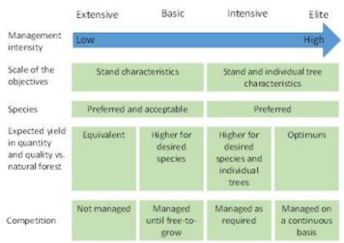

Issues and perspectives on the use of exotic species in the sustainable management of Canadian forests

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Abstract

Plantations offer a high potential to respond to the increasing pressure on forests to deliver social, economic, and environmental services. Exotic tree species have a long history of use in plantation forestry, mostly because of their improved productivity compared with that of native species. Because of their impacts on land management and the environment, questions arise regarding the compatibility of exotic tree plantations with sustainable forest management (SFM), the overarching paradigm driving forest legislations in Canada. Our objectives were thus to *i*) briefly review the historical and current use of exotic tree species in Canada, *ii*) identify the social, economic and environmental issues related to the use of exotic tree species in Canadian forestry, based on sustainable forest management criteria, and *iii*) identify perspectives related to the use of exotic tree species in the sustainable management of Canadian forests. Results show that six out of ten Canadian provinces do not have specific legislations to control the use of exotic tree species for reforestation within their borders. The use of exotic tree species is mainly controlled through third-party certification agencies. Exotic tree species represent a small proportion of the planted seedlings in Canada and Norway spruce is the most common one. The use of exotic tree species is compatible with sustainable forest management criteria used in Canada, but forest managers must take into account several issues related to their use and maintain a social license to be entitled to plant them. Issues are highly dependent upon scale. The zoning of management intensity could provide environmental, economic and social benefits, but costs/benefits analyses should be carried out. The concept of naturalness could also be useful to integrate plantations of exotic species in jurisdiction where SFM strategies are based on ecosystem management principles. Monitoring of hybridization and invasiveness of exotic species must be included in landscape analyses to forestall loss of resilience leading to compromised structural and functional ecosystem states. The use of exotics species is recognized as a tool to sequester carbon and facilitate adaptation of forests to global changes, but it is necessary to carefully identified contexts where assisted migration is justified and disentangle planned novel ecosystems coherent with global changes generated by assisted migration from those emerging from invasive species forming undesired states.

Keywords

Exotic Tree Species, Reforestation, SFM, Biodiversity Issues, Plantation, Forest Certification

Contents

1 Introduction

Reforestation is a silvicultural treatment that is widely used in forest management. Planted forests offer a high potential to respond to the increasing pressure on forests to deliver social, economic, and environmental services (Paquette and Messier 2010). Indeed, it is estimated that areas of planted forests have increased by 50% between 1999 and 2010 worldwide (FAO 2010). Eastern Asia, Europe and North America account for 75% of the planted forest worldwide (FAO 2010). Because their productivity can exceed that of naturally regenerated forests, the increase in planted forest areas is expected to continue over the next decades (Anderson et al. 2015). This increase will also be exacerbated as the pressure to set aside areas of forests for full protection while maintaining and even increasing the output of forest products continues (Messier et al. 2003; Park and Wilson 2007; Paquette and Messier 2010). Improved access to sea ports and infrastructures that help to gain access to international markets, increased use of wood for energy and construction, and incentive to use plantations as efficient ways for fixing atmospheric CO_2 to minimize global warming are other drivers of forest plantation expansion (Barua et al. 2014). Planted areas are expected to reach 300 million ha by 2020 (FAO 2010).

Box 1. Canadian Forests

Spanning over 348 Mha, forests in Canada roughly account for 10% of the world forests. Canada is divided into 15 ecozones, 12 of which are significantly forested. The Boreal Shield ecozone, characterized by a patchwork of conifer dominated forests at various stages of maturity owing to wildfires is distributed across six provinces. It is the largest one and accounts for 26% of the area. The Taiga Shield ecozone, stretching across the subarctic, is composed of forests, wetlands and shublands, and accounts for 19% of the forested area. Other examples of forested ecozones include the Boreal and Taiga Plains, the Mountain and Boreal Cordilleras, and the Prairies (see Beaudoin et al. 2014 for more details). Ninety-four percent of the Canadian forests are publicly owned, most of it being under provincial or territorial jurisdictions. About 3.6% of the Canadian forests are under aboriginal or federal jurisdictions. Forest management activities are thus mainly controlled by provincial bodies, with their own forest legislations, by-laws and annual allowable cut level calculations.

The biophysical characteristics of Canada result in a much diversified forest land base (Box 1). Plantation forestry in Canada is thus used under various intensity of management (Fig. 1). For example, plantations are used in extensive forestry scenarios in the boreal forest, as a complement to natural regeneration. In such cases, expected yields are those of the natural forests, competing species are not managed following planting, and the main objective is to maintain (or restore) forest cover. At the other end of the management intensity spectrum, exotic species are used in elite scenarios (sensu Bell et al. 2008) to optimize wood production (Messier et al. 2003). Inputs are important; competition is managed on a continuous basis, fertilizer are often applied, protection from browsing might be necessary (depending on the planted species), and rotations are short.

