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Browsing damage in planted silver birch (*Betula pendula* Roth) stands

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ABSTRACT

Herbivory is a source of damage for Fennoscandia commercial stands. Silver birch (*Betula pendula* Roth) plantations are of increased interest to address the climate and biodiversity crises, but there are concerns about browsing risk. We inventoried 92 planted silver birch stands from a survey focused on browsing variables (e.g. symptom, severity, cause, and position), and one on tree measurements. We estimated ungulate density from national surveys and pellets observation. We assessed landscape characteristics (neighbouring land use/land cover classes and distance to roads). We observed considerable browsing risk for silver birch plantations, with 38 ± 35% and 23 ± 19% of planted birches browsed in younger and older stands, respectively, with mean height <5 and >5 m. Moose were considered responsible for almost half of browsing (44%), while other species accounted for a small amount (4.1%), the majority by unidentified cervids. Especially, crown damage in younger stands developed into vertical branches in older stands, leading to low stem external quality. In a model predicting the number of browsed stems at stand level, damage occurrences were dependent only on stand characteristics and abundance of browsing animals. Our analysis could not provide site selection recommendations for lower browsing risk sites. However, avoiding early damage seems the most crucial step.

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Alces alces; Finland; moose; roe deer; white-tailed deer; ZIP model

Introduction

Mammalian herbivores (cervids, lagomorphs, and rodents) can be an important cause of damage in commercial forests (Gill 1992a, 1992b; Rao et al. 2003; Huitu et al. 2009; Korhonen et al. 2024). In Fennoscandia, most of the browsing damage in young forests is caused by moose (*Alces alces* L.) (Lavsund 1987; Nevalainen et al. 2016; Pfeffer et al. 2021). Moose population in Fennoscandia has risen since the 1960s to be amongst one of the highest in the world. This was due to changes in forestry practices (increase of clear-cutting that led to more edge habitats and early-successional stages with abundance of palatable plants), hunting practices (age and sex selection that led to increasing proportion of productive adult females), and absence of predators (Lavsund et al. 2003). Other deer species have increased their abundance as well during the last decades (Pfeffer et al. 2021; Felton et al. 2024), and their role as forest damage agents is increasing (Ramirez et al. 2018).

Silver birch (*Betula pendula* Roth) is susceptible to being eaten by many mammalian herbivores like moose, roe deer (*Capreolus capreolus* L.), white-tailed deer (*Odocoileus virginianus* Zimmerman) (Anderson and Koivisto 1980; Danell and Ericson 1986; Bergqvist et al. 2014), mountain hares (*Lepus timidus* L.) (Rao et al. 2003; Kuokkanen et al. 2004), and field voles (*Microtus agrestis* L.) (Rousi et al. 1997; Kuokkanen et al. 2004). From a commercial forestry perspective, the most considerable damage is caused by moose (Korhonen et al. 2024), but in population peaks, field voles have also caused substantial damage on young seedling stands (Huitu et al. 2009), especially under 50 cm height (Müller 2011). During winter, moose and other cervids feed on tree twigs, due to other food sources being under snow cover, and cause stem breakage when feeding off the top shoots; in summer, moose also feeds on leaves (Anderson and Koivisto 1980; Kullberg and Bergström 2001; Bergqvist et al. 2014). The damage on the shoots, either leader or lateral, leads to growth losses, technical defects on the stems, and lower timber quality (Heikkilä et al. 1993; Viherä-Aarnio and Heikkilä 2006).

When measured as total area, most of the herbivory damage in Finland has been on young Scots pine (*Pinus sylvestris* (L.) H. Karst) forests and mainly caused by moose (Nevalainen et al. 2016; Korhonen et al. 2024). However, a bigger proportion of broadleaved-dominated stands is affected by moose damage than

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Scots pine stands, thus showing a higher damage risk (Nevalainen et al. 2016). Amongst the birch species, silver birch seems to be more favoured by moose than downy birch (*Betula pubescens* Ehrh.) (Danell and Ericson 1986). However, food consumption and thus damage are also conditional to the availability of different food species (Danell and Ericson 1986; Milligan and Koricheva 2013; Nevalainen et al. 2016). Furthermore, as national forest inventories (NFI) usually merge birches and other broadleaves in large-scale damage summaries (Korhonen et al. 2024), we lack precise information on the herbivory risk on silver birch-dominated stands. According to the National Forest Inventory in 2019–2023, the proportion of broadleaves in young (height < 1.3 m) and advanced (1.3 m < height <7 m and dbh <8 cm) seedling stands in south Finland is 3.5% and 11.6%, respectively (Korhonen et al. 2024).

Various macrotrends, such as climate change and biodiversity loss, have recently increased the interest of birch and other broadleaves in the Nordic countries, presently dominated by even-aged conifer monocultures. Environmental and societal changes are shifting the focus to alternative forest management options that provide a wider scale of ecosystem services, among other by diversifying species composition, and increasing resilience against biotic and abiotic damage that are endangering conifer monocultures (Huuskonen et al. 2021). Furthermore, silver birch has demonstrated the potential to acclimate to thermal conditions predicted for Finland at the end of the twenty-first century (Rousi et al. 2012). Based on the statistics of tree seedlings delivered for planting, there is a recent increase of silver birch stands originated by artificial regeneration with genetically improved material in Finland (The Finnish Food Authority 2025). Hence, there are increasing concerns in the forestry sectors about the impact of herbivores on birch stands. Earlier, Härkönen et al. (2009) studied the effects of moose damage on the internal and external quality of birch wood prior to the first commercial thinning (age < 20 years, mean height < 16 m) in stands with a known history of moose damage. They found that internal colour defects and decay reduced the quality of damaged birch trees even in the absence of visible external defects. Therefore, the risk of browsing damage and its effects on the early development of silver birch stands need to be studied to prepare recommendations for protective measures.

In the present study, we investigated young silver birch plantations. Our aims were: (i) to analyse the extent, symptoms, and severity of browsing damage through extensive empirical data, and (ii) to investigate the main stand and site variables influencing the extent of browsing damage.

