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Factors affecting the occurrence of biomass-dense forests in Sweden

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ABSTRACT

Energy production from wood-based biomass is recognized as a sustainable energy source under current EU regulations. This approach could significantly contribute to Sweden's energy strategy, given the country's vast forestlands, which cover 27.9 million ha. This study explores factors influencing the occurrence of biomass-dense forests' – stem-dense forests with small diameter trees (BDFs) – across Sweden, considering large-scale variables, site characteristics, and management settings. Using Swedish National Forest Inventory data, we found that stand age and site productivity were the strongest predictors of BDF occurrence nationally and regionally, with older, low-productivity stands accumulating high biomass due to prolonged periods without thinning. BDFs were most common in northern regions (Northern and Southern Norrland) where long rotation cycles and seasonal thinning constrains, and high-elevation sites favored BDFs formation. Additionally, soil conditions played a critical role, with BDFs more frequent on wet, and peat soils, which are less productive and are less frequently thinned. Our results also demonstrated high complexity of site conditions and their interactive effects on the occurrence of BDFs. Nevertheless, we suggest that stand age, site productivity, tree species composition, and soil moisture can guide biomass management decisions, including thinning practices, in the context of increasing demand for renewable energy.

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Small diameter trees; small tree harvesting; wood-based fuels; bioenergy; Swedish National Forest Inventory

Introduction

Forest biomass is seen as a promising alternative to fossil fuels for energy production, supported by the European Union (2023/2413/EU) and the Intergovernmental Panel on Climate Change recommendations for bioenergy use, especially in conjunction with carbon capture and storage (IPCC 2018). In Sweden, forests cover approximately 68.5% of the country's land area, totaling nearly 27.9 million ha (Swedish NFI 2023). Therefore, the forest sector could play a crucial role in achieving the nation's 2045 net-zero greenhouse gas (GHG) emissions target (Klimatlag 2017, p. 720). To meet these ambitious goals and reduce dependence on fossil fuels – which still represent approximately 25% (130 TWh) of the total energy supply (518 TWh) – Sweden is tasked with developing and implementing alternative energy sources, including sustainable forest biomass. In 2022, bioenergy, which is predominantly wood-based forest biomass, comprised nearly 30% (154 TWh) of the total energy supply (SEA 2022, 2023). The anticipated 25% increase in biomass demand (Börjesson et al. 2017) underscores the need for careful balance between energy production and sustainable forest management practices to obtain the demanded biomass. Since by-products from the forests industry are already utilized close to its maximum potential (SEA 2022), alternative sources of biomass are needed (Börjesson et al. 2017). Biomass-dense forests (BDFs), which are stem-dense forests with small diameter trees, with an average height over 7.5 m, an average diameter at breast height (dbh) of more than 9 cm, and a tree density averaging more than 3000 trees ha^{-1}, have recently expanded and can offer a suitable source of wood-based biomass (Fernandez-Lacruz et al. 2015).

Sweden's productive forestlands (Swedish NFI 2023) are traditionally managed using an even-aged system involving cycles of forest regeneration, thinning and final felling (Roberge et al. 2020). The standard practice for forest regeneration is planting high-density (2000–2500 seedlings ha^{-1}) of improved seedlings on scarified soil – primarily *Pinus sylvestris* (Scots pine) and *Picea abies* (Norway spruce). Disc trenching, which aims to enhance the conditions for planted trees, also improve the natural regeneration of pioneer tree species, mainly *Betula spp.* (silver and downy birch;

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Holgén and Hånell 2000; Karlsson et al. 2002; Götmark et al. 2005; Ilisson et al. 2007; Lidman et al. 2023). To reduce competition and enhance growth of high-quality conifers, pre-commercial (PCT) and later commercial (CT) thinnings are consequently applied (Pettersson et al. 2012; Agestam 2015). However, a legislative shift in 1994 (i.e. "New Swedish Forestry Act"), made PCT a voluntary forest management measure (Roberge et al. 2020), leading to a decrease in PCT and subsequently increased the occurrence of young forests characterized by high stem densities (Bergquist et al. 2016).

These dense forests, particularly those on sites where natural regeneration is more successful (e.g. forests on mesic-moist soil and after soil scarification; Karlsson et al. 2002; Hynynen et al. 2010; Lidman et al. 2023), likely developed into BDFs. Although the southern regions of Sweden provide more favorable site and climate conditions (e.g. high site index and longer growing season) for the occurrence of BDFs (Swedish NFI 2023), approximately 65% of Swedish BDFs were found in the northern part of the country (Northern and Southern Norrland; Fernandez-Lacruz et al. 2015). This suggests that factors other than site conditions and legislative changes, such as local forest characteristics and management practices, can play a significant role in the occurrence of BDFs. For example, forests in northern regions are predominantly owned by large commercial enterprises, whereas forests in southern regions are characterized by a greater proportion (approximately 80%) of small, privately-owned forests (Roberge et al. 2020). These differences in ownership structure, and thus possibly different forest management approaches, may contribute to the observed distribution of BDFs. Similarly, considering the cost for transportation (Kärhä 2006), proximity to trafficable roads might also determine forest owners' decision to perform thinning, consequently affecting whether the stand develops into BDFs. Although the nationwide distribution of BDF occurrences in Sweden has been described (Fernandez-Lacruz et al. 2015), the influence of large- and small-scale factors, as well as specific forest management practices, on the occurrence of BDFs has not been thoroughly examined. For example, Fernandez-Lacruz's (2015) definition of BDFs did not consider stand age or other variables with the potential to have an impact on the development of BDFs such as soil moisture and other soil properties, or site index. Knowledge about the importance of these variables can be useful for both mapping of BDFs, and in developing silvicultural measures to established BDFs, a resource that already today has been suggested to offer significant biomass potential if the energy sector adapts to using this biomass source (Fernandez-Lacruz 2019, 2015; Sängstuvall 2019). If biomass from BDFs can be effectively integrated into the energy supply chain, its contribution could be further enhanced by developing cost-effective biomass extraction methods (Bergström 2009; Bergström et al. 2010, 2007; Bergström and Di Fulvio 2014). Harvesting the entire above stump biomass could become profitable operation, offering an alternative to costly thinnings (Chang et al. 2023). This, in turn, may increase the willingness to refrain from late PCT or early CT in favor of a biomass thinnings (BT). Nevertheless, the adoption of new approaches for BDF management, i.e. the deliberate transformation of forests into BDFs and thinning using BT techniques, requires a sound understanding of where and under which conditions BDFs currently occur.

In this study, we assessed how landscape-level, forest management, and site factors influence the occurrence of BDFs in Sweden. We used the newest Swedish NFI data (2016–2020) available, and investigated factors that have not been previously assessed in relation to BDF occurrence (see for example, Fernandez-Lacruz et al. 2015). Our main research questions (RQs) are: (*i*) which landscape-level, site, and management factors can help to explain the occurrences of BDFs in Sweden?; (*ii*) how do forest management settings (stand age, dominant tree species, thinning activities, forest ownership and proximity to road) influence the occurrence of BDFs in Sweden?; and (*iii*) do site properties (site index, soil moisture, type, and depth) exert a strong controls over the occurrence of BDFs in Sweden? We hypothesized (h_1) that large-scale predictor variables, such as geographical location within Sweden (i.e. regions) or elevation, will be identified as strong indicators of BDF occurrence. Additionally, we expected (h_2) that BDF occurrence would be greater in older stands than in younger stands due to the longer growth period. We also expected (h_3) that forests stands subjected to multiple rounds of selective thinning would exhibit lower BDF occurrences than forest stands where selective thinning has been absent. Furthermore, we expected (h_4) that BDF occurrence will be less common near roads, as shorter in-terrain distances from roadsides reduce thinning costs, and we predict (h_5) that BDFs will be more prevalent in forests owned by non-industrial private forests owners or by the public than in those owned by large commercial enterprises. Finally, we hypothesize (h_6) that fertile soils, i.e. those characterized by a high site index, mesic-moist soils and moraine soils will exhibit higher BDF occurrence due to the higher likelihood of natural regeneration of pioneer species, as opposed to poorer soils.

