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Long-term compositional changes following partial disturbance revealed by the re-survey of logging concession limits in the northern temperate forest of eastern Canada

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Manuscripts

1   **Long-term compositional changes following partial disturbance revealed by the re-**

2   **survey of logging concession limits in the northern temperate forest of eastern Canada**

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13   **Abstract**

14   Land use changes that are linked to European settlement of North America have transformed

15   north-eastern temperate forest landscapes. Many studies report a regional increase of young

16   early-successional forests due to high disturbance rates since the preindustrial era (fire, land-

17   clearing, clear-cuts). In this study, we document specific compositional changes to present

18   day mature forest landscapes, which have only been managed with partial cutting (high-

19   grading and diameter-limit cuts) since the preindustrial era in south-western Quebec. We re-

20   surveyed 108 forest observations that were extracted from logbooks of former logging

21   concession limits (surveyed between 1870 and 1890). Results highlight an increase in mid-

22   to late-successional shade-tolerant taxa (*Betula alleghaniensis*, *Thuja occidentalis*, *Acer*

23   *saccharum*) at the expense of preindustrial dominant conifers (*Abies balsamea, Pinus*

24   *strobus*). Former logging activities and spruce budworm outbreaks appear to be the main

25   drivers of these changes, which were also strongly structured across the topographic

26   gradient. To some extent, these results highlight the relevance of partial cutting management

27   since it has allowed long-term maintenance of a mid- to late-successional forest composition,

28   while also pointing the need for *Pinus strobus* restoration. We conclude that by allowing site-

29   specific comparisons, the re-survey of historical observations greatly improve the analytical

30   strengths of historical reconstruction.

31   **Keywords**: Forest succession, historical ecology, ecosystem-based management,

32   preindustrial   forests,   presettlement   forests.

33   **Résumé**

34   La colonisation européenne de l'est de l'Amérique du Nord a engendré une profonde

35   transformation des paysages forestiers. De nombreuses études ont décrit une augmentation

36   des jeunes forêts de début de succession comme conséquence des forts taux de perturbation

37   liés à la colonisation (feux, défrichement, coupes à blanc). Dans cette étude, nous

38   documentons les changements de composition spécifiques à des paysages forestiers

39   aujourd'hui matures, qui n'ont été exploités que par des coupes partielles (coupes d'écrémage

40   et coupes à diamètre limite) depuis l'époque préindustrielle. Nous avons réarpenté 108

41   observations de composition issues de rapports d'arpentage d'anciennes limites de

42   concessions forestières (arpentées entre 1870 et 1890). Les résultats indiquent une

43   augmentation de taxons de milieux à fin de succession (*Betula alleghaniensis*, *Thuja*

44   *occidentalis*, *Acer saccharum)* au détriment des conifères dominant à l'époque préindustrielle

45   (*Abies balsamea, Pinus strobus*). Ces changements de composition sont principalement la

46   conséquence des coupes et des épidémies de tordeuse des bourgeons de l'épinette, et se sont

47   aussi largement structurés le long du gradient topographique. Ceci témoigne de la pertinence

48   de l'aménagement par coupes partielles, puisqu'il a permis le maintient d'une composition de

49   milieux à fin de succession. Cependant, la restauration des populations de *Pinus strobus*

50   parait aussi nécessaire. Nous concluons qu'en permettant la comparaison de sites appariés, le

51   réarpentage d'observations historiques améliore remarquablement la compréhension des

52   changements de composition survenus depuis l'époque préindustrielle.

53   **Mots clefs** : Succession forestière, écologie historique, aménagement écosystémique, forêts

54   préindustrielles, forêts précoloniales.

55 **Introduction**

56 Global change is responsible for major shifts in forest ecosystems characteristics. In north-

57 eastern North America, land use changes that are linked to European settlement have

58 transformed forest landscapes (Whitney 1994). Modern landscapes are generally considered

59 to be younger, and composed of an increased proportion of early-successional species

60 compared to preindustrial landscapes (Mladenoff et al. 1993; Foster et al. 1998; Dupuis et al.