Material and methods

Experimental design

We inventoried young, planted silver birch stands (mean height less than 20 m or age less than 20 years, and stand area more than 0.5 ha) with across central and southern Finland (Figure 1). We first searched all stands fulfilling these requirements in the forest resource databases of commercial enterprises. Then, we conducted a stratified random sampling to have a balanced representation of different site types, stand heights, and moose and white-tailed deer census conditions (Table 1). We used the following strata: mean height classes (<1.3 m, 1.3–5 m, 5–10 m, >10 m); temperature sum (i.e. sum of degree days above 5°C, below and above 1200 dd); site type (high fertility *Oxalis-Myrtillus* type, OMT, or grove-like heath; and moderate fertility *Myrtillus* type, MT, or fresh heath) (Cajander 1949; Tonteri et al. 1990); moose census (below and above 3 per 1000 ha); and deer census (below and above 20 per 1000 ha). Previous wildlife surveys provided the censuses data (LUKE 2025a, 2025b). Juvenile stand management, i.e., pre-commercial thinning aimed at reducing density and promoting potential crop trees, was carried out according to age (none in class mean height < 1.3 m, in 52% of the stands for class mean height 1.3–5 m, and for all stands in the taller classes, Table 1).

We applied different protocols in the inventory. For the first, we aimed at collecting detailed information about browsing damage and only generic tree data ("browsing database") from planted birch stands with mean height <5 m, which are the stands most susceptible to browsing. For the second, we aimed at more standard tree measurements ("yield database") from planted birch stands with mean height of 1.3–20 m. We inventoried 46 stands for the browsing database and 68 for the yield database. Note that in 22 stands with mean height of 1.3–5 m we collected both browsing and yield data. To avoid excessive replications, for those stands we used only the data from the browsing database in the analyses when combining the databases. The browsing database (mean height <5 m) provided more detailed and up-to-date information on browsing. In the stands with mean height above 5 m, there are fewer new occurrences of browsing, so the yield database provided additional information on its future consequences. The yield database was primarily used in a separate analysis of juvenile development of silver birch stands.

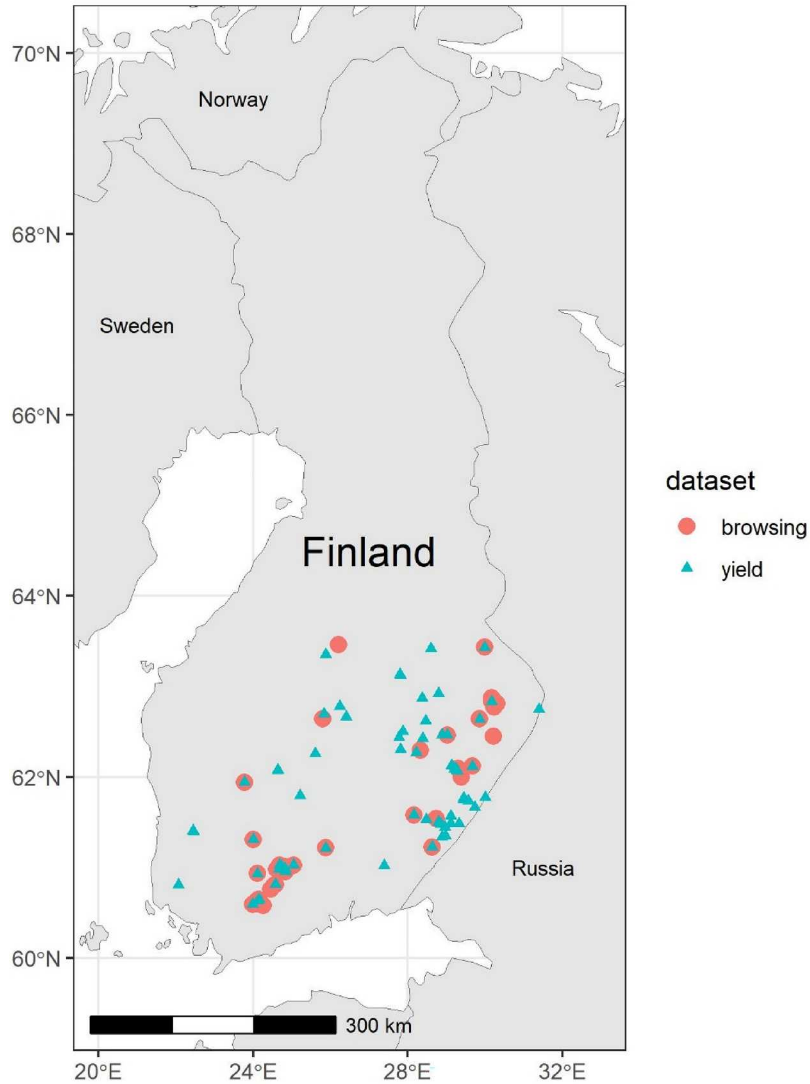

Figure 1. Map of inventoried stands.

Measurements

Browsing database

In each stand, we laid out plots with a 50 m^2 area (radius 3.99 m) for measurements. Number of plots for each stand varied from 5 to 22 (average 14), according to stand size. They were pre-selected randomly on a map, at least 10 m from the plot boundary and from each other, and identified in the field with GPS. If we could not place a plot in its original position, we moved it 10 m in a north-east direction, if possible, otherwise, we rejected it.

On each plot, we measured separately for each tree species: total number of stems, number of damaged stems and mean diameter. We treated naturally regenerated and planted silver birch as separate entities. Compared to natural seed-origin silver birches, planted silver birches were faster growing and located on the mounds that had been prepared as planting spots. For planted silver birch, we also measured mean height. For each damaged silver birch only, we also recorded: origin (planted, seed, sprout); height; diameter at breast height (1.3 m from ground); time of most recent damage (less than a year, or older); cause of the damage; symptom of damage (multiple symptoms could be recorded); severity of damage; diameter and height of the main stem cut-off point; estimated percentage of eaten foliage in percentages (Table 2). On each plot, we also counted faecal pellets of moose and white-tailed deer found on the forest floor, and averaged them at stand level, as an alternative method to the census data to assess population density (Matala and Uotila 2013).

We obtained land use/land cover classes data from the Multi-Source Finnish National Forest Inventory (MS-NFI), which identifies them from satellite images, field plots, and digital maps (Tomppo et al. 2008). Further,

Table 1. Summary of stand characteristics for both databases.