Material and methods

Data acquisition

In this study, we used BDF data from the Swedish NFI over a period spanning 2016–2020 representing the four historical regions of Sweden (i.e. Northern Norrland, Southern Norrland, Svealand, and Götaland; Figure 1). The Swedish NFI data are collected using a systematic sampling method, which utilizes circular sample plots with a radius of 20 m. These plots are organized into tracts that form a comprehensive grid across Sweden. The data used here comes from both types of sample plots used in the NFI, i.e. permanent plots (revisited every five years) and temporary plots (assessed just once). The distribution of sample plot clusters varies across regions due to the uneven sizes of each region (Fridman et al. 2014). The number of sample plots representing BDFs and the corresponding BDF areas across various regions are summarized in Table 1.

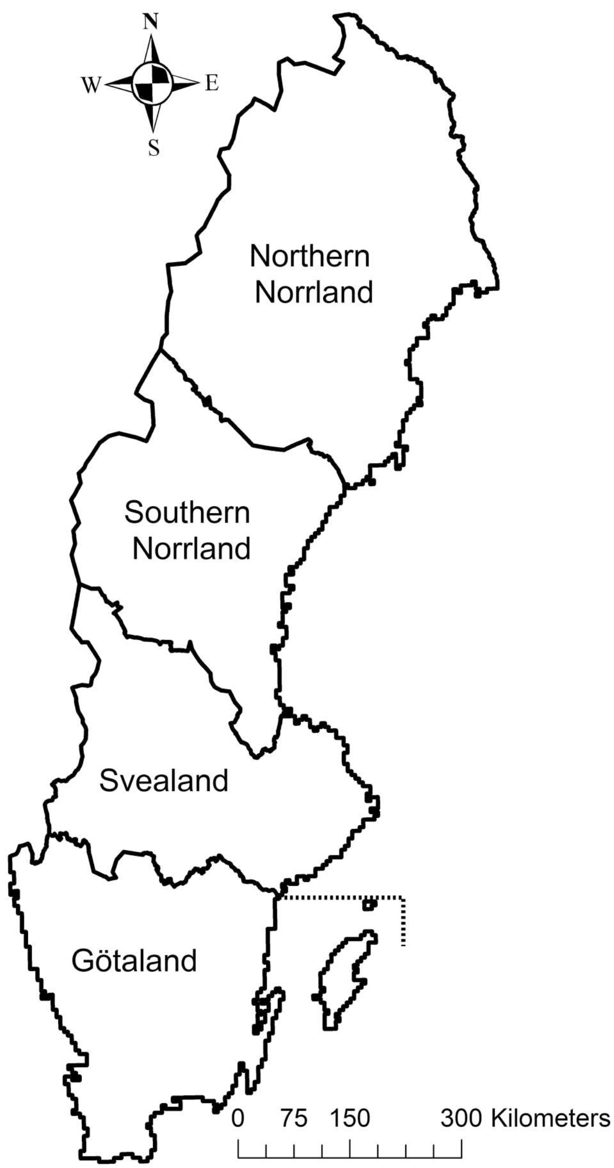

Figure 1. Historical regions of Sweden used for data collection by the Swedish National Forest Inventory.

For a sampling plot to be classified as a plot representing a BDF, it must fulfill all the following criteria: (*i*) a mean tree height between 3 and 12 m, (*ii*) dbh for each individual tree was below 15 cm, (*iii*) an under bark stem volume for each tree that was less than 0.12 cubic meters (m^3), and (*iv*) a stand above ground biomass density from all small diameter trees (i.e. trees with dbh <15 cm) that was above 30 oven-dry (OD) metric tons (t) per hectare (ha^{-1}).

In the Swedish NFI database, variables such as area, standing volume, and OD biomass are presented as weighted values. These weighted values are calculated using the *k*-nearest-neighbor (k – NN) method, which incorporates both ground and remote sensing data to identify the *k* most similar forest features in the surrounding area (Fridman et al. 2014). In this study, we used the weighted aboveground biomass (measured in ODt ha^{-1}) from trees within defined BDF plots, hereinafter referred to as BDF biomass yield ha^{-1}, as the response variable to analyses the occurrence of BDF.

Together with the response variable (i.e. BDF biomass yield ha^{-1}), thirteen explanatory variables were obtained from the Swedish NFI database (Table 2). The explanatory variables that are closely related to landscape and topographic aspects (region, elevation, slope) will be referred to as “landscape properties” throughout this study, while the explanatory variables that are related to stand properties (stand age, dominant tree species) and management-related aspects (thinning activities, forest ownership structure, and proximity to road) will be referred to as “forest management settings”. Finally, the explanatory variables that are intricately linked to

Table 1. Distribution of biomass-dense forest (BDF) sample plots and area by region, including the proportion of BDF area to total productive forestlands. Source: Swedish NFI 2016–2020.

Region	Number of plots	BDF area (1000 ha)	Total productive forest land (1000 ha)	Proportion of BDF to total productive forest land (%)
Northern Norrland	963	1009	7145	14.1
Southern Norrland	1100	946	5846	16.2
Svealand	864	558	5437	10.3
Götaland	923	500	5046	9.9
Total	3850	3011	23474	12.8

Table 2. Characteristics of the sites selected from the Swedish National Forest Inventory to analyze the occurrence of biomass-dense forests.

Variable	Variable type	Description of predictor classes used in the analyses
Elevation	Continuous	The height above sea level. Min: 0 m; Max: 805 m
Dominant tree species	Categorical	The tree species that contributes the most above-ground biomass (i.e. > 50%) at the defined BDF site. The tree species include: *Picea abies; Pinus sylvestris; Pinus contorta;* other coniferous; *Betula spp.; Populus tremula;* and "other broadleaf species".
Ownership	Categorical	Public: Includes the Swedish Property Agency, other state owners, ecclesiastical owners, savings forests, municipal and county council-owned land, as well as other general owners. Corporate: Covers all Swedish limited liability companies other than limited liability companies linked to non-profit housing. Private: Forests owned by individuals or estates, community forests, and forests belonging to companies that are not limited companies or other general owners.
Proximity to the road	Continuous	Sample plot distance to road. Min: 0 m; Max: 4360 m
Region	Categorical	Northern Norrland; Southern Norrland; Svealand; Götaland
Site index	Continuous	Top height (m) of the dominating trees at an age of 100 years based on ground vegetation (Hägglund and Lundmark 1977).
Slope	Categorical	0–5%; 5.1–10%; 10.1–20%; 20.1–35%; >35%:
Soil depth	Categorical	<0.2 m; 0.2–0.7 m; >0.7 m; Various diff.[a]
Soil moisture	Categorical	Dry; Mesic; Mesic-Moist; Moist; Wet
Soil type	Categorical	Rock; Moraine; Sediment; Peat
Stand age	Continuous	Mean age of BDFs in Northern Norrland is 64 years, 55 years in Southern Norrland, 43 years in Svealand, and 33 years in Götaland.
Thinning activities	Categorical	Binary variable representing either the presence or absence of pre-commercial (PCT) and commercial (CT) thinning.