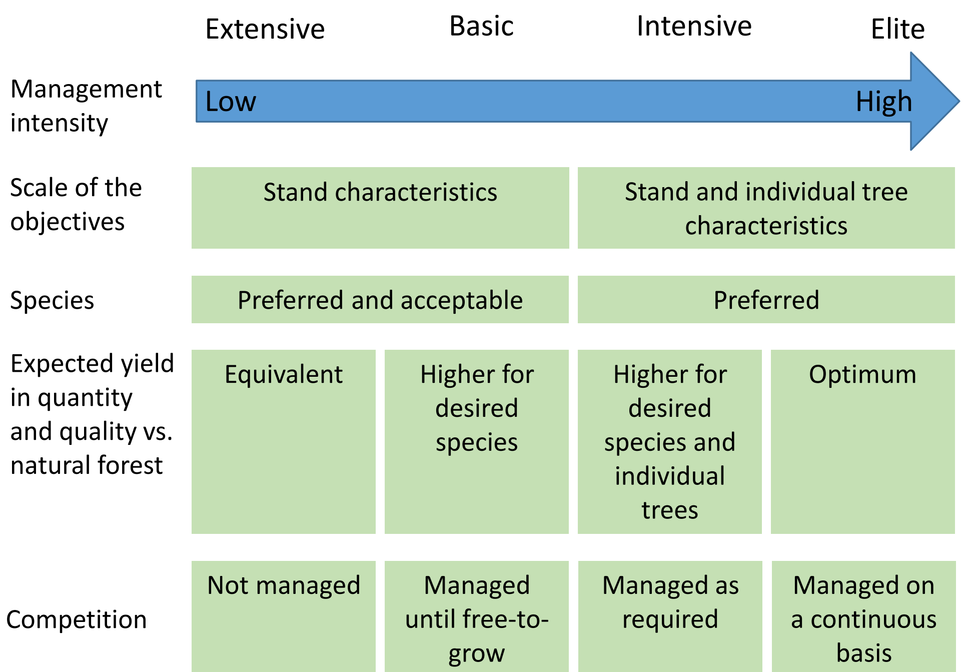

Figure 1. A simplified description of the gradient of forest management intensities used in Canada. Adapted from Bell et al. (2008).

In 1992, Canada and eleven other countries committed to sustainable forest management (SFM) during the United Nations Conference on Environment and Development (CCFM 2008). Sustainable forest management is based on the paradigm that forest resources should be managed to meet the social, economic, ecological, cultural and spiritual needs of present and future generations, and protected against the harmful effects of pollution, fires, pests and diseases (United Nations 1992). In response to this international commitment, the Canadian Council of Forest Ministers (CCFM) established a national framework comprising six criteria and 46 indicators adapted to the Canadian forestry context, so that management approaches can be objectively evaluated within the SFM paradigm (CCFM 2008). The six criteria reflect the environmental, economic, social and cultural Canadian forest values (Tab. 1).

Exotic tree species have a long history of use in plantation forestry (e.g. O'Hehir and Nambiar 2010; Kjær et al. 2014), mostly because of their improved productivity compared with that of native species (e.g., Elfving et al. 2001; Morris et al. 2011). Their superior growth rates, compared with those of native species, can indeed result in shorter rotations (Zobel et al. 1987). Exotic tree species constitute 25% of planted forests worldwide (FAO 2010) and represent most of the planted species in many countries including Brazil, New Zealand and the United Kingdom (Brockerhoff et al. 2008).

Table 1. The CCFM (2003) criteria of sustainable forest management.

Criteria	Description
Biological diversity	Biodiversity refers to the variability among living organisms and the ecosystems in which they are found. It can be measured at the ecosystem, species, and genetic levels.
Ecosystem condition and productivity	Ecosystem condition refers to their relative freedom from stress (health, stability), relative ability to recover from disturbance (resilience), and relative level of physical/biological energy (vitality). When integrated, they provide a measure of ecosystem functioning. Productivity refers to the ability for biomass accumulation, a process that depends on nutrients, water, and solar energy absorption and transfers within the ecosystem.
Soil and water	Forests are filters for pollution and constitute habitats for aquatic and riparian species. Forest management can modify forest soils through disturbance, erosion, and compaction. Ecosystem sustainability depends on their capacity to maintain these roles.
Role in global ecological cycles	Forests are at the center of major ecological cycles. They depend on and contribute to processes responsible for recycling nitrogen, water, carbon and other key elements at the global scale.
Economic and social benefits	Forests should provide a broad range of good and services over the long term, thus offering significant economic and social benefits.
Society's responsibility	Management practices should reflect social values as forest operations are often conducted on publicly owned lands. Moreover, many communities depend on forest ecosystems for their cultural, social and economic well-being.