Variable	Browsing database				Yield database			
	46				68			
Stands	Min.	Mean ± st.dev.		Max.	Min.	Mean ± st.dev.		Max.
Temperature sum (degree days)	1171	1346 ± 66		1441	1135	1332 ± 65		1448
Age (year)	2	5 ± 3		12	4	14 ± 6		31
Mean height (m)	0.29	2.8 ± 2.1		7.09	1.49	8.17 ± 4.6		20.65
Mean diameter (cm)	0.15	2.35 ± 1.6		5.89	0.85	7.05 ± 3.9		18.92
Stems per ha (all trees)	1080	6962 ± 4549		25,657	533	2669 ± 2651		13,466
Stems per ha (planted silver birch)	650	1183 ± 319		1771	300	1193 ± 353		1900
Basal area (m2 ha-1)		NA			0.05	8.46 ± 6.7		21.34
Height class	<1.3 m	1.3–5 m	5–10 m	10+ m	<1.3 m	1.3–5 m	5–10 m	10+ m
No. of stands (with PCT)	24 (0)	22 (11)	0	0	0	24 (13)	20 (20)	24 (24)

the MS-NFI uses k-nn method for producing estimates of tree volume, age and several other parameters for each tree species and other stand characteristics for each pixel corresponding to a 16 × 16 m land area. The MS-NFI data used corresponded to the year 2021. We combined tree volume layers and other land use layers to a single land use and cover layer using total tree volume as a proxy of forest development stage (Tomppo et al. 1998). In the resulting data, each pixel can belong to one of various classes, such as open land, forest (considering various stages of development and mineral/peatland soil), water, agricultural land, inhabited land, and other manufactured areas. We used the survey plot locations to establish the percentage of each class in a circle or 0.5, 1, and 2 km radii around each plot. We classified digital maps of roads (source: Finnish Transport Agency, FTA) in four road classes according to the road class definitions of the FTA and calculated the distance to the plots. More detail on the methodology is available in Nikula et al. (2019), but since none of these landscape characteristics resulted in significant findings in the current study, we do not provide further details.

Yield database

In each stand we laid out plots with 300 m^2 area (radius 9.77 m) for measurements. Number of plots for stand varied from 1 to 3 (average 2), according to stand size. They were pre-selected randomly on a map, at least 25 m from the plot boundary and from each other, and identified on the field with GPS. If we could not place a plot in its original position, we moved it 15 m in a north-east direction, if possible, otherwise rejected it.

For each silver birch, we recorded: origin (planted, seed, sprout); diameter at breast height (1.3 m from ground); cause of the damage; symptom(s) of

Table 2. Summary of variables related to observed damage on planted silver birches.

Variable	Explanation
Damage cause	1 = moose 2 = roe deer 3 = white-tailed deer 4 = cervid, if unknown species 5 = hare 6 = other than browsing
Damage symptom	1 = dead tree (including: tree broken in the lower half of the crown, internally rotten, fallen and standing dead trees) 2 = bark damage 3 = crown damage (including: main stem broken in the upper half of the living crown, with or without leader shoot replacement, multi-leader, or other deformities) 4 = foliage damage (due to external cause) 5 = vertical branch (large-side branch growing upwards).
Damage severity	(*ordinal category of ascending severity*) 0 = minor damage from which the seedling has recovered 1 = minor damage from which the seedling will recover 2 = damage, i.e. moderate damage that will reduce the amount or quality of wood 3 = dead or will die, i.e. severe damage.
Cut-off point	Height (m) from the ground and diameter of the stem at the location of most recent browsing damage observed
Time of damage	"Recent" or "older", respectively if the most browsing damage occurred less or more than one year earlier
Eaten foliage	Estimation of foliage removed (%)
External quality	(ordinal category of descending quality) 1 = optimal 2 = curved or twisted 3 = excessive branchiness or forked 4 = both class 2 and 3

damage; severity of damage; technical quality; and height only for the first and then every fifth tree (i.e. 1st, 6th, 11th, …) (Table 2). In both databases, the surveyors estimated the likely browsing animal based on footprints and characteristics of damages, if possible.

Statistical analyses

First, we reported average values and general trends related to browsing, according to the observed development class levels: measured mean height <1.3 m, 1.3–5 m, 5–10 m, >10 m. When necessary, we showed statistical differences using linear models when the dependent variable was continuous or categorical. For the latter, if the variable was ordinal (i.e. ordered category), we used ordered logistic regressions (a regression method extended from the logistic model best suited for ordinal factors) from the package *MASS* (Ripley et al. 2013). According to the type of analysis, we used only the browsing database, only the yield database, or the combined databases (without replicated stands from the yield database), as specified in the text.

Second, we aimed at investigating the causes of browsing damage (browsing database only) with a generalised linear mixed model (GLMM). The variable of interest was the amount of damaged planted silver birch stems at the plot level. Preliminary diagnostics with the package *DHARMa* (Hartig 2024) showed overdispersion and zero-inflation in the data. Thus, we fitted a zero-inflated mixed model with Poisson family using the package *GLMMadaptive* (Rizopoulos 2025). The model structure was:

$$y = b_0 + (b_1 * cov_1 + \cdots + b_n \times cov_n) + u_s + \varepsilon_{sm}$$

where y was % of browsed planted silver birch stems at plot level; b_0 is an intercept term; $b_{1..n}$, coefficients for each covariate; $cov_{1..n}$, the covariates tested in the model; u_s a random term at stand level accounting for the spatial correlation of plots within the same stand; ε_{sm} an error term for each stand and measurement. The tested covariates were: total number of planted silver birch trees (stems ha^{-1}); total number of trees from each other species (stems ha^{-1}); mean height of planted silver birch (m); vegetation type (OMT or MT); temperature sum (degree days); wildlife survey data (animals ha^{-1000}); mean of faecal pellets at stand level; distance to roads; surrounding land use/land cover classes. We removed covariates in a process aimed at decreasing the Akaike Information Criteria, and if we detected multicollinearity. We carried out all statistical analyses in R Statistical Software (R Core Team 2025).