61 2011; Thompson et al. 2013). Knowledge of forest composition prior to Euro-American

62 settlement is therefore used as a reference for restoration and forest management (Egan &

63 Howell 2001; Foster et al. 2003).

64 In northern temperate forests, several studies have reported that preindustrial landscapes

65 were dominated by old uneven-aged forests (Lorimer & White 2003; Boucher et al. 2009),

66 the dynamics of which were mainly controlled by natural partial disturbances (gaps, insect

67 outbreaks). In order to maintain forest landscapes within their range of natural variability,

68 ecosystem-based management of these forests should be based mainly upon different types

69 of partial cutting (Seymour et al. 2002; Raymond et al. 2009). In south-western Quebec, a

70 substantial proportion of the landscape has only been managed through partial cutting (high-

71 grading and diameter-limit cuts) since the preindustrial era. These present day mature forest

72 landscapes appear to have followed distinct post-industrial compositional trajectories,

73 compared with those of highly disturbed landscapes, which were converted into younger

74 early-successional forests (Danneyrolles et al. 2016). The knowledge of long-term

75 compositional changes after these types of partial cutting management could help in

76 assessing the relevance of such practices, and in developing management tools adapted to

77 these mature forest landscapes.

78 Reconstructions of post-industrial compositional changes that are methodologically based on

79 regional-scale comparisons between historical data-sets (i.e. historical land survey data) and

80   modern forest inventories commonly reveal general trends (eg. Friedman & Reich 2005;

81   Thompson et al. 2013). However, these reconstructions are not sufficiently reliable to

82   properly characterize more precise compositional changes that concern only specific

83   landscapes. Since the main objective of this study was to document specific compositional

84   changes that occurred in landscapes having only been managed by partial cutting, our

85   reconstruction is based on the re-survey of historical observations (i.e. historical and modern

86   observations that were paired at the same location). Yet, few studies have used this original

87   methodological approach (Siccama 1971; Fahey & Lorimer 2014), even though it may allow

88   a deeper understanding of long-term compositional changes. More particularly, we addressed

89   two main questions: (1) what were the main drivers of these compositional changes? (2)

90   How have environmental gradients, particularly the topographic gradient, structured these

91   compositional changes?

92   **Study area**

93   The study covers an area of about 4000 km^2 along the south-west boundary of the Canadian

94   province of Quebec (Fig. 1). The forests in the study area form the northern end of the Great

95   Lakes St. Lawrence mixed forest region (Rowe 1972), which also corresponds to the limits

96   between the maple-yellow birch and balsam fir-yellow birch bioclimatic domains of the

97   provincial classification (Robitaille & Saucier 1998). The principal surface deposits are

98   either undifferentiated or rocky glacial till. The closest weather station (Barrage

99   Témiscamingue, 46°42'N, 76°06'W; 181 m asl.) has recorded a mean annual temperature of

100   4.9°C and annual total precipitation of 937 mm for the period 1981-2010.

101   Elevation varies from 290m to 415m (asl.). Several factors that are related to topography

102   influence forest composition (drainage, nutrient availability, soil depth and micro-climate ;

103   MacHattie & McCormack 1961). Natural stand-replacing fire rotation has been estimated to

104   be about 200 years in duration within the balsam fir-yellow birch domain (Grenier et al.

105   2005), and 500 years within the maple-yellow birch domain (Drever et al. 2006). Outbreaks of

106   spruce budworm (*Choristoneura fumiferana*) also have been identified as a major source of

107   disturbance of forest dynamics over the last century (Bouchard et al. 2006a,b).

