Supporting information

S1: Leaf area index calculation

Foliage masses for pine and spruce were calculated using Marklund's (1988) biomass models. Foliage mass of deciduous trees was calculated using the biomass model of Smith et al., (2014), because Marklund does not have separate model for deciduous trees. All three models were developed under Fennoscandic boreal forest conditions. Marklund's dbh- and tree height (h) -dependent models were used for pine and spruce (T-18 and G-16, respectively), whereas for small trees (i.e. dbh< 5cm) Marklund's dbh-dependent models (T-17 and G-15) were used. In Norwegian NFI data, small trees were counted based on either h or dbh (i.e. three classes: h<1.3 m, dbh=0-2.5 cm and dbh=2.5-5 cm), whereas in Swedish NFI data, small trees were counted only based on h (i.e. two classes: h<0.5 m and h<1.3 m).

For Norwegian small trees, foliage mass was obtained by multiplying the number of trees with the class (i.e. dbh=0-2.5 cm and dbh=2.5-5 cm) mean diameter values (i.e. 1.25 cm and 3.75 cm, respectively). For the smallest height class (i.e. h<1.3 m), the dbh-constant was set to 0.3 cm, because dbhs for trees shorter than 1.3m were not measured. For the two Swedish height classes (i.e. h<0.5 m and h<1.3 m), the dbh-constants were set to 0.1 cm and 0.5 cm. LAI was calculated by dividing plot total foliage mass with plot area and multiplying with Specific Leaf Area (SLA) value. The SLA values were: 6.2 m^2/kg for pines (Palmroth and Hari, 2001), 4.95 m^2/kg for spruces (Stenberg et al., 1999), and 13.55 m^2/kg for deciduous trees (Lintunen et al., 2011). The LAI may be interpreted as the maximum growing season LAI of all forest canopy layers.

The highest mean canopy LAI values (LAI_{canopy}) were found from spruce dominated plots and the smallest in plots dominated by either pine or deciduous species (**Table S1.**). For conifer dominated plots the mean LAI_{canopy} values were higher in Norway than in Sweden. The influence of small trees (LAI_u) on plot mean LAI were systematically larger in Norway than in Sweden, due to differences in definition of small trees in NFI measurements (i.e. in Norwegian NFI trees with dbh less than five centimeters are recoded as small trees, whereas in Sweden the breast height (1.3 m) threshold is used to count small trees). In addition, as Norway has alpine birches growing in mountainous areas the influence of LAI_u on plot total mean LAI was larger in Norway than in Sweden and Finland.

Our results showed that the LAI_u accounted for on average 2-8 % of total LAI, and thus should be taken into account while estimating the estimating the forest LAI. The contribution of LAI_u on total LAI was the largest in deciduous plots, which are in the center of climate change mitigation and adaption by forest management. To our knowledge, this is the first paper to report how the information of small trees in the NFI data may be used to estimate LAI of understory trees to approximate forest total maximum LAI.

Table. S1. The mean Leaf Area Index (LAI) of plots dominated by different species groups: LAI_{canopy} is the forest canopy LAI, LAI_u refers to LAI of small trees i.e. understory trees (Note, the different counting method of small trees in Norway and in Sweden), and $LAI_{u\%}$ is the percentage of LAI_u for the total mean LAI (LAI_{canopy}+LAI_u).

	Norway			Sweden		
	LAI_{canopy}	LAI_u	$LAI_{u\%}$	LAI_{canopy}	LAI_u	$LAI_{u\%}$
Spruce	5.59	0.24	4.05	4.90	0.10	1.91
Pine	2.58	0.12	4.34	2.31	0.07	2.83
Deciduous	2.33	0.21	8.31	2.76	0.15	5.17

References

Lintunen, A., Sievänen, R., Kaitaniemi, P., and Perttunen, J. Models of 3D crown structure for Scots pine (Pinus sylvestris) and silver birch (Betula pendula) grown in mixed forest. Can. J. For. Res., 41, 1779-1794, 2011.