Results

Effects of browsing

For planted silver birch in the younger stands (browsing database, mean h < 5 m), on average 38 ± 35% (standard deviation in percentage points, here and elsewhere) of the total stems showed signs of damage. Aspen (*Populus tremula* L.), rowan (*Sorbus aucuparia* L.) ($p < 0.0001$), and willow (*Salix* spp.) ($p = 0.0278$) were

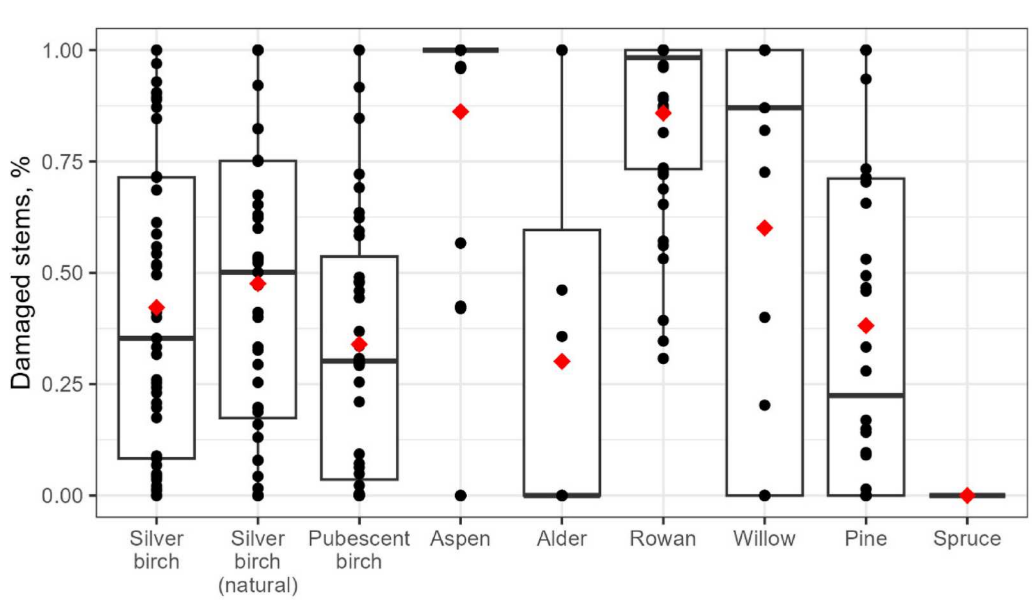

Figure 2. Percentage of damaged stems (all causes) by tree species. Black points represent each stand level observation, the red square the mean, the boxplot the .25 and .75 quantiles. [browsing database].

damaged significantly more often when compared to planted silver birch (Figure 2). Natural silver birch and most other species, namely downy birch, alder (*Alnus* spp.), and Scots pine, had similar levels of damage to planted silver birch. Although Norway spruce (*Picea abies* (L.) H. Karst.) was common in the stands (on average 434 stems/ha, ranging from 20 to 2950, absent only in one stand), there was no sign of damage at all in spruces.

For almost all the damaged birches the identified cause was browsing (except 3 trees out of 1226) (only browsing database). Amongst browsed trees, there was no clear animal attribution for around half of them (51.4%). Then, most were clearly attributed to moose (44.2%), and only few to roe deer (0.9%), white-tailed deer (1.5%), and hares (1.7%). Thus, due to uncertainty in attribution, we could not conduct further separate species-specific analyses.

The total number of stems damaged decreased with increased development class (Figure 3, $p < 0.0001$) (browsing & yield databases), such that there were only 23 ± 19%. Moreover, there were also changes in the kind of damaged recorded ($p < 0.0001$). Crown damage and deformities, including vertical branches, were the most common symptoms observed in all classes (on average 82%), and the vertical branches replaced the crown damage class in taller stands (mean h > 5 m). In such stands, there was also no leaf damage recorded, and an increase in bark damage.

Most of the damaged trees (58.8%) had a severity recorded as 1 or more (browsing & yield databases). However, there was a significant trend of damage severity increasing with older development classes (Figure 4, top, $p < 0.0001$). Bark/trunk damage and vertical branches showed significantly higher damage severity recorded than other symptoms (Figure 4, bottom, $p < 0.0001$).

In the younger stands (mean height 1.3–5 m), 42% of damaged trees still an optimal stem external quality (yield database only). This percentage decreased in the older stands (overall 20%), especially due to an increase in curved/twisted stems (Figure 5.1). This was related to the increase in vertical branches in trees, which were mostly recorded as curved/twisted (Figure 5.2). As a comparison, 69% of undamaged trees had an optimal stem quality (Figure 5.2), similarly across all development classes.

Additionally, only 20% of trees did not show any sign of defoliation through browsing, and the intensity of defoliation decreased with development class (respectively 17% and 9% of leaves removed for stands with mean height < and > 1.3 m). Higher defoliation was significantly correlated with overall damage severity recorded ($p < 0.0001$).