108   First Nations have inhabited the study area for at least 5000 years (Riopel 2002). However,

109   patterns of land use and management by Algonquin tribes during preindustrial times remain

110   unknown. Logging did not begin until 1840, and was mainly focused on high-grading cutting

111   of tall pines trees (*Pinus* spp.) until 1917 (Riopel 2002). Following the construction of a

112   paper mill in the city of Témiscaming in 1917, diameter-limit cuts of smaller diameter

113   spruces (*Picea* spp.) and balsam fir (*Abies balsamea* [L.] Mill.) for wood pulp became the

114   main logging activity until the end of the 20th century (Lienert 1966), although high-grading

115   cutting of tall trees for lumber remained frequent.

116   **Material and methods**

117   <u>Site selection and field measurements</u>

118   This study is based on the re-survey of 108 historical observations of forest composition that

119   were extracted from 10 logbooks reporting the first survey of logging concession boundaries,

120   which were realized by four different surveyors between 1870 and 1890. These logbooks

121   contain point observations mentioning taxa lists (e.g., *"Pine, spruce, birch, cedar and a few*

122   *maples*"), which were usually 10 chains (about 200 m) apart along the survey lines. Point

123   observations have been geo-referenced using historical maps with a resolution of about 20

124   meters. These 10 logbooks were selected for their consistent methodology.

125   A total of 108 observations that were to be re-surveyed had been selected according to four

126   criteria. (1) Observations had to be spaced at least 200 m apart to minimize spatial auto-

127   correlation. (2) To restrict sampling to the most ecologically accurate observations, only taxa

128   lists mentioning at least two taxa were retained (90 % of selected observations mentioned

129   three to five taxa). (3) To document dynamic trajectories of forests that had not experienced

130   stand-replacing disturbance since preindustrial times, observations that were retained had to

131   be located in present-day mature forests. These forests corresponded to a dominant age class

132   of 90 year, 120 year, or as uneven-aged in the modern forest maps (Berger 2008). Their old

133   ages had to be confirmed in the field through the presence of old trees and irregular

134   structure. (4) Only observations that were located within 4 km of the road network were

135   finally retained.

136   In the field, each observation point was registered using a GPS with a 10 m precision. These

137   locations determined the centres of 11.28 m diameter circular plots of (400 m^2). Within each

138   plot, all stems greater than 10 cm in diameter at breast height (DBH, 1.3 m) were inventoried

139   at the species level, and their DBH measured. Evidence of former cuts (stumps) or spruce

140   budworm outbreaks (numerous standing or lying dead stems) were recorded if they were

141   recognizable either inside of or in proximity to the plots.

142   <u>Data-base construction and analysis</u>

143   For all historical and modern observations, taxa were classified according to 5 abundance

144   ranks (r). Despite the possible existence of bias in these types of ranked list, for example

145   giving more prominence to highly visible or commercially valuable taxa, a recent study

146   demonstrated that taxa positions within lists are well correlated with their relative basal area

147   (Terrail et al. 2014). Thus, for historical observations, taxa were ranked according to their

148   position in the taxa list. The dominant taxon (first position in the list) was ranked as 4; the

149   following two taxa in the list were ranked as 3 and 2, and rank 1 was assigned to the

150   remaining taxa in the list. For example, the observation "*Pine, spruce, yellow birch, cedar*

151   *and a few maples*" would have been transcribed as pines (r = 4), spruces (r = 3), yellow

152   birch ($r = 2$), cedar ($r = 1$), maples ($r = 1$) and ($r = 0$) for non-cited taxa. The same process

153   was used to assign ranks to taxa that were inventoried in the re-surveyed plots, according to

154   their relative basal area. Some species from the modern plots were grouped at the genus level

155   to match the taxa that were mentioned by surveyors, while rarely mentioned taxa (<5%)

156   within historical and modern observations were grouped in as "others". Taxa that represented

157   less than 5% of the total basal area of a plot were removed from the list, to obtain an

158   equivalent number of taxa for historical and modern observations.

159   Several simple metrics were used to document changes in forest composition. First,

160   frequency and dominance indices were computed (Scull & Richardson 2007; Dupuis et al.