[a]Soil depths vary widely, for example, in the case of fractured surfaces with the bedrock partially visible.

soil characteristics and site productivity, i.e. site index, soil moisture, soil type, and soil depth, will be referred to as "site properties".

Analysis of the importance of individual predictors across Sweden

The first RQ_1 focused on how the thirteen potential explanatory variables obtained from the Swedish NFI data (Table 2) were related to the occurrences of BDF across Sweden. We did not have specific a prior hypothesis about all thirteen variables; rather we were interested to compare the extent to which different variables can explain the potential occurrence of BDF. We assumed that some of the predictors would be correlated with each other (e.g. elevation and region); because of this assumption, also combined with the fact that variables were measured using different scales and units, we applied a Random Forest (RF) model (randomForest package; Liaw and Wiener 2002) to the entire dataset to determine the importance scores of all of the 13 explanatory variables (Table 2). This method provided us with insights of how the thirteen variables compare with each other in their importance for occurrence of BDFs. The random forest models have an advantage over regression analyses because they make no assumptions about the distributions of variables and they handle collinear data (Breiman 2001). This analysis provides relative importance of all assessed predictors; however, the method does not provide traditional statistical outcomes (e.g. *p*-values, effect sizes).

To utilize the RF machine-learning model effectively, we randomly split the original dataset of 3850 sample plots into training and test datasets at a ratio of 80% to 20%, respectively. Then, we applied the permutation method on the training data to shuffle the values of each variable and measure the effect and importance on the accuracy of the RF model. The importance score for each variable is based on how much the prediction error increases when the variable is randomly permuted (permutation importance mean squared error; pi-MSE), and is calculated as the difference between the out-of-bag error and the permuted error. The out-of-bag error is an estimate of the performance of the RF model on unseen data, and – as such – differs from original accuracy, which describes the performance of the model on the training data. A higher pi-MSE value reflects a variable that has more importance for the model. This RF model was built using training data spanning 500 trees ($ntrees = 500$) and seven random explanatory variables ($mtry = 7$) as the response variables.

We used the test dataset to evaluate the performance of the RF model, after which we made predictions for the output variable based on the input variables. Then, we compared the predictions with the actual values to measure the prediction accuracy (R^2), along with the error parameters Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE).

After this initial screening analyses using the RF model, we focused more in detail on groups of variables related to forest management setting and site properties separately.

Effects of forest management settings

To answer the second RQ_2, i.e. how do forest management settings (e.g. stand age, dominant tree species, thinning activities, forest ownership, and proximity to road) affect the occurrence of BDF, we used a linear model (LM: the stats package; R Core Team 2022). Fernandez-Lacruz et al. (2015) indicated significant among-region variations in BDF area and growing stocks, with a notable increase from south to north, therefore we performed the linear models separately for each region (Figure 1). This approach was chosen to decrease the influence of geographic location within Sweden on the assessment of how forest management settings can affect the occurrence of BDFs. We built linear models with BDF biomass yield ha^{-1} as the response variable and stand age, dominant tree species, thinning activities, forest ownership, and proximity to road as the explanatory variables. In the models, we only tested the individual effects of forest management settings' variables, i.e. we did not include interactions or perform model selection of only significant effects. To assess differences in groups within each significant explanatory variable, we used Tukey post-hoc test (emmean package; Lenth 2022).

Effect of site properties

To answer our third RQ_3, i.e. how do site properties affect the occurrence of BDFs, we also used LM, with site index, soil moisture, type, and depth serving as the explanatory variables. As was the case with the previous analysis, LM was separately applied to each of the four regions, and used Tukey post-hoc test to assess group differences. A significance level of $p \leq 0.05$ was chosen as the threshold for statistical significance in all of the analyses. Regarding RQ_2 and RQ_3, we first attempted to use linear mixed-effects models (Bates et. al., 2015) to account for the random factors of the inventory tracts and the district where sample plots are situated. However, the standard errors of the random effects were zero; hence, we adopted LMs which do not account for random effects.

Results

Predictor importance for biomass-dense forest occurrence

The RF model exhibited reasonable performance when predicting the occurrence of BDFs at the national scale, as indicated by an RMSE of 47.7 and an R^2 value of 0.35, i.e. the model explains 35% of the variation in BDF occurrence. Out of the 13 explanatory variables, the highest importance, by far, was attributed to stand age (63%), with site index scoring the second highest (25%). The factors of region and elevation ranked third and fourth in importance, at 14% and 13%, respectively. The rest of the variables demonstrated importance scores $\leq$ 10%, with CT and forest ownership structure showing the lowest importance scores, of 3% and 2%, respectively (Figure 2).

Effects of forest management settings

Linear models assessing the forest management setting variables (stand age, dominant tree species, thinning activities, forest ownership, and proximity to roads) explained 16% of the variance ($R^2 = 0.16$) in Northern Norrland, 23% ($R^2 = 0.23$) in Southern Norrland, 23% ($R^2 = 0.23$) in Svealand, and 34% ($R^2 = 0.34$) in Götaland. Stand age was significant ($p < 0.001$) for BDF occurrence across all regions (i.e. Northern Norrland, Southern Norrland, Svealand, and Götaland), with older stands typically yielding higher BDF biomass yields ha^{-1} (Figure 3).

Dominant tree species was also significant ($p < 0.001$) for all regions, however the effects that dominant tree species had on BDF biomass yield ha^{-1} differed among regions (Table 3). Specifically, in Northern Norrland, *Betula spp*. was the dominant species ($p = 0.003$), and was associated with significantly higher BDF biomass yields ha^{-1} (131 ± 7.8 ODt ha^{-1}) when compared to *Pinus sylvestris* (115 ± 7.5 ODt ha^{-1}). The difference between the two most common tree species in Sweden (*Picea abies* and *Pinus sylvestris*) was also significant ($p = 0.035$) in Northern Norrland, as sites dominated by *Picea abies* (127 ± 7.4 ODt ha^{-1}) were associated with higher BDF biomass yields ha^{-1} than site dominated by *Pinus sylvestris*. None of the other tree species differed significantly in their effect on BDF in Northern Norrland (Table 3). In Southern Norrland and Svealand, the presence of *Picea abies* (131 ± 8.2 ODt ha^{-1}, 101 ± 5.7 ODt ha^{-1}, respectively) as the dominant species was associated with significantly higher BDF biomass yields ha^{-1} ($p = 0.002$), when compared to stands dominated by *Pinus sylvestris* (114 ± 8.5 ODt ha^{-1}, 86 ± 5.9 ODt ha^{-1}, respectively). Further, in Svealand, stands dominated by *Pinus sylvestris* (86 ± 5.9 ODt ha^{-1}) and *Betula spp*. (86 ± 7.4 ODt ha^{-1}) showed significantly ($p = 0.008$, $p = 0.012$, respectively) lower BDF biomass yields ha^{-1} when compared to sites dominated by *Populus tremula* (144 ± 17.2 ODt ha^{-1}). In Götaland, sites dominated by *Populus tremula* (263 ± 23.8 ODt ha^{-1}) demonstrated significantly higher BDF biomass yields ha^{-1} ($p < 0.025$) than stands with any other tested dominant tree species (Table 3).