Many authors are studying and discussing the effects of exotic forest plantations on biodiversity and ecosystem functioning (e.g. Brockerhoff et al. 2008; Paritsis and Aizen 2008; Chen et al. 2013). Because of its impacts on land management and the environment, as well as its influence on wood markets, the use of exotic species raises social, economic and environmental issues (Felton et al. 2013). Questions thus arise regarding the compatibility of exotic tree plantations with sustainable forest management, the overarching paradigm driving forest legislations in Canada. Our main goal was thus to identify issues related to the use of exotic tree species for reforestation in Canada in the specific context of sustainable forest management. More specifically, we aimed to *i*) briefly review the historical and current use of exotic tree species in Canada, *ii*) identify the social, economic and environmental issues related to the use of exotic tree species in Canadian forestry, based on sustainable forest management criteria, and *iii*) use our analysis to identify perspectives related to the use of exotic tree species in the sustainable management of Canadian forests. Since Canada is largely forested (Box 1), we identified issues and perspectives within the context of reforestation, and did not address the activities related to afforestation. Moreover, we acknowledge that some issues identified here are not specific to the use of exotic species in reforestation; they can however be exacerbated compared to plantations with native species.

2 What is an exotic tree species?

In the broad sense, an exotic species is an organism that was directly or indirectly introduced by anthropogenic activities but the definition of exotic tree species varies according to jurisdictions and contexts. Exotic tree species are usually distinguished from native species based on their spatial distribution, but the scale considered varies considerably. For example, some jurisdictions divide their territory in ecozones, ecoregions or ecosystems, based on geographical, physical, biological and climatic characteristics. A species considered native at the national scale can thus be considered as exotic if planted outside its natural ecological range within the same jurisdiction. Species can also be considered as exotic because of a temporal factor, which varies according to context. For example, whereas most would consider *Fagus sylvatica* as a native species in Norway (Kjaer et al. 2014), genetic analyses have shown that it was introduced from Denmark 1500-1000 years AD (Myking et al. 2011). In contrast, *Larix sibirica* was considered as exotic in Sweden until the discovery of macrofossils that suggests it is native to this country (Kullman 1998). In some jurisdictions, an exotic tree species that has naturalized (i.e. able to naturally reproduce as to maintain its population; Richardson et al. 2000), can be considered as native (CSA 2013).

Table 2. Definitions of “exotic species”.

Source	Definition
FSC (2012)	Alien species: A species, subspecies or lower taxon, introduced outside its natural past or actual distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce.
SFI (2015)	Exotic tree species: A tree species introduced from outside its natural range. This does not include species that have become naturalized in an area and have a naturally reproducing population. (Note: Hybrids of native species or native plants that have been derived from genetic tree improvement and biotechnology programs are not considered exotic species.)
CSA (2013)	Invasive alien species: Plants, animals, or micro-organisms that have been introduced by human action outside their natural past or present distribution, and whose introduction or spread threatens the environment, the economy, or society, including human health.
Dodet and Collet (2012)	Alien plants that sustain self-replacing populations for at least 10 years without direct intervention by human, and that produce reproductive offsprings, often in very large numbers and at considerable distances from parent plants and thus have the potential to spread over a large area.
Sax (2002)	Exotics are species that have been introduced by humans, or have been able to expand their range because of anthropogenic disturbances, into regions where they were not historically present.
Alberta Forestry Division of Environment and Sustainable Resource Development (2009)	Non-local material: Material of unknown adaptation. Either of: 1) wild material collected from outside the seed zone in which deployment is proposed, 2) stream material that is not deemed to be locally adapted.
CCFM (2006)	Alien or nonnative species are those introduced by human action outside of their natural, past, or present distribution.
Felton et al. (2013)	Introduced taxa: A species that occurs outside of its natural range. A species is ‘‘naturalized’’ if it is able to independently reproduce and sustain populations over several life cycles.
Zobel et al. (1987)	The term exotic applies to trees that are growing in an area in which they do not naturally occur.
Kjaer et al. (2014)	An exotic species is present only because it was introduced as a result of human activities. The term exotic is also applied in a more vague definition, where exotics exclude species that may be of foreign origin (introduced by humans), but already “fully naturalized”.
Boulet and Huot (2013)	A species that originates from a foreign country or that grows outside of its natural range as a result of its intentional or accidental introduction through human activities.
FAO (2015)	Species, subspecies or inferior taxon out of its natural range (past or actual) and of potential dissemination.

For the purpose of this analysis, it was essential to adopt a definition of exotic tree species so that various sources of data related to Canadian forestry could be integrated. Based on the definitions presented in Table 2, we established a working definition of exotic tree species that comprises any tree species that is present outside its natural range following direct or indirect introduction through anthropogenic activities, notwithstanding the period of introduction. Hybrids are also considered as exotic if at least one of the parents is a known exotic. Due to the limitations of the data sources (mainly based on data provided by provincial bodies; see below), we used provincial boundaries rather than natural habitats as the spatial scale to define exotic species. Thus, for a given province, we considered a tree species as being exotic if it does not naturally occur in the said province.

3 Early use of exotic tree species in Canada

Tree plantation in Canada started at the end of the 19th century. In the Prairies region, there are mentions of tree planting going back to 1830 (Arseneau and Chiu 2003). In Quebec, interest in reforestation appeared around 1872 as a mean to restore forest lands that were "degraded" during colonization (Castonguay 2006). The first documented seeding operations were carried out in 1904-1905 in Manitoba, Ontario and Nova-Scotia (Waldron 1973).