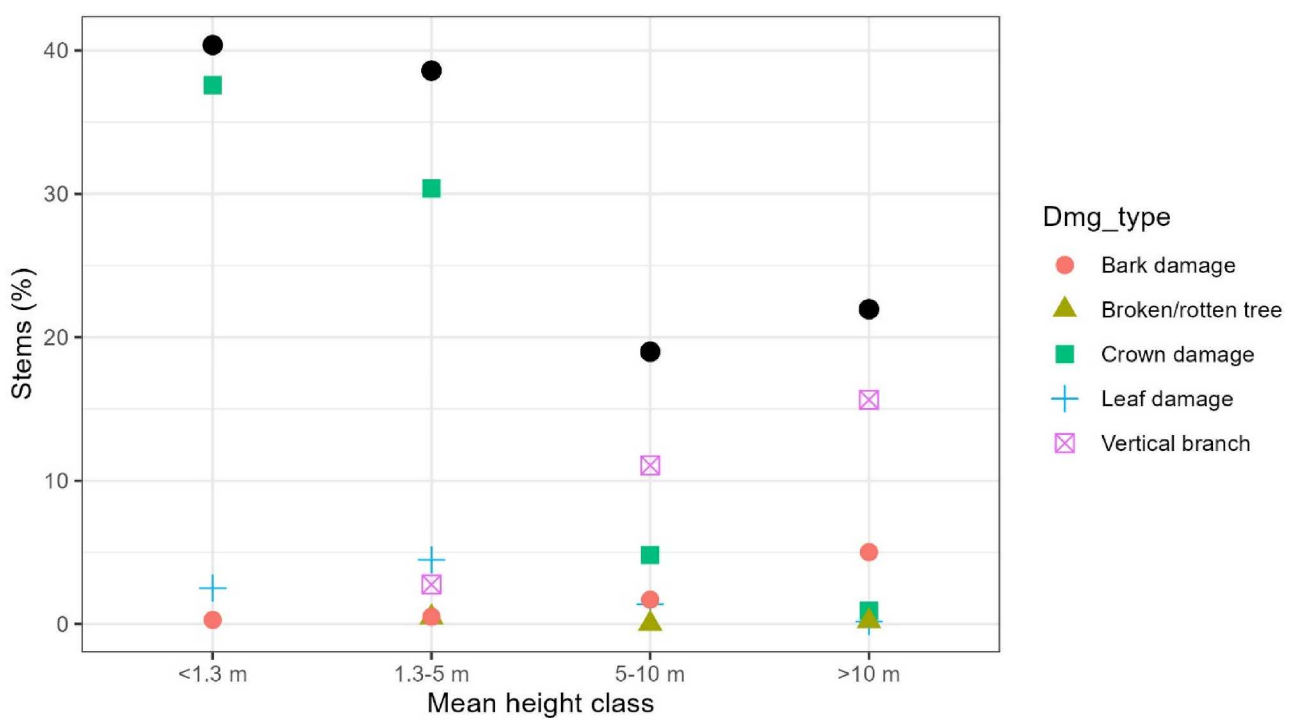

Figure 3. Percentage of damaged planted silver birch trees for various observed development classes, showing all symptoms (black points) and subclasses (coloured points) [browsing and yield database].

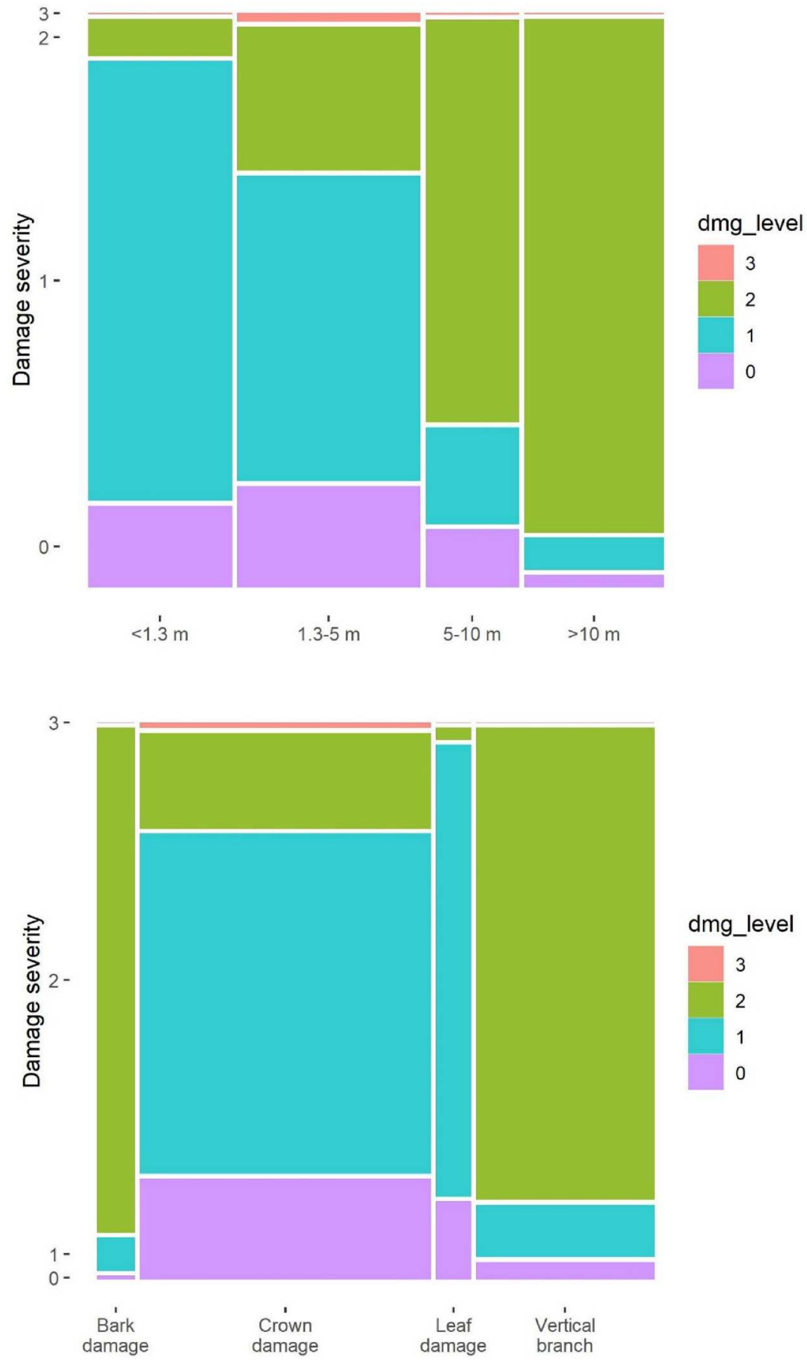

Figure 4. Distribution of damage severity in browsed planted silver birches for different stand development classes (represented by mean basal-area weighted height) and for different damage symptoms, respectively in top and bottom rows. Damage severity scale: 0 and 1 = recovery, i.e. minor damage from which the seedling has recovered or will recover, respectively; 2 = moderate damage that will reduce the amount or quality of wood; 3 = dead or will die. [browsing and yield database]

Damage position on the stem

Most of the recent browsing damage (happened less than one year earlier) was below 2.2 m height (95% of occurrences) and towards the top of trees (on average around 81% of the total tree height) (Figure 6.1). While the height of the damage did not influence damage severity (data not shown), the latter was significantly higher with larger diameter at the location of the browsing event ($p < 0.0001$, Figure 6.2).