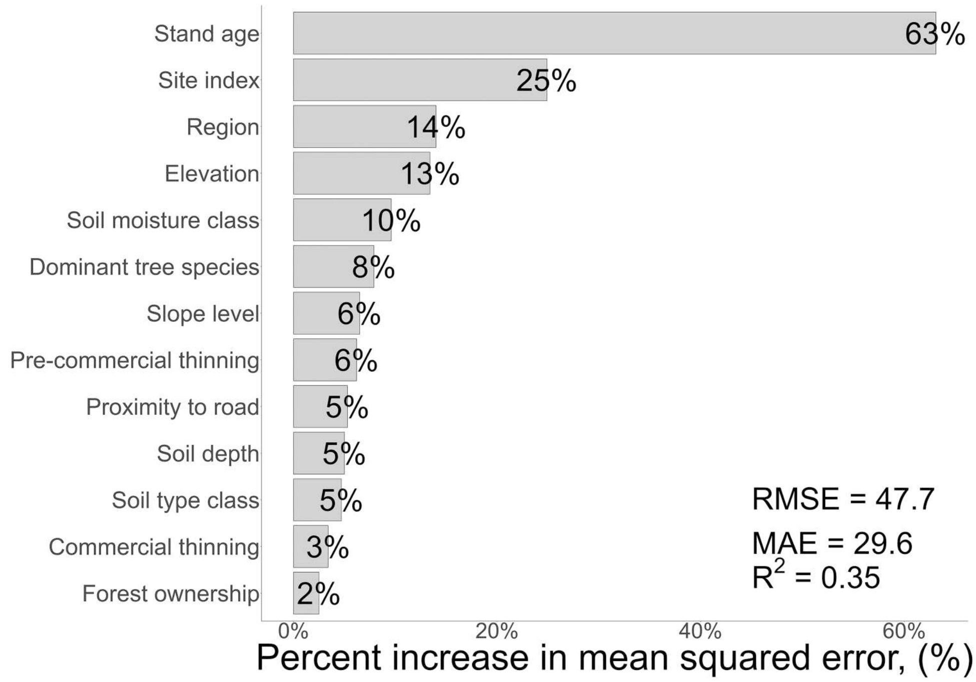

Figure 2. The results of a random forest model concerning explanatory variable importance in predicting biomass-dense forest occurrence in Sweden. A higher percent reflects that the variable is more important in predicting the occurrence of biomass-dense forests.

Forest management practices, such as PCT and CT, were found to exert varying effects on BDF biomass yield ha^{-1} on a regional level; nevertheless, both practices generally showed significant effects on yields. The absence of PCT significantly ($p < 0.001$) increased BDF biomass yield in all regions but Northern Norland (Table 3). In contrast to the PCT, the presence of CT was associated with higher BDF biomass yields ha^{-1} in

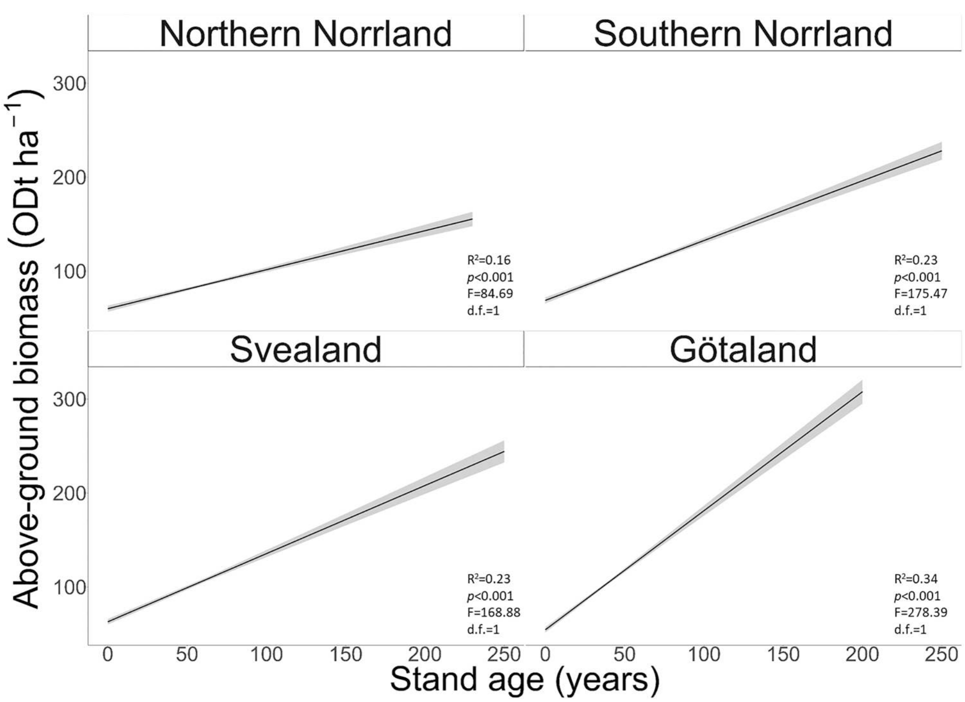

Figure 3. The relationship between stand age (x-axis) and biomass yield from biomass-dense forests (BDF, y-axis) across the four regions in Sweden. The trend lines represent the outcomes of the linear models and the grey shaded area represents the 95% confidence interval.

Table 3. Regional distribution of biomass-dense forests (BDFs) by area (1000 ha), BDF biomass yield (ODt ha^{-1}), and mean BDF stand age, categorized by categorical forest management settings such as dominant tree species, pre-commercial and commercial thinning activities, forest ownership structure, and proximity to roads. Values for BDF biomass yield (ODt ha^{-1}) are presented as mean (±SD) across tested forest management settings variables and their categories. The statistical results (*p*-value, *F* statistics and degrees of freedom) for the main effects of the tested variables are presented by each variable (grey shading). Values highlighted in bold with superscript letters indicate significant differences ($p < 0.05$) between categories of each tested variable, as determined by Tukey's multiple comparison test.