The development of the pulp and paper industry increased the pressure on forest to produce more wood (Castonguay 2006). Private companies were granted access to larger and larger areas of Crown forests so they could avoid a shortage in wood fiber (Blais and Chiasson 2005). Forest renewal was not a concern to foresters, as a seemingly unlimited forested land base was available. Issues related to forest conservation, road access, increasing value of pristine forests, and losses due to pests, diseases and wildfires however emerged during the 1920's (Weetman 1982). Provincial bodies reacted differently to these issues, but a common approach was to transfer silviculture responsibilities (including forest renewal) to the industrial licensees. Artificial regeneration, which was cheaper than getting wood from natural forests that were located further and further away, then appeared as a promising silvicultural treatment.

Foresters however needed tree species that were suitable for pulp and paper production, characterized by high growth rates, and recognized for their resistance to pests and diseases. Local indigenous species were shared across provinces, with many success and failures. For example, Ponderosa pine (*Pinus ponderosa*), a species indigenous to British Columbia, proved to be able to grow in the northeastern region of Ottawa (Ontario) as an exotic species, but not in the western Prairies or Quebec (Mulloy 1935). The early use of seeds from European sources for species such as *Pinus sylvestris* that were not well adapted to the North American biophysical context contributed to create a bad reputation for the use of exotic tree species in reforestation (Zobel et al. 1987). Morandini (1964) attributed these failures to an overly rapid transition from the experimental to the large-scale use of exotic tree species.

Reforestation efforts gradually increased over the decades, backed-up by the development of tree nurseries. In 1970, artificially regenerated areas represented 0.3% of forest lands in Canada (Paillé 2012). Reforestation efforts continued to increase over the years; at the national level, planting efforts reached 27% of the harvested areas during the 1975–76 to 1985–86 period (Kuhnke 1989). Although the indigenous black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) represented about 70% of the planted seedlings at that time, the development of new ecological knowledge and of silvicultural treatments adapted to the autecology of exotic species enabled Norway spruce (*Picea abies*), European larch (*Larix decidua*), Japanese larch (*Larix kaempferi*), Austrian pine (*Pinus nigra*) and Sitka spruce (*Picea sitchensis*) seedlings to be successfully produced and planted (Kuhnke 1989; Dancause 2008). In Quebec, Norway spruce was used on 3% of the land submitted to artificial seeding in 1972 (Waldron 1973), which represented more than 10,000 ha.

4 Current use of exotic tree species in Canada

Provincial bodies are responsible for legislations related to forest management activities in Canada (see Box 1). Each province thus has its own forest renewal policies and by-laws. Using data obtained from governmental websites and official representatives (see Supplementary material 1: Sources for Table 3. for a complete list of sources), we synthesized the current use of exotic tree species in forestry in Canada (Tab. 3). Results show that six out of ten Canadian provinces do not have specific legislations to control the use of exotic tree species for reforestation within their borders. The use of exotic tree species is mainly controlled through third-party certification agencies, of which only the Forest Stewardship Council (FSC) has clear criteria regarding the use of exotics (Box 2). Overall, exotic tree species represent a small proportion of the planted seedlings in Canada, and Norway spruce is the most common one.

Box 2. Exotic tree species and forest certification in Canada

About 153 million ha of the Canadian forests are certified by a third-party agency, which corresponds to 70% of the forests under a management plan. The three main certification systems used in Canada are the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI) and the Canadian Standards Association (CSA). Some forest lands are certified under more than one system. Certification processes vary in their interpretation of "exotic species" (see Tab. 2) but all of them can have impacts on the use of exotic tree species in resource management.

The Forest Stewardship Council

FSC allows the use of exotic species, although the use of native species should be preferred when establishing plantations. Exotic species can only be used for a given plantation project if they present increased growth rates compared to native species, and are known to be adapted to site characteristics and management objectives. The use of exotic species with a known potential for invasion is strictly prohibited, and in some cases it must be demonstrated that they are no risks that they can act as vectors for new pathogens. Their use must be controlled and appropriate monitoring (including potential invasion) must be carried out to avoid negative ecological impacts. For most Canadian regions where it is applied, the FCS certification limits to 5% the proportion of the productive land base that can be planted using exotic species (FSC 2004; 2005; 2008; 2010; 2012).

The Sustainable Forestry Initiative

The SFI certification specifies that the use of exotic tree species for plantation should reduce to a minimum the risk for natural ecosystems. Under this certification process, a species is no longer considered as exotic in a given territory when it starts to naturally reproduce. Hybrids of indigenous species are not considered as exotics, with no mention if this rule concerns only one or both of the parents (SFI 2015).

The Canadian Standard Association

The CSA advocate the conservation of genetic biodiversity, indigenous species and ecosystems. Forest managers must thus take into account the proportion of indigenous species and prioritize them in reforestation activities. Although the CSA certification does not dictate any particular procedures related to the use of exotic species, it stipulates that exotics known to be invasive must be avoided (CSA 2013).

