.	Plant as early as possible and carry out all intermediate treatments and final cutting at the appropriate time. Choose the right stock type. Leave branches on the cutover and maintain a vegetation cover. Fertilize soils if needed.
Repetition of plantation scenario	Repetition of the plantation scenario on the same site accentuates all the other issues, particularly loss of productivity and of natural forest attributes and resilience.	Diversify successive plantation scenarios on a same site or alternate between plantation and naturally regenerated stands.

attributes (presence of snags, wood debris, tree density, vertical and horizontal heterogeneity) and compositional attributes (type of cover, diversity of companion tree species as well as understory species) that influence stand functions and resilience. Resilience translates into the capacity of an ecosystem to absorb disturbances and reorganize itself to restore the structure, composition, functions and dynamic regime that prevailed prior to the disturbances (Folke *et al.* 2004, Walker *et al.* 2004, Messier *et al.* 2013). A dynamic regime can be defined as the set of disturbance and regeneration dynamics shaping the ecosystem, along with feedback loops contributing to its maintenance. For instance, recurrent spruce budworm outbreaks and subsequent mortality and regeneration cycles of balsam fir (*Abies balsamea* [L.] Mill.) form a dynamic regime that contributes to maintaining balsam fir stands. Resilience can be compared with the flexibility of an elastic band that can return to its former shape after stretching. Exceeding a resilience threshold can cause a shift of dynamic regime (causing the elastic to break), leading to the creation of a novel ecosystem historically absent from the natural forest landscape (Duncan *et al.* 2010, Bridgewater *et al.* 2011). This new dynamic regime is associated with a different

Box 3. Description of the Comprehensive Plantation Productivity and Fertility Issue

In general, silvicultural scenarios that help to optimize the growth of planted trees are well known. They include the use of genetically improved material from sources adapted to the regional climatic conditions (Beaulieu *et al.* 2009). Stock types and species must be adapted to the ecological conditions of the sites, particularly to the abundance and nature of competing vegetation (Thiffault and Roy 2011). Handling and planting stages must be optimal, since they can directly impact seedling survival and growth (e.g., McKay 1996). The creation of microsites, which supply adequate quantities of resources during seedling establishment, most often requires site preparation focusing on managing stems, slash, competing vegetation, humus and soil mineral horizons (Prévost and Thiffault 2013, Buitrago *et al.* 2014). Site preparation aims to facilitate and optimize subsequent treatments, including planting and release treatments. A production objective targeting a specific crop species (usually the planted species) involves limiting competition for environmental resources to allow their availability for the selected species (Radosevich and Osteryong 1987). In addition, management of plantation density during planting, as well as thinning, increases product consistency and distributes growth over a limited number of selected stems (Prégent 1998).

Modulating silvicultural scenarios to encompass biodiversity issues can potentially influence plantation productivity. For instance, reducing the intensity of site preparation can significantly impact the growth of planted trees. When inadequate scarification insufficiently disrupts organic matter or does not expose the mineral soil over an appropriate surface, significant yield losses can occur (Simard *et al.* 2007). Lastly, maintaining secondary species in plantations can undermine the growth of planted trees (Jobidon 2000, Pitt *et al.* 2004, Wagner *et al.* 2006).

resilience than that of the natural forest and its alternative stable states. The novel ecosystem resulting from a shift of dynamic regime is hardly reversible within a context of forest management (i.e., >300 years or two rotations). Stands of the five naturalness classes (Table 1) maintain the resilience of the natural forest. However, stands in the *artificial* class (Table 1) can maintain the resilience of the natural forest or that of a novel ecosystem. For instance, a plantation of exotic species with advance regeneration comprised of species of the natural forest could still maintain the resilience of the natural forest. However, this same plantation would have the resilience of a novel ecosystem if the regeneration was dominated by the exotic species, meaning this exotic species can regenerate under its own cover. It is therefore important to acknowledge the relationship between resilience and naturalness, because if the gap between a natural and a managed forest is wide enough (i.e., if naturalness is sufficiently low) to trigger a shift in dynamic regimes, it must be recognized. A shift in dynamic regimes invalidates the premise that forests will return to more natural conditions on their own after a disturbance. Given the resilience of a new dynamic regime, the forest will rather evolve towards the conditions of a novel ecosystem.