	Northern Norrland			Southern Norrland			Svealand			Götaland		
	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)
Dominant species[a]												
Picea abies	360.4	**127^{a} ± 7.4**	85	476.1	**131^{a} ± 8.2**	65	273.6	**101^{ac} ± 5.7**	43	343.2	**108^{a} ± 9.2**	29
Pinus sylvestris	369.0	**115^{b} ± 7.5**	53	235.5	**114^{b} ± 8.5**	46	200.2	**86^{b} ± 5.9**	44	72.3	**99^{a} ± 9.8**	47
Pinus contorta	50.7	114^{ab} ± 10.5	33	59.1	110^{ab} ± 11.2	31	5.2	85^{abc} ± 21.5	31	–	**–**	–
Betula spp.	217.2	**131^{a} ± 7.8**	55	155.1	124^{ab} ± 9.1	48	59.0	**86^{bc} ± 7.4**	39	56.1	**107^{a} ± 10.3**	35
Populus tremula	2.4	146^{ab} ± 28.5	46	2.2	156^{ab} ± 34.8	43	4.2	**144^{a} ± 17.2**	36	2.9	**263^{b} ± 23.8**	49
Other coniferous species	1.2	120^{ab} ± 48.3	28	–	–	–	0.6	127^{abc} ± 51.4	19	4.2	**123^{a} ± 19.5**	18
Other broadleaf species	8.4	152^{ab} ± 17.5	42	17.5	139^{ab} ± 15.1	31	15.6	95^{abc} ± 11.3	43	21.2	**117^{a} ± 11.6**	43
ANOVA results:	$p < 0.001$	$F = 3.86$	d.f. = 6	$p = 0.001$	$F = 3.97$	d.f. = 5	$p < 0.001$	$F = 4.75$	d.f. = 6	$p < 0.001$	$F = 11.85$	d.f. = 5
Pre-commercial thinning												
Absent	885.3	130 ± 10.8	68	751.9	**138^{a} ± 10.1**	61	406.1	**111^{a} ± 10**	48	311.5	**144^{a} ± 10.4**	38
Performed	123.9	128 ± 11.6	43	193.6	**120^{b} ± 10.6**	34	152.2	**96^{b} ± 10.3**	31	188.3	**128^{b} ± 10.6**	24
ANOVA results:	$p = 0.7$	$F = 0.14$;	d.f. = 1	$p < 0.001$	$F = 15.81$	d.f. = 1	$p < 0.001$	$F = 13.82$	d.f. = 1	$p < 0.001$	$F = 22.31$	d.f. = 1
Commercial thinning												
Absent	998.5	**92^{a} ± 8.9**	64	927.2	**114^{a} ± 8.8**	55	544.9	97 ± 8.7	43	483.5	131 ± 9.5	33
Performed	10.7	**166^{b} ± 15.6**	67	18.3	**144^{b} ± 13.6**	58	13.5	110 ± 13.1	49	16.4	141 ± 12.6	34
ANOVA results:	$p < 0.001$	$F = 33.45$	d.f. = 1	$p = 0.007$	$F = 7.34$	d.f. = 1	$p = 0.21$	$F = 1.6$	d.f. = 1	$p = 0.19$	$F = 1.71$	d.f. = 1
Owner structure												
Commercial	498.7	128 ± 10.8	67	499.4	**113^{a} ± 8.4**	56	237.9	104 ± 9.9	44	93.4	130 ± 7.2	34
Private	471.4	128 ± 10.7	61	438.8	**122^{b} ± 8.5**	54	284.6	108 ± 9.9	42	405.4	126 ± 6.4	33
Public	39.2	131 ± 13.5	71	7.3	153^{ab} ± 20.1	60	35.9	98 ± 11.9	50	1.8	152 ± 25.3	57
ANOVA results:	$p = 0.97$	$F = 0.04$	d.f. = 2	$p < 0.008$	$F = 4.5$	d.f. = 2	$p = 0.31$	$F = 1.19$	d.f. = 2	$p = 0.34$	$F = 1.07$	d.f. = 2

[a]The tree species that contributes the most to above-ground biomass (i.e. > 50%) at the BDF site.

all regions (Table 3), but the difference compared to absence of CT was significant only in Northern Norrland ($p < 0.001$; 166 ± 15.6 ODt ha^{-1}) and Southern Norrland ($p = 0.007$; 144 ± 13.6 ODt ha^{-1}).

The type of forest ownership and proximity to roads also showed region-specific effects. For example, in Southern Norrland, forest ownership was identified as a significant factor in terms of biomass yields ($p = 0.02$), with a significantly higher ($p = 0.039$) BDF yield associated with private ownership (122 ± 8.5 ODt ha^{-1}) in comparison with commercial ownership (113 ± 8.4 ODt ha^{-1}; Table 3). No such trend was detected in any other region. Across all studied regions, a negative trend was observed for the BDF biomass yield ha^{-1} and road proximity (Figure 4). However, this trend was only statistically significant in Götaland ($p = 0.02$) and Svealand ($p = 0.05$; Figure 4), which demonstrate that BDF biomass yields decrease as the distance from the road increases.

Effect of site properties

The region-specific linear models that tested the effects of site properties (i.e. site index, soil moisture, type, and depth) on the occurrence of BDF explained 3% of the variance ($R^2 = 0.03$) in Northern Norrland, 2% ($R^2 = 0.02$) in Southern Norrland, 4% ($R^2 = 0.04$) in Svealand, and 1% ($R^2 = 0.01$) in Götaland. Thus, the explanatory power of site properties was substantially lower compared to the forest management settings models. Nevertheless, a statistically significant positive trend between BDF biomass yield ha^{-1} and site index (Figure 5) was found in Svealand ($p < 0.001$) and similar, although not significant trend, was also observed across the other three regions (Figure 5).

Soil moisture class significantly affected BDF biomass yields ha^{-1} only in Southern Norrland where mesic-moist soils (132 ± 19.7 ODt ha^{-1}) supported significantly higher ($p < 0.001$) BDF yield compared to mesic soils (114 ± 19.4 ODt ha^{-1}; Table 4). In general, mesic and mesic-moist soils were found to support higher BDF biomass yields ha^{-1} when compared to dry, moist, and wet soil moisture classes, however these two soil types also encompass larger areas and feature younger BDF sites across all regions (Table 4). Remarkably, wet soils in the southern regions, e.g. Svealand and Götaland, supported the highest biomass yields, more specifically, 168 ± 35.1 ODt ha^{-1} and 145 ± 36.8 ODt ha^{-1}, respectively (Table 4) yet, this difference was not statistically significant.

Soil type had a significant effect on BDF biomass yields ha^{-1} only in Northern Norrland ($p < 0.001$). There, peat (101 ± 17.9 ODt ha^{-1}) and sediment (92 ± 17.1 ODt ha^{-1}) soils had significantly higher ($p = 0.003$, $p = 0.005$, respectively) BDF yields compared to moraine soils (79 ± 16.9 ODt ha^{-1}). In general, peat soils were found to have highest BDF yields across all regions compared to the other soil types, but the trend was significant only in Northern Norrland (Table 4). Finally, we found no significant effect of soil depth class on the BDF biomass yields ha^{-1} (Table 4).

Discussion

Landscape properties and large-scale predictors

Based on previous research (Fernandez-Lacruz et al. 2015), and the general forest distribution across Sweden (Swedish NFI 2023), we expected that region will strongly determine the occurrence of BDFs in the whole-country analyses. Surprisingly, region did not fall out as the most important variable explaining the occurrence of BDFs in the random forest model, where stand age and site index were identified to be far more important than region. Stand age likely affects the occurrence of BDFs because older stands have had more time to accumulate biomass, leading to higher density. Similarly, the site index, which measures the potential productivity of a forest stand, influences BDF occurrence as more productive sites can support faster and more substantial biomass growth. Additionally, forest managers may leave low site index forests under-managed (i.e. unthinned) for long periods, which may also contribute to the accumulation of biomass in these older, low site index, unthinned sites.

These factors are critical in determining BDFs because they directly affect the growth and development of forest stands over time. Similar to the Fernandez-Lacruz et al. (2015) we found that BDFs are more common in the north (i.e. Northern and Southern Norrland), likely due to the extensive productive forestlands in these regions (Table 1), which increases the likelihood of BDFs formation. Additionally, the shorter fieldwork season in north, which limits the season for motor-manual PCT may contribute to the long-term accumulation of BDFs in these regions. Furthermore, this seasonal constraint, largely driven by snow, may also lead forest managers to prioritize thinning in stands with higher growth and economic potential, leaving lower productivity sites (i.e. low site index) unthinned. The last variable with an importance greater than 10% in the random forest model was elevation. In Sweden, elevation increases from south to north and from east to west. Consequently, areas with higher elevations are predominantly located in the northern regions (i.e.

