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Improving the representation of high-latitude vegetation distribution in dynamic global vegetation models

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Supplement S1 – Locations of 20 study plots

Table S1 – Centre coordinates (latitude and longitude) and climatic data for the 20 plots used in this study. Estimates of mean annual precipitation and mean annual temperature are obtained from two sources; data from seNorge (C. Lussana et al., 2018; Lussana, Tveito, & Uboldi, 2018) interpolated to each centre point and from CORDEX (the forcing climate dataset in DGVM).

					seNorge v2 data (used in DM)		CORDEX climate data (used in DGVM)	
ID	Plot # from (AR18×18)	LAT	LONG	Elevation (m a.s.l) at centre	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)
3	405	6.061	58.635	200	2662	6.3	2916	4.7
2	513	6.035	59.934	710	2628	1.0	3530	2.9
1	622	5.956	61.392	596	2520	2.0	2606	2.0
6	801	7.429	58.074	184	1542	6.7	2055	5.9
4	922	6.957	61.456	1437	1799	-3.6	2958	-2.9
5	1131	7.264	62.935	454	1976	4.0	1716	4.8
8	1304	8.862	58.638	88	1395	7.1	1640	4.9
7	1322	8.298	61.529	1670	827	-3.1	2418	-6.1
9	1623	9.278	61.735	852	555	-0.1	808	-3.9
10	2015	10.812	60.496	606	804	1.9	1517	0.5
12	2108	11.268	59.377	130	1072	5.5	1223	4.4
11	2238	11.000	64.223	222	1349	4.3	1542	2.1
13	2332	11.492	63.266	721	1029	0.3	2001	-0.2
14	2425	11.968	62.145	744	715	-1.2	1013	-2.0
16	2948	13.508	65.886	529	1513	1.1	1819	-0.3
15	2962	13.363	68.146	393	1339	5.8	1075	4.4
17	4268	19.167	69.072	354	715	0.7	1122	-1.8
18	5369	24.147	69.040	395	466	-4.0	695	-3.1
19	6473	29.382	69.334	69	503	-1.1	640	-2.5
20	6380	29.703	70.465	387	552	0.2	1132	-2.5

Supplement S2 – Assessment of climatic representativeness of selected plots

We assessed the representativeness of the 20 plots, selected from the original AR18×18 dataset which consists of 1081 plots, by comparing frequency distributions with respect to the two main bioclimatic gradients in Norway, expressed as annual mean temperature and annual precipitation. We also included a comparison of precipitation seasonality, as the only one of the three tested new parameters that improved the DGVM in the sensitivity tests. For each of temperature, precipitation and precipitation seasonality, we obtained values for the centre point of each AR18×18 plot (cf. Fig. S1) and compared the frequency distributions of the selected plots with those of all plots (Fig. S3). A series of Kolmogorov-Smirnov tests for these three variables (comparison of sample mean and variance) indicate that the subsample does not deviate from the full dataset substantially. The 20 selected plots span elevations from 88 to 1670 m a.s.l., covers an annual temperature range from -4°C to 7.1°C, and an annual precipitation range from 466 to 2661 mm (Fig. S1), which accords well with the variation in the AR18×18 dataset (Fig. S2).

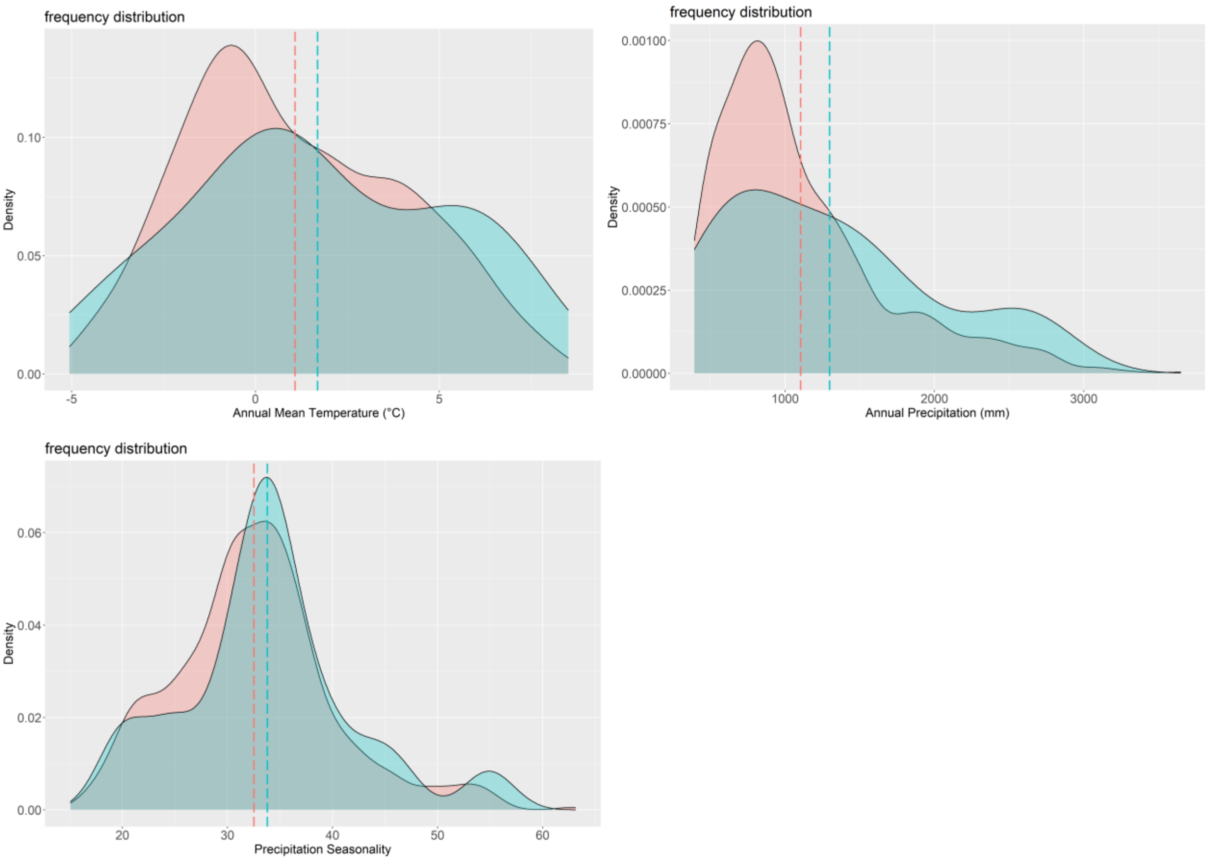


Figure S2– Frequency distributions of plots in the original AR18×18 dataset (n=1081; in red) and in the set of 20 plots selected for this study (in blue), with respect to annual mean temperature (top left),annual precipitation (top right) and precipitation seasonality (bottom left). Dashed lines indicate means for the respective datasets.

Supplement S3 – Assessment of the representativeness of PFT profiles

We also assessed the representativeness of the 20 study plots, selected from the original AR18×18 dataset which consists of 1081 plots, by comparing the aggregated PFT profiles for the two datasets given in Table S4. PFT profiles were first obtained for each plot by the conversion scheme in Table S5, thereafter aggregated to dataset level by calculation of mean frequencies for each of the six PFTs (and 'EXCL'; land not assigned to any PFT type).