161   2011). The frequency index represents the proportion of taxon occurrences regardless of rank

162   (i.e., $r \neq 0$), while the dominance index represents the proportion of taxon dominance (i.e., r

163    $= 4$). These indices were computed for each taxon and for each period, within the whole

164   data-set and for three topographic positions (lower slopes, middle slopes and upper slopes;

165   Fig. 1). Second, a simple relative rank difference (D_i) was computed according to the

166   formula:

167    $$D_i = R1880_{ip} - R2014_{ip}$$

168   where $R1880_{ip}$ corresponds to the rank of taxon i within plot p during the period 1870-1890,

169   and $R2014_{ip}$ is the rank of taxon i within plot p in 2014. Paired sample tests (Wilcoxon

170   signed-rank tests) were used to assess the significance of rank differences ($R1880_{ip}$ vs.

171    $R2014_{ip}$) for the entire data-set and by topographic position.

172   **Results**

173   During the preindustrial period (1870-1890), the 108 stands were dominated by balsam fir

174   (*A. balsamea*), pines (*Pinus* spp.) and yellow birch (*Betula alleghaniensis* Britten) with

175   dominance indices of 46 %, 17 % and 17 %, respectively (Table 1). Although less dominant,

176   eastern white cedar (*Thuja occidentalis* L.), spruces (*Picea* spp.) and paper birch (*Betula*

177   *papyrifera* Marshall) were frequent (41 %; 37 % and 28 %, respectively; Table 1). Evidence

178   of former partial cuts (stumps) and spruce budworm outbreaks (numerous standing and lying

179   dead stems) were found in all stands. Unfortunately, an obvious distinction between these

180   two kinds of disturbance was not always possible, and most stands had likely been subjected

181   to both kinds of disturbance during the 20th century.

182   These stands have experienced major composition changes since the end of the 19th century.

183   Overall balsam fir dominance decreased from 46 % to 7 % (Table 1), while its ranking

184   within plots significantly decreased by an average of 1.6 ranks (Fig. 2). Balsam fir

185   preindustrial dominance was high at the three topographic positions (Fig. 3) but its ranks

186   mostly decreased at mid- and upper slope positions (Fig. 4). Consequently, balsam fir has

187   maintained a greater dominance on lower slopes (Fig. 3), with a high density of small stems

188   (Fig. 5). Despite these changes, balsam fir is still one of the most frequent taxa in the study

189   region, with an overall frequency of occurrence greater than 50% (Table 1).

190   The taxon "pines" corresponds mainly to white pine (*Pinus strobus* L.*;* Table 2). This taxon

191   experienced a sharp decrease in dominance (from 17 % to 3 %) and frequency (57 % to 7 %;

192   Table 1) since preindustrial times. Pine rankings within plots significantly decreased for the

193   entire data-set (Fig. 2) at all topographic positions (Fig. 4), especially on lower slopes where

194   pine was very dominant during preindustrial times.

195   Overall yellow birch dominance increased from 17% to 37%, while its frequency also

196   increased from 62 % to 83 % (Table 1). Its rank within plots significantly increased for the

197   whole data set (Fig. 2), particularly on lower and mid-slopes where it was less abundant

198   during preindustrial times (Fig. 3 and 4). Yellow birch is currently characterized by low

199   densities of large stems (Fig. 5). Its dominance and frequency are constant along the

200   topographic gradient (Fig. 3).

201   Dominance and frequency of white cedar have increased from 8 % to 28 % and from 41 % to

202   60 % respectively (Table 1). White cedar ranking within plots has significantly increased for

203   the entire data-set (Fig. 3), especially on lower and middle slopes positions (Fig. 4), where

204   cedar is currently the most abundant taxon.

205   The taxon "maples" corresponds mainly to sugar maple (*Acer saccharum* Marshall; Table 2).

206   This taxon experienced the strongest increase in dominance (from 2 % to 19 %) and

207   frequency (7 % to 76 %; Table 1). Maple ranking within plots significantly increased for the

208   whole data-set (Fig. 2), especially on middle and upper slopes (Fig. 4) where maples

209   currently are remarkably abundant.