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S2: Crown ratio models

Crown Length (CL) can be modeled directly or alternatively via Crown Ratio (CR), which is defined as CL divided by h (i.e. CL = h*CR). We used a mixed effects modeling approach with maximum likelihood estimator (R package 'mle') to develop the CR models for the three main species (i.e. spruce, pine, and birch) in Norway and in Sweden. Separate CR models were developed for Norway and Sweden to account for possible differences in forest management (i.e. harvesting) and environmental conditions. The number of trees used to develop the CR models was nearly 24,000 (i.e. spruce: 10,403, pine: 7,830 and deciduous: 5,828) in Norwegian NFI data. In Swedish NFI data the number of trees used to compile the models was almost 29,500 (i.e. spruce: 12,228, pine: 13,171 and deciduous: 4,081). The model was created based on forest variables which are influenced by forest management operations and are widely available from forest inventory databases (i.e. species, h, and V). The number of predictor variables was selected based on the Akaike Information Criterion (AIC), which quantifies the trade-off between model complexity and fit. To account for non-independencies between observations (i.e. several model trees from one plot) model intercept was allowed to vary between individual trees and plots. CR models were developed based on NFI trees for which both h and CL were measured (**Fig. S1**).

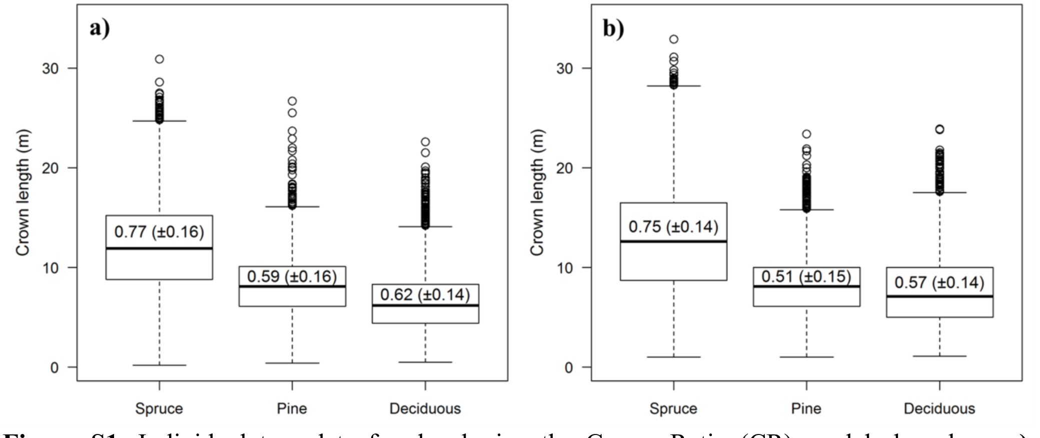

Figure S1. Individual tree data for developing the Crown Ratio (CR) models based on **a)** Norwegian National Forest Inventory (NFI) trees, and **b)** Swedish NFI trees. Mean and standard deviation (±sd) of measured CR are plotted inside the boxes. Box contains 50% of the values and dark horizontal line denotes the median value.

The fixed effect of the CR was modeled based on h and V (**Table S2.**). Both h and V were found to be significant predictors for CR (p=0.00) for each species (i.e spruce, pine, and birch). The variance explained by fixed effects of the CR models varied between 0.11-0.37 (**Table S3.**). In Norway, the largest portion of variance explained by fixed effects was noted for spruce CR model, whereas in Sweden the pine CR model explained the highest portion of variance of fixed effects. For both countries the variance explained by fixed effect remained the lowest for birch CR models. Including both fixed and random effects increased the portion of explained variance to range between 0.45 and 0.63.

The relatively low explanatory power of the CR models is due to large scatter of CR estimates. Higher prediction power could have been obtained by developing models for CL, which has larger dynamic range compared CR. However, by modeling CR instead of CL, the problem of negative CLs was avoided, and as a tradeoff we had to accept the lower prediction power of our CR models. CL reflects the vigor of trees and is influenced by both stand density via competition over time and environmental factors (e.g. water availability and temperature). Increasing stand density reduces CL due to decreasing light conditions near the crown base (i.e. foliage respiration exceeds the net photosynthesis) and mechanical damage as tree canopies collide with each other. Thus, thinnings have important role in controlling CL development and hence to the aerodynamic properties of forests.