Lastly, with the integration of resilience into the measurement of naturalness, ecosystems are acknowledged as dynamic, able to evolve and acquire a greater degree of naturalness over time. For instance, a plantation in which several natural forest attributes are missing or are highly altered can achieve a greater degree of naturalness over the years, especially if silvicultural treatments are less frequent or outright abandoned, or if they are used to maintain or restore the attributes of a natural forest.

Fig. 4 illustrates the application of this concept using hypotheses of scenarios that could generate stand characteristics associated with the different naturalness classes. With regard to plantations, we consider that a stand developed through a plantation scenario could be deemed *semi-natural*, *altered* or *artificial* (Fig. 4d to 4f).

Solutions

The documentation of issues also allowed identifying existing solutions at each stage of the plantation scenario. From this list, we present 17 comprehensive solutions to address the comprehensive issues (Fig. 3). One to 10 comprehensive solutions are needed to address each comprehensive issue. Conversely, certain comprehensive solutions help address a single comprehensive issue, while others can each address up to six comprehensive issues. Although some solutions may address only a few issues, they are nonetheless essential because they can be applied at large spatial and temporal scales. For instance, the solution aiming at establishing the maximum proportion of stands of the *altered* or *artificial* classes across the landscape addresses three comprehensive issues, yet it is fundamental to landscape-level concerns. This very logic applies when defining a strategy for the localization and spatial arrangement of plantations across the landscape. Other solutions, such as the application of good practices to enhance the naturalness of plantations, address several comprehensive issues at once. These solutions frequently refer to measures mitigating the potential impacts of common practices; they include maintaining biological legacies during harvesting prior to plantation establishment, maintaining patches of naturally regenerated forests during site preparation, maintaining fruit-bearing trees or species that have become rare during clearing, cleaning and precommercial thinning or modulating how commercial thinning is carried out to encourage greater heterogeneity in plantations. These good practices must be combined with a first-rate solution that involves planting as early as possible and carrying out all the intermediate treatments and final cutting at the appropriate time to obtain expected production.

Some solutions considered as impact mitigation measures can lead to lower timber production and plantation profitability. It is therefore important to consider solutions that enhance the naturalness of stands with little or no impact on plantation yield and profitability. In the absence of such solutions, the application of solutions likely to enhance naturalness should be considered despite the risk of more impact on timber yield and plantation profitability. A few possible solutions are presented to face this forest engineering challenge and reconcile the apparent paradox between the application of mitigation measures and loss in plantation productivity.

First, the creation of mixed or multi-species plantations could help address several ecological and productivity issues simultaneously (Pawson *et al.* 2013). In fact, natural or planted multi-species stands can be more productive than mono-specific stands when species occupying complemen-