Table 3. Synthesis of reforestation statistics and planting of exotic tree species in Canada

	QC	ON	MA	SK	AL	BC	PEI	NB	NS	NF/LB
Forests / provincial landbase (%)	46	66	57	53	60	60	44	85	77	57
Public forests (%)	91	90	95	97	100	95	12	51	47	96
Harvested forests submitted to reforestation (%) (years)	20 (2010)	40 (2014)	55 (2006-2010)	50 (2010)	76 (2012-2013)	75[4] (2005-2006)	30 (2010)	33[5] (2012)	20[5] (2012)	72[5] (2012)
Presence of a specific law or bylaw concerning the use of exotic tree species in forestry	No	Yes	No	Yes	Yes	Yes	No	No	No	No
Productive forest (%)[1]	56	44	na	34.4[3]	na	37	na	49[6]	14[6]	33[7]
Certified forests (%)[2]	50	38	31	19	51	94	0,2	68	30	6
FSC certified forests (%)	67	69	0	27	15	4	0,2	0.006	53	100
SFI certified forests (%)	47	51	7	71	29	48	0	100	96	0
CSA certified forests (%)	0	3	24	29	7	49	0	0	0.8	95
Main exotic tree species used for reforestation (%)	PIA (0.8)[8] HLA (0.2)[8] HPO (0.6)[8] JUN (0.0003)[8]	na	na	na	na	LAS (0.01)[9] PIA (na) HPO (na) ABB (na)	PIA (4.8)[10] PIP (0.4)[11] LAK(1.7)[10] PIN (0.1)[10] LAD (0.3)[10] HPO (1.1)[11]	PIA (13)[12]	PIA (2)[13] HLA (1.1)[13] LAK (0.08)[14]	PIA(10)[15]

[1] Forests that can be harvested. [2] From the total forest landbase, including private forests. [3] Public forests submitted to a management agreement. [4] Ratio between reforested and perturbated areas (harvesting, wildfire, insects and diseases, regeneration failure). [5] Planting only, as data on artificial seeding were not available. [6] Public forests submitted to a management agreement. [7] Productive forests available or partially available for harvesting. [8] Based on the number of seedlings delivered in 2014. [9] Plantations on Crown lands, between 2006 and 2007. [10] 2013 database on forest plantations. [11] Based on seed production between 2001 and 2010. [12] Base on the number of planted seedlings in 2014. [13] Based on 2013 seeding. [14] Based on the number of seeding produced in 2005. [15] Seeds delivered to the Wooddale provincial nursery between 2008 and 2009. At this time, this nursery was producing 94% of the seedlings in the province. QC: Québec. ON: Ontario. MA: Manitoba. SK: Saskatchewan. AL: Alberta. BC: British Columbia. PEI: Prince Edward Island. NB: New Brunswick. NS: Nova Scotia. NF/LB: Newfoundland and Labrador. na: data non available. PIA: *Picea abies*. PIP: *Picea pungen*. HLA: Hybrids of *Larix*. LAS: *Larix sibirica*. LAD: *Larix decidua.* LAK: *Larix kaempferi.* JUN: *Juglans nigra*. HPO: Hybrids of *Populus.* ABB: *Abies balsamea*. PIN: *Pinus nigra*. See Supplementary material 1 for sources

5 Issues

When dealing with complex environmental questions, the identification of issues enables summarizing trends or changes in a problem-oriented manner so that knowledge and practice can be used to develop solutions (Wilshusen and Wallace 2009). This approach is used in a wide range of fields, including coastal ecosystems (Dennison 2008), forested ecosystems (Brandt et al. 2013) or wildlife management (Miller and Miller 2016). Using the CCFM framework of criteria for sustainable forest management

(Tab. 1), we thus analyzed how the use of exotic trees species for reforestation as the potential to create significant environmental, economic and social issues in Canada (Tab. 4). We further identified key perspectives emerging from these issues so that stakeholders can build a shared vision and adapt management approaches to take them into account.

Table 4. Issues and perspectives on the use of exotic species in the context of sustainable forest management.

Criteria	Issue	Perspectives
Biological diversity	Loss of habitat for species sensitive to forest management Decrease in species diversity Potential for hybridization and invasion	Monitor biodiversity in exotic plantations. Promote multi-species plantations aimed at the complementarity of niches between exotic and indigenous species. Monitor hybridization and invasiveness of exotic species.
Ecosystem condition and productivity	Increase in wood production Concordance between exotic species autecology and site characteristics	Study resilience of forest landscapes harboring exotic plantations to forestall compromised structural and functional states (e.g. landscape traps; Lindenmayer et al. 2011).
Soil and water	Decrease in soil fertility	Monitor soil fertility and promote soil restoration that mitigates environmental impacts.
Role in global ecological cycles	Adaptation of forests to global change using assisted migration Conservation of C sink	Develop assisted migration strategies to facilitate adaptation of forests to global change. Disentangle novel ecosystems (Hobbs et al. 2006) generated by assisted migration from invasion and hybridization issues. Study dependence to sustained silvicultural treatments of novel migrated ecosystems.
Economic and social benefits	Increase in yields Profitability High production costs Potential loss of ecosystems services Needs for highly qualified jobs	Promote legislations contributing to profitability of exotic plantations. Carry out costs/benefits analyses of exotic plantations to ensure their profitability.
Society's responsibility	Low social acceptability Visual impacts Incoherence with society' environmental values Low confidence regarding governmental decisions Lack of political stability to ensure program durability and research investments	Evaluate conservation benefits of planting exotics in a functional zoning context. Evaluate naturalness of exotic plantations and landscapes harboring them. Thrive to obtain or maintain the social license to plant exotic species.

