Are operational plantations meeting expectations? A large-scale assessment of realized vs anticipated yield in eastern Canada

Martin Barrette[1,2], Isabelle Auger[1], Nelson Thiffault[2,3], Julie Barrette[1]

ORCID: Martin Barrette (0000-0001-5937-382X), Nelson Thiffault (0000-0003-2017-6890)

[1]Direction de la recherche forestière, ministère des ressources naturelle et des forêts, Québec, QC, Canada;

[2]Centre d'étude de la forêt, Université Laval, Québec, QC, Canada;

[3]Canadian Wood Fibre Centre, Canadian Forest Service, Natural Resources Canada, Québec, QC, Canada

Corresponding author, Martin Barrette (2700, rue Einstein, Québec, QC G1P 3W8, Canada; Phone, 418-643-7994 # 6689; Fax, 418-643-2165; Email, martin.barrette@mrnf.gouv.qc.ca)

Abstract

Forest plantations play an increasingly important role in meeting global demand for wood. They usually have higher yield than naturally regenerated forests. Thus, plantations can support economically viable wood production, enable forest conservation elsewere, help mitigate climate change by contributing to carbon sequestration and increase forest resilience and resistance to biotic and abiotic stressors. If yield of plantations is not as high as anticipated, then their use could generate important sustainability issues. There are still major gaps in our understanding of the factors that influence yield, even with respect to black spruce, white spruce, and jack pine, three of the most commonly planted tree species in northeastern North America. Our objective was to evaluate the yield of forest plantations of these species over a 416 000 km^2 region that was representative of northeastern North American forests. Contrary to our prediction, realized yield of operational plantations was consistently lower than anticipated. Site index and competition both played a significant role in determining the yield of plantations. In the context of uncertain realized yield of operational plantations, we emphasize the necessity of relying on adaptive management to determine harvest levels that are compatible with sustainable management objectives.

Keywords: sustainable forest management, allowable cut, silviculture, boreal forest, temperate forest

Introduction

Forest plantations play an increasingly important role in meeting global demand for wood products (McEwan et al. 2019) and are established to meet economic, conservation and climate change issues (Thiffault et al. 2023). They usually have higher yield than naturally regenerated forests, given that they make better use of the space due to optimized stocking that maximize space use, and applications of cultural treatments such as vegetation management and are based upon genetically improved material (e.g., Ackzell 1993; Paquette and Messier 2010). Thus, plantations can support economically viable wood production (Gardiner and Moore 2014), while enabling forest conservation elsewere (Betts et al. 2021; Royer-Tardif et al. 2021). Plantations can also help mitigate climate change by contributing to carbon sequestration (Wade et al. 2019; Ménard et al. 2022; Portmann et al. 2022), and by increasing forest resilience and resistance to biotic and abiotic stressors (Ray et al. 2015; Palik et al. 2022). Hence, issues related to sustainability, such as ensuring economically viable wood production, supporting forest conservation, and promoting carbon sequestration, may arise if the yield of plantations does not meet anticipated levels.

In forest management plans, forest yield is typically estimated using a combination of field measurements, remote sensing data, and growth and yield models. Yield models for plantations are usually developed for specific tree species, site fertility and management regimes (e.g., Stiell and Berry 1967; Bolghari and Bertrand 1984). They are based upon data that are collected from long-term research plots or from networks of permanent sampling plots, taking into account factors such as tree growth rates, mortality rates, and competition among trees. Yet, yield in forest plantations is driven by a complex array of factors, including species selection, site preparation, planting density, and management practices. For example, Fu et al. (2007) demonstrated a significant increase in the growth of planted jack pine (Pinus banksiana Lamb.), black spruce (Picea mariana [Mill.] B.S.P.), white pine (Pinus strobus L.), and white spruce (Picea glauca [Moench] Voss) over a 15-year period. This growth was observed to be significantly higher following high mechanical site preparation intensity, without additional vegetation management treatments. However, when chemical vegetation management was applied, site preparation showed no discernible impact on tree growth. Thus, the yield of plantations that are incorporated into forest management plans is highly dependent upon the data that are used for constructing growth and yield models. This dependence stresses the importance of establishing and managing plantations according to the same standards that are used to generate growth and yield models, to ensure that anticipated production is realized. Failure to do so would compromise the attainment of sustainable forest management objectives.

Moreover, regional differences in climate, soil and other environmental factors can substantially affect the yield of forest plantations, stressing the need for region-specific predictors of growth. For example, recent research that has simulated the effects of various CO_2 emission scenarios has suggested that stand-level yield under a changing climate will vary by species, site quality, geographic locale, and emission scenario (Newton 2016). Yet, significant gaps remain in our understanding of the factors that influence yield, even with respect to black spruce, white spruce, and jack pine, three of the most frequently planted tree species in northeastern North America (CCFM 2023).

In this context, our objective was to evaluate the yield of forest plantations, which were established in Quebec, Canada, over a 416 000 km^2 region that is representative of northeastern North American forests. More specifically, we aimed to identify the drivers of forest plantation yield. We predicted that plantation yield would be as high as anticipated, given that silviculture scenarios usually comprise adequate vegetation management strategies (MRN 2013). We also predicted that site index, planting density and competition would be important drivers of plantation yield (Wiensczyk et al. 2011; Neufeld et al. 2014; Barrette et al. 2019, 2021; Sharma 2022). To verify our predictions, we studied yield in operational plantations of the three most commonly planted tree species in northeastern North America.

Materials and methods

Study area

Our study area encompasses the actively managed forest region of Quebec (eastern Canada), which includes temperate and boreal forests that have been classified into four ecological regions (Grondin et al. 2007; Fig. 1). Climatic conditions in southern ecological regions are warmer than in northern regions, as would be expected, while precipitation regimes are generally similar (Table 1).

The main natural disturbances include insect outbreaks (e.g., eastern spruce budworm [*Choristoneura fumiferana*]), windthrows and wildfires (Barrette et al. 2020). The most abundant tree species are black spruce, balsam fir (*Abies balsamea* [L.] Mill.), white or paper birch (*Betula papyrifera* Marsh.), yellow birch (*B. alleghaniensis* Britt.) and sugar maple (*Acer saccharum* Marsh.). Depending on the ecological region, these species are found in mixtures with varying densities of companion species, such as white spruce, red spruce (*Picea rubens* Sarg.), jack pine, eastern white pine, red pine (*Pinus resinosa* Sol. ex Aiton), eastern hemlock (*Tsuga canadensis* [L.] Carrière), eastern white cedar or arborvitae (*Thuja occidentalis* L.), eastern larch or tamarack (*Larix laricina* [Du Roi] K. Koch), balsam poplar (*Populus balsamifera* L.), bigtooth aspen (*Populus grandidentata* Michx.), trembling aspen (*Populus tremuloides* Michx.), red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), red oak (*Quercus rubra* L.), silver maple (*Acer saccharinum* L.), American ash (*Fraxinus americana* L.), American basswood (*Tilia americana* L.), and American elm (*Ulmus americana* L.) (MRN 2013).

Data

We used a network of 475 sample plots that were established by the Government of Quebec to monitor operational plantation yield of the three most commonly planted tree species in northeastern North America, i.e., black spruce, white spruce and jack pine (Fig. 1). These plots were established from 1995 to 1999 in plantations that were about 8-years-old at the time. Planted trees were then tagged for monitoring purposes. Trees with DBH (diameter at breast height, 1.3 m) ≥ 1.1 cm were counted within 400-m^2 circular plots, by species, origin (i.e., planted or naturally regenerated). DBH of each tree was measured in millimeters. Height (cm) of the 4 highest planted trees of the stand was also measured for dominant height estimation. Measurements were repeated up to six times in each plot, on a 5-year cycle. Vegetation management was performed based on governmental guidelines which includes site preparation and a number of tendings dependent on competition levels (MRN 2013; Barrette et al. 2020b).

