Ozone causes substantial reductions in the carbon sequestration of managed European forests

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Supplementary information

Table S1. DO$_3$SE stomatal flux model parameterisation for each bioregion (NE = Northern Europe; ACE = Atlantic Central Europe; CCE = Continental Central Europe; M = Mediterranean) specific species.

Parameter	Units	Birch (NE)	Norway Spruce (NE)	Temperate Oak (ACE) **	Scots pine (ACE) **	Beech (CCE)	Norway spruce (CCE)	Mediterranean Deciduous oak (M)	Mediterranean Evergreen oak (M)
Canopy height (h)	m	20	20	25	20	25	20	20	20
Root depth (RD)	m	1	1	1	1	2	2	2	2
Leaf dimension (l)	m	0.05	0.008	0.05	0.008	0.07	0.008	0.042	0.03
Albedo (A) ‡	fraction	0.16	0.12	0.16	0.12	0.16	0.12	0.16	0.12
gmax	mmol O3 m-2 PLA s-1	240	125	225	190	155	130	265	195
fmin	fraction	0.1	0.1	0.06	0.1	0.13	0.16	0.13	0.02
light_a	fraction	0.0042	0.006	0.003	0.006	0.006	0.01	0.006	0.012
Tmin	fraction	5	0	0	0	5	0	0	1
Topt	fraction	20	20	20	20	16	14	22	23
Tmax	fraction	200	200	35	36	33	35	35	39
VPDmax	fraction	0.5	0.8	1	0.6	1	0.5	1.1	2.2
VPDmin	fraction	2.7	2.8	3.25	2.8	3.1	3	3.1	4
SWPmin	fraction	-1.5	-1.5	-1.5	-1.5	-4	-4	-4	-4
SWPmax	fraction	-0.5	-0.5	-0.5	-0.5	-1	-1	-1	-1

ASWmin	% ASW	75	75	75	75	75	75	75	75
ASWmax	% ASW	100	100	100	100	100	100	100	100
LAI at SGS	m2/m2	0	5	0	5	0	5	4	4
LAI_b	m2/m2	4	5	4	5	4	5	4	4
LAI_c	m2/m2	4	5	4	5	4	5	4	4
LAI at EGS	m2/m2	0	5	0	5	0	5	4	4
LAI_1	days	15	30	20	30	15	30	20	30
LAI_2	days	30	30	30	30	20	30	30	30
fphen at SGS	days	0	0	0	0.8	0.4	0	0.3	1
fphen_b	fraction	1	1	1	1	1	1	1	1
fphen_c	fraction	1	1	1	1	1	1	1	0.31
fphen_d	fraction	1	1	1	1	1	1	1	1
fphen at EGS	fraction	0	0	0	0.8	0.4	0	0.3	1
fphen_1	days	20	20	15	20	20	0	15	0
fphen_4	days	30	30	30	40	20	0	20	0
Rsoil	s/m	200	200	200	200	200	200	200	200

N.B. The values come from a variety of sources; those values that are not sourced from UNECE LRTAP Mapping Manual 2017 are indicated as follows: ** From Bueker et al. 2015; ǂ Simpson et al 2012.

Table S2. Details of the selection of species- or PFT-specific DO$_3$SE stomatal flux model parameterisation and dose response relationships (DRRs) used for i). GAI and ii). Whole tree biomass for each bioregion. Details are also provided of the associated species coverage by EMEP grid, with the value in parenthesis after each bioregion.