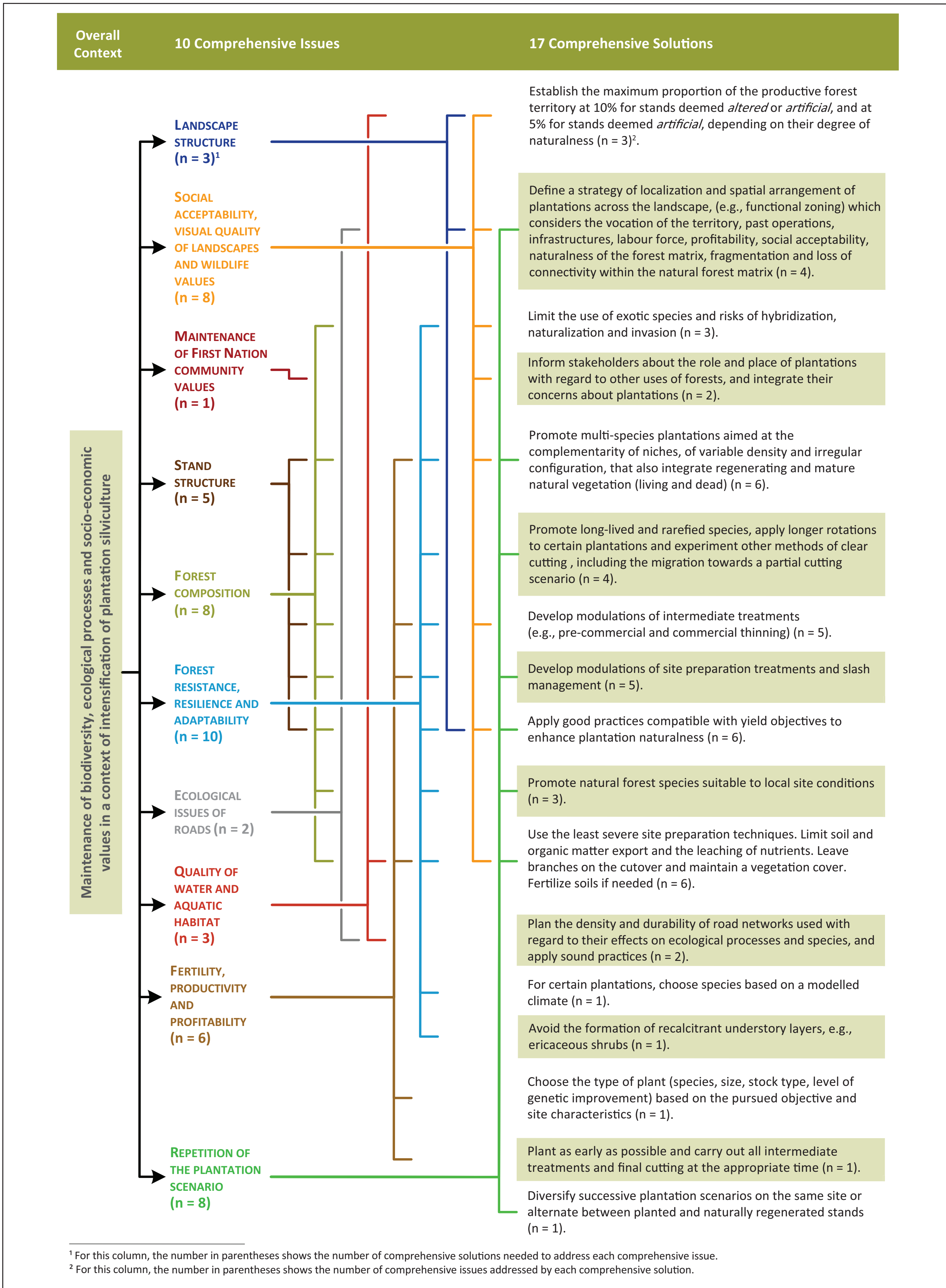


Fig. 3. Solutions to comprehensive issues.

tary niches allow the optimal use of site resources (Paquette and Messier 2011, Pretzsch 2009, Pretzsch *et al.* 2010, Zhang *et al.* 2012). Therefore, higher productivity can be observed in mixed plantations comprised of functionally different species occupying niches distinct enough to promote a complementarity effect (Kelty 2006, Paquette and Messier 2013). Several experimental designs around the world tend to demonstrate this complementarity and growth enhancement effect with increasing biodiversity (Hooper *et al.* 2005). In particular, current research deals with trees and mechanisms likely to encourage such complementarity through niche partition (Tobner *et al.* 2014). Operational testing is under way to demonstrate the feasibility of multi-species plantations, often referred to as a major issue restricting their establishment (Paquette and Messier 2013). However, it is important to ensure that gains measured in the short term translate into improved forest yields over the long term for selected species, at both the individual stem and stand levels. Expert opinions are needed to ensure that the implementation of these types of solutions considers potential risks associated with anticipated modifications of natural processes by global changes (climate change, pollution, invasive species, anticipated or present exotic insects and diseases). For instance, the maintenance in a plantation of natural forest species like ash (*Fraxinus* spp.), at risk of attack by the emerald ash borer (*Agrilus planipennis* Fairmaire), should be analyzed thoroughly.