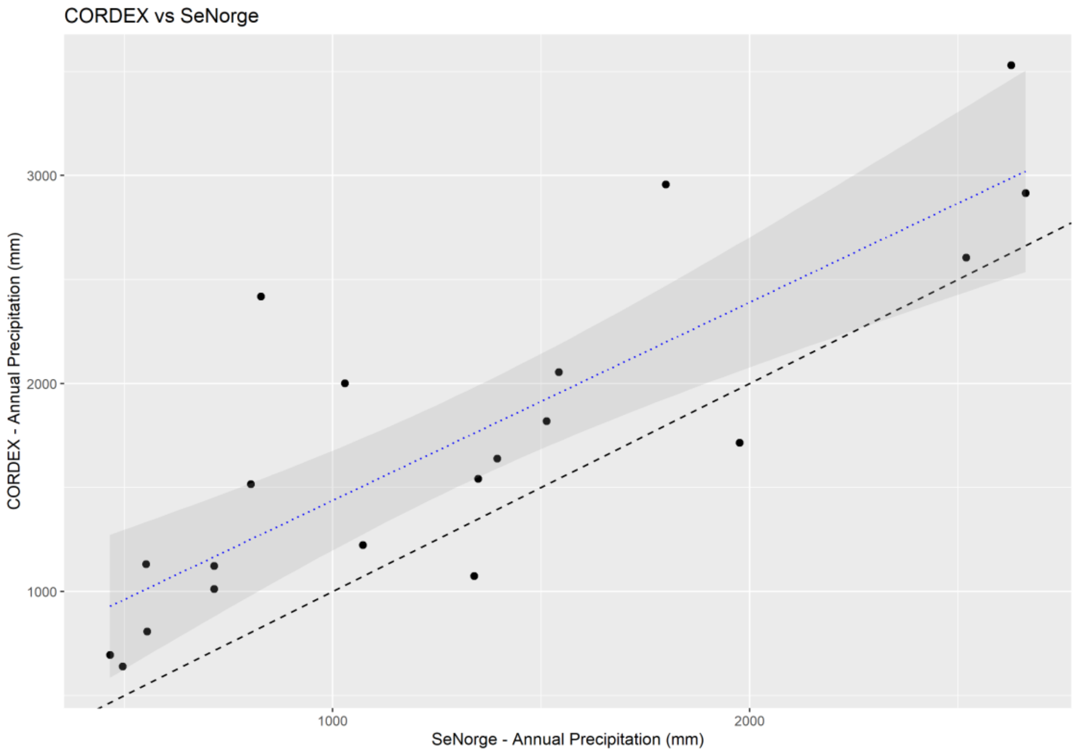
The comparison between the aggregated PFT profiles in Table S4 by use of the chi-square test (see section 2.6 for method) shows that the two datasets are much more similar than expected by chance (χ^2=1.991, df = 6, p = 0.079). Despite slight overrepresentation of the boreal NET PFT and underrepresentation of boreal BDT and C3 grasses, we conclude that the selected plots are sufficiently representative for the conclusions drawn from the sample of 20 plots to be acceptably representative for Norway. Note that percentage for EXCL category has been proportionally re-distributed through relevant PFTs in the study as shown on the Table S3 (so that the six PFTs cover 100%).

Table S3 – PFT profiles of the full AR18×18 dataset (n = 1081) and the 20 plots selected for this study.

PFT code	PFT name	Fraction of PFT in 1081 plots (%)	Fraction of PFT in 20 plots (%)
BG	Bare Ground	10.37	10.95
Boreal NET	needleleaf evergreen tree - boreal	21.50	31.18
Temp BDT	broadleaf deciduous tree - temperate	0.46	0.40
Boreal BDT	broadleaf deciduous tree - boreal	16.02	12.55
Boreal BDS	broadleaf deciduous shrub - boreal	25.11	24.35
C3	C3 grass	7.27	3.00
EXCL	excluded	19.27	17.57

Supplement S4 – Assessment of the representativeness of climate forcing data

The comparison of seNorge and CORDEX estimates of temperature and precipitation in Fig. S5.1 shows that precipitation estimates by CORDEX for the 20 plots were generally higher than seNorge estimates while the converse (but less strongly) was true for temperature.



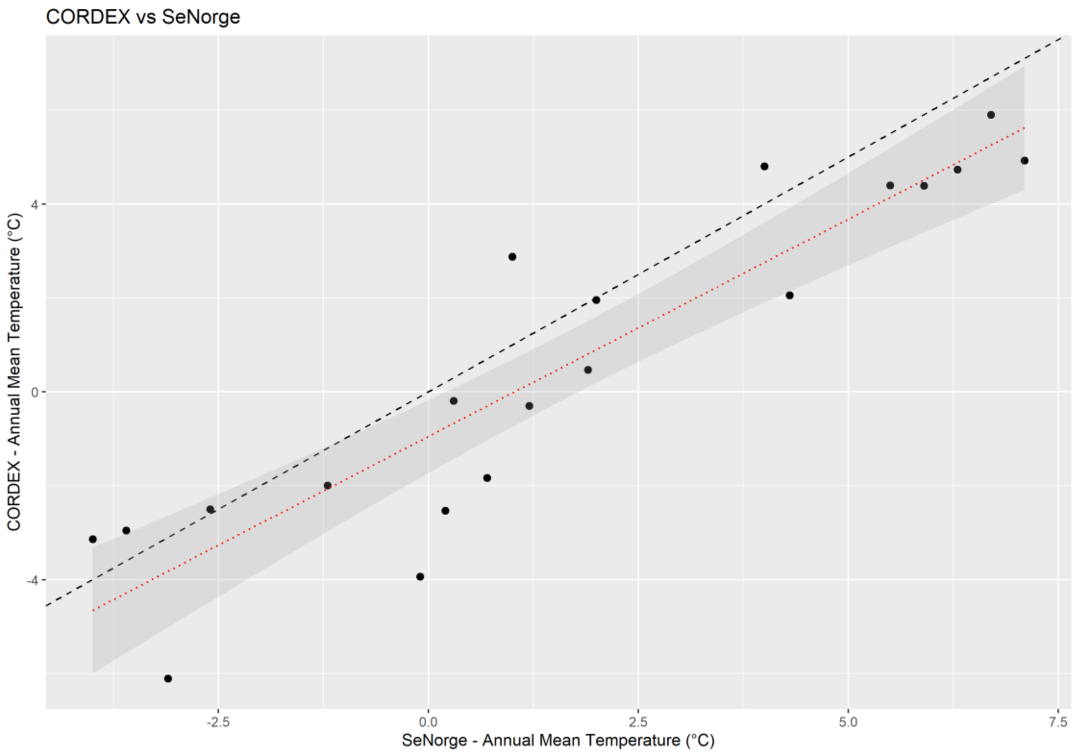


Figure S4 – Scatterplots showing the relationship between temperature and precipitation estimates obtained by the two data sources used in this study; seNorge for DM (see Sect. 2.4.3) on the horizontal axes and CORDEX for climate forcing data used in DGVM (see Sect. 2.4.1) on the vertical axis. The dashed black line represents the 1:1 relationship, while the dotted red line represents a linear model of y~x.

Supplement S5 – PFT Conversion scheme

Table S5– Conversion scheme for harmonizing vegetation and land cover types across methods (RS, DM and AR) into plant functional types (PFTs). DGVM – dynamic global vegetation model, RS – remote sensing, DM – distribution model, AR – reference dataset. PFT – plant functional type and VT – vegetation type.