5.1 Biological diversity

Forest ecosystems harbor 80% of all terrestrial species. Maintaining biodiversity is thus considered an important issue of forest management since the 1990's, and is frequently cited as such when it comes to plantation silviculture (Hartley 2002; Carnus et al. 2006). For example, Fang et al. (2014) have measured lower plant diversity in native *Picea asperata* Mast. plantations relative to naturally regenerated stands of similar ages. Impacts of exotic tree plantations on local biodiversity are not fully understood (Hartmann et al. 2010; Roberge and Stenbacka 2014; Zamorano-Elgueta et al. 2015) but they are generally recognized as offering habitats less favorable than natural forests to native species (Tab. 4; e.g. Hansen et al. 1995; Hartley 2002; Thompson et al. 2003; Carnus et al. 2006; Woodley et al. 2006). Indeed, plantations of exotic species are sometimes referred to as ecosystems that have lost most of the attributes of natural forests (Brockerhoff et al. 2008; Barrette et al. 2014). Some of these attributes such as structure, composition or dead wood act as habitats for species (Hunter et al. 1988). Hence, a loss of key attributes in plantations leads to habitat loss, which can in turn lead to a decrease in species diversity (Tab. 4), notably those sensitive to management (Brockerhoff et al. 2008).

Exotic species can hybridize with indigenous species if they have parents that are phylogenetically close to each other (Schierenbeck and Ellstrand 2009; Dodet and Collet 2012). In some cases, hybrids can be more vigorous than indigenous species (Morris et al. 2011), thus becoming significant competitors with an increased potential for invasion (Tab. 4). Some authors argue that the risk for hybridization is low in northern regions (Kjaer et al. 2014), but hybridization between indigenous and exotic hybrid poplars have been reported in North America (Beaulieu et al. 2001). Meirmans et al. (2014) have shown that there is a potential for hybridization between the exotic European and Japanese larches and the indigenous *Larix laricina*. Moreover, it is known that some exotic species can thrive in ecosystems presenting climatic characteristics very different from those or their native range (Morandini 1964), which raise potential invasion issues. Invasion problems are also exacerbated when natural enemies are absent for the new ecosystems in which the exotic species are planted (Maron and Vilà 2001; Adams et al. 2009). Invasive hybrid and exotic species can have prolonged effects on natural habitats and species diversity (Pimentel et al. 2005; Schierenbeck and Ellstrand 2009).

5.2 Ecosystem conduction and productivity

Plantation silviculture using exotic tree species is usually carried under elite management scenarios (sensu Bell et al. 2008), and is most often intended to increase wood production (Fig. 1; Tab. 4). The use of exotic species does not always confer growth benefits compared with the use of native species (e.g. Larchevêque et al. 2010 for a short term comparison). Productivity of exotic tree plantations can however be up to five times that of natural forests and is usually higher than that of indigenous species plantations (Elfving et al. 2001; Rytter and Stener 2005; Paquette and Messier 2010; Nelson et al. 2011; Tullus et al. 2012). The rapid canopy closure in exotic tree plantation can accelerate successional processes (Hébert et al. 2016), and favor the establishment of tree regeneration (Brockerhoff et al. 2008). Exotic tree productivity is however highly dependent upon site characteristics and management practices; these must be well adapted to the species autecology so they present the expected growth rates (Tab. 4; Fortier et al. 2012). Moreover, research efforts on productivity comparisons between different clones or species are still needed to maximize fibre production (Larocque et al. 2013).

5.3 Soil and water

Because of their high demand in soil nutrients, the growth of exotic species can negatively affect soil fertility in some contexts (Tab. 4; Zobel et al., 1987). Fertilization can be used to compensate for nutrient needs that may be higher than the inherent capacity of the soil to provide them; this costly practice however creates other environmental risks (such as water contamination) and may or may not be effective in promoting planted seedling growth (DesRochers et al. 2006; Lteif et al. 2007; Guillemette and DesRochers 2008; Bilodeau-Gauthier et al. 2011).

The rapid growth rates of exotic tree species can require large volume of water from the soil to sustain evapotranspiration, which can affect water availability and site hydrology. Such impacts have been observed in dry ecosystems such as those found in

Africa, Asia and South America (Zobel et al. 1987; Richardson 1998; Swaffer and Holland 2015). It is unlikely that this issue would be significant in eastern Canada though, which is characterized by very different hydrogeological and climatic conditions. Other parts of the country, such as the western boreal forest, could however be susceptible to this issue because of their dryer climate, and hence, higher potential for drought problems. Water quality can be affected by the increased amount of sediments resulting from the construction, maintenance and heavy use of forest roads associated with intensive and elite (sensu Bell et al. 2008) forest management scenarios (Hartmann et al. 2010).