The management of plantations of irregular configuration that integrate regenerating and mature natural vegetation (living and dead) is another way to increase naturalness with little effect on timber yield. For example, plantations can be managed in strips or gaps on a site featuring a certain proportion of natural regeneration (Paquette *et al.* 2006). Patches of natural forests can be preserved during pre-plantation harvest (variable retention cutting). Thus, these measures would apply at the scale of the planted stand rather than the planted trees. The return on the silvicultural investment on planted sites could then be maximized, because mitigation measures would hardly or not affect planted trees.

Lastly, modulations are proposed for site preparation treatments and intermediate treatments (release, cleaning, precommercial thinning and commercial thinning). At the commercial thinning stage, operations can be modulated to foster greater complexity in internal stand structure without reducing the value of the residual stands (variable density thinning; Franklin *et al.* 2007). Silvicultural testing in the Lower St. Lawrence region has shown that thinning by crop tree release (i.e., a certain number of dominant or co-dominant trees released from their competitors) combined with small gaps creates heterogeneity in the horizontal structure of a stand, while initiating the complexification of its vertical structure through regeneration establishment. In more general terms, the complexification of stands through silviculture is an avenue known for promoting their capacity to adapt and self-organize, particularly in the face of global changes (Puettmann *et al.* 2009, Puettmann 2011).

Solutions concerning the extent, localization and spatial arrangement of plantations

The extent, localization and spatial arrangement of plantations across the landscape raise several complex issues (Fig. 2 and Table 2) regarding interactions between maintenance of an extensive road network, landscape fragmentation and the movement of species (Tittler *et al.* 2012, Fahrig 2013). To address these issues, we used the compilation of stand naturalness classes within four landscapes of the Lower St. Lawrence region (Fig. 5). These landscapes, illustrating different spatial arrangements of plantations belonging to the *altered* and *artificial* classes of the naturalness gradient, served as a basis for our thinking process to develop solutions at the landscape level.

Following an analysis of the first aggregation scenario (Fig. 5a), we judge that the aggregation of a large proportion of plantations of the *altered* and *artificial* classes generates problematic landscapes with regard to several issues, in particular ecological ones. Locally, there are very few stands of *natural* or *near-natural* classes left and the overall forest matrix is deemed *altered*. However, if plantations of *altered* and *artificial* classes (Fig. 5b) are aggregated in a lower proportion, the landscape will be less problematic regarding these issues, since it preserves a matrix deemed *near-natural*.