DGVM		RS	DM	AR
PFT	plant functional type	vegetation / land cover type – remote sensing	vegetation type – distribution model	vegetation type – area frame survey
BG	Bare ground	Exposed alpine ridges, scree and rock complex	Frozen ground, leeward	Frozen ground, leeward
			Frozen ground, ridge	Frozen ground, ridge
			Boulder field	Sand dunes and gravel beaches
			Exposed bedrock	Pioneer alluvial vegetation
				Barren land
				Boulder field
				Exposed bedrock
Boreal NET	Boreal needleleaf evergreen tree	Coniferous forest – dense canopy layer	Lichen and heather pine forest	Lichen and heather pine forest
		Coniferous forest and mixed forest - open canopy	Bilberry pine forest	Bilberry pine forest
		Lichen rich pine forest	Lichen & heather spruce forest	Meadow pine forest
			Bilberry spruce forest	Pine forest on lime soils
			Meadow spruce forest	Lichen & heather spruce forest
			Damp forest	Bilberry spruce forest
			Bog forest	Meadow spruce forest
				Damp forest
				Bog forest
Temperate BDT	Temperate broadleaf deciduous tree	Low herb forest and broadleaved deciduous forest	Poor / Rich broadleaf deciduous forest	Poor broadleaf deciduous forest
				Rich broadleaf deciduous forest
Boreal BDT	Boreal broadleaf deciduous tree	Tall herb - tall fern deciduous forest	Lichen and heather birch forest	Lichen and heather birch forest
		Bilberry- low fern birch forest	Bilberry birch forest	Bilberry birch forest
		Crowberry birch forest	Meadow birch forest	Meadow birch forest
		Lichen-rich birch forest	Alder forest	Birch forest on lime soils
			Pasture land forest	Alder forest
			Poor / rich swamp forest	Pasture land forest
				Poor swamp forest
				Rich swamp forest
Boreal BDS	Boreal broadleaf deciduous shrub	Heather-rich alpine ridge vegetation	Lichen heath	Lichen heath
		Lichen-rich heathland	Mountain avens heath	Mountain avens heath
		Heather- and grass-rich early snow patch communities	Dwarf shrub / Alpine calluna heath	Dwarf shrub heath
		Fresh heather and dwarf-shrub communities (u/l)	Alpine damp heath	Alpine calluna heath
			Coastal heath / Coastal calluna heath	Alpine damp heath
			Damp heath	Flood-plain shrubs
				Coastal heath
				Coastal calluna heath
				Damp heath
				Crags and thicket
C3	C3 grass	Graminoid alpine ridge vegetation	Moss snowbed / Sedge and grass snowbed	Moss snowbed
		Herb-rich meadows (up-/lowland)	Dry grass heath	Sedge and grass snowbed
		Grass and dwarf willow snow-patch vegetation	Low herb / forb meadow	Dry grass heath
				Low herb meadow

				Low forb meadow
				Moist and shore meadows
EXCL	Excluded	Ombrotrophic bog and low-grown swamp vegetation	Bog / Mud-bottom fen and bog	Bog
		Tall-grown swamp vegetation	Deer-grass fen / fen	Deer-grass fen
		Wet mires, sedge swamps and reed beds	Sedge marsh	Fen
		Glacier, snow and wet snow-patch vegetation	Pastures	Mud-bottom fen and bog
		Water		Sedge marsh
		Agricultural areas		Cultivated land
		Cities and built-up areas		Pastures
		Unclassified and shadow affected areas,		Built-up areas
				Scattered housing
				Artificial impediment
				Glaciers and perpetual snow
				Sea and ocean
				Water bodies (fresh)

Supplement S6 – Sampling design – RS, DM and AR

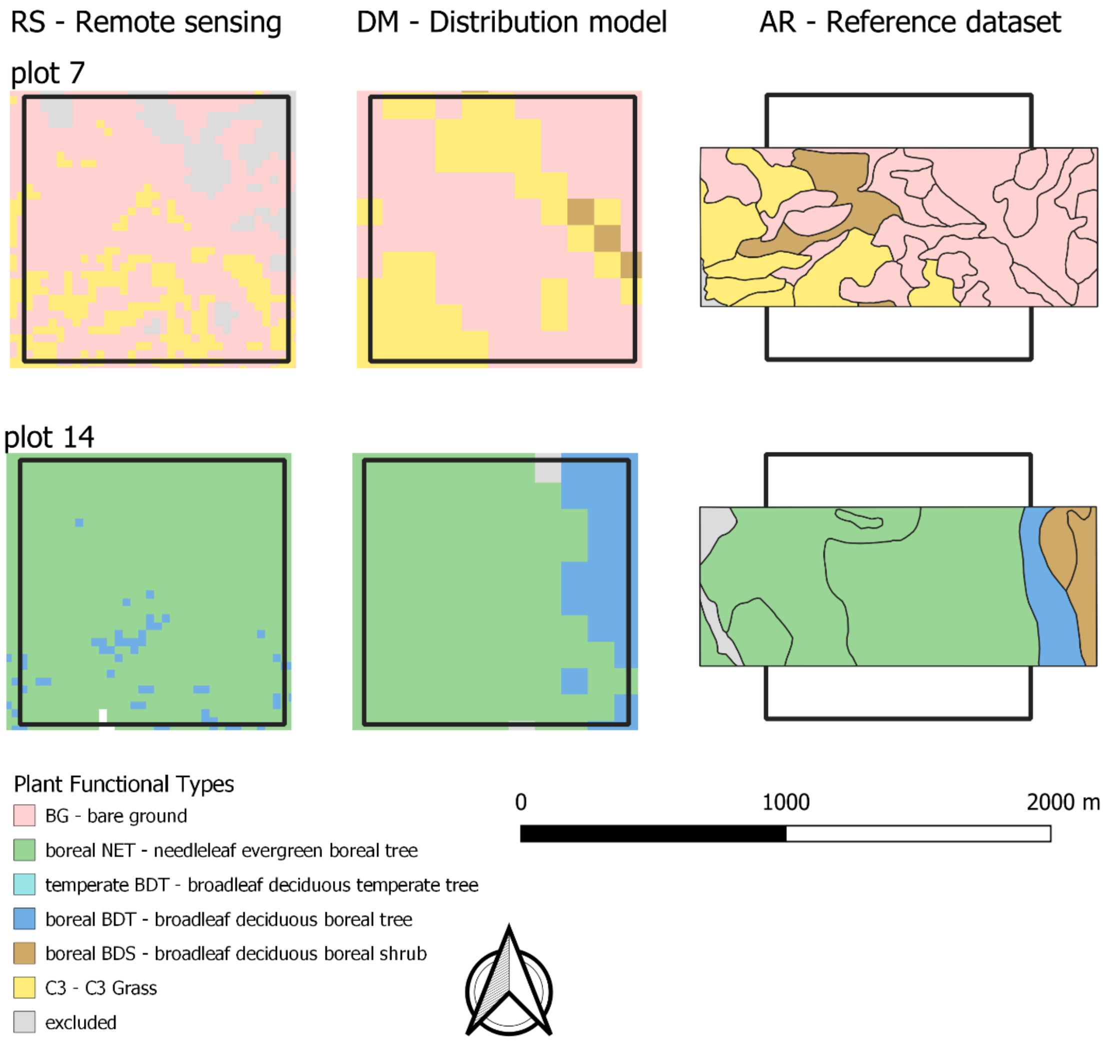


Figure S6 – Sampling design used by the remote sensing (RS) and distribution modelling (DM) methods and to obtain the AR reference dataset. Like DGVM plots (see Fig. S7), the RS and DM plots are 1×1 km, while the AR plots are 1.5×0.6 km. Plots 7 and plot 14 (AR18×18 plot #1322 and plot #2425) are used as examples.