5.4 Role in global ecological cycles

Forests worldwide are estimated to contain 650 billion tons of carbon, of which 44% is found in their biomass, 11% in dead wood and the forest floor, and 45% in the soil (FAO 2010). Boreal forests act as a natural regulator of atmospheric carbon levels, but global changes pose a significant threat to their health worldwide. This ecosystem, which represents the major part of the Canadian forested land base (Box 1), is indeed expected to face the largest increase in temperature of all forest biomes (Gauthier et al. 2015). These changes will undoubtedly affect biological community composition (Elmendorf et al. 2012) and have impacts on ecosystem stability, productivity and resilience (MacDougall et al. 2013; Price et al. 2013). For example, areas submitted to forest fires are expected to significantly increase in the Canadian boreal forest over the next century (Bergeron et al. 2010).

In this context, and given the important role that forest ecosystems play as carbon sinks, efforts must be invested to restore the forest cover using species that will be adapted to future climatic conditions (Tab. 4; Johnston et al. 2009; Kjaer et al. 2014). Exotic tree species can sometime offer this opportunity (Dodet and Collet 2012), as they can be effective in fixing atmospheric C due to their rapid growth rates (Tab. 4; Carle and Holmgren 2008) and contributing to maintain or rapidly restore a forest cover. For example, species from northern United States of America could be more adapted to future climatic conditions of southern Canada, as global changes favor the northern migration of species (Langor et al. 2014). Owing to their relatively low diversity in structure and species composition, exotic tree monocultures might however be less resilient than native tree monocultures to pests, diseases and other natural disturbances (Jactel and Brockerhoff 2007; Paquette and Messier 2013). Also, although assisted migration of widespread, commercially valuable species is already implemented and presents an opportunity to maintain forest productivity and health under climate change (Pedlar et al. 2011; Kreyling et al. 2011), many uncertainties regarding the real outcome of this practices fuel an ongoing debate in the context of Canadian forests and elsewhere (Aubin et al. 2011; McLachclan et al. 2007).

5.5 Economic and social benefits

Plantations already play a major role in providing society with significant economic returns (Barua et al. 2014), and this role will increase in the future (White et al. 2013). The plantation of exotic tree species in particular contribute to the local or national economy in many developing countries (FAO 2010; Dodet and Collet 2012), and there is a worldwide trend towards the increased use of fast-growing species (Sedjo 1999; Anderson et al. 2015). The short rotations usually associated with the use of exotic species reduce the probability of damages caused by natural perturbations (Arbez

2001), which increases the probability that the planted trees will provided the expected outcomes. Canadian forestry has historically relied mostly on harvesting of natural forests that did not necessitate investments to be regenerated, which has enabled keeping management costs relatively low and fiber quality relatively high. However, the forest sector in Canada must now cope with international economic pressure coming from competitors that largely rely on high-yield plantations for wood production, and that often operate under less restrictive environmental legislations (Park and Wilson 2007). The use of fast-growing exotic tree species in plantations managed under elite scenarios (sensu Bell et al. 2008) is viewed as a promising tool to ensure the viability of this sector, by increasing wood production (Tab. 4; Messier et al. 2003; Anderson et al. 2013) and maintaining employment opportunities for qualified workers in regional communities (Epanda and Leblanc 2008).

Plantation success requires significant investments in stock type production (including breeding programs) and silviculture (site preparation, release and cleaning treatments), especially under intensive and elite management scenarios (Fig. 1; Bell et al. 2008). These costs, which appear early in the silvicultural scenarios, have an important impact on costs/benefits ratio calculations that takes into account discount rates over the rotation period. Shorter rotations and high production rates contribute to profitability (Tab. 4; Tullus et al. 2012). Although some exotic species might require relatively long rotation periods compared others (e.g. exotic conifers compared with hybrid poplars), overall rotation lengths are likely to be shorter than for natural forests. At the landscape level, the potential effect of establishing high-yield plantations on small areas on reducing the management pressure on natural forests could generate economic benefits if non-market and market values of ecosystem services were taken into account (e.g. Messier et al. 2009; Dupras et al. 2015). The environmental risks associated with the use of exotic species can however generate important indirect costs (Pimentel et al. 2005).

5.6 Society's responsibility

Social acceptability of forest management activities varies according to the social, temporal and spatial context, risks associated with specific management tools, visual impacts of silviculture, and trust in decision makers (Wyatt et al. 2011). The use of exotic tree species in elite management scenarios (sensu Bell et al. 2008) raises significant social issues that can ultimately influence policy-making. Obtaining and maintaining the social licence to operate – the acceptance of operations by those local community stakeholders who are affected by it (Moffat et al. 2015) – plays an essential role in the sustainable use of intensive plantation forestry and in entitling managers to plant exotic species (Tab. 4; Barrette et al. 2014). This social licence to operate must be maintained in the long term so that investments needed to achieve plantation objectives are secured (Howe et al. 2005; Dare et al. 2011).