210   Spruces and paper birch have not experienced significant changes in their abundance in the

211   whole data-set (Fig. 2) and at all topographic positions, except for spruces, which decreased

212   significantly on lower slopes (Fig. 3).

213   **Discussion**

214   Our results attest to major compositional shifts in mature stands over the last 130 years.

215   Industrial logging started towards the end of the 19th century with high-grading cutting of

216   tall pines, then intensified from 1917 (Témiscaming paper mill construction) onward with

217   diameter-limit cutting of smaller spruces and balsam fir (Lienert 1966; Riopel 2002). These

218   former management practices were mainly focused on harvest, and did not aim to favour

219   particular stand characteristics. Intensive exploitation of pines was undoubtedly the main

220   factor explaining their disappearance from these stands. Diameter-limit cuts at the beginning

221   of the 20th century may also explain, in part, the decline in balsam fir abundances. The

222   widespread mortality in balsam fir populations caused by the two major spruce budworm

223   outbreaks of the 20th century (1910-1930 and 1970-1990; Bouchard et al. 2006a,b) has been

224   superimposed on the impacts of logging activities. Surprisingly, the abundance of spruces

225   has not significantly decreased in these stands (except on lower slopes), while they

226   represented the main target species for the paper industry. This likely reflect the fact that

227   spruces were not particularly dominant in these stands in preindustrial times, and thus their

228   diminution is not as marked as for balsam fir or pines.

229   Parallel with the decrease in abundance of balsam fir and pines, our results highlight a strong

230   increase in mid- to late-successional shade-tolerant taxa (yellow birch, white cedar, sugar

231   maple). As such, our results contrast with the increase in early-successional intolerant taxa

232   (eg. poplars, paper birch) that has been documented in highly disturbed area within the

233   region (Pinto et al. 2008; Danneyrolles et al. 2016) and more generally in north-eastern

234   North America (eg. Friedman & Reich 2005; Boucher et al. 2006; Bouchard et al. 2006a;

235   Dupuis et al. 2011; Thompson et al. 2013). Canopy openings created by partial cuts and

236   spruce budworm outbreaks are clearly the main driver that favoured the recruitment of

237   shade-tolerant taxa (Heitzman et al. 1997; Gasser et al. 2010; Duchesne & Prévost 2013;

238   Larouche & Ruel 2015). Moreover, the large amount of stumps and rotten wood generated

239   by these disturbances may have favoured the regeneration of yellow birch (Lambert et al.

240   2016) and sugar maple (Caspersen & Saprunoff 2005).

241   The compositional changes were also significantly structured across the topographic

242   gradient. Lower slopes remained dominated by conifers (white cedar, balsam fir, spruces),

243   while upper slopes became dominated by hardwood species (sugar maple and yellow birch).

244   These divergent trajectories could be explained by distinct site characteristics. First, the

245   colder and moister micro-climate of poorly drained lower slopes may have favoured the

246   increase in white cedar, where it can multiply by layering (Hofmeyer et al. 2009), while also

247   allowing balsam fir and spruces to maintain an important abundance. Conversely, well-

248   drained upper slopes, which lie outside of cold air drainage areas, were particularly

249   favourable to the development of sugar maple (Barras & Kellman 1998). A second possible

250   explanation for these divergent trajectories is that lower slopes were dominated by conifers

251   in preindustrial times, while yellow birch dominated a large proportion of upper slopes.

252   Thus, the greater abundance of deciduous litter could have promoted the establishment of

253   sugar maples at mid- and upper slope positions (Barras et Kellman 1998; Caspersen et

254   Saprunoff 2005), while conifer-dominated lower slopes have been more resistant to the

255   development of hardwoods.

256   **Conclusions**

257   Our study documents the long-term cumulative effects of partial cutting management and

258   spruce budworm outbreak on north-eastern temperate forest composition. Although these

259   former management practices (high-grading and diameter-limit cuts) focused on harvest and

260   did not aim to favour particular stand characteristics, they allowed mid- to late-successional

261   forest composition to persist. Thus, to some extent, our results highlight the relevance of

262   partial cutting management in north-eastern temperate forests.