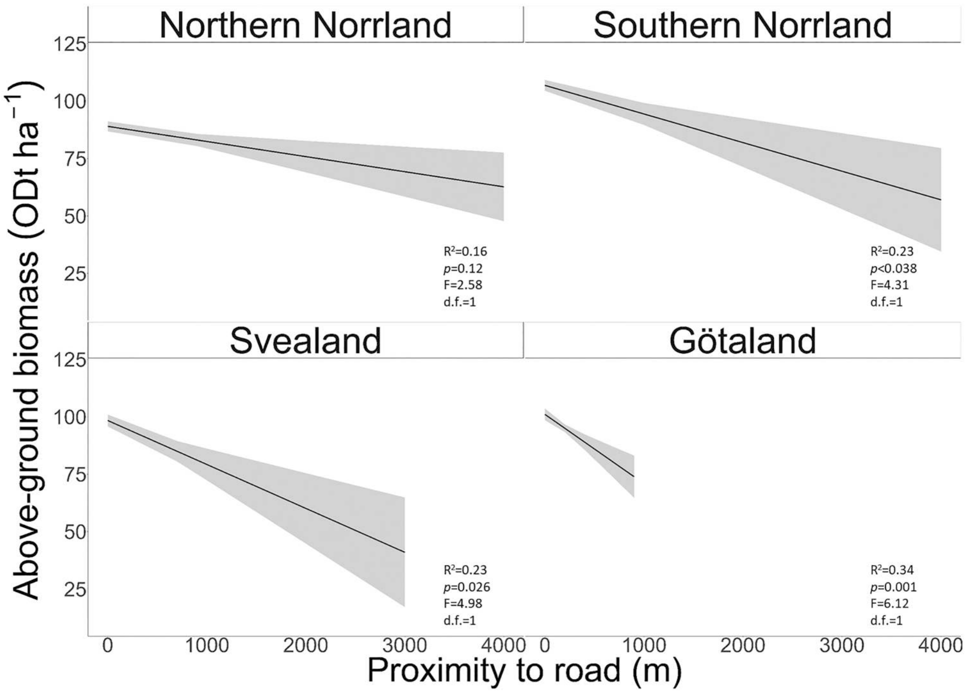

Figure 4. The relationship between road proximity (x-axis) and biomass yield from biomass-dense forests (BDF, y-axis) across the four regions in Sweden. The trends illustrate represent the outcome of the liner model and the grey shaded area represents the 95% confidence interval.

Northern and Southern Norrland), where there is a higher occurrence of BDFs (Table 1).

It is important to mention here that although none of the other nine predictors had importance scores > 10%, it does not mean that they don't have effect on the occurrence of BDF. In fact, many of them were identified to have significant controls over BDF occurrence in the regional analyses. The advantage of the random forest model is that it compares all variables across the whole country at once making it possible to assess their relative importance against each other. As such, stand age, site index, region, and to some extent elevation are parameters that can be considered by forest manager when looking for sites suitable for biomass extractions using efficient methods of biomass thinning (BT; Bergström 2009; Bergström et al. 2010).

Forest management settings

Stand age was not only the most important nationwide factor, but also consistently emerged as a significant factor in regional analyses. Stand age plays a key role in predicting BDF occurrence, as it directly relates to biomass accumulation. Based on our definition of BDF, it is likely that older BDFs, not yet at final felling age, accumulate more biomass, especially in the first 40–60 years when the current annual increment is highest (Husch et al. 1982). The effect of stand age on the occurrence of BDF was anticipated (h_2), however, our results also showed that stand age needs to be considered alongside other variables. For example, within all regions, the BDF biomass yield was highest in older stands that were situated on peatlands (Table 4), and older BDF stands were more common on sites with a lower site index (Figure 6). This is important finding from a management perspective because BDF management has been suggested as a biomass extraction strategy for young, dense forests, particularly those on previously neglected fertile sites (Bergström 2009; Ahnlund Ulvcrona et al. 2017). Less productive old stands, often found on wet and/or peat soils (Table 4; Supplementary Information: Table 1S), experience longer rotation periods, taking more time for trees to reach the 15 cm in dbh threshold used in our definition of BDFs. In some cases, particularly on poor sites, the trees may never reach that threshold, remaining as BDFs throughout the entire rotation period.

Selective thinning (i.e. PCT and CT), a common practice in Sweden aimed at enhancing timber quality and growth rates for the remaining trees (Nilsson et al. 2010; Holmström et al. 2016), reduce stand volume production (Gizachew et al. 2012; Holmström et al. 2016; Nilsson et al. 2010) and hence hinders BDF formation. Therefore, as expected (h_3), the absence of PCT significantly increased the occurrence of BDFs in all regions

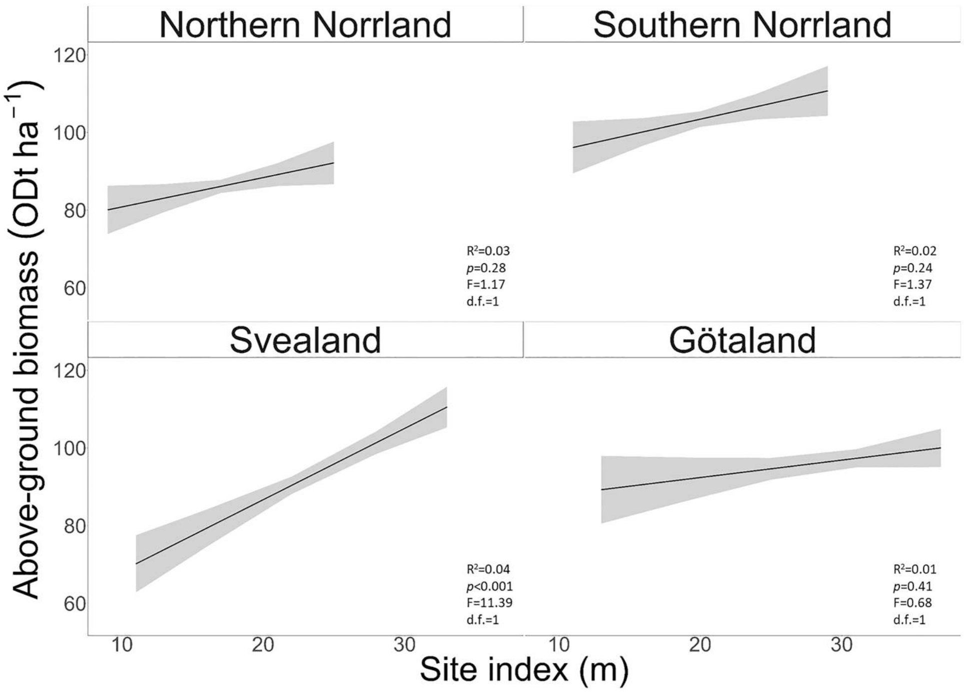

Figure 5. The relationship between site index (x-axis) and biomass yield from biomass-dense forests (BDF, y-axis) across the four regions in Sweden. The trend line represent the outcome of a linear model and the grey shaded area represents the 95% confidence interval.

but Northern Norrland (Table 3). Interestingly, CT practices were found to increase the likelihood of BDF occurrence, significantly in two regions (Northern and Southern Norrland, Table 4). This finding contradicts multiple studies suggesting that the absence of CT fosters greater biomass accumulation (Nilsson et al. 2010; Gizachew and Brunner 2011; Gizachew et al. 2012; Ahnlund Ulvcrona et al. 2017). Commercial thinning is applied more often than PCT in Swedish forestry, with the average stand age or site index chosen for CT showing little variation across various owner groups (Table 2S). A key distinction, however, lies in road proximity: CT is more often conducted on sites closer to roads (Table 3S), minimizing transportation costs and reflecting economic rationale in forest management (Kärhä 2006). Another possible reason for this preference could be that more fertile stands (high site index) with a higher need for CT were located closer to the road network. This was particularly evident in Northern regions, where BDFs with a higher site index were located closer to roads (Figure 7).