Intensive plantation silviculture presents a potential for artificialization of natural forests (Brockerhoff et al. 2008), which influences the public perception of environmental risks associated with this type of management (Wyatt et al. 2011). The visual impacts of intensive silviculture practices also contribute to the public concerns towards high-yield plantations (Tab. 4; Ford et al. 2009; Pâquet 2013). Moreover, First Nations acceptability regarding the use of exotic tree plantations might be low, especially in territories used for traditional practices such as hunting, fishing, and spiritual activities (Wyatt 2008). The impact of silviculture on job opportunities and regional economy could however be seen as a positive effect of establishing and managing high-yield plantations (Wyatt et al. 2011).

6 Perspectives

The use of exotic tree species is compatible with sustainable forest management criteria used in Canada. The use of introduced species is however a typical example of a complex problem that could benefit from participatory decision-making (Mårald et al. 2015). Forest managers must thus take into account issues related to their use and maintain a social license to be entitled to plant exotic species. We present perspectives to help reach this goal (Tab. 4).

Issues related to the use of exotic trees species in the Canadian context of SFM are highly dependent upon scale. While planting exotic species can affect biodiversity at the local scale, the increased wood production resulting from the intensively managed exotic plantations can have a positive effect on the conservation at the scale of the management unit (Paquette and Messier 2010; Gravel and Meunier 2013). Zoning of management intensity, including of the use of exotic tree species, is argued to provide environmental, economic and social benefits (Tab. 4; Messier et al. 2009). By providing high wood yields (for example, 37 m^3 ha^{-1} yr^{-1} for poplar plantations in Coastal British Columbia; Messier et al. 2003), intensive silviculture activities can be concentrated over smaller areas reducing operation costs and enabling larger forest areas to be dedicated to other uses (e.g.: conservation, low impact management, recreation and traditional or cultural activities). For example, a modeling exercise conducted for a forest management unit located in central Quebec supports that intensive management on a small part of the unit is better than less intensive management over a much larger part of the landscape when it comes to reduce road construction and maximize the amount of old-growth forest (Tittler et al. 2012). For the anticipated high wood yields to be beneficial, they must be profitable. To ensure profitability of exotic plantations, costs/benefits analyses should be carried out. Such plantations must also be supported by legislations that ensure profitability and secure investments (Tab. 4; Anderson et al. 2015).

On the other hand, some provincial jurisdictions of Canada (such as Quebec) have adopted SFM strategies based on ecosystem management principles that apply to the entire public land base. Hence, even intensively managed plantations (including those established with exotic species) are subjected to these principles, which aim at reducing the gaps between natural and managed forests in terms of forest attributes (Jetté et al. 2008). Although this implies legal obligations to take into account biodiversity issues when planning forest management activities, it does not prevent the use of exotic plantations in silvicultural scenarios (Groupe d'experts sur la sylviculture intentive des plantations 2013). The concept of naturalness could be useful to integrate plantations of exotic species in such a management context (Tab. 4; Barrette et al. 2014). Naturalness is an ecological gradient varying from a state deemed natural to a state deemed artificial, that can be subdivided in classes (i.e. natural, near-natural, semi-natural, altered and artificial) to evaluate and manage gaps between natural and managed forests (Colak et al. 2003; Winter et al. 2010; Barrette et al. 2014). The use of this concept has the advantage of avoiding a "binary" classification of managed forests, i.e. being classified as either natural or planted based solely on the silvicultural scenario.

In other words, planting trees does not necessarily create altered or artificial stands. For example, with this concept managers can take into account ecological benefits of establishing exotic tree plantations that include indigenous species (planted or occurring naturally) or that are managed to increase complexity and resilience (Tab. 4; Paquette and Messier 2013). If such multi-species plantations are aimed at the complementarity of niches between exotic and indigenous species, they could also be more productive than monocultures (Hooper et al. 2005). Naturalness can also help managers address issues by clarifying the landscape context. For instance, including artificial stands in an already altered forest landscape does not raise the same issues as including artificial stands in a near-natural landscape. Such assessments could be conducted at the scale of the forest management unit to be compatible with the scale of annual allowable cut calculations, natural disturbances and home range of large mammals, for example. Monitoring of hybridization and invasiveness of exotic species must be included in landscape analyses and national survey programs to forestall loss of resilience leading to compromised structural and functional states (e.g. landscape traps; Lindenmayer et al. 2011). Such compromised states may not represent adequate habitats for species sensitive to forest management (Rompré et al. 2010). Large scale monitoring would allow adjusting management strategies.

Finally, the use of exotics species is recognized as a tool to sequester carbon and facilitate adaptation of forests to global changes, but it is necessary to carefully identified contexts where assisted migration is justified. Much of the Canadian debate around assisted migration appears to be related to the lack of distinction between the economic and conservation goals of the process (Sansilvestri et al. 2016). Notably it will be necessary to disentangle planned novel ecosystems coherent with global changes (Hobbs et al. 2006) generated by assisted migration from those emerging from invasive species forming undesired states judged as being artificial. Moreover, novel ecosystems should have a resilience of their own enabling them to recover from disturbances, otherwise they will be dependent upon sustained silvicultural treatments.

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