On average, planted silver birch passed the 3 m height threshold (when its leader shoot is safe from browsing) at around 6 years, but due to high variability it could take up to 10–12 years (Figure 7.1). Recent damage was still observed on taller trees, but its

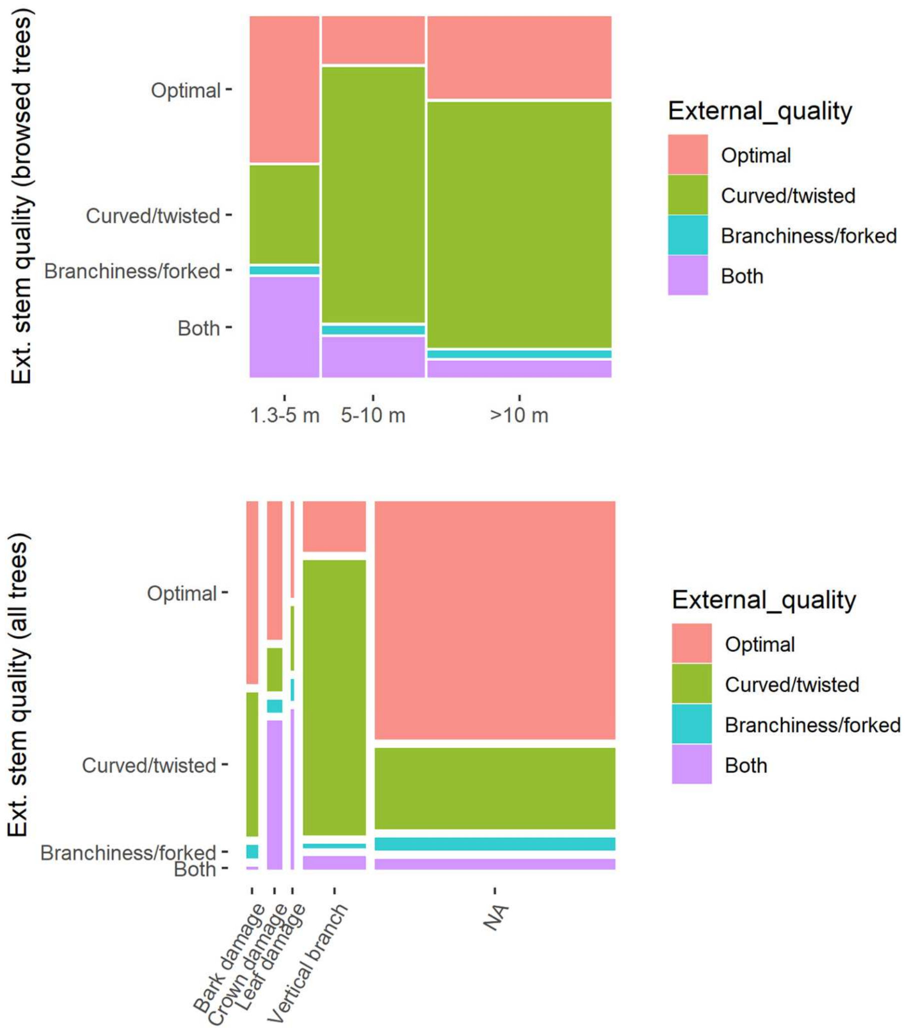

Figure 5. (1) Top row: stem external quality according to development class, only for damaged trees. (2) Bottom row: stem external quality according to damage symptom for all trees (NA indicated trees without any damage sign). "Both" indicates trees with both a curved/twisted and branchiness/forked symptom [yield database]

probability dropped with increasing tree height, from more than 80% for trees less than 0.5 m height, to 50% for trees 3–4 m height (Figure 7.2).

Causes of browsing

The percentage of browsed silver birches increased with higher stem densities of that species and decreased with stand development (Table 3). Variables related to animal presence, either from the census (for white-tailed deer) or from field observations (for moose and pellets count) were significantly and positively correlated with the number of damaged trees. While there was a small but positive significant correlation between white-tailed deer and moose census numbers ($p < 0.0001$, $R^2 = 0.30$), we did not detect multicollinearity. No other stand, site, or landscape characteristics resulted in significant results in the model.

Discussion

We verified the high browsing risk for silver birch plantations. Since there is an aim to increase broadleaves stands in the future to provide a wider range of ecosystem services in response to the intertwined climate and biodiversity crises, forest management also needs solutions for damage caused by cervid populations.

In our data, we found a high average rate of damaged trees in silver birch plantations (38% and 23%, respectively, for stands with mean height <5 m and >5 m), although with high variability. Those values are strikingly higher than the average for all silver birch young stands inventoried during NFI8–NFI10 (1986–2008) in Finland (9%) (Nevalainen et al. 2016). As further comparison, the latest NFI (2019–2023), for broadleaves of all stand development phases, ungulates affected around 6% in terms of area, slightly less than for rot fungi and snow