Potential natural vegetation in each plot was obtained from the Eco-Forest Stand Map (MRNF 2009). Potential natural vegetation is a stand-level land classification unit that is determined by climate, superficial deposits, soil texture, slope, drainage and indicator plant species in the understory (Grondin et al. 2014). By considering potential natural vegetation, we can anticipate the composition and resilience-driven successional trajectories of a given site (Barrette et al. 2019, 2021). Resilience refers to the capacity of a system to absorb a disturbance and reorganize so that the same structure and functions are essentially recovered (Gunderson, 2000). Assessing potential natural vegetation can assist in determining whether the plantation scenario aligns with or deviates from the resilience-driven successional trajectories. For example, a black spruce plantation scenario carried out on a black spruce potential natural vegetation or a black spruce plantation scenario carried out on a balsam fir potential natural vegetation, respectively. This assignment helps predict whether planted trees would be prone to intraspecific or interspecific competition (Barrette et al. 2019, 2021). Thus, the four ecological regions of our study can support a diversity of potential natural vegetation types, but they will typically maintain the potential natural vegetation of the species that denotes the region, e.g., black spruce-moss region will typically hold black spruce potential natural vegetation (Grondin et al. 2007). It should be noted that a white spruce plantation scenario will always deviate from resilience-driven successional trajectories, given that white spruce potential natural vegetation does not occur within the four ecological regions (Grondin et al. 2007; Barrette et al. 2014; Grondin et al. 2014).

Data analysis

To evaluate the yield of operational plantations, we compared their realized with their anticipated yield. To obtain realized plantation yield, we calculated stand basal area based on DBH of planted trees for each plot, by time-since-planting, i.e., classes of 10-15, 16-

20, 21-25 and 26-34 years. These age classes were used to balance the number of plantations in each class, while representing age classes that are relevant to silviculture. To obtain anticipated yield of planted trees, we used stand basal area growth models that were developed for black spruce and jack pine plantations (Auger et al. 2021) and for white spruce plantations (Prégent et al. 2010; Auger and Power 2021). Anticipated yield of planted trees for each plantation at each measurement was estimated with the growth model according to their age, planting density and site index (i.e., mean height of the 100 highest trees per hectare in meters at age 25-years-old, estimated using equations from Auger et al. 2021 and Prégent et al. 2010). To evaluate competition, we calculated stand basal area based on the DBH of naturally regenerated trees for each plot, by species and time-since-planting. Competition was quantified as a percentage of the total stand basal area, calculated as: (basal area of naturally regenerated trees / (basal area of naturally regenerated trees + basal area of planted trees)) × 100. Planted trees were excluded from the assessment of potential competitors, as our focus was on their yield. Composition of the competition was analyzed specifically in plantations with a scenario that deviates from or is aligned with resilience-driven successional trajectories. We used potential natural vegetation to determine whether the plantation scenario aligns with or deviates from resilience-driven successional trajectories (Barrette et al. 2019, 2021).

The difference between realized plantation yield and anticipated yield of planted trees (i.e., yield gap) was calculated for each plantation for the oldest age class (i.e., 26- to 34-years-old) since it provides an extended time depth for comprehensive analysis. The yield gap of a given plantation was expressed as a percentage of anticipated yield for that plantation: (realized yield – anticipated yield)/anticipated yield × 100). Plantations with a realized yield lower than anticipated by more than 5% were considered to be unsuccessful; otherwise, they were considered successful. We analyzed the linear relationship between the yield gap and potential yield drivers (i.e., site index, planting density or competition; Wiensczyk et al. 2011; Neufeld et al. 2014; Barrette et al. 2019, 2021; Sharma 2022) with simple linear regressions by ecoregion and species (PROC MIXED, SAS/STAT 15.1; SAS Institute, Cary, NC) .We also analyzed differences between successful and unsuccessful plantations for each potential yield driver with analysis of variance (one-way ANOVA), using yield status (i.e., successful or unsuccessful) as a fixed effect. We used $\alpha = 0.05$ as the significance threshold. Analyses conformed to normality and homogeneity of variance requirements.

Results

Realized plantation yield

Realized yield was always lower than anticipated yield 26 to 34 years after planting (Fig. 2). Site index was a significant yield driver in boreal regions, more so than in the temperate regions. The yield gap generally decreased with increasing site index in all ecological regions (Fig. 3). In boreal regions, site index of successful plantations was always higher than the site index of unsuccessful plantations, while site index was generally similar between successful and unsuccessful plantations in temperate regions (Tables 2 and 3).

Planting density was rarely a significant yield driver. The yield gap was almost always not related to planting density (Fig. 4). Moreover, planting density was generally similar between successful and unsuccessful plantations (Tables 2 and 3).

Competition was a significant yield driver in both boreal and temperate regions. The yield gap generally decreased with increasing competition (Fig. 5). Moreover, competition was always higher in successful plantations than in unsuccessful plantations (Tables 2 and 3).

Composition of the competition in unsuccessful plantations

In unsuccessful black spruce plantations, balsam fir and hardwoods were the main naturally regenerated species when the plantation scenario deviated from resilience-driven successional trajectories, i.e., black spruce plantations that were located on balsam fir potential natural vegetations (Fig. 6). Other conifers and black spruce also regenerated naturally but mainly in boreal regions. When the plantation scenario was aligned with resilience-driven successional trajectories (i.e., black spruce plantations located on black spruce potential natural vegetations), black spruce was the main naturally regenerated species followed mostly by other coniferous and hardwoods in the black spruce moss region, by other conifers in balsam fir-white birch region, and by balsam fir and hardwoods in the balsam fir-yellow birch region (Fig. 7).

In unsuccessful white spruce plantations, for which the scenario always deviates from resilience-driven successional trajectories, balsam fir and hardwoods were the main naturally regenerated species (Fig. 6). Black spruce and other conifers also regenerated naturally but mainly in boreal regions.

In unsuccessful jack pine plantations, balsam fir and hardwoods were the main naturally regenerated species when the plantation scenario deviated from resilience-driven successional trajectories, i.e., jack pine plantations that were located on balsam fir potential natural vegetation types (Fig. 6). Jack pine also regenerated naturally but only in boreal regions. When the plantation scenario was aligned with resilience-driven successional trajectories (i.e., jack pine plantations located on black spruce potential natural vegetations), black spruce was the main naturally regenerated tree species, followed mostly by jack pine and other coniferous in the black spruce moss region, by jack pine in the balsam fir-white birch region, and by hardwoods in the balsam fir-yellow birch region (Fig. 7).

Discussion

Contrary to our prediction, realized yield of operational plantations was consistently lower than anticipated yield that had been projected by growth and yield models for plantations of similar ages, planting densities and site indices. The yield gap at ages 26-34 varied between -97% and +83%, depending on ecological region and planted species. This finding suggests that anticipated yield may not be achieved in operational plantations, thereby potentially compromising the attainment of sustainable forest management objectives. For instance, in Quebec, where about 20% of annual harvested sites are regenerated using plantation scenarios (Lapointe 2022), the calculation of allowable cut levels considers the potential increase in yield of planted areas compared to natural regeneration (Poulin 2013). To account for differences between anticipated and realized yield, an adaptive management process is necessary. Adaptive management is a process involving periodic monitoring to assess the achievement of objectives and the need for adaptations in response to new contexts or knowledge (Barrette et al 2014). As such, the calculation of allowable cut levels in Quebec is revised every five years, taking into account the most recent survey data and research findings. This practice is crucial in the context of sustainable forest management, where the success of plantation forestry plays a pivotal role in determining the level of sustainable harvest (BFeC 2015).

As predicted, site index played a significant role in determining the yield status of plantations in boreal regions, but it did not have much influence on yield status in temperate regions. In boreal regions, we observed that yield of plantations that were established on sites with low site indices was lower than anticipated, while those that were established on sites with higher indices exhibited the anticipated yield. One possible explanation for the yield gap in sites with lower site index could be their underrepresentation in the plot network that was used for constructing growth models. Prégent and Végiard (2000) studied the growth and yield of 41 of the oldest black spruce plantations in northern Quebec on mesic sites (~98%) and found that nearly 34% of the plots that were studied had site quality indices below the minimum value used to construct yield tables for this species at that time (Prégent et al. 1996). Although the latest growth models have incorporated a greater number of plantations, there continues to be an underrepresentation of lower site index classes, notably for black spruce and white spruce plantations (Prégent et al. 2010; Auger et al. 2021).

Another factor could be variation in plantation establishment techniques. After harvest, low fertility sites in boreal ecosystems of northeastern Canada are typically colonized by ericaceous shrubs, which negatively affect conifer establishment and growth (Mallik 2003). Studies have demonstrated that mechanical site preparation treatments can enhance seedling growth, particularly by reducing understory vegetation cover and rhizomatous growth (Wotherspoon et al. 2020; Reicis et al. 2023). Yet, the intensity of the treatment can influence its effect on seedling growth, with more intensive treatments favouring faster height growth compared to lower intensity treatments (Thiffault et al. 2004), thereby affecting the site index over time. Consequently, differences between establishment practices in the modelling plots and operational plantations may lead to variation in yield.