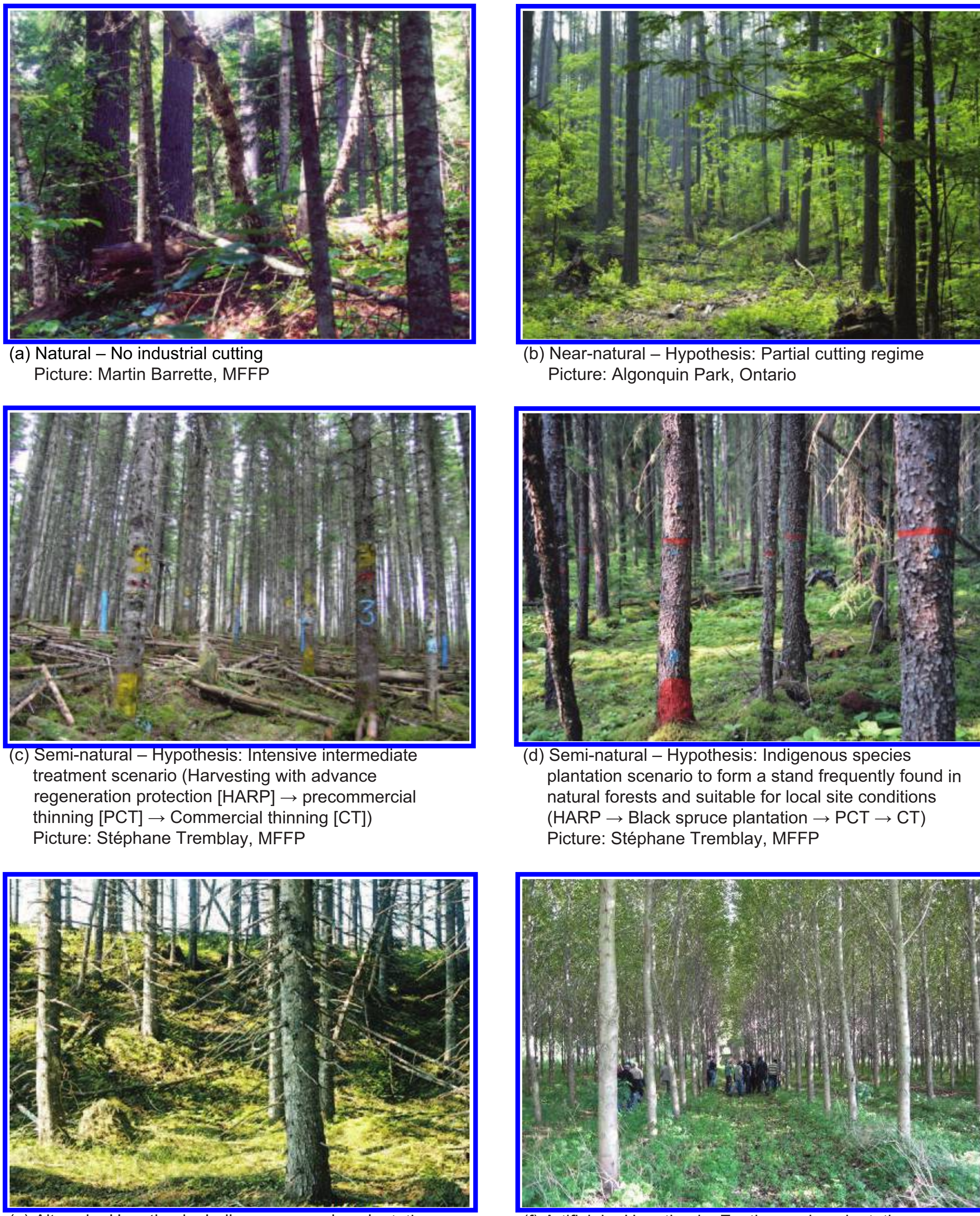
From the analysis of the first dispersion scenario (Fig. 5c), we judge that the dispersion across the landscape of a large proportion of plantations in the *altered* and *artificial* classes dilutes the naturalness of the forest matrix toward a *semi-natural* class, exacerbating several issues. However, the dispersion of a lower proportion of plantations in the *altered* or *artificial* classes (Fig. 5d) reduces the number of problematic issues because the landscape will preserve a matrix deemed *near-natural*. Hence, a first-rate solution is to restrict the proportion of landscape occupied by plantations representing stands of *altered* or *artificial* classes (Fig. 3).

In addition, issues are exacerbated if the naturalness of the matrix is reduced. The nature and significance of plantation issues depend on the naturalness not only of plantations themselves, but also of the forest matrix in which they are found (Fig. 5). For instance, the same spatial arrangement of plantations in the *altered* class (aggregation or dispersion) should be less problematic in a matrix deemed *near-natural* than in a matrix deemed *semi-natural*. Another determining solution at the landscape level would therefore be to maintain the highest possible degree of naturalness in the forest matrix (Fig. 3).