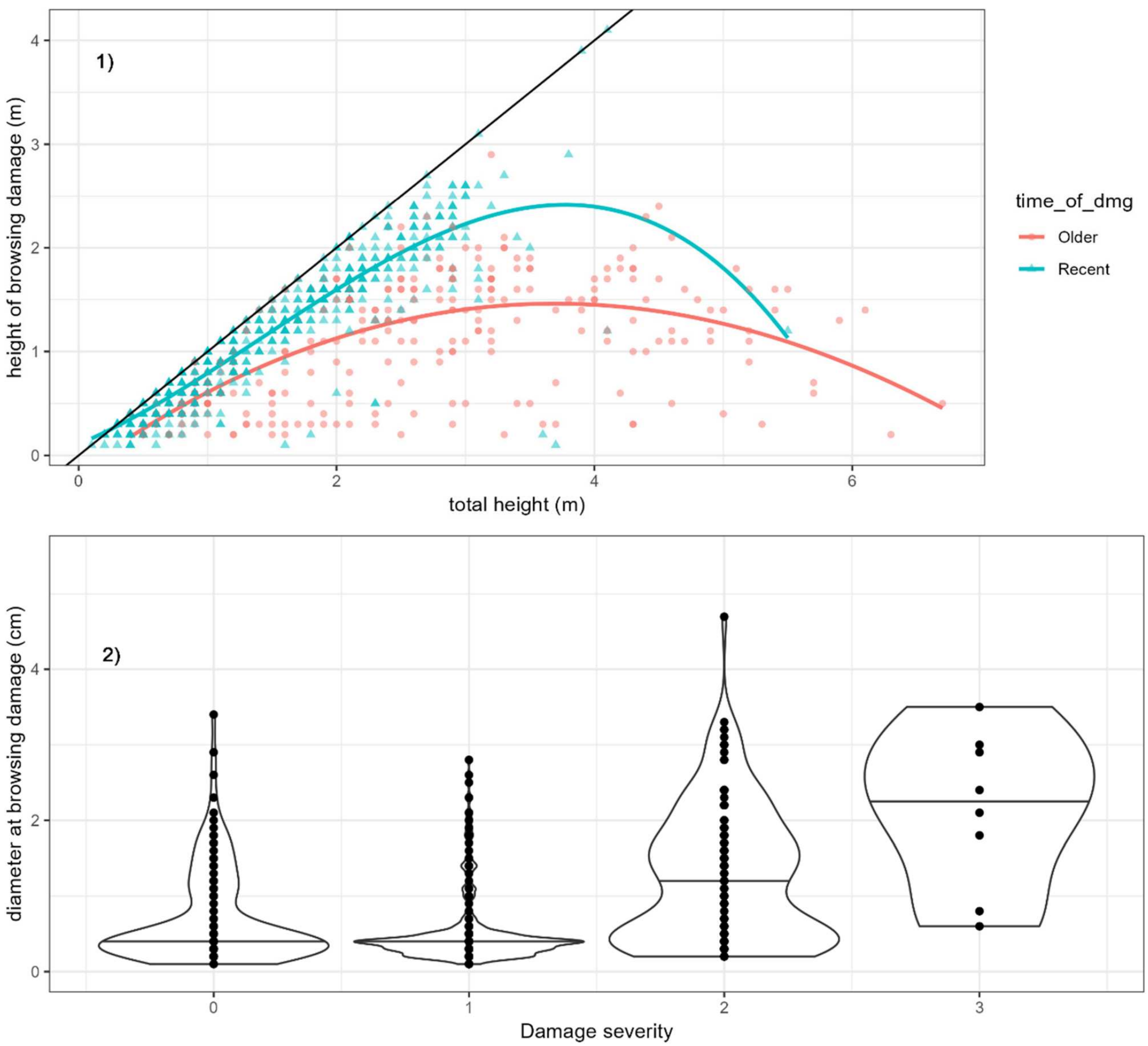

Figure 6. (1) Height location of the most recent browsing damage as related to total tree height, and its timing (recent or older, respectively less or more than a year before inventory). (2) Relation between diameter at location of most recent browsing damage and recorded damage severity. Damage severity scale: 0 and 1 = recovery, i.e. minor damage from which the seedling has recovered or will recover, respectively; 2 = moderate damage that will reduce the amount or quality of wood; 3 = dead or will die. [browsing database]

(Korhonen et al. 2024). Nevalainen et al. (2016) considered mean diameter 8 cm as the threshold for young stands, a comparable size to our browsing database but slightly smaller than the yield database. A possible explanation for our observed higher damage could be the soil preparation and juvenile stand management accomplished in this dataset. Nevalainen et al. (2016) found higher browsing in artificially regenerated stands with such activities accomplished. Nikula et al. (2008) also found more browsing with ploughing or mounding compared with light soil scarification, the former being the main soil preparation in our dataset. Potential causes of higher browsing in more intensively managed stands are the higher nutritional value of the trees and their easier access and visibility to browsing animals.

We found some expected differences of browsing intensity across species. Aspen, rowan, and willow were more affected than silver birch (either planted or natural) (Jalkanen 2001; Bergqvist et al. 2014). However, amongst them, only aspen may have relevant importance in commercial forestry related to its high biodiversity potential (Myking et al. 2011). The presence of accessory species did not significantly influence