Contrary to our prediction, planting density was rarely a driver of yield. Planting density is usually recognized to play an important role in plantation yield (Thiffault et al. 2021). Yet, we may have not been able to link plantation density to the yield status of plantations, given that it did not vary significantly in our plots. Moreover, yield tables for black spruce, white spruce and jack pine are more strongly affected by site index than by planting density (Prégent et al. 2010, Auger et al. 2021).

As predicted, competition was a significant driver of yield in both boreal and temperate regions where it played a major role in determining the yield status of plantations. Paquette and Messier (2011) also found that tree yield was determined mostly by the intensity of competition in such regions. Moreover, it is widely recognized that yield of forest plantations is closely linked to competition by naturally regenerating tree species (Wiensczyk et al. 2011; Hawkins et al. 2012; Faure-Lacroix et al. 2013; Neufeld et al. 2014; Bérubé-Deschênes et al. 2017). Finally, Anyomi et al. (2014) also found that species composition and successional changes drive yield more so than do climatic effects and site index.

Despite vegetation management was performed (MRN 2013; Barrette et al. 2020b), competition from naturally regenerated trees likely occurred in forest plantations because of resilience-driven, successional trajectories. Depending on whether the plantation scenario was aligned with or deviated from resilience-driven successional trajectories, planted species respectively suffered mostly from intraspecific or interspecific competition. It is recognized that naturally regenerating tree species can recover to the detriment of planted species because of the resilience of the natural forest (Barrette et al. 2019, 2021).

Forest management implications

Forest plantations could generate important sustainability issues if their yield is not as high as anticipated (Gardiner and Moore 2014; Wade et al. 2019; Betts et al. 2021; Portmann et al. 2022). To ensure that plantations promote sustainability, forest managers could favour establishment of plantations in stands with high site indices, but more importantly, favour plantation scenarios that are aligned with resilience-driven, successional trajectories that would reduce interspecific competition (Barrette et al. 2019, 2021).

Efforts have already been made to map site index values for white spruce, black spruce and jack pine plantations in eastern Canada (Barrette et al. 2022). Yet these maps do not consider the potential effects of competition that are incurred by naturally regenerated trees. Integrating plantation scenarios that are aligned with resilience-driven successional trajectories to these existing site index maps could help to identify the best sites for establishing forest plantations. Moreover, integration of this information could help determine the level of tending that is needed to reach anticipated plantation yield. A within-hectare specific predictors of growth would also eventually be useful to ensure plantation reach anticipated yield (Watt et al. 2017).

Reducing interspecific competition in white spruce plantations may prove more difficult, since there is no resilience-driven successional trajectory that is oriented towards white spruce stands (Grondin et al. 2007; Grondin et al. 2014; Barrette et al. 2014). White spruce plantations, therefore, may need more intensive tending for them to achieve anticipated yield even with the use of site index maps. Finally, in the context of uncertain realized yield of operational plantations, we emphasize the necessity of relying on adaptive management to determine harvest levels that are compatible with sustainable management objectives.

Acknowledgements

This work was supported by Project 142332110, Direction de la recherche forestière of the Ministère des Ressources Naturelles et des Forêts, de la Faune et des Parcs du Québec (MRNFQ). This work aligns with the objectives of the IUFRO Task Force on Resilient Planted Forests Serving Society and Bioeconomy, of which Nelson Thiffault is a member. We thank Jean Noël for help in figure preparation and W.F.J. Parsons for English language revision. There are no competing interests for all authors. Data are located at and can be accessed following a consent from the government of Québec.

References

Ackzell, L. 1993. A comparison of planting, sowing and natural regeneration for *Pinus sylvestris* (L.) in boreal Sweden. For. Ecol. Manag. 61(3-4): 229-245. doi: 10.1016/0378-1127(93)90204-Z.

Anyomi, K.A., Raulier, F., Bergeron, Y. Mailly, D., and Girardin M.P. 2014. Spatial and temporal heterogeneity of forest site productivity drivers: a case study within the eastern boreal forests of Canada. Landsc. Ecol. 29: 905–918. https://doi.org/10.1007/s10980-014-0026-y

Auger, I., Ward, C., DeBlois, J., and Lambert, M-C. 2021. Tables de rendement pour les plantations d'épinette noire et les plantations de pin gris au Québec. Gouvernement du Québec. Ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière. 25 p.

Auger, I. and Power, H. 2021. Évaluation des tables de rendement pour les plantations d'épinette blanche au Québec. Gouvernement du Québec. Ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière. 10 p.

Barrette, M., Thiffault, N., and Auger, I. 2021. Resilience of natural forests can jeopardize or enhance plantation productivity. For. Ecol. Manag. 482: 118872. doi:10.1016/j.foreco.2020.118872.

Barrette, M., Dumais, D., Auger, I., Boucher, Y., Bouchard, M., and Bouliane, J. 2020. Naturalness assessment performed using forestry maps to validate forest management sustainability. Ecol. Indic. 119: 106832. doi:10.1016/j.ecolind.2020.106832.

Barrette, M., Thiffault, N., Tremblay, J.P., and Auger, I. 2019. Balsam fir stands of northeastern North America are resilient to spruce plantation. For. Ecol. Manag. 450. doi:10.1016/j.foreco.2019.117504.

Barrette, M., Bélanger, L., De Grandpré, L. and Ruel, J.-C. 2014. Cumulative effects of chronic deer browsing and clear-cutting on regeneration processes in second-growth white spruce stands. For. Ecol. Manag. 329: 69–78. https://doi.org/10.1016/j.foreco.2014.06.020

Barrette, M., Leblanc, M., Thiffault, N., Paquette, A., Lavoie, L., Bélanger, L., Bujold, F., Côté, L., Lamoureux, J., Schneider, R., Tremblay, J-P., Côté, S., Boucher Y., and Deshaies, M-È. 2014b. Issues and solutions for intensive plantation silviculture in a context of ecosystem management. Forestry Chronicle. 90: 748-762. https://doi.org/10.5558/tfc2014-147

Barrette, J., Poliquin, R., and Ward, C. 2020b. Effets réels des traitements sylvicoles en plantations. Protocole d’inventaire forestier. Sixième cycle de mesurage des plantations. Ministère des Forêts, de la Faune et des Parcs, Secteur des Forêts, Direction de la recherche forestière. 31 p.

Barrette, J., Auger, I., and Sylvain, J.-D. 2022. Cartographie des indices de qualité de station des plantations monospécifiques d’épinette blanche, d’épinette noire et de pin gris au Québec. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière. Avis technique SSRF-30. 21 p.

Bérubé-Deschênes, A., Franceschini, T., and Schneider, R. 2017. Quantifying competition in white spruce (*Picea glauca*) plantations. Ann. For. Sci. 74. doi: 10.1007/s13595-017-0624-3.

Betts, M.G., Phalan, B.T., Wolf, C., Baker, S.C., Messier, C., Puettmann, K.J., Green, R., Harris, S.H., Edwards, D.P., Lindenmayer, D.B., and Balmford, A. 2021. Producing wood at least cost to biodiversity: integrating Triad and sharing–sparing approaches to inform forest landscape management. Biol. Rev. 96: 1301–1317. doi:10.1111/brv.12703.

Bolghari, H.A., and V. Bertrand. 1984. Tables préliminaires de production des principales essences résineuses plantées dans la partie centrale du sud du Québec. Ministère de l’Énergie et des Ressources, Service de la recherche (Terres et Forêts). Mémoire de recherche forestière n° 79. 392 p.

Bureau du forestier en chef. 2015. Succès des plantations. Avis du Forestier en chef. Report FEC-AVIS-04-2015. Roberval, QC. 23 p.

Canadian Council of Forest Ministers (CCFM). 2023. National Forestry Database: Regeneration. [Accessed July 11, 2023]. http://nfdp.ccfm.org/en/data/regeneration.php

Faure-Lacroix, J., Tremblay, J.P., Thiffault, N., and Roy, V. 2013. Stock type performance in addressing top-down and bottom-up factors for the restoration of indigenous trees. For. Ecol. Manag. 307: 333–340. doi:10.1016/j.foreco.2013.07.031.