263   Nevertheless, these former management practices have led to significant compositional

264   changes, which bring out an important avenue for restoration and management of these

265   mature forest landscapes. Particularly, white pine populations that had been present in the

266   area for thousands of years (Liu 1990), and which were largely removed by the early 20th

267   century logging activities, should be restored. Stands and seed-trees preservation could

268   ensure the establishment of white pine trees in adjacent cuts areas (Uprety et al. 2013).

269   However, the strong expansion of sugar maple have led to stable deciduous stands, given

270   that maple litter tends to inhibit regeneration of conifers (Barras & Kellman 1998). Thus,

271   these stands should be carefully managed in order to maintain or reintroduce white pine.

272   Irregular shelterwood systems can allow the maintenance of mid-tolerant species, such as

273   white pine or yellow birch, in uneven-aged stands dominated by shade-tolerant species

274   (Raymond et al. 2009; Suffice et al. 2015). Moreover, enrichment planting within patch cuts

275   (Fahey & Lorimer 2013; Hébert et al. 2013) could be used to reintroduce white pine in stand

276   from which it was completely removed.

277   More broadly, our study also demonstrate the analytical strength of site-specific comparisons

278   through the resurvey of historical observations (Fahey & Lorimer 2014). This

279   methodological approach was highly relevant to characterize compositional changes with

280   precise spatial resolution and allowed us to distinguish different dynamics trajectories across

281   the topographic gradient. Such an approach can be used to complement regional-scale

282   comparisons between historical land survey data and modern forest inventories (eg.

283   Friedman & Reich 2005; Thompson et al. 2013) in order to refine our knowledge of post-

284   industrial dynamics trajectories across disturbance or environmental gradients.

285   **Acknowledgements**

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295 **Table 1.** Dominance and frequency indices of each taxon in the 1870-1890

296 preindustrial period and in 2014 for the whole data-set (n = 108).

TAXA	1870-1890		2014	
	Dom.	Freq.	Dom.	Freq.
Balsam fir	45.9	87.2	7.3	51.4
Pines	16.5	56.9	2.8	7.3
Spruces	7.3	37.6	2.8	32.1
W. cedar	8.3	41.3	27.5	59.6
Y. birch	17.4	62.4	36.7	82.6
Maples	1.8	7.3	19.3	51.4
P. birch	2.8	25.5	1.8	29.4
Others	0.0	6.4	1.8	12.8

17

297 **Table 2.** Details of species of pines, spruces and maples that were cited by surveyors

298 (1870-1890) and identified on the field (2014). In many cases, surveyors cited these

299 taxa at the genus level, so the data have been regrouped by genus level for the

300 remaining analyses.

301

TAXA	1870-1890		2014	
	Dom.	Freq.	Dom.	Freq.
white pine	16.5	27.5	2.8	7.3
red pine	x	x	x	0.9
pines	x	29.4	x	x
ALL pines	16.5	56.9	2.8	7.3
sugar maple	x	x	19.3	40.7
red maple	x	x	x	30.6
maples	1.8	7.3	x	x
ALL maples	1.8	7.3	19.3	51.3
white spruce	x	x	0.9	28.7
black spruce	x	x	1.9	8.3
spruces	7.3	37.6	x	x
ALL spruces	7.3	37.6	2.8	32.1