Roads often lead to these more fertile areas, allowing BDF site with CT to maintain relatively high biomass yields even post-thinning. This can explain the unexpected (h_4) negative trend between BDF and proximity to roads (Figure 4), as high BDF productivity as well as thinning will occur in close proximity to roads (Figure 7). At the same time, sites with high growth potential (also closer to roads) may partially recover harvested biomass through accelerated growth among remaining trees. Thus, while infrastructure plays a role in CT application and BDF occurrence, it is primarily the fertility of forestland that drives the development of road infrastructure and preferred forest management strategies. This means that these two variables may follow each other, both aligning with the most fertile forestlands. Such a relationship highlights how forest management strategies can be dependent on road development (Zeide 2001; Henningsson et al. 2007). The interaction among these factors – including site productivity, management practices, road proximity – highlights the complex interplay of variables influencing BDF occurrence and is likely an explanation why CT had a relatively low importance in the national model (3%).

We also expected (h_5) that forest ownership structure would play an important role in the occurrence of BDF. However, forest ownership had only 6% importance in the national analysis and in the regional models we observed significant differences only in Southern Norrland (Table 3), where BDFs were less likely to occur on commercially-owned (i.e. large commercial forest enterprises) forestlands compared to private and public owners. This unexpected result could be due to several factors. One possibility is that the majority of Swedish forest owners, driven by economic incentives, behave similarly due to the high industrial demand for wood

Table 4. Regional distribution of biomass-dense forests (BDF) by area (1000 ha), BDF biomass yield (ODt ha^{-1}), and mean BDF stand age, categorized by site properties such as soil moisture, soil type, and soil depth. Values for BDF biomass yield (ODt ha^{-1}) are presented as mean (±SD) across tested site characteristics variables and their categories. The statistical results (*p*-value, *F* statistics and degrees of freedom) for the main effects of the tested variables are presented by each variable (grey shading). Values highlighted in bold with superscript letters indicate significant differences ($p < 0.05$) between categories of each tested variable, as determined by Tukey's multiple comparison test.

	Northern Norrland			Southern Norrland			Svealand			Götaland		
	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)	Total BDF area (1000 ha)	BDF biomass yield (ODt ha^{-1})	Mean age of BDF (years)
Soil moisture class												
Dry	14.2	70 ± 19.0	50	9.9	109^{ab} ± 26.7	60	16.1	129 ± 15.0	48	10.1	108 ± 14.1	34
Mesic	543.0	98 ± 16.5	54	575.3	***114^{b} ± 19.4***	47	330.2	122 ± 11.5	37	332.5	103 ± 11.0	29
Mesic-Moist	406.4	104 ± 16.7	76	323.7	***132^{a} ± 19.7***	65	188.3	134 ± 11.8	51	137.9	103 ± 11.6	40
Moist	40.8	105 ± 18.5	85	36.6	120^{ab} ± 22.0	83	21.8	125 ± 15.4	61	17.6	102 ± 15.5	56
Wet	4.9	76 ± 30.8	111	–	–	–	2.0	168 ± 35.1	72	1.6	145 ± 36.8	88
ANOVA results:	$p = 0.098$	$F = 1.96$	d.f. = 4	$p < 0.001$	$F = 5.47$	d.f. = 3	$p = 0.06$	$F = 2.26$	d.f. = 4	$p = 0.81$	$F = 0.4$	d.f. = 4
Soil type class												
Rock	–	–	–	–	–	–	–	–	–	1.1	100 ± 40.9	34
Moraine	669.3	***79^{a} ± 16.9***	63	716.9	113 ± 20.1	52	379.6	127 ± 13.1	43	335.8	109 ± 10.7	30
Sediment	254.8	***92^{b} ± 17.1***	61	165.1	117 ± 20.3	54	141.9	130 ± 13.3	38	120.6	112 ± 11.3	31
Peat	85.1	***101^{b} ± 17.9***	83	63.6	127 ± 21.4	84	36.8	149 ± 15.5	66	42.4	128 ± 12.6	57
ANOVA results:	$p < 0.001$	$F = 8.64$	d.f. = 2	$p = 0.19$	$F = 1.66$	d.f. = 2	$p = 0.038$	$F = 3.28$	d.f. = 2	$p = 0.14$	$F = 1.84$	d.f. = 3
Soil depth class												
Various diff.[a]	1.9	124 ± 37.0	85	0.6	93 ± 66.4	26	1.1	217 ± 41.2	70	5.2	110 ± 21.3	37
<0.2 m	1.1	74 ± 52.7	33	2.3	171 ± 38.8	66	8.1	108 ± 16.8	48	11.3	125 ± 19.2	43
0.2 m–0.7 m	32.8	83 ± 10.9	75	35.0	105 ± 12.0	57	55.4	107 ± 9.8	38	79.6	109 ± 14.0	35
>0.7 m	973.5	83 ± 6.3	64	907.6	107 ± 5.7	55	493.8	110 ± 7.8	43	403.6	105 ± 12.7	32
ANOVA results:	$p = 0.72$	$F = 0.45$	d.f. = 3	$p < 0.41$	$F = 0.97$	d.f. = 3	$p = 0.07$	$F = 2.36$	d.f. = 3	$p = 0.52$	$F = 0.76$	d.f. = 3

[a]Soil depth varies widely and, for example, fractured surfaces in the bedrock are partially visible.

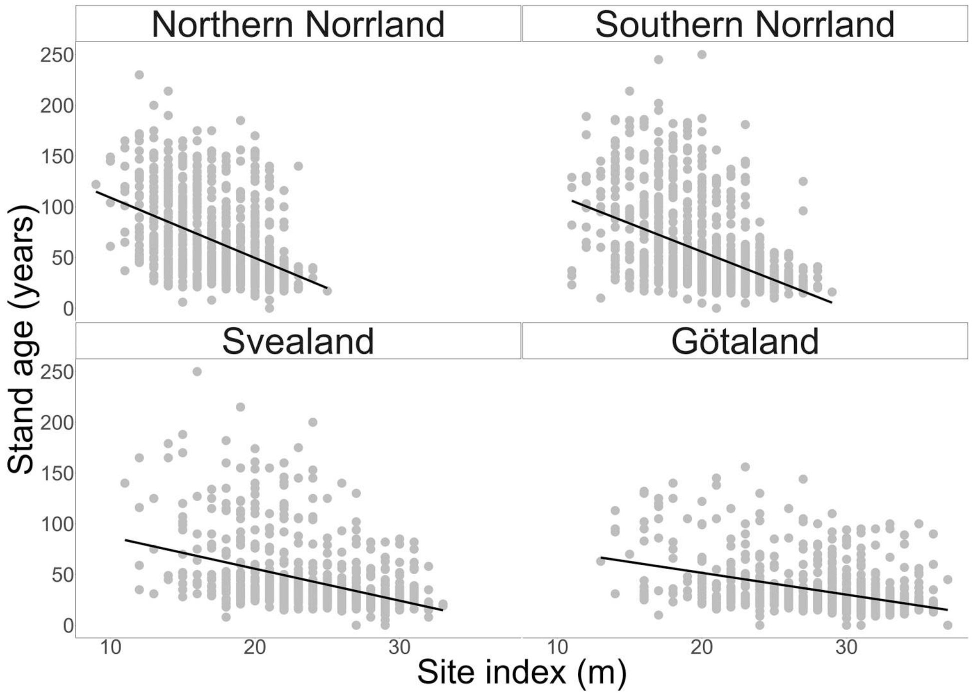

Figure 6. Density plots of stand age (y-axis) and site index (x-axis) across the four studied regions in Sweden. The points represents individual observations and the black lines represent a fitted linear trend for each region.

(Bostedt et al. 2016). Additionally, forest companies and forest owners' associations have a strong impact on forest management also on private forestland through their timber merchants and contractors leading to similar management practices (Hertog et al. 2022). These factors could contribute to the minimal impact of ownership structure on the occurrence of BDFs.