Supplement S7 – DGVM parameters for PFTs (CLM4.5-BGCDV)

Table S7 – Some important PFT parameter settings for DGVM (CLM4.5-DV). PFTs relevant for the study area (Norway) are shaded grey. Prescribed heights for the canopy are indicated by the upper and lower limits in columns "ztop" and "zbot" respectively. Limiting temperatures for survival and establishment are mentioned in columns "Tc,min" and "Tc,max" respectively. Minimum growing degree days for establishment are contained for relevant PFTs in column "GDDmin". The last three columns contain the new parameter thresholds used in the sensitivity experiment. swe_10 – snow water equivalent in October (mm); tmin_5 – minimum temperature in May (°C) bioclim_15 – precipitation seasonality (coefficient of variation).

		Prescribed heights		Survival	Establishment		Sensitivity tests		
Plant functional type (PFT)	Acronym	ztop (m)	zbot (m)	Tc,min (°C)	Tc,max (°C)	GDDmin	swe_10 (mm)	tmin_5 (°C)	bioclim_15
Needleleaf evergreen tree – temperate	Temp NET	17	8.5	–2	22	900			
Needleleaf evergreen tree – boreal	Boreal NET	17	8.5	–32.5	–2	600	150	–5	50
Needleleaf deciduous tree – boreal	Boreal NDT	14	7						
Broadleaf evergreen tree – tropical	Trop BET	35	1	15.5	No limit	0			
Broadleaf evergreen tree – temperate	Temp BET	35	1	3	18.8	1200			
Broadleaf deciduous tree – tropical	Trop BDT	18	10	15.5	No limit	0			
Broadleaf deciduous tree – temperate	Temp BDT	20	11.5	–17	15.5	1200			
Broadleaf deciduous tree – boreal	Boreal BDT	20	11.5	No limit	–2	350	180	–7.5	
Broadleaf evergreen shrub – temperate	Temp BES	0.5	0.1						
Broadleaf deciduous shrub – temperate	Temp BDS	0.5	0.1	–17	No limit	1200			
Broadleaf deciduous shrub – boreal	Boreal BDS	0.5	0.1	No limit	–2	350	380	–10	
C3 arctic grass	C3 A	0.5	0.01	No limit	–17	0			
C3 grass	C3	0.5	0.01	–17	15.5	0			
C4 grass	C4	0.5	0.01	15.5	No limit	0			
Non vegetated/bare ground	BG								

Supplement S8 – Representation of grid-cells in the CLM 4.5 model

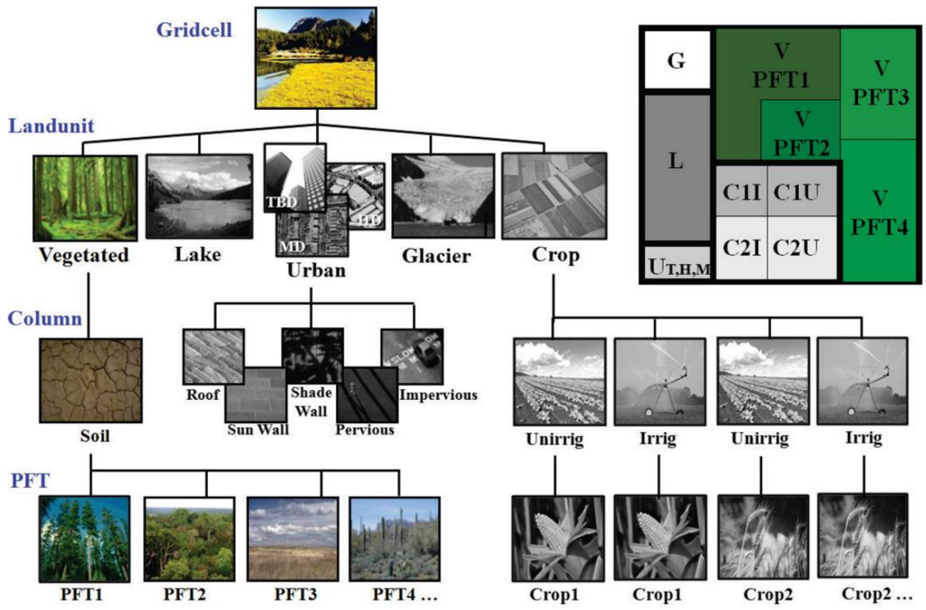


Figure S8 – Representation of a grid-cell in the DGVM model (obtained by CLM4.5-BGCDV method); figure adapted from Oleson et al. (2013). Land units in grey (lake, urban, glacier and crop) were excluded from this study.

Supplement S9 – DM- and RS-units reclassified to PFT units

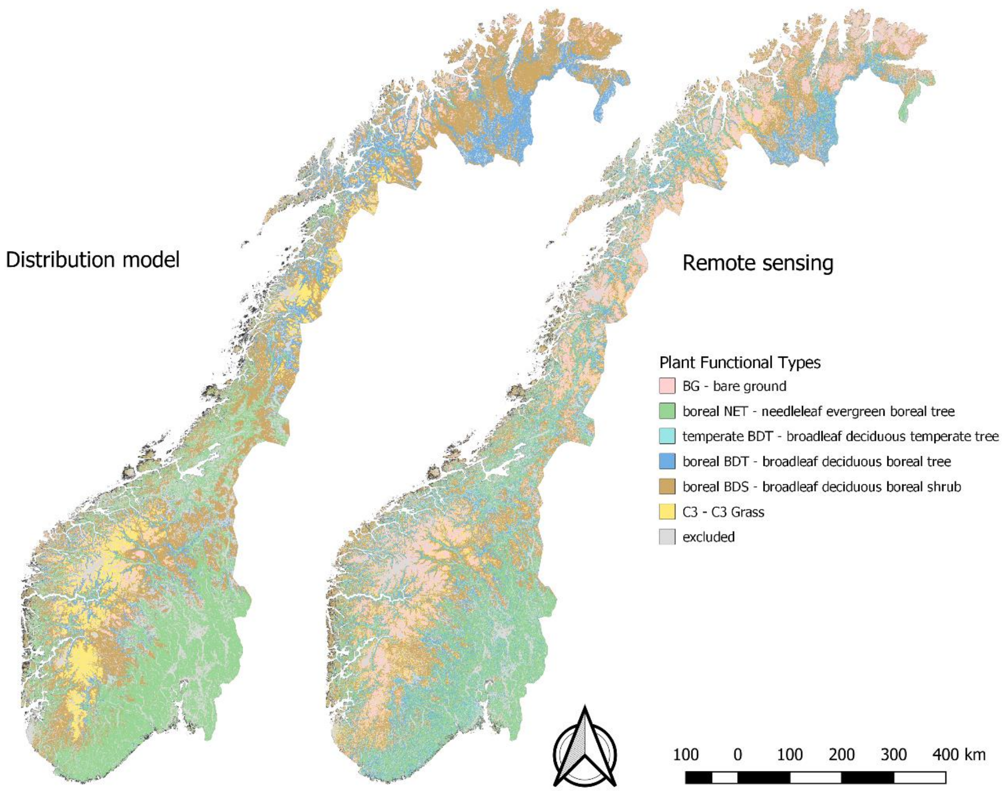


Figure S9– The distribution in Norway of vegetation types (used in distribution modelling – DM) and units obtained by remote sensing (RS), after reclassification to PFT units (see Table S5 for conversion scheme and explanation of PFT codes). The dominating PFT in each grid cell (of 100×100 m for DM and 30×30 m for RS) is shown.