In conclusion, if only a few plantations are included in the landscape, the spatial analysis shows that it is better to disperse them. However, if their proportion across the landscape increases, it then becomes better to create small plantation aggregates. Based on the case study, we believe that the dispersion of small aggregates of plantations of the *altered* and *artificial* classes should permit inclusion of a sufficient proportion of these plantations in the landscape to allow the practice of intensive plantation silviculture while minimizing its impacts. However, our semi-quantitative analysis has limitations that must be acknowledged, and is proposed solely to stimulate discussions on this complex topic. Indeed, the spatial arrangement of plantations is echoed in the debate on the spatial arrangement of protected areas. After more than 20 years, scientists are still trying to determine whether it is better, to preserve biodiversity, to establish a single large protected area or several small scattered ones (SLOSS debate: single large or several small; Burkley 1989, Tjørve 2010, Fahrig 2013).

Management implications

Given their potentially high timber yields, plantations will very likely continue to play a significant role in timber production strategies. However, plantations raise ecological, economic and



(a) Natural – No industrial cutting
Picture: Martin Barrette, MFFP

(b) Near-natural – Hypothesis: Partial cutting regime
Picture: Algonquin Park, Ontario

(c) Semi-natural – Hypothesis: Intensive intermediate treatment scenario (Harvesting with advance regeneration protection [HARP] → precommercial thinning [PCT] → Commercial thinning [CT])
Picture: Stéphane Tremblay, MFFP

(d) Semi-natural – Hypothesis: Indigenous species plantation scenario to form a stand frequently found in natural forests and suitable for local site conditions (HARP → Black spruce plantation → PCT → CT)
Picture: Stéphane Tremblay, MFFP

(e) Altered – Hypothesis: Indigenous species plantation scenario of a stand rarely found in natural forests, or unsuitable for local site conditions (HARP → White spruce plantation → PCT → CT)
Picture: Martin Barrette, MFFP

(f) Artificial – Hypothesis: Exotic species plantation scenario (Hybrid poplar plantation → PCT → CT)
Picture: Réseau Ligniculture Québec

Fig. 4. Examples of silvicultural scenarios that could generate stands in each class of the naturalness gradient.

social issues. We believe that the diagnostic approach and the solutions offered can promote the establishment of intensive plantation silviculture in line with environmental, social and economic values of sustainable forest management.

The management of the extent (quantity), localization (choice of site on the landscape) and spatial arrangement (aggregation or dispersion) represents the main challenge in the integration of plantations into ecosystem management.

We think that measuring stand and landscape naturalness is a solution to encourage, since it allows control over stands that belong to the most altered classes that are likely to significantly affect biodiversity. In addition, a binary approach can be avoided with the concept of naturalness, considering the fact that a plantation does not necessarily create an artificial stand, and that even plantations excluding exotic species can lead to altered stands. Hence, the assessment of naturalness can become a powerful tool to drive social consensus. Notably, evaluating the naturalness of the forest matrix not only becomes a neutral input facilitating the sharing of information among experts and stakeholders, but it also informs the decisions to be made regarding the location and spatial arrangement of plantations. From an economic perspective, the principles of financial and economic profitability foster the concentration of plantations. Consideration of the economic proximity of wood-processing plants (near main highways, accessible anytime, free from harvesting constraints) and the productivity of sites when installing plantations addresses these principles. In addition, existing infrastructure on the land and its vocation (e.g., territories with a wildlife vocation), site productivity, management history, available labour force, social acceptability, fragmentation and connectivity within the natural forest matrix must also be considered when planning the extent, localization and spatial arrangement of plantations.