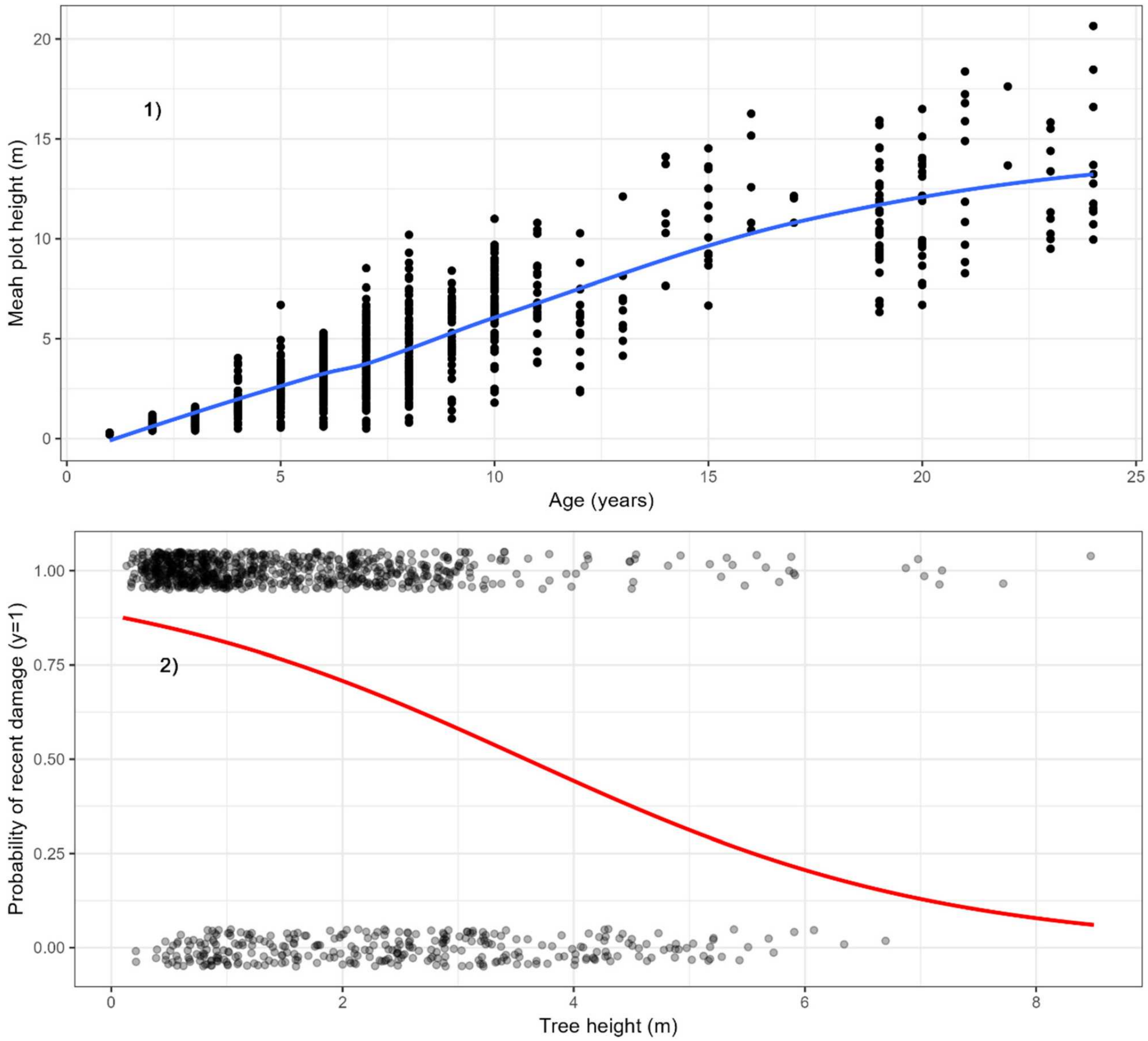

Figure 7. (1) Average trend of plot mean height (m) as a function of age for planted silver birch. The blue curve is LOESS (Locally Estimated Scatterplot Smoothing) curve, plotted from the data. (2) Occurrence of recent (y = 1) or older (y = 0) damage to planted silver birch. The red curve is showing the probability of a tree of a certain height of having recent damage, plotted from the data.

browsing in either way on planted silver birch, contrary to what was observed for Scots pine (Jalkanen 2001; Nikula et al. 2008; Nevalainen et al. 2016). Additionally, there were no differences in the damage rate between naturally regenerated, planted silver birch, and downy birch: all *Betula* species, regardless of the origin, seemed at high risk.

We found major differences in browsing damage across development class, mostly related to the aftermath of past browsing events in older trees. On one hand, there was a lower percentage of damaged trees in older and taller stands (Jalkanen 2001; Nevalainen et al. 2016). Although there could have been an accumulation of damages, some of the already browsed trees died with time or may have been removed during management. Additionally, moose created less damage in taller trees. Most of the recent damage was on or closer to the top shoot (and below 2.2 m, as in Danell 1982), and planted silver birch may be safe already after around 6–8 years on average, although considering high variability even within stand. We reckon this does not account for damage on the stem (such as moose breaking the stem to reach the top, thus also possibly causing confounding effects on measured tree height) or on lower branches that may still translate into future lower stem quality. However, on average, trees with increasing height showed less recent damage regardless of position. On the other hand, the aftermath of the damage looked more severe with tree development. Early crown damage, one the most diffuse symptom

Table 3. Zero-inflated mixed model with Poisson distribution for number of damaged silver birches. We remind the reader that since the Zero-Inflated model is simulating the excess 0s in the data, positive coefficients are indicating higher probabilities of no damage, while for the Count model, negative coefficients are indicating lower occurrences of damaged trees (in other words, they have the opposite sign for a similar effect).

	Silver birch damaged stems		
Predictors	Log-Mean	Std. Error	*p*
Count Model			
(Intercept)	0.376	0.125	0.003
Silver birch stems (per ha)	0.392	0.039	<0.001
Silver birch mean height (m)	−0.516	0.108	<0.001
White-tailed deer density (1000 ha)	0.484	0.098	<0.001
Pellets moose	0.250	0.083	0.003
Zero-Inflated Model			
(Intercept)	−2.347	0.624	<0.001
Silver birch mean height (m)	2.477	0.517	<0.001
Pellets moose	−1.219	0.494	0.014
Random Effects			
$\tau_{00\ \text{PLOT}}$	0.26		
N_{PLOT}	46		
Observations	603		
Marginal R^2	0.748		

(Nevalainen et al. 2016), developed into vertical branches in older trees. Such phenomena were clearly associated with higher damage severity and lower external stem quality. Bark damage, although not as common in absolute number, also impaired severely tree external quality and increased with development class.

We investigated the potential causes of browsing damage with explanatory models. Predictors related to moose and white-tailed deer presence (respectively the observed pellet count and the estimated census data) significantly increase damage. That likely indicates that both animals were significantly browsing on silver birch (Anderson and Koivisto 1980; Danell and Ericson 1986; Bergqvist et al. 2014). However, this contrasts with the field identification of the browsing animal during inventory, which was predominantly moose.

Importantly, we could not find significant landscape-level variables describing the extent of damage: in our data, wherever there were cervids and birches, there was browsing. Similarly, moose presence was the only significant variable to explain recent damage to birch in the hemiboreal zone of Sweden, accounting for 64% of the explained variation (Bergqvist et al. 2014). This could also partly explain why a more local indication of moose presence (pellets) was significant in our study instead of the census data. Månsson (2009), in the southern boreal zone of Sweden, suggested that moose freely moved between habitats, distributing the population in proportion only to resource availability. Site fertility, indicated by the ground vegetation classes, was not a significant indicator of browsing in our data. In previous studies, moose was found to browse more in more fertile sites (Jalkanen 2001), in less fertile sites, albeit with confounding effects due to species distribution (Nevalainen et al. 2016), or with no differences across sites (Nikula et al. 2008). However, our database was limited in area coverage, constrained by the availability of silver birch planted stands, and that may have hindered the landscape analyses. For example, Nikula et al. (2019) analysed all coniferous and broadleaf stands in a wider and more northern region in Finland. They found instead that the presence of nearby mature forests and of inhabited areas and the road network respectively increased and decreased browsing damage. Concluding, based on our analyses, we cannot provide silvicultural recommendations, in terms of site selection, to reduce the considerable risk of cervid browsing on planted silver birch.

Regarding stand management, we identify the early crown damage that develops in vertical branches and severe quality loss over time as the main threat. For that, we can suggest testing the use of repellents. The timing of application and the need for several replicates due to fast stem growth can be, however, challenging. We wish to highlight that even amongst trees without apparent browsing damage, only 69% of trees had an optimal external quality (no forking or excessive branching). Increasing stem density is not an option for controlling stem quality and providing more options at the time of thinning, since silver birch needs adequate growing space with early intensive thinnings (Niemistö and Huuskonen 2025).

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