Bioregion (no. of EMEP grids)	Land cover type	Stomatal flux model parameterisation	GAI DRR (*Developed in this paper*)	Whole tree biomass DRR	% land cover coverage in bioregion
Alpine (251)	Birch Norway spruce Other deciduous Other coniferous Mixed	Birch (NE) Norway spruce (NE) Birch (NE) Norway spruce (NE) Birch (NE) & Norway spruce (NE)	Beech/Birch Norway spruce/Scots pine Broadleaf deciduous Needleleaf Broadleaf deciduous & Needleleaf	Beech/Birch* Norway spruce* Broadleaf deciduous** Needleleaf ** Broadleaf deciduous & Needleleaf**	11% 37% 19% 24% 9%
Arctic (4)	Birch Mixed	Birch (NE) Birch & Norway spruce	Beech/birch Broadleaf deciduous & Needleleaf	Beech/Birch* Broadleaf deciduous & Needleleaf**	90% 10%
Atlantic (515)	Temperate Oak Scots pine Other deciduous Other coniferous Mixed	Temperate oak (ACE) Scots pine (ACE) Beech (CCE) Norway spruce (CCE) Beech (CCE) & Norway spruce (CCE)	Temperate deciduous oak Norway spruce/Scots pine Broadleaf deciduous Needleleaf Broadleaf deciduous & Needleleaf	Broadleaf deciduous** Needleleaf** Broadleaf deciduous** Needleleaf** Broadleaf deciduous & Needleleaf**	16% 13% 27% 30% 15%
Black sea (9)	Beech Other deciduous Other coniferous Mixed	Beech (CCE) Mediterranean deciduous oak (M) Mediterranean evergreen oak (M) Mediterranean deciduous oak (M) & Mediterranean Evergreen oak (M)	Beech/birch Broadleaf deciduous Aleppo pine/Holm oak Aleppo pine/Holm oak	Beech/birch* Mediterranean deciduous oak* Mediterranean evergreen* Mediterranean deciduous oak & Mediterranean evergreen*	23% 9% 49% 20%
Boreal (416)	Birch	Birch (NE)	Beech/birch	Beech/birch*	7%

	Norway spruce Scots pine Other deciduous Other coniferous Mixed	Norway spruce (NE) Scots pine (ACE) Birch (NE) Norway spruce (NE) Birch (NE) & Norway spruce (NE)	Norway spruce/Scots pine Norway spruce/Scots pine Broadleaf deciduous Needleleaf Broadleaf deciduous & Needleleaf	Norway spruce* Norway spruce* Needleleaf** Beech/birch Beech/birch & Norway spruce*	32% 46% 9% 5% 1%
Continental (613)	Beech Norway spruce Scots pine Other deciduous Other coniferous Mixed	Beech (CCE) Norway spruce (CCE) Scots pine (ACE) Beech (CCE) Norway spruce (CCE) Beech (CCE) & Norway spruce (CCE) & Scots pine (ACE)	Beech/birch Norway spruce/Scots pine Norway spruce/Scots pine Broadleaf deciduous Needleleaf Broadleaf deciduous	Beech/birch* Norway spruce* Needleleaf** Beech/birch* Norway spruce* Broadleaf deciduous & Needleleaf**	13% 16% 23% 18% 13% 15%
Mediterranean (507)	Mediterranean deciduous oak Mediterranean evergreen Other deciduous Other coniferous Mixed	Mediterranean deciduous oak (M) Mediterranean evergreen oak (M) Mediterranean deciduous oak (M) Mediterranean evergreen oak (M) Mediterranean deciduous oak (M) & Mediterranean Evergreen oak (M)	Broadleaf deciduous Aleppo pine/Holm oak Broadleaf deciduous Aleppo pine/Holm oak Broadleaf deciduous & Aleppo pine/Holm oak	Mediterranean deciduous oak* Mediterranean evergreen* Mediterranean deciduous oak* Mediterranean evergreen* Mediterranean deciduous oak* & Mediterranean evergreen*	4% 27% 34% 22% 14%
Pannonian (57)	Other deciduous Other coniferous Mixed	Beech (CCE) Norway spruce (CCE) Beech CCE & Norway spruce (CCE)	Broadleaf deciduous Needleleaf Broadleaf deciduous & Needleleaf	Broadleaf deciduous** Needleleaf** Broadleaf deciduous** & Needlelead**	41% 26% 33%
Steppic	Beech Temperate oak	Beech (CCE) Temperate Oak (ACE)	Beech/birch Oak deciduous	Beech/birch* Broadleaf deciduous**	9% 23%

	Other deciduous	Beech (CCE)	Broadleaf deciduous	Broadleaf deciduous**	29%
	Other coniferous	Norway spruce (CCE)	Needleleaf	Needleleaf**	19%
	Mixed	Beech (CCE) & Norway spruce (CCE)	Broadleaf deciduous & Needleleaf	Broadleaf deciduous** & Needleleaf**	20%

N.B. * DRRs from UNECE LRTAP Mapping Manual 2017; ** DRRs from Bueker et al. 2015.