Fu, S., Bell, F.W., and Chen, H.Y.H. 2007. Long-term effects of intensive silvicultural practices on productivity, composition, and structure of northern temperate and boreal plantations in Ontario, Canada. For. Ecol. Manag. 241(1-3): 115-126. doi: 10.1016/j.foreco.2007.01.032.

Gardiner, B., and Moore, J. 2014. Creating the wood supply of the future. In Challenges and Opportunities for the World's Forests in the 21st Century; Fenning, T., Ed.; Springer: Dordrecht, The Netherlands, 2013; Volume 81 of the Series Forest Science, pp. 677–704. doi:10.1007/978-94-007-7076-8_30.

Gunderson, L.H., 2000. Ecological resilience—in theory and application. Annu. Rev. Ecol. Syst. 31, 425–439. https://doi.org/10.1146/annurev.ecolsys.31.1.425

Grondin, P., Noël, J., and Hotte, D. 2007. Atlas des unités homogènes du Québec méridional selon la végétation et ses variables explicatives. Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière. Québec, Canada. 138 p.

Grondin, P., Gauthier, S., Borcard, D., Bergeron, Y., and Noël, J. 2014. A new approach to ecological land classification for the Canadian boreal forest that integrates disturbances. Landsc. Ecol. 29: 1–16. doi:10.1007/s10980-013-9961-2.

Hawkins, C.D.B., Dhar, A., Rogers, B.J., and George, P. 2012. How much birch (*Betula papyrifera*) is too much for maximizing spruce (*Picea glauca*) growth: a case study in boreal spruce plantation forests. J. For. Sci. 58: 314–327. DOI: 10.17221/8/2012-JFS.

Lapointe, E. 2022. Ressources et industries forestières du Québec - Portrait statistique 2021. Ministère des Ressources naturelle et des Forêts. Québec, QC. 138 p.

Mallik, A.U. 2003. Conifer regeneration problems in boreal and temperate forests with ericaceous understory: Role of disturbance, seedbed limitation, and keystone species change. Crit. Rev. Plant Sci. 22(3-4): 341-366. doi: 10.1080/713610860.

McEwan, A., Marchi, E., Spinelli, R., and Brink, M. 2019. Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. J. For. Res. 31(2): 339-351. doi: 10.1007/s11676-019-01019-3

Ménard, I., Thiffault, E., Kurz, W.A. and Boucher J-F. 2022. Carbon sequestration and emission mitigation potential of afforestation and reforestation of unproductive territories. New For. (Dordr.). https://doi.org/10.1007/s11056-022-09955-5

MRNF (Ministère des Ressources Naturelles et de la Faune). 2009. Norme de cartographie écoforestière; troisième inventaire écoforestier. Forêt Québec, Direction des inventaires forestiers. Québec, Canada.

MRN (Ministère des Ressources Naturelles). 2013. Le guide sylvicole du Québec, Tomes 1 et 2. Les fondements biologiques de la sylviculture. Les Publications du Québec,

Québec. 1753 p.

Neufeld, B.A., Morris, D.M., Luckai, N., Reid, D.E.B., Bell, F.W., Shahi, C., Meyer, W.L., and Adhikary, S. 2014. The influence of competition and species mixture on plantation-grown white spruce: Growth and foliar nutrient response after 20 years. For. Chron. 90: 70–79. https://doi.org/10.5558/tfc2014-012

Newton, P. 2016. Simulating the potential effects of a changing climate on black spruce and jack pine plantation productivity by site quality and locale through model adaptation. Forests 7(12). doi: 10.3390/f7100223.

Palik, B.J., Clark, P.W., D'Amato, A.W., Swanston, C., and Nagel, L. 2022. Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. Ecosphere 13(10). doi: 10.1002/ecs2.4260.

Paquette, A., and Messier, C. 2010. The role of plantations in managing the world’s forests in the Anthropocene. Front. Ecol. Environ. 8 (1), 27–34.

Paquette, A., and Messier, C. 2011. The effect of biodiversity on tree productivity: from temperate to boreal forests. Global. Ecol. Biogeogr. 20: 170–180. https://doi.org/10.1111/j.1466-8238.2010.00592.x

Portmann, R., Beyerle, U., Davin, E., Fischer, E.M., De Hertog, S., and Schemm, S. 2022. Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation. Nat. Commun. 13: 5569. https://doi.org/10.1038/s41467-022-33279-9

Poulin, J. 2013. Plantation. Fascicule 3.1. In Manuel de détermination des possibilités forestières 2013-2018. Bureau du Forestier en Chef. Gouvernement du Québec, Roberval, QC. pp. 77-81.

Prégent, G., Bertrand, V., and Charette, L. 1996. Tables préliminaires de rendement pour les plantations d'Épinette noire au Québec. Direction de la recherche forestière, Ministère des Ressources naturelles du Québec. Mémoire de recherche forestière 118. Québec, QC. 70 p.

Prégent, G., Picher G., and Auger, I. 2010. Tarif de cubage, tables de rendement et modèles de croissance pour les plantations d'épinette blanche au Québec. Gouvernement du Québec, ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière. Mémoire de recherche forestière no 160. 73 p.

Prégent, G., and Végiard, S. 2000. Rendement anticipé des plantations d'épinette noire dans les domaines écologiques de la pessière noire. Direction de la recherche forestière, Ministère des Ressources naturelles du Québec. Note de recherche forestière 109. Québec, QC. 12 p.

Ray, D., Bathgate, S., Moseley, D., Taylor, P., Nicoll, B., Pizzirani, S., and Gardiner, B. 2015. Comparing the provision of ecosystem services in plantation forests under alternative climate change adaptation management options in Wales. Reg. Environ. Change 15(8): 1501-1513. doi: 10.1007/s10113-014-0644-6.

Reicis, K., Bradley, R.L., Joanisse, G., Thiffault, N., Scott, D., and Parsons, W.F.J. 2023. Mechanical scarification can reduce competitive traits of boreal ericaceous shrubs and improve nutritional site quality. Forestry 96(2): 293-303. doi: 10.1093/forestry/cpac047.

Royer-Tardif, S., Bauhus, J., Doyon, F., Nolet, P., Thiffault, N., and Aubin, I. 2021. Revisiting the functional zoning concept under climate change to expand the portfolio of adaptation options. Forests 12(3). doi: 10.3390/f12030273.

Sharma, M. 2022. Modeling climate effects on site productivity of plantation grown jack pine, black spruce, red pine, and white spruce using annual/seasonal climate values. Forests 13: 1600. https://doi.org/10.3390/f13101600

Stiell, W.M., and Berry, A.B. 1967. White spruce plantation growth and yield at the Petawawa Forest Experiment Station. Minister of Forestry and Rural Development, Forestry Branch. Departmental Publication 1200. 15 p.

Thiffault, N., Cyr, G., Prégent, G., Jobidon, R., and Charette, L. 2004. Régénération artificielle des pessières noires à éricacées : effets du scarifiage, de la fertilisation et du type de plants après 10 ans. For. Chron. 80(1): 141-149. doi: 10.5558/tfc80141-1.

Thiffault, N., Hoepting, M.K., Fera, J., Lussier, J-M., and Larocque, G.R. 2021. Managing plantation density through initial spacing and commercial thinning: yield results from a 60-year-old red pine spacing trial experiment. Can. J. For. Res. 51(2): 181-189. https://doi.org/10.1139/cjfr-2020-0246

Thiffault, N., Lenz, P.R.N., and Hjelm, K. 2023. Plantation Forestry, Tree Breeding, and Novel Tools to Support the Sustainable Management of Boreal Forests. In Boreal Forests in the Face of Climate Change. Sustainable Management. Advances in Global Change Research 74. Edited by M. Montoro Girona, H. Morin, S. Gauthier and Y. Bergeron. Springer, Cham. pp. 383-401.

Wade, C.M., Baker, J.S., Latta, G., Ohrel, S.B., and Allpress, J. 2019. Projecting the spatial distribution of possible planted forest expansion in the United States. J. For. 117: 560–578. doi:10.1093/jofore/fvz054

Watt, M.S., Kimberley, M.O., Dash, J.P., and Harrison, D. 2017. Spatial prediction of optimal final stand density for even-aged plantation forests using productivity indices. Can. J. For. Res. 47(4): 527-535

Wiensczyk, A., Swift, K., Morneault, A., Thiffault, N., Szuba, K., and Bell, F.W. 2011. An overview of the efficacy of vegetation management alternatives for conifer regeneration in boreal forests. For. Chron. 87: 175–200. 10.5558/tfc2011-007

Wotherspoon, A., Thiffault, N., and Bradley, R.L. 2020. Resource availability and physiological response of black spruce to scarification in two climatic regions of Québec (Canada). Silva Fennica 54(4). doi: 10.14214/sf.10375.