The distributions in Norway of PFTs obtained by conversion of DM- and RS-units using the conversion scheme in Table S5 exhibit considerable similarities (Fig. S8). Both methods show dominance of boreal needleleaf evergreen forest (boreal NET) in south-eastern Norway, while most of the western and northern Norway is covered by boreal broadleaf deciduous shrub (boreal BDS) and boreal broadleaf deciduous forest (boreal BDT). Slight differences between the two methods can be seen in the western mountainous part of Norway, where DM predicts dominance by C3 grasses where RS suggests bare ground, and in North Norway where DM predicts boreal BDS where RS predicts bare ground. Accordingly, the fractional area classified to PFTs that are converted to bare ground is three times higher with RS than with DM (Table S8). Full resolution raster images are available at the Dryad repository (https://doi.org/10.5061/dryad.dfn2z34xn).

Table S9 – Area statistics for Norway for vegetation types (used in distribution modelling – DM) and units obtained by remote sensing (RS), after reclassification to PFT units (see Table S5 for conversion scheme and explanation of PFT codes).

	RS (%)	DM (%)
BG	17.1	5.6
Boreal NET	25.3	31.4
Temperate BDT	5.2	0.1
Boreal BDT	16.9	15.0
Boreal BDS	27.9	39.0
C3	7.5	8.9

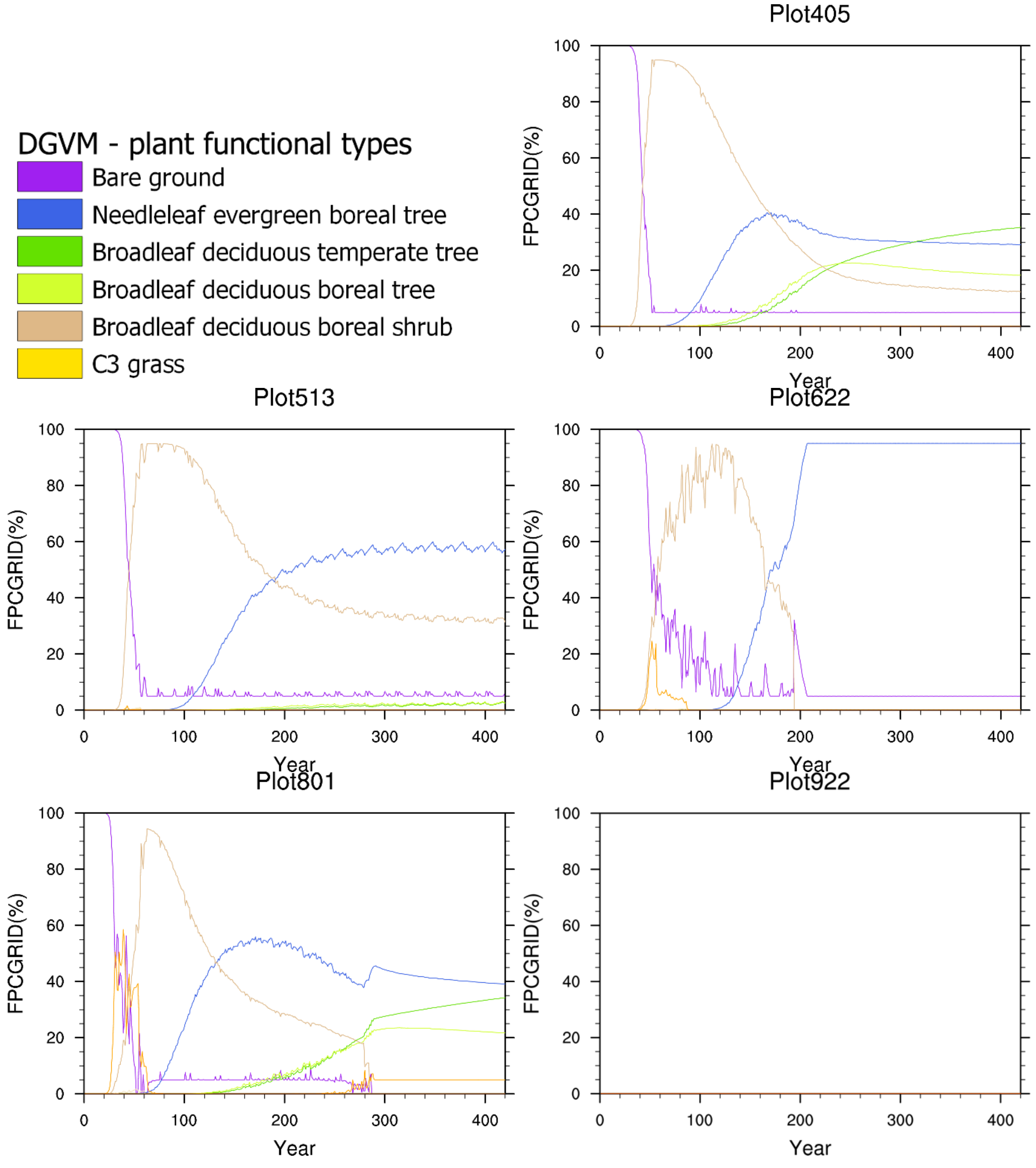
Supplement S10 – PFT profiles for each of the 20 plots

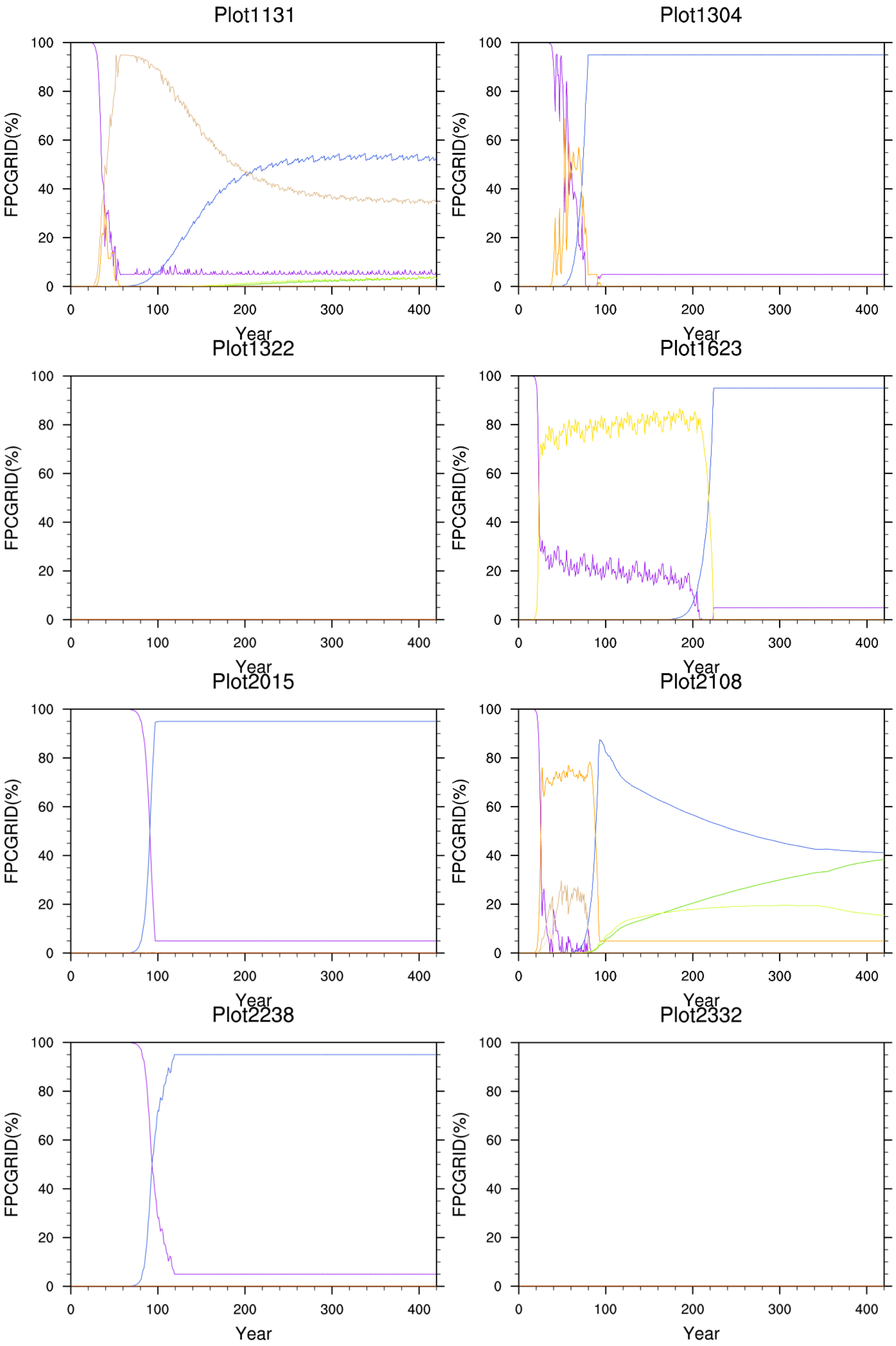
Table S10– PFT profiles (percentage of vegetated land assigned to each of six PFTs) for each of the 20 plots in this study, obtained by remote sensing (RS) and distribution modelling (DM) methods and for the AR reference dataset. Original units (vegetation types, etc.) are converted to PFTs by use of the scheme in Table S5.