In addition, the *altered* and *artificial* naturalness classes include stands with characteristics that are far from the natural reference state. Therefore, these stands present the highest risk of impact on biodiversity and ecosystem functions. The larger their proportion across the landscape, the greater the risk will be. To achieve the intensive silviculture objectives, silvicultural operations conducted as part of the plantation scenario will tend to simplify the characteristics of natural forests to the extent of making some disappear. The result of these operations could translate into a low degree of naturalness. To address the issues raised by ecosystem management and timber production, we believe that some thresholds must be proposed in the context of forest management. Given the scarcity of scientific information available on the topic, we propose that the total area occupied by stands of *altered* or *artificial* naturalness classes (whether or not they result from plantations) be allowed to reach a maximum 10% of the productive forest territory of each management unit. In Quebec, management units serve as a basis to calculate the allowable cut and to plan forest operations. Their area varies between 132 km^2 and 25 724 km^2, and averages 4969 km^2. Considering the high risk of impact on the biodiversity of stands of the *artificial* class (the lowest degree of naturalness), we judge that their proportion should be limited to 5% of the productive forest territory in each management unit, and that a greater weight should be allotted to these stands. According to this weighting, the total land area occupied by stands of the *artificial* naturalness class accounts for twice the total land area occupied by stands of the *altered* class. Therefore, a management unit without any stands of the *artificial* class could sustain stands of the *altered* class on 10% of its productive forest territory, whereas a management unit with 5% of its productive forest lands already occupied by stands of the *artificial* class could not sustain stands of the *altered* class. We think that these maximum proportions of *altered* and *artificial* class stands leave enough territories for intensive plantation silviculture (e.g., much lower proportions are expected for the TRIAD project currently under way in Quebec; Messier *et al.* 2009). However, these proportions should not be prescriptive; in other words, it should not become mandatory to achieve them in a given management unit.

To address ecological issues, silviculturists should also identify and apply the best possible practices to enhance the degree of naturalness of plantations and, consequently, that of the forest matrix. For example, the intensity of site preparation treatments sometimes exceeds the level required to achieve production objectives (Buitrago *et al.* 2014). Such excessive practices have potentially avoidable consequences like humus scalping, which not only impacts the survival and growth of plants, but also creates potential erosion problems. Instead, we suggest reducing the intensity of site preparation treatments to the lowest possible level required to achieve production objectives, based on the latest scientific knowledge. For instance, piling should be limited to cases where the safety of forest workers (tree planters and brush cutters) may be compromised by the abundance of slash.

Monitoring activities are an often-disregarded part of the planning cycle. Nonetheless, from a perspective of adaptive management, essential to the continuous adjustment of ecosystem management deployment, monitoring is fundamental to verify whether objectives are achieved (monitoring of efficiency) and whether pursued objectives are still valid or other objectives can be added (monitoring of relevance). Hence, it is important to plan the necessary resources (human, financial and technical) and identify hypotheses for production of services as soon as plantation scenarios are implemented in order to verify, during standard operations, whether objectives are achieved regarding expected timber yields as well as plantation naturalness.

Finally, we consider that research efforts should be pursued or undertaken regarding biodiversity issues associated with plantation silviculture at both the stand and landscape levels. Indeed, research efforts are required to document the impacts of plantation distribution across the landscape on different forest attributes, as well as on target species (Tittler *et al.* 2012). Research efforts on invasion risk and genetic drift caused by planted exotic forest species should also be pursued (Gagné 2010). It is important to validate the proposed thresholds to manage the proportion of stands deemed *altered* and *artificial*, determine the financial and economic profitability of cleaning, precommercial thinning and commercial thinning modulations, and the impacts of these treatments on ecological issues and the real timber yields of plantations within an operational context. Applied research should also look into the development of operational modulations of silvicultural plantation scenarios to foster a greater degree of naturalness in plantations, for instance during site preparation and intermediate treatments. Research should include the assessment of the financial and economic profitability of these plantation scenarios, by integrating the socio-economic and ecological benefits of plantations with a greater degree of naturalness. Lastly, it is imperative to document the contribution of multi-species plantations to timber production, naturalness and the development of other services.