Table 1. Climatic conditions in the four ecological regions.

	Mean annual temperature (°C)	Mean annual precipitation (mm)	Mean annual number of frost-free days
Boreal regions			
Black spruce-moss region	-2.0	1000	165
Balsam fir-white birch region	0.5	1200	175
Temperate regions			
Balsam fir-yellow birch region	1.5	1100	180
Sugar maple-yellow birch region	3.0	1100	190

Table 2. Characteristics of successful (Succ.) and unsuccessful (UnSucc.) plantations by ecological region and planted species. Different superscript letters indicate significant differences (see Table 3) .

	Number of plots		Site index (m)		Planting density (trees·ha^{-1})		Competition (%) *	
	Succ.	UnSucc.	Succ.	UnSucc.	Succ.	UnSucc.	Succ.	UnSucc.
Boreal regions								
Black spruce-moss region								
Black spruce plantation	11	53	8^{a}	7^{b}	2458^{a}	2424^{a}	7^{a}	50^{b}
Jack pine plantation	10	33	11^{a}	9^{b}	2587^{a}	2308^{b}	4^{a}	27^{b}
Balsam fir-white birch region								
Black spruce plantation	28	54	9^{a}	8^{b}	2565^{a}	2339^{b}	13^{a}	44^{b}
White spruce plantation	10	52	11^{a}	9^{b}	2602^{a}	2443^{a}	4^{a}	33^{b}
Jack pine plantation	9	44	12^{a}	10^{b}	2327^{a}	2300^{a}	4^{a}	22^{b}
Temperate regions								
Balsam fir-yellow birch region								
Black spruce plantation	16	42	10^{a}	10^{a}	2570^{a}	2576^{a}	10^{a}	26^{b}
White spruce plantation	15	28	11^{a}	11^{a}	2334^{a}	2618^{a}	6^{a}	26^{b}
Jack pine plantation	3	17	14^{a}	13^{a}	2359^{a}	2682^{a}	5^{a}	7^{a}
Sugar maple-yellow birch region								
Black spruce plantation	13	11	10^{a}	11^{a}	2808^{a}	2716^{a}	8^{a}	10^{a}
White spruce plantation	10	16	12^{a}	11^{b}	2657^{a}	2638^{a}	6^{a}	19^{b}

* 26–34-year-old plantations

Table 3. ANOVA and associated *p*-values of characteristics of plantations by ecological region and planted species. Numerator degrees-of-freedom is 1 for all analyses, with one fixed effect (yield status, i.e., successful or unsuccessful). *Df* den. is denominator degrees-of-freedom. Significant effects ($p < 0.05$) are highlighted in boldface.

		Site index		Planting density		Competition (%) *	
	Df den.	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value
Boreal regions							
Black spruce-moss region							
Black spruce plantation	79	6.91	**0.010**	0.12	0.734	39.23	**< 0.001**
Jack pine plantation	51	16.04	**< 0.001**	4.60	**0.037**	12.14	**0.001**
Balsam fir-white birch region							
Black spruce plantation	104	5.05	**0.027**	9.78	**0.002**	63.34	**< 0.001**
White spruce plantation	79	20.49	**< 0.001**	2.29	0.134	18.28	**< 0.001**
Jack pine plantation	68	5.81	**0.019**	0.05	0.830	15.15	**< 0.001**
Temperate regions							
Balsam fir-yellow birch region							
Black spruce plantation	68	2.14	0.148	0.00	0.957	9.03	**0.004**
White spruce plantation	46	1.49	0.228	4.03	0.051	14.92	**< 0.001**
Jack pine plantation	28	3.22	0.084	2.72	0.110	0.71	0.406
Sugar maple-yellow birch region							
Black spruce plantation	28	1.35	0.256	0.15	0.706	0.32	0.578
White spruce plantation	29	4.48	**0.043**	0.02	0.884	10.99	**0.003**

* 26–34-year-old plantations

Figure captions

Fig 1 Locations of plots in plantations of black spruce (black triangles; *n* = 228), white spruce (white triangles; *n* = 131) and jack pine (white circles; *n* = 116). Figure 1 was created using ArcMap version 10.4.1 and assembled from the open access data of the MRNF available at https://mffp.gouv.qc.ca/le-ministere/acces-aux-donnees-gratuites/.

Fig 2 Realized vs anticipated plantation yield.

Fig 3 Yield gap according to site index in 26- to 34-year-old plantations.

Fig 4 Yield gap according to planting density in 26- to 34-year-old plantations.

Fig 5 Yield gap according to competition in 26- to 34-year-old plantations. X-axis runs from 100 to 0%. Competition was quantified as a percentage of the total stand basal area, calculated as: (basal area of naturally regenerated trees / (basal area of naturally regenerated trees + basal area of planted trees)) × 100.

Fig 6 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario that deviates from resilience-driven successional trajectories, i.e., black spruce and jack pine plantations that are located on balsam fir potential natural vegetations types and white spruce plantations that are located on balsam fir or on black spruce potential natural vegetation types.

Fig 7 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario aligned with resilience-driven ,successional trajectories, i.e., black spruce and jack pine plantations that are located on black spruce potential natural vegetation types.

Fig 1 Martin Barrette et al.

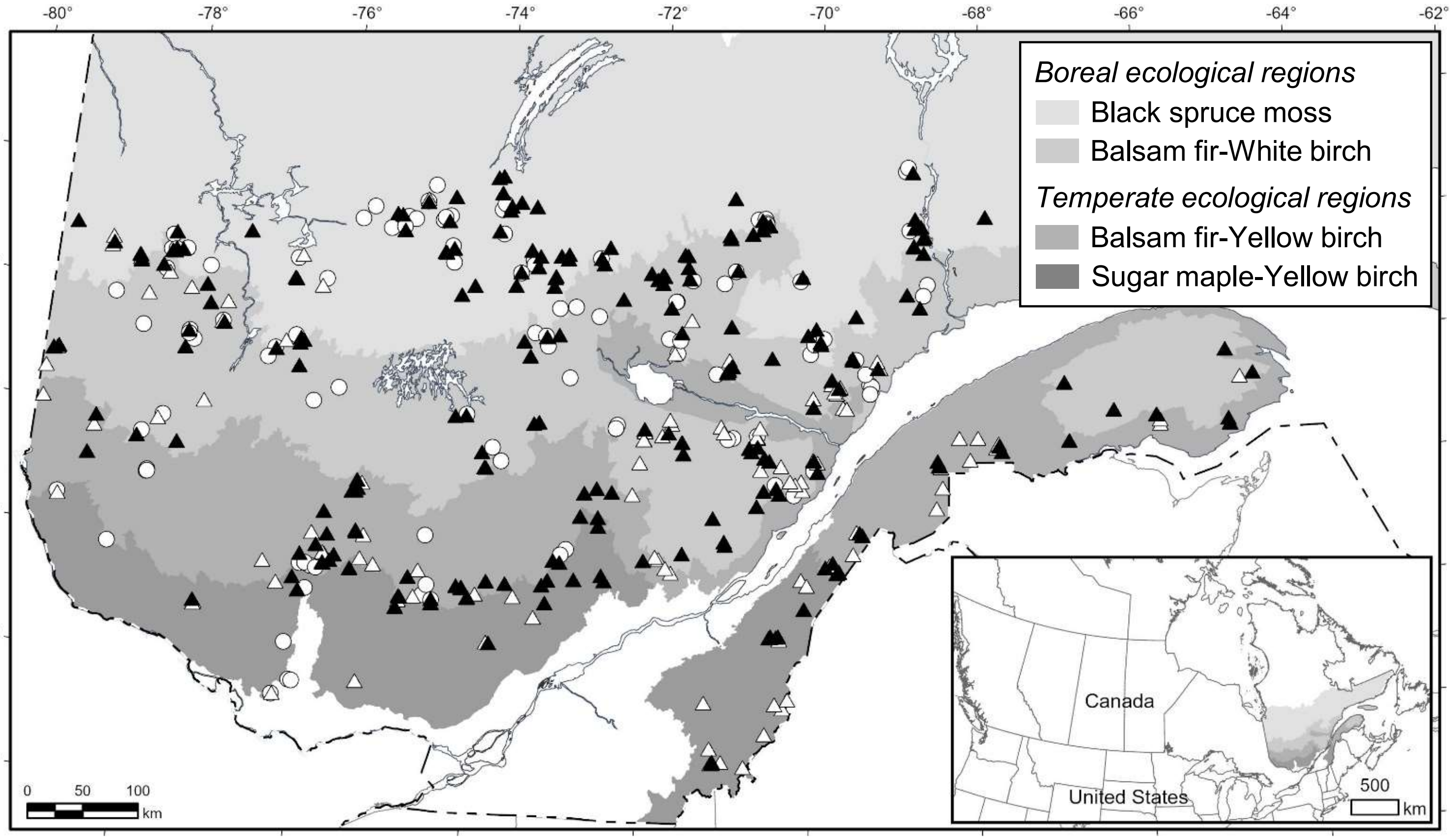

Fig 1 Locations of plots in plantations of black spruce (black triangles; $n = 228$), white spruce (white triangles; $n = 131$) and jack pine (white circles; $n = 116$).