Method	PFT shortcut	plot 3	plot 2	plot 1	plot 6	plot 4	plot 5	plot 8	plot 7	plot 9	plot 10	plot 12	plot 11	plot 13	plot 14	plot 16	plot 15	plot 17	plot 18	plot 19	plot 20
DGVM	BG	5	6	5	0	100	6	5	100	5	5	0	5	100	5	100	5	28	5	100	5
DGVM	boreal NET	29	58	95	39	0	52	95	0	95	95	41	95	0	95	0	92	72	95	0	95
DGVM	temp. BDT	35	2	0	34	0	4	0	0	0	0	38	0	0	0	0	0	0	0	0	0
DGVM	boreal BDT	18	2	0	22	0	4	0	0	0	0	16	0	0	0	0	0	0	0	0	0
DGVM	boreal BDS	13	32	0	0	0	35	0	0	0	0	0	0	0	0	0	3	0	0	0	0
DGVM	C3	0	0	0	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
RS	BG	9	7	4	0	92	8	0	78	0	0	0	0	7	3	24	52	0	1	54	1
RS	boreal NET	30	2	0	75	0	0	68	0	93	75	69	91	0	86	0	0	20	0	0	70
RS	temp. BDT	6	0	0	6	0	0	15	0	0	2	7	1	0	0	0	0	0	0	0	1
RS	boreal BDT	2	1	1	19	0	0	17	0	7	22	20	8	0	8	0	0	48	68	0	28
RS	boreal BDS	18	68	80	0	1	85	0	0	0	1	3	0	78	3	35	37	28	30	9	1
RS	C3	35	23	14	0	7	7	0	22	0	0	1	0	16	0	41	11	3	0	37	0
DM	BG	0	8	0	0	2	0	0	70	0	0	0	0	0	0	0	33	0	0	46	0
DM	boreal NET	60	1	0	100	0	0	96	0	47	100	100	100	0	72	0	0	0	0	0	0
DM	temp. BDT	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
DM	boreal BDT	0	0	0	0	0	0	0	0	53	0	0	0	0	23	0	0	77	91	0	100
DM	boreal BDS	40	91	100	0	0	100	0	3	0	0	0	0	100	4	100	63	23	9	54	0
DM	C3	0	0	0	0	98	0	0	26	0	0	0	0	0	0	0	4	0	0	0	0
AR	BG	0	4	0	0	87	0	0	66	0	0	0	0	0	0	11	13	0	0	78	0
AR	boreal NET	63	0	0	79	0	0	79	0	82	84	83	86	0	82	1	0	0	0	0	97
AR	temp. BDT	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
AR	boreal BDT	9	12	35	21	0	0	11	0	18	16	17	14	5	9	3	0	66	70	0	3
AR	boreal BDS	28	75	63	0	0	99	0	10	0	0	0	0	87	9	79	83	34	30	18	0
AR	C3	0	9	1	0	13	1	0	25	0	0	0	0	8	0	6	5	0	0	3	0

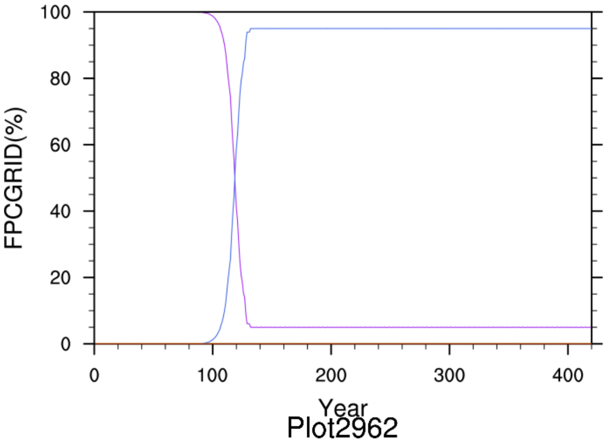
Supplement S11 – DGVM spin-up and simulation of PFT profiles for each plot

DGVM spin-up for 400 years and 20 years of simulation of PFT profiles for each of the 20 plots used in this study. For plots #801, #2108 and #4268, the spin-up was extended by additional 400, 200 and 200 years respectively.

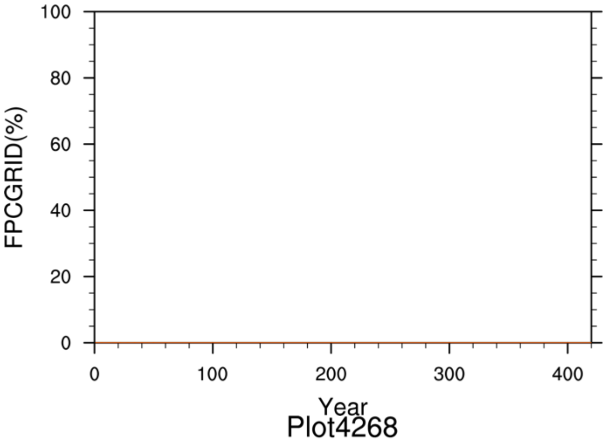



Plot1131
Plot1304
Plot1322
Plot1623
Plot2015
Plot2108
Plot2238
Plot2332
FPCGRID(%)
Year
0
20
40
60
80
100
0
100
200
300
400