Table S2. Description of the Crown Ratio (CR) models (CR ~ h + V + ε.). Abbreviations: h=tree height (dm),V=plot total stem volume (m^3/ha), sd=standard error and ε=residual.

		Fixed effects:		Random effects:		
Area	Species		value	sd (plot)	sd (tree)	ε
Norway	Spruce	Intercept	0.821	0.055	0.055	0.100
		h	0.008			
		V	-0.001			
	Pine	Intercept	0.659	0.067	0.067	0.102
		h	0.005			
		V	-0.001			
	Birch	Intercept	0.612	0.058	0.058	0.105
		h	0.008			
		V	-0.001			
Sweden	Spruce	Intercept	0.802	0.058	0.056	0.101
		h	0.006			
		V	-0.001			
	Pine	Intercept	0.618	0.065	0.066	0.091
		h	0.001			
		V	-0.001			
	Birch	Intercept	0.606	0.059	0.059	0.105
		h	0.005			
		V	-0.001			

Table S3. Variance explained by fixed effects and both fixed and random effects of the Crown Ratio (CR) models. RMSE is the Root Mean Square Error.

Area	Species	RMSE	Fixed effects	Fixed + Random effects
Norway	Spruce	0.11	0.37	0.61
	Pine	0.11	0.26	0.60
	Birch	0.11	0.11	0.45
Sweden	Spruce	0.11	0.20	0.51
	Pine	0.10	0.24	0.63
	Birch	0.10	0.14	0.47

S3: Lorey's height model for Norway

The model was developed based on Norwegian NFI data to predict the Lorey's height (H) from plot median tree height (H_m) and plot total stem volume (V) (**Table S4.**). Median tree was used instead of mean tree while developing the model, because median tree exists in the data and is less affected by outliers than the mean. Coefficient of determination (variance) explained by fixed effects was 0.82, and both fixed and random effects was 0.98. Model RMSE was 1.40. The model was not applied if either pixel H_m or V was zero.

Table S4. Description of the Lorey's height model ($H \sim H_m + V + \varepsilon$.). Abbreviations: H=Lorey's height (m), H_m=median tree height (m), V=plot total stem volume (m^3/ha), sd=standard error and ε =residual.

			Fixed effects:	Random effects:	
Area	Species		value	sd (plot)	ε
Norway	All	Intercept	3.015	1.841	0.692
		H_m	0.756		
		V	0.013		

S4: Background information concerning MS-NFI data

The forest masks used to produce the MS-NFI maps are developed by local forest authorities, and thus mask definitions may vary between countries. In addition, forest authorities apply statistical calibration at municipality level to correct errors in the map data. However, the forest area on the MS-NFI maps is not corrected, and thus it is commonly overrepresented on the map (i.e. a pixel inside forest mask may have V=0 or H=0. Note, however, that in our classification such pixel would not be classified as forest). Due to local calibration of the MS-NFI maps, the values do not directly correspond with the official forestry statistics. If forest authorities would provide these calibrated MS-NFI maps instead of the uncalibrated maps the MS-NFI estimates and forest statistics would agree.

The underlying assumptions of our classification scheme are that NFI field data represents different forest types and variation in key structural variables within a country (i.e. samples the whole population) and that MS-NFI maps represent the extent of forests. MS-NFI maps are intended to represent large forest areas, and while the errors at pixel level are relatively high at fine spatial resolution, the error decreases as the size of the estimation area increases. For example, in Finnish MS-NFI the average error of the V estimates at pixel level is 57.8 m^3/ha and H is 4.6 m (errors calculated as an average of mineral soil and peatland estimates and are reported in MS-NFI 2013 metadata). According to Tomppo et al. (2014): "For a sufficiently large area consisting of a group of pixels, e.g., for areas of 200 000–300 000 ha, the MS-NFI estimates are compared to the estimates and error estimates based solely on field data". As the land area of e.g. Finland is 33,842,400 ha, and majority of the land area is covered by forest, the estimation errors of the MS-NFI data may be assumed small.

References

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