Fig 2 Martin Barrette et al.

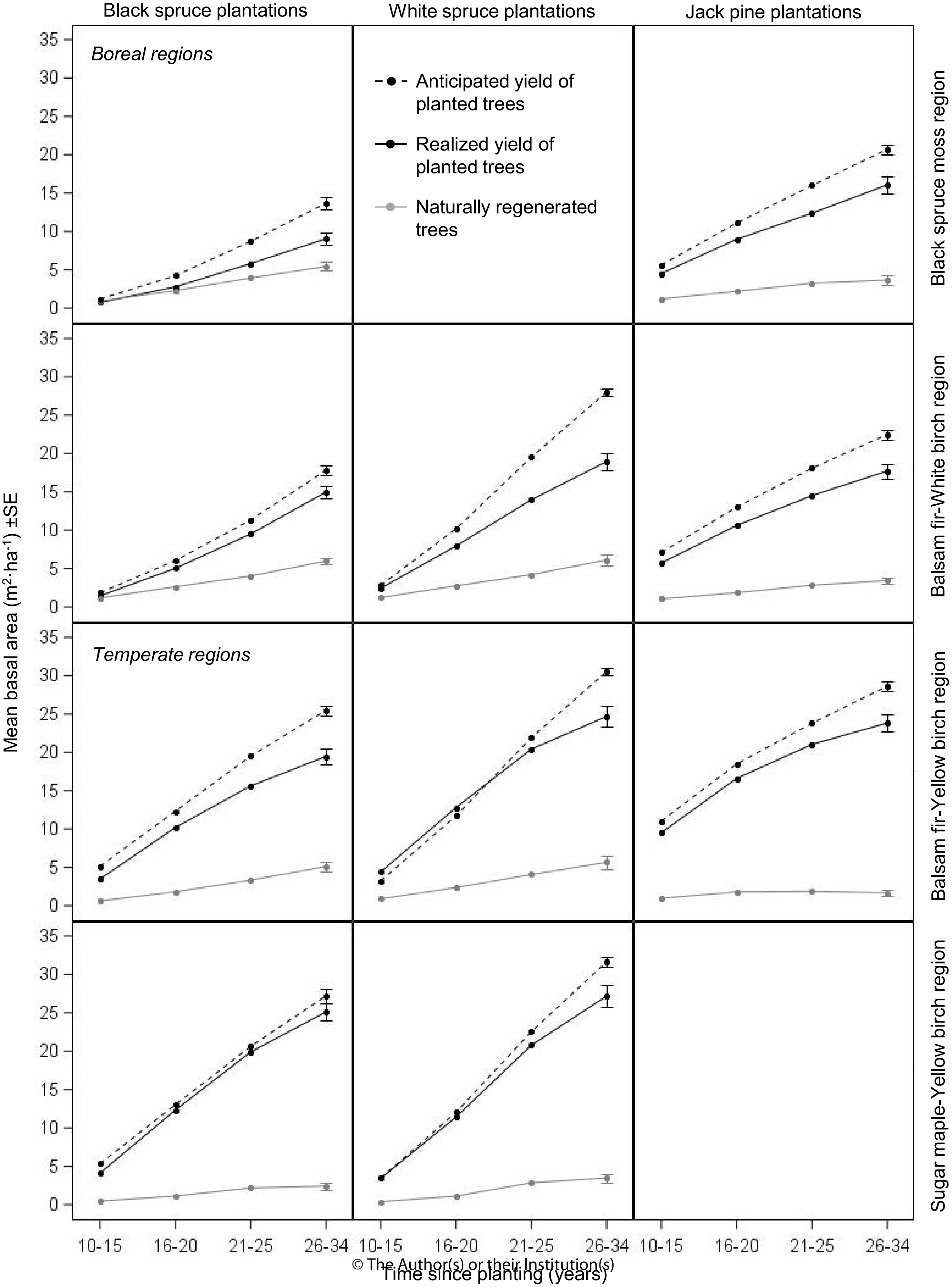

Fig 2 Realized vs anticipated plantation yield.

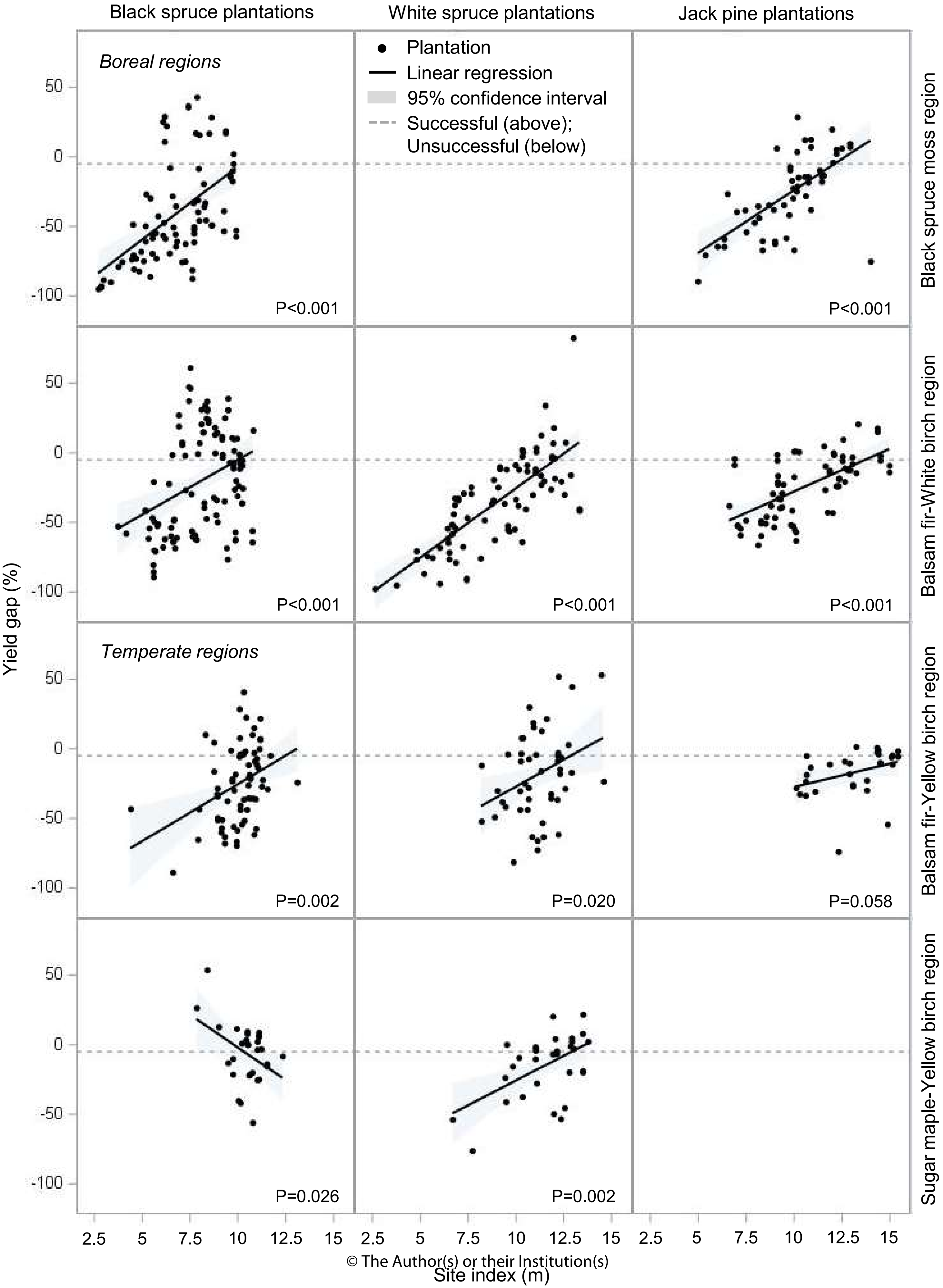

Fig 3 Yield gap according to site index in 26- to 34-year-old plantations.