In conclusion, the integration of intensive plantation silviculture into ecosystem management draws upon the expertise and creativity of teams of silviculturists and forest managers. Within the context of ecosystem management and

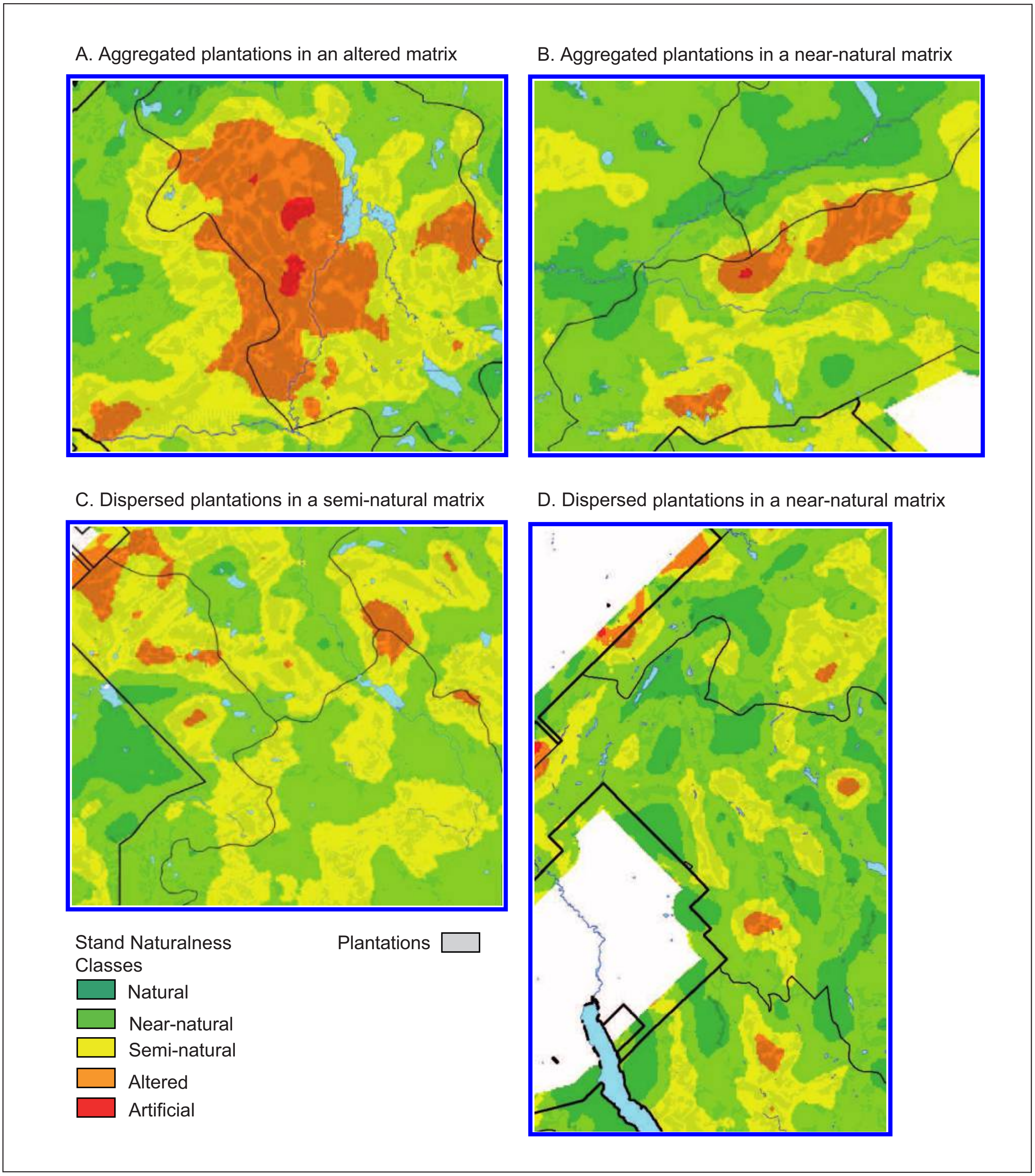


Fig. 5. Spatial arrangement scenarios in the landscape of stands of the altered and artificial classes, corresponding to plantations in the case study.

even in the broader context of sustainable forest management, we believe that it would be difficultly defendable not to apply the types of solutions presented when managing forests as the ones found in Quebec which, *a priori*, have largely preserved several attributes of the natural forest.

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