18

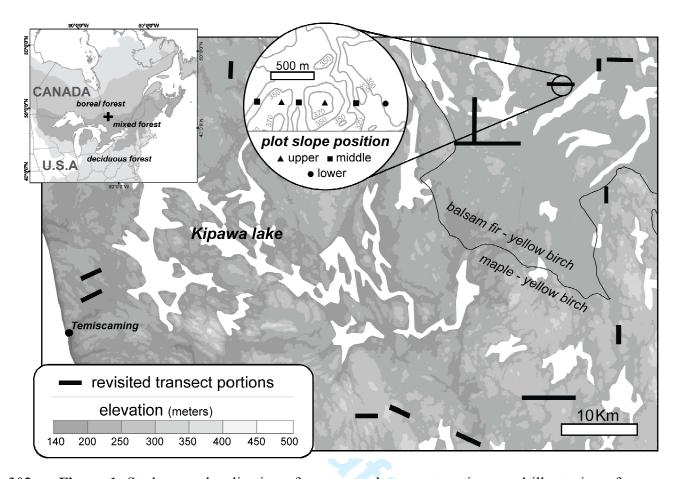302   **Figure 1.** Study area, localization of re-surveyed transect portions, and illustration of

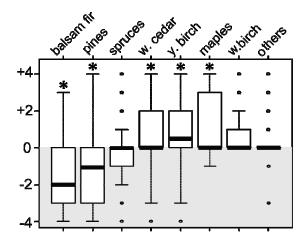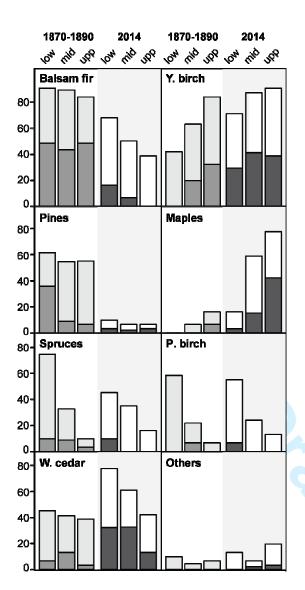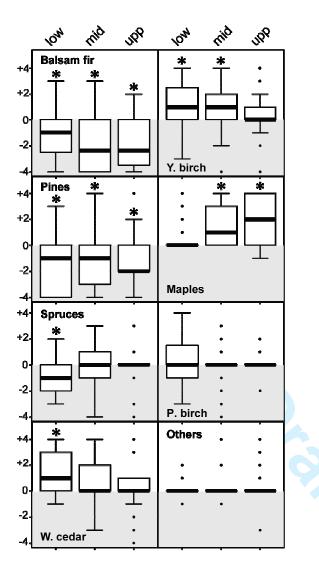303   the   three   topographic   positions.

19

304   **Figure 2.** Relative rank difference (D_i) of each taxon for the whole data-set ($n = 108$).

305   The asterisks indicate significant ($P < 0.001$) rank differences (Wilcoxon signed-rank
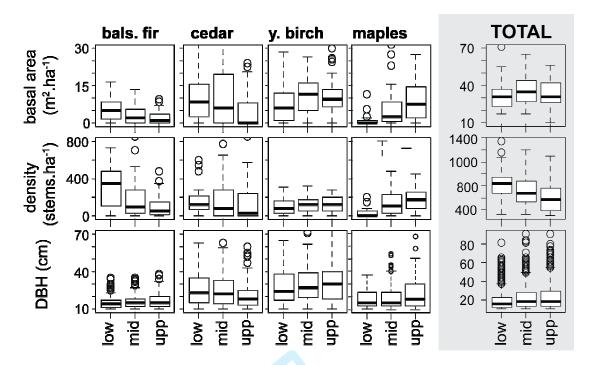
306   test).

307   **Figure 3.** Dominance (dark grey) and frequency (light grey) of each taxon during the

308   1870-1890 period and in 2014, for lower slope (low; n = 31), mid-slope (mid; n = 46)

309   and   upper   slope   (upp; n =   31)   positions.

310   **Figure 4.** Relative rank difference (D_i) of each taxa for lower slope (low; $n = 31$), mid-

311   slope (mid; $n = 46$) and upper slope (upp; $n = 31$) positions. The asterisks indicate

312   significant ($P < 0.01$) rank differences (Wilcoxon signed-rank tests).

22

313 **Figure 5.** Overall structural characteristics of present-day forests (total), and of the

314 four currently most abundant taxa by topographic position.

23