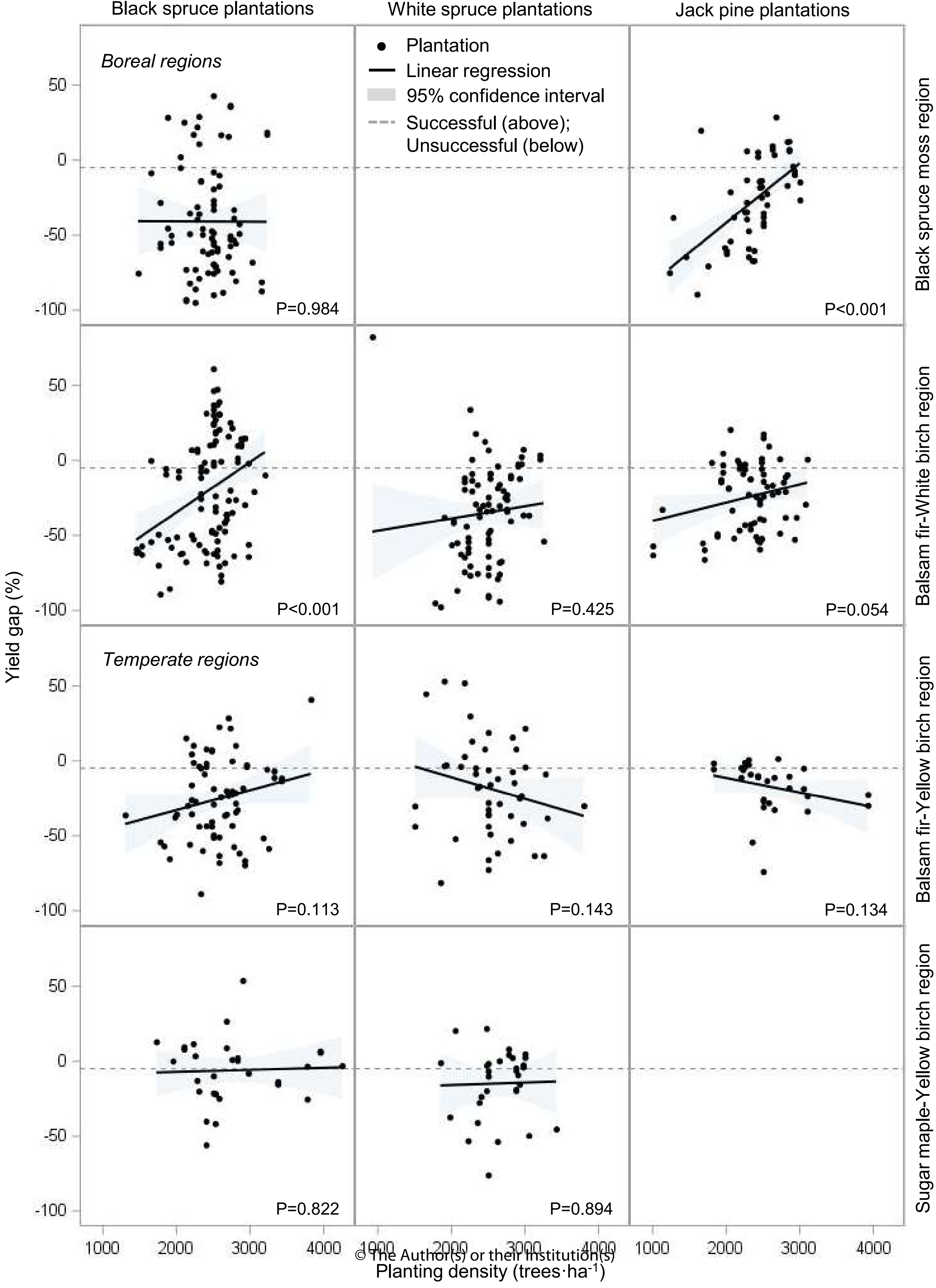

Fig 4 Yield gap according to planting density in 26- to 34-year-old plantations.

Fig 5 Martin Barrette et al.

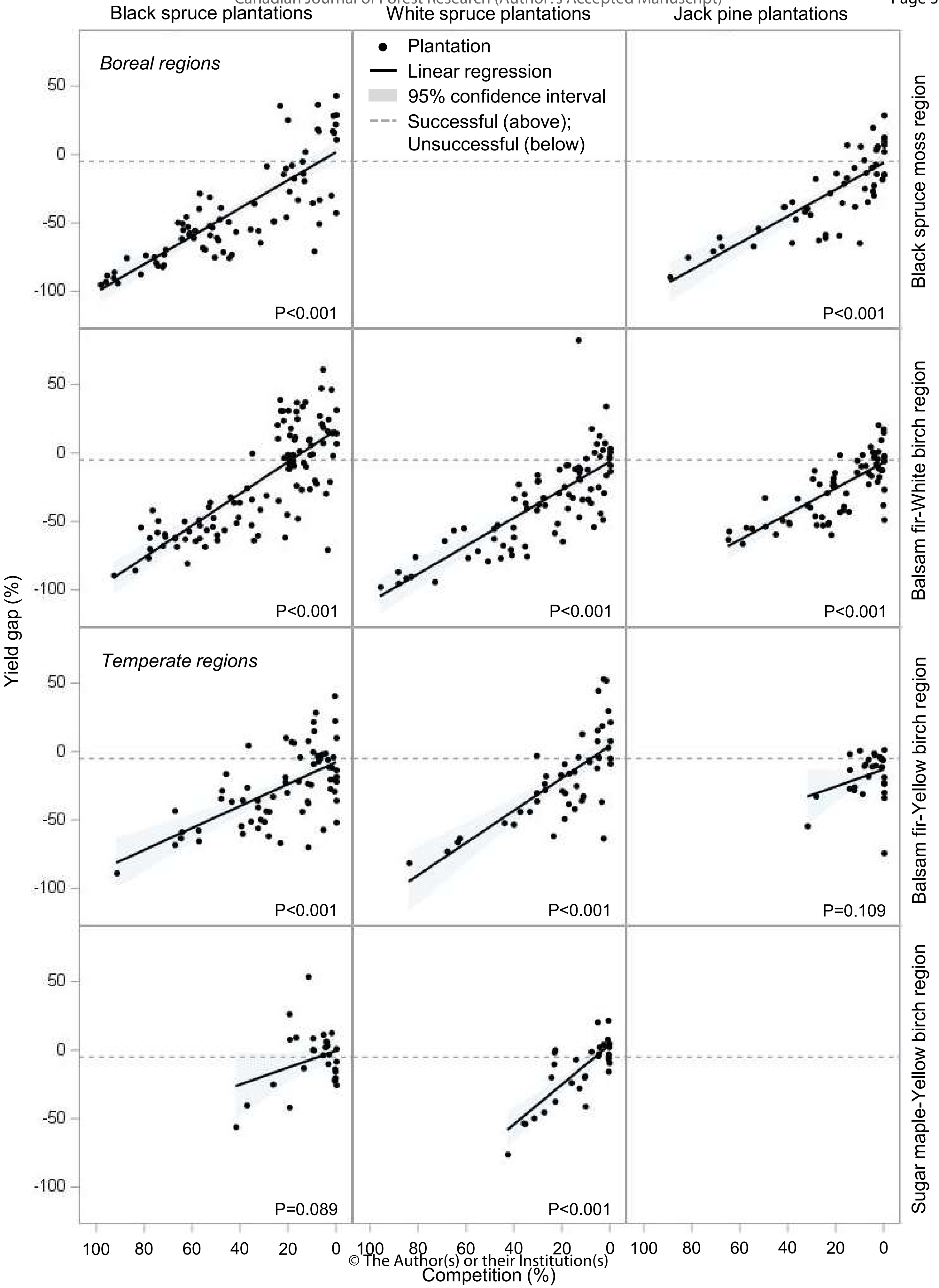

Fig 5 Yield gap according to competition in 26- to 34-year-old plantations. X-axis runs from 100 to 0%.