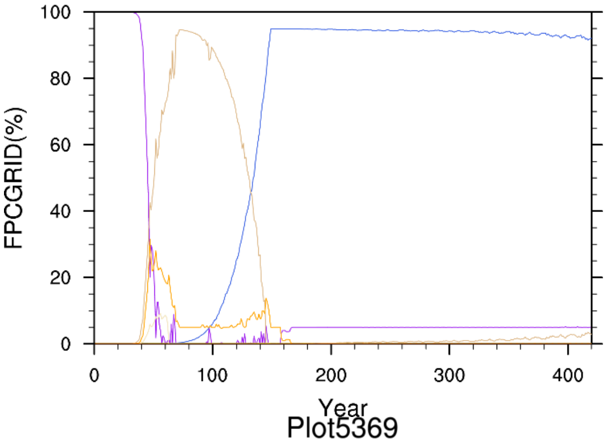
Plot2425



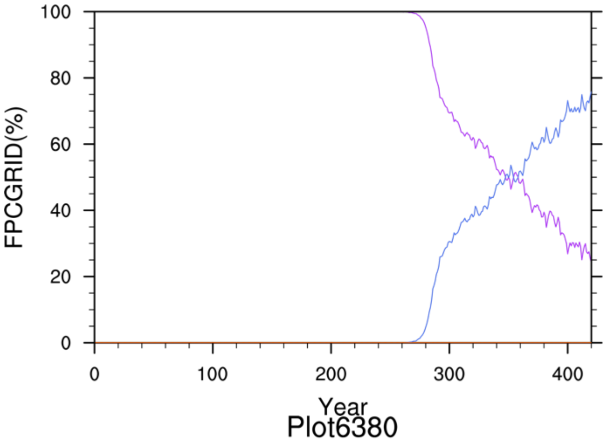
Plot2948



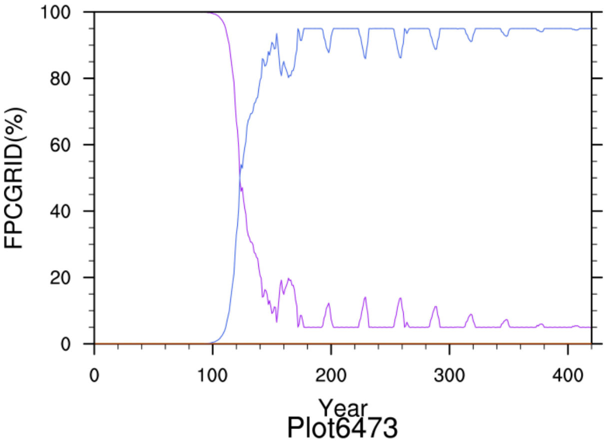
Plot2962



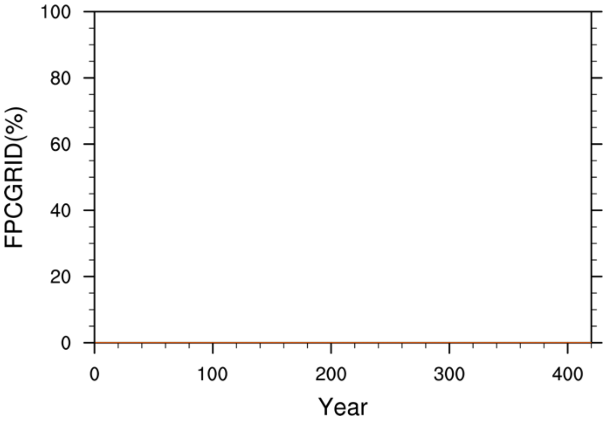
Plot4268



Plot5369



Plot6380



Plot6473

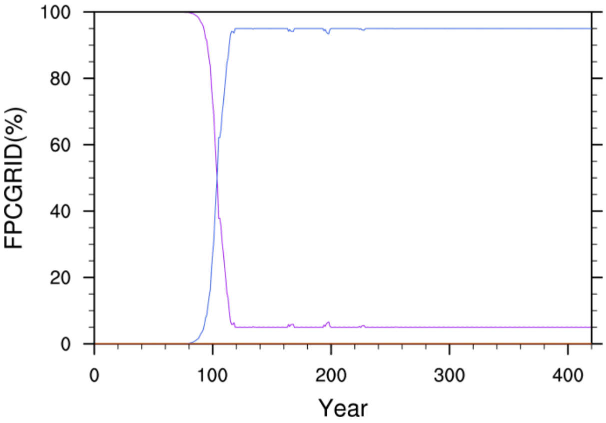


Figure S11.1 – DGVM spin-up for 400 years and simulation of PFT profiles for each of the 20 plots used in this study. FPCGRID – estimated percentage per PFT per grid cell. Reference number of plots accords with the AR18×18 dataset, and plot numbers can be found in Table S1.

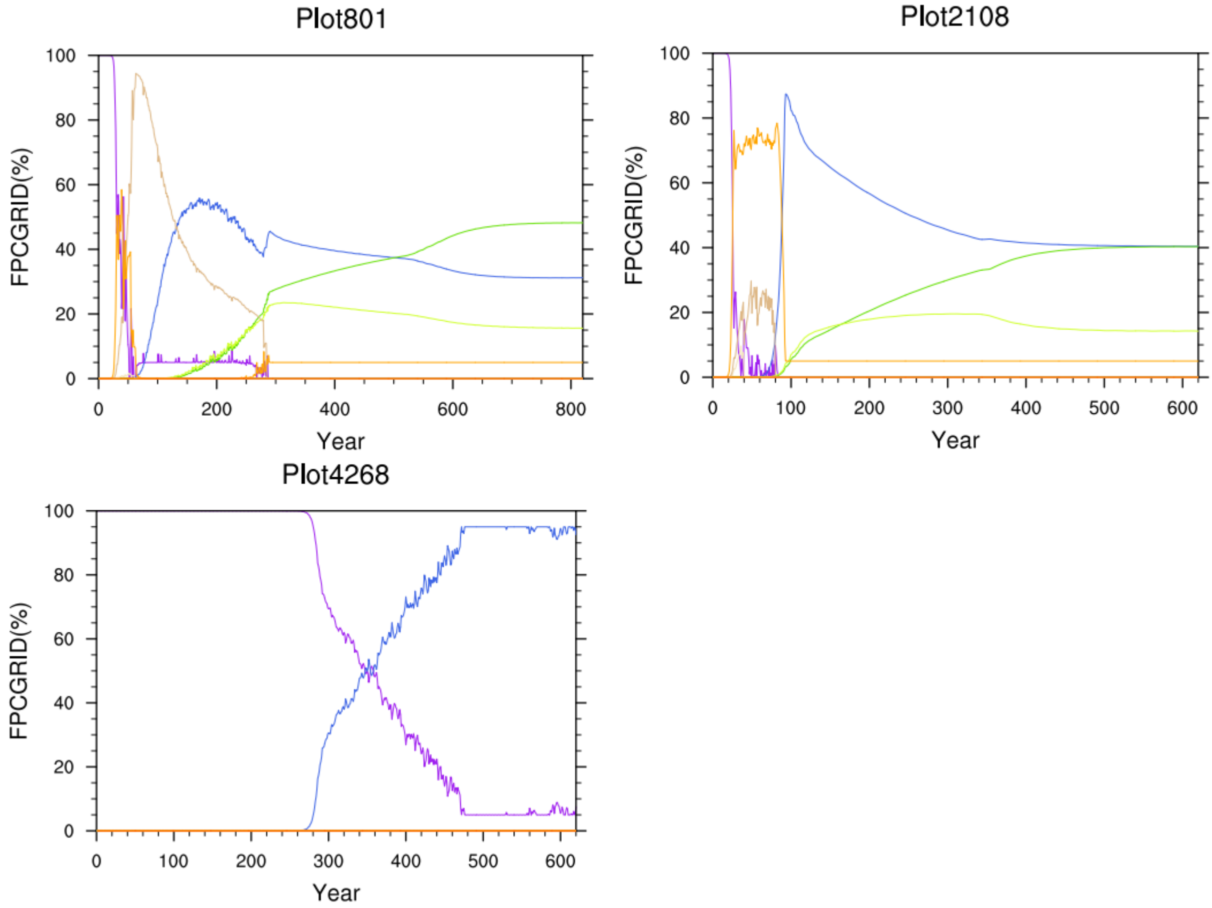


Figure S11.2 – Three plots (number 6, 12, 17) where DGVM spin-up was prolonged beyond 400 years and simulation of PFTs was extended by 400, 200 and 200 years respectively in order to check for equilibrium. FPCGRID – estimated percentage per PFT per grid cell. Reference number of plots accords with the AR18×18 dataset, and plot numbers can be found in Table S1