The absence of PCT on sites dominated by *Picea abies, Populus tremula*, and – to a lesser degree – *Betula spp*. emphasized the importance of these species for BDF

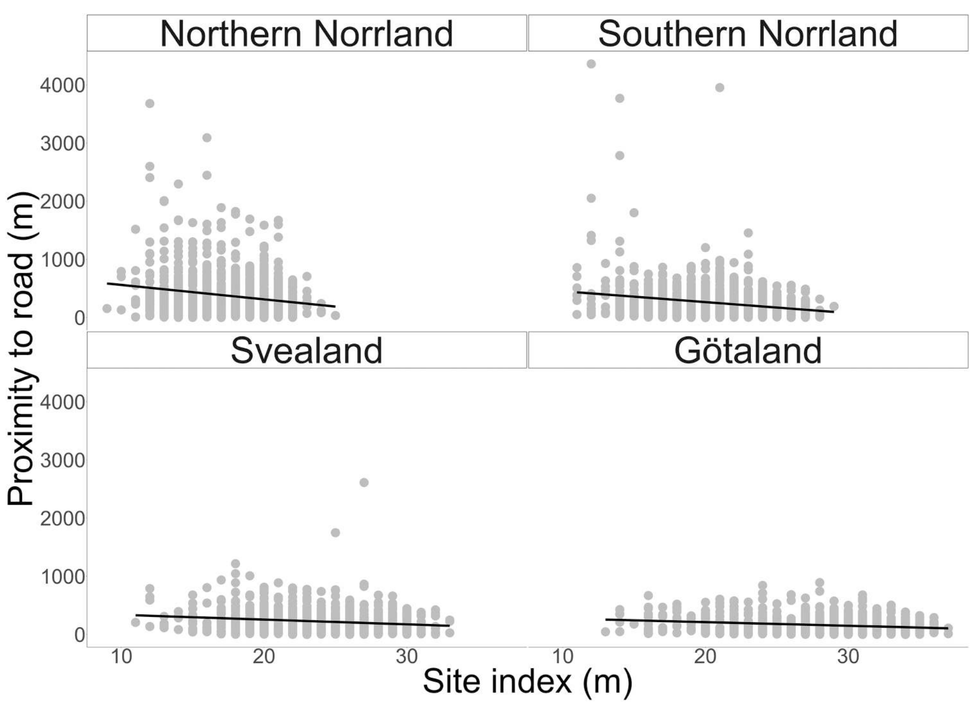

Figure 7. Density plots depicting the relationship between road proximity (y-axis) and site index (x-axis) across the four studied regions in Sweden. The points represent individual observations, and the black lines represent a fitted linear trend for each region.

occurrence. Surprisingly, *Picea abies* dominance was found significant in BDFs across Northern and Southern Norrland, despite expectations that timely thinning would prevent such development due to the high importance that *Picea abies* has in Swedish forestry (Ekö et al. 2008). This could reflect failed management objectives or simply the species' abundance in Swedish forests (Swedish NFI 2023). In contrast, the occurrence of BDFs where *Populus tremula* and *Betula spp*. aligns with our hypothesis (h_6) that fertile soils will exhibit higher BDF occurrence due to the higher likelihood of natural regeneration of pioneer species. These results likely reflect rapid natural regeneration and accelerated growth of these pioneer tree species, potentially overshadowing planted species like *Picea abies* and *Pinus sylvestris* (Hynynen 1993; Worrell 1995; Hynynen et al. 2010; Tullus et al. 2012). Consequently, forest managers may need to implement more frequent and efficient thinning to control the expansion of *Populus tremula* and *Betula spp*. These additional measures may result in the temporary negligence of stands already dominated by these species; for instance, forest managers may allow these stands to reach the size and quality required to conduct BT instead of PCT in order to maximize the profits from these sites.

Site properties (site index, soil moisture, soil type, soil depth)

In our regional analyses, we found generally increasing BDFs occurrence with increasing site index, but the relationship was significant only in Svealand (Figure 5). We already discussed the reasons why more fertile sites might support BDF creation because site index was the second most important variable in the country-wide analyses. Nevertheless, site index is also important to consider in the light of the other site properties and management decisions. For example, forest managers seems to perform PCT on sites with higher productivity (Table 1S). This preference may stem from the greater need for PCT on more productive sites, where competition from natural regeneration often is intense (Hynynen et al. 2010; Lidman et al. 2023). Moreover, the low site index indicates a higher BDF biomass yield, most likely due to limited thinning interventions. Stands on wet soils and peat soils showed some of the highest values of BDF biomass yields across most regions but they were as well some of the oldest stands (Table 4). This phenomenon could be attributed to wet and peat soils often having low site index values, and therefore, low productivity (Hägglund and Lundmark 1977; Crawford et al. 2021; Swedish NFI 2023). As a result, stands that occur on these soils tend to be of low interest for active forest management; hence, forests on these sites are likely to remain untouched over long time periods. These dynamics ensure that these sites accumulate more biomass (Table 1S; Figure 6) and may develop into BDFs.

Finally, our findings highlight the indirect effect of soil moisture on BDF occurrence through the effect on stand age and site index. For example, the mean age of BDFs generally increased and site index generally decreased with increasing soil moisture (from dry to wet soil). Here, the mesic-moist soil moisture class is particularly noteworthy due to its higher water content, which supports seed germination during the early stages of natural forest regeneration (Götmark et al. 2005; Lidman et al. 2023). Following mesic soils, mesic-moist soils accounted for the second-largest area of BDFs in Sweden (Table 4), demonstrating that managers can utilize the soil moisture index for making active decisions about BDF management.

Suggestions for the management of biomass-dense forests

In northern regions BT adaptation could, for example, be considered on sites where *Betula spp*. is the dominant tree species or on young sites dominated by *Pinus contorta*, which have the lowest thinning rates among the BDF sites (Table S1), possibly due to high sensitivity to wind and snow damage following conventional selective thinning (Teste and Lieffers 2011). Possible risks associated with wind and snow damage in BDFs following traditional CT could be reduced by employing BT in narrow strips (Becs et al. 2024).

Sediment and moraine soil types within the mesic-moist moisture class supported relatively high biomass yields. Thus, such sites could potentially be managed to become biomass dense by promoting natural regeneration after final felling through soil scarification using disc trenching (Karlsson et al. 2002), and by delaying the PCT (Holmström et al. 2016), and/or implementing BT methods (Bergström 2009; Bergström et al. 2010; Karlsson et al. 2013; Ahnlund Ulvcrona et al. 2017; Nuutinen et al. 2021; Segtowich et al. 2023). This approach would not only speed up the expansion of BDFs, but also allow for the introduction and testing of BT on a larger scale, which could potentially reduce the need for traditional early selective thinnings (i.e. PCT and CT). Interestingly, there is evidence that the implementation of BDF management approaches could lead to forest practices that are more economically viable (Sängstuvall et al. 2012; Jundén et al. 2013; Bergström and Di Fulvio 2014), potentially on sites that have been underutilized in terms of active forest management (Fernandez-Lacruz 2019), including older stands on low productive sites (e.g. on peat). This approach could boost biomass production, which aligns well with the increasing need for wood-based biomass (Börjesson et al. 2017). Nevertheless, it is important to state that more research, including tailored recommendations to different types of sites and stands to provide systematic and well-informed suggestions, should precede the widespread adoption of BDF management.

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Disclosure statement

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Data availability statement

Data analyzed during this study are available from the corresponding author upon request and also through the Swedish NFI.

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