Fig 6 Martin Barrette et al.

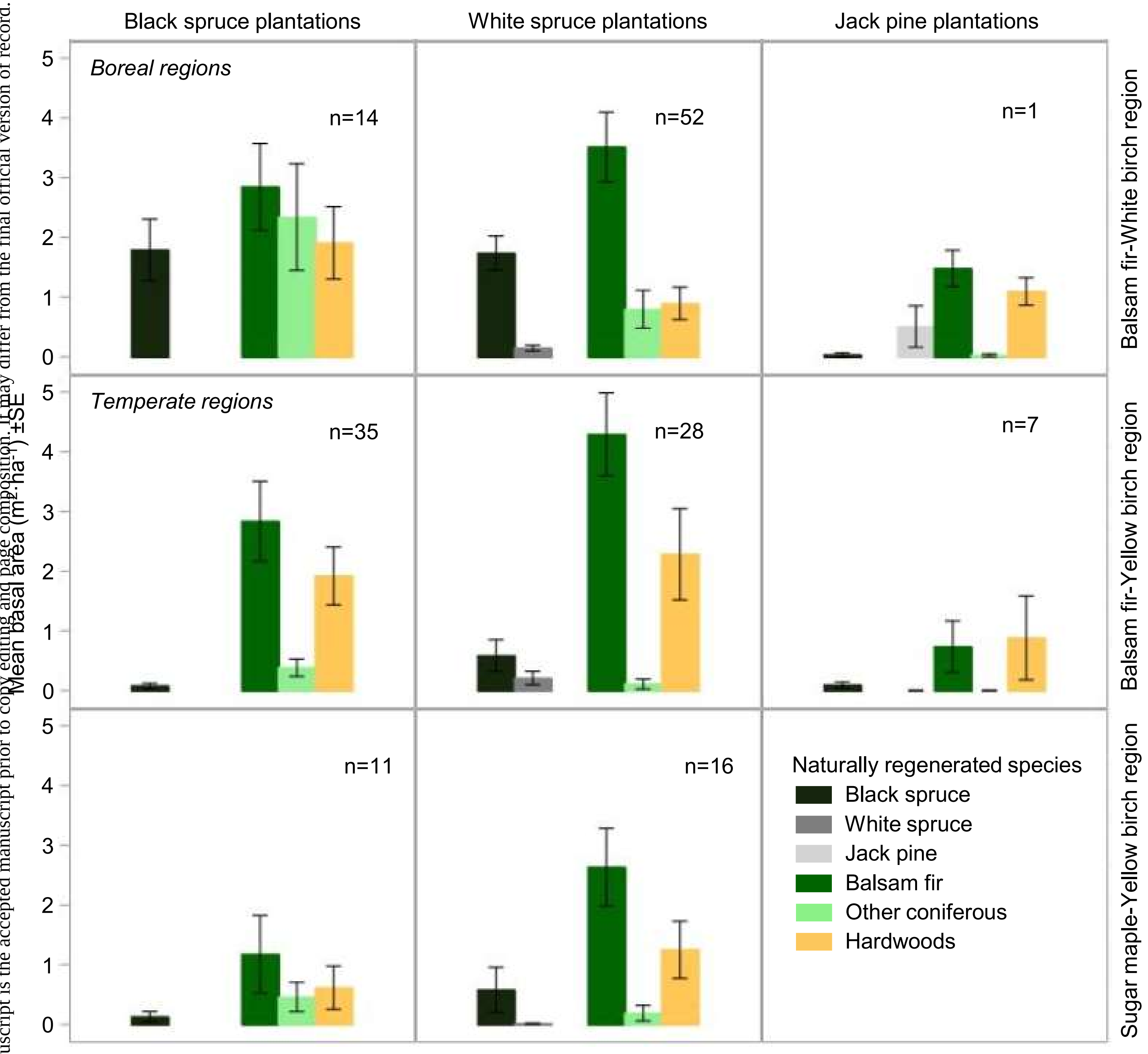

Fig 6 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario that deviates from resilience-driven successional trajectories, i.e., black spruce and jack pine plantations that are located on balsam fir potential natural vegetations types and white spruce plantations that are located on balsam fir or on black spruce potential natural vegetation types.

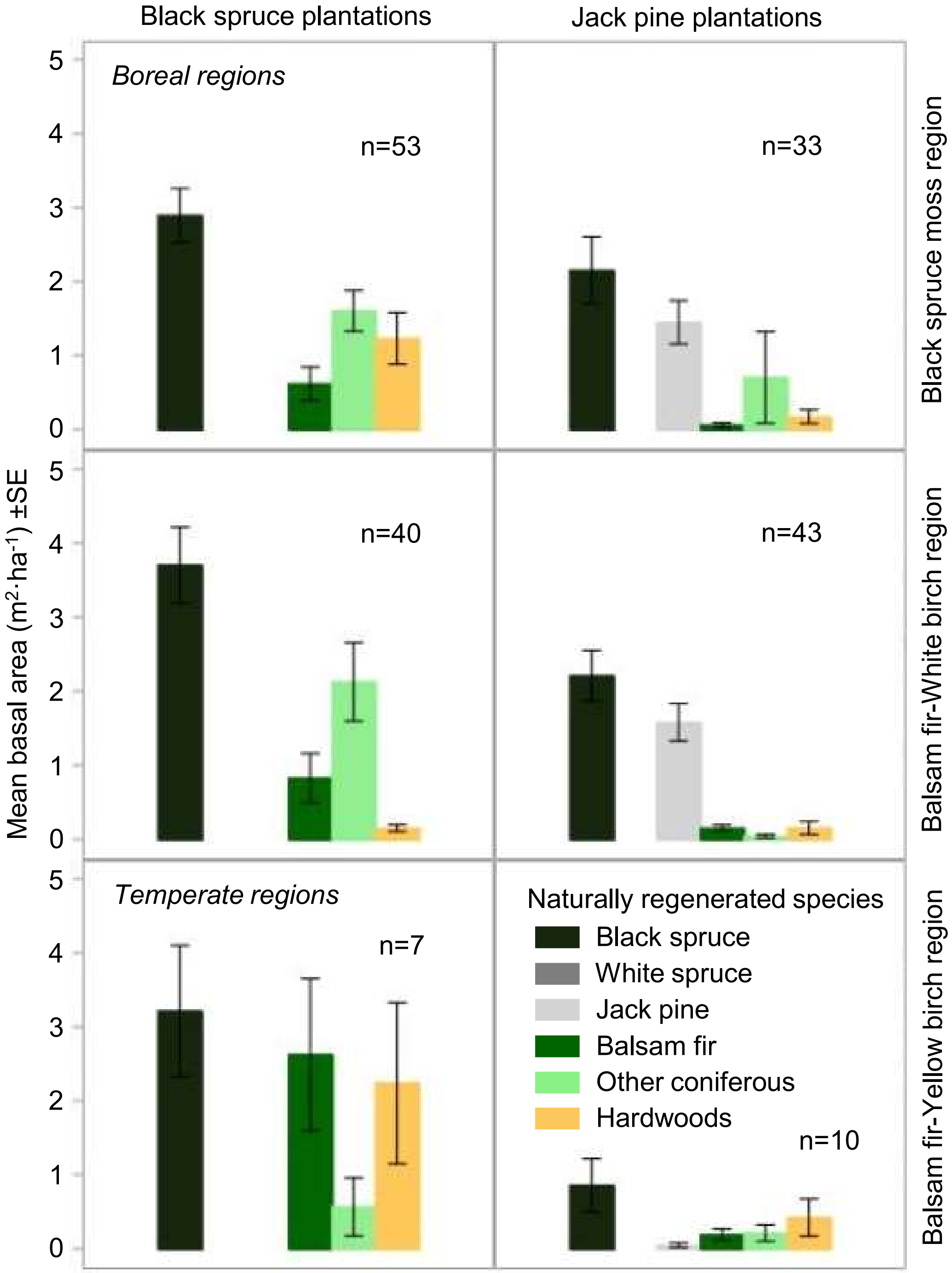

Fig 7 Composition of the competition in unsuccessful 26- to 34-year-old plantations with a plantation scenario aligned with resilience-driven ,successional trajectories, i.e., black spruce and jack pine plantations that are located on black spruce potential natural vegetation types.