Supplement S12 – Sensitivity experiments: frequency-of-presence (FoP) plots

Frequency-of-presence (FOP) plots based upon output from distribution models (DM) for the nine combinations of three environmental variables and three vegetation types modelled, used to indicate threshold values that were explored in the sensitivity experiments, are shown in Fig. S11. Thresholds for new variables in DGVM models were chosen based upon visual inspection of the FoP plots. For example, while boreal BDS are abundant below swe_10 value of 380mm, boreal BDT and boreal NET are abundant at values of swe_10 below 180mm and 150mm respectively. Also, while we identified no clear threshold of variable bioclim_15 for boreal BDS and BDT (frequency of presence is never zero along the variable x-axis - lower left and middle panel of Fig S12), threshold for boreal NET was set to 50 (a value above which no presences occur - lower right panel of Fig S12).

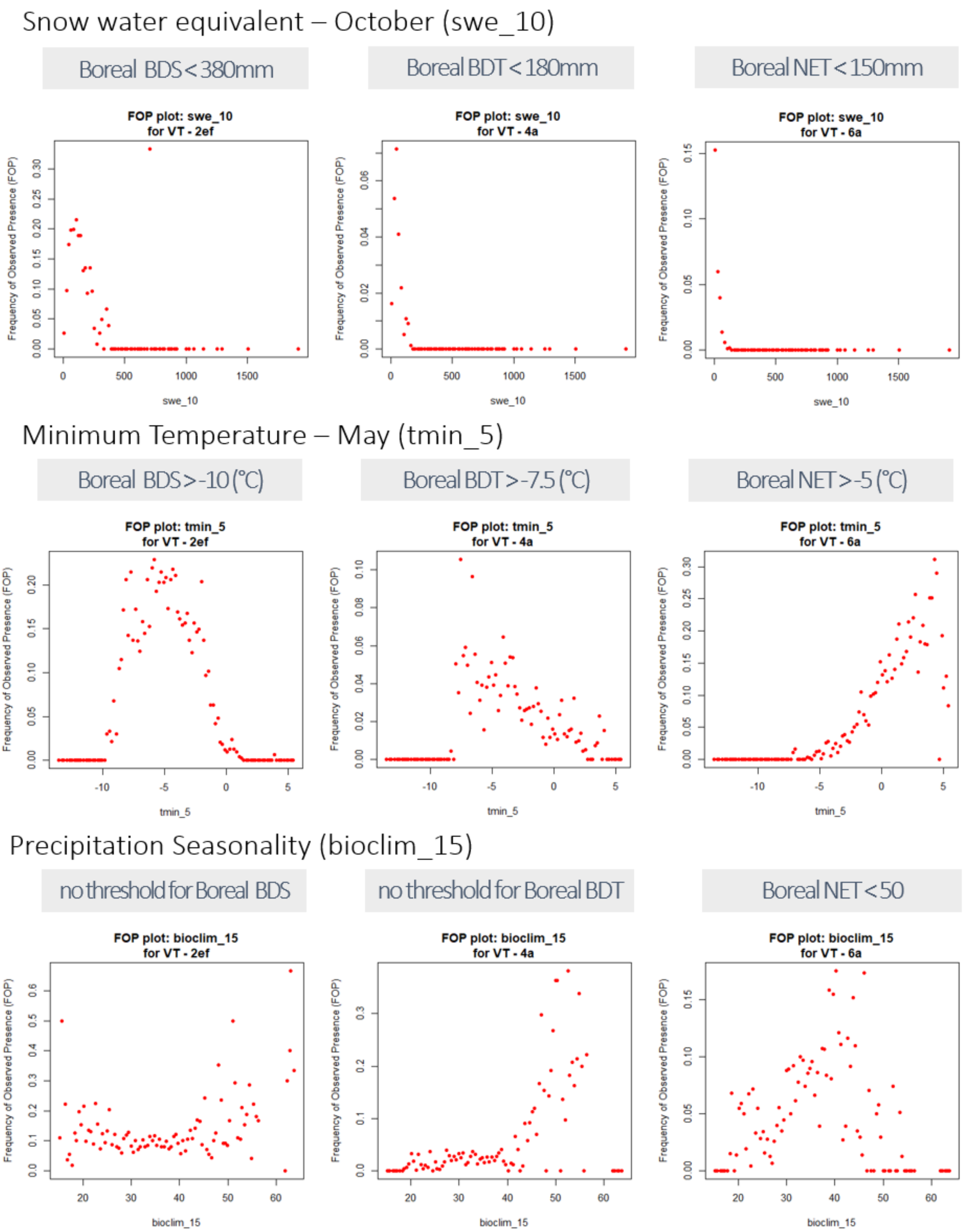


Figure S12 – Frequency-of-presence plots from the distribution modelling (DM) study by Horvath et al. (2019) for the combinations of environmental predictors and vegetation types (VTs) used in the sensitivity experiments with DGVM. FOP is the frequency of 100×100 m pixels in the AR18×18 dataset in which the VT in question is present, expressed as a fraction of all pixels in that interval along the environmental variable. All environmental variables were a priori divided into 100 intervals with the same number of pixels. The environmental gradients were: swe_10 – snow water equivalent in October (mm); tmin_5 –- minimum temperature in May (°C); bioclim_15 – precipitation seasonality (unitless index). Boreal BDS – boreal broadleaf deciduous shrubs, Boreal BDT - boreal broadleaf deciduous trees, Boreal NET - boreal needleleaf evergreen shrubs.

Supplement S13 – Sensitivity experiments: results

Table S13 – PFT profiles for the six out of the 20 plots (plot numbers 1, 2, 5, 15, 17, 18) which were included in the sensitivity experiments, for four 'generations' of DGVM parameter settings and the AR reference dataset. From left to right the column represent: DGVM before addition of parameter thresholds; DGVM_adj1 after first adding parameter threshold of swe_10; DGVM_adj2 after also adding parameter threshold of tmin_5; DGVM_adj3 after finally adding parameter threshold of bioclim_15; and the PFT profile of the reference dataset AR. All parameter thresholds were added cumulatively. Full names for the PFTs are given in Table S7 and names of parameters and their values in Table 3.

	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR	DGVM	DGVM adj1	DGVM adj2	DGVM adj3	AR
	plot 1					plot 2					plot 5					plot 15					plot 17					plot 18				
BG	5	5	5	9	0	6	5	5	5	4	6	6	6	7	0	5	5	5	3	13	28	100	100	100	0	5	100	100	100	0
boreal NET	95	95	95	0	0	58	58	58	0	0	52	52	52	0	0	92	92	92	0	0	72	0	0	0	0	95	0	0	0	0
temp. BDT	0	0	0	0	0	2	2	2	33	0	4	4	4	13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
boreal BDT	0	0	0	0	35	2	2	2	31	12	4	4	4	13	0	0	0	0	2	0	0	0	0	0	66	0	0	0	0	70
boreal BDS	0	0	0	91	63	32	32	32	31	75	35	35	35	67	99	3	3	3	89	83	0	0	0	0	34	0	0	0	0	30
C3	0	0	0	0	1	0	0	0	0	9	0	0	0	0	1	0	0	0	6	5	0	0	0	0	0	0	0	0	0	0