Table S3. Dose response relationships (DRRs) for POD_1SPEC for i. GAI and ii. Whole tree biomass by bioregion specific species.

Bioregion specific species	GAI DRRs	R^2	Whole tree biomass DRRs	R^2
Beech/Birch	y = -0.0093x + 0.9461	0.59	y = -0.0093x + 1.002	0.67
Norway spruce	-		y = -0.0022x + 0.998	0.31
Norway spruce/Scots pine	y = -0.0057x + 1.0015	0.56	-	
Oak (deciduous)	y = -0.0057x + 1.0167	0.75	-	
Aleppo pine/Holm oak	y = -0.0047x + 1.001	0.64	-	
Mediterranean oak	-		y = -0.0032x + 1.003	0.41
Mediterranean evergreen*	-		y = -0.0009x + 0.998	0.42
PFTs				
Broadleaf deciduous	y = -0.0066x + 0.9381	0.47	y = -0.0057x + 0.9388	0.42
Needleleaf	y = -0.0052x + 0.999	0.69	y = -0.0044x + 0.9988	0.68

N.B. *Refers to above ground biomass

Relative GAI DRRs for all species and PFTs.

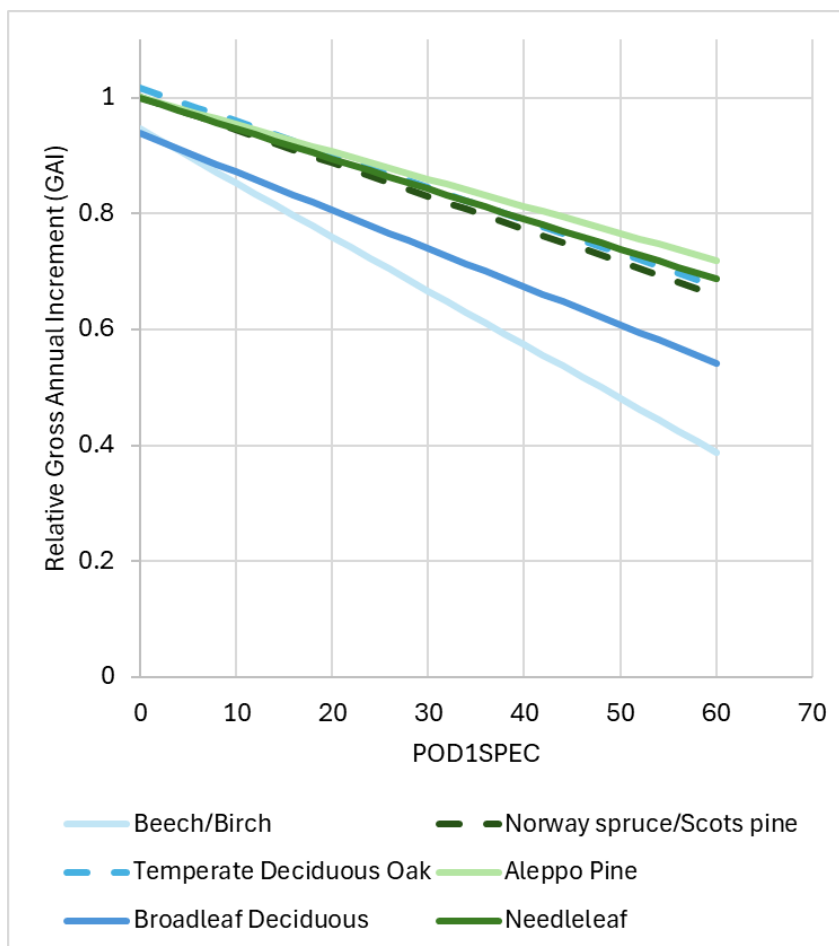



Figure S1. The 'default', 'minimum' (min) and 'maximum' (max) parameterisations of the Richards equation (Richards, 1959; Nishizono, 2010) in relation to European Forest data collected from the literature representing five countries (Sweden (S), Finland (FIN), Austria (AT), Switzerland (CZ) and Germany (G)); and 6 forest genera (*Pinus, Betula, Picea, Larix, Fagus, Abies*) (c.f. Fellner & Rechberger, 2009; Mund et al., 2002). All biomass data are scaled to equal 1 at a stand age of 100 years to allow comparison of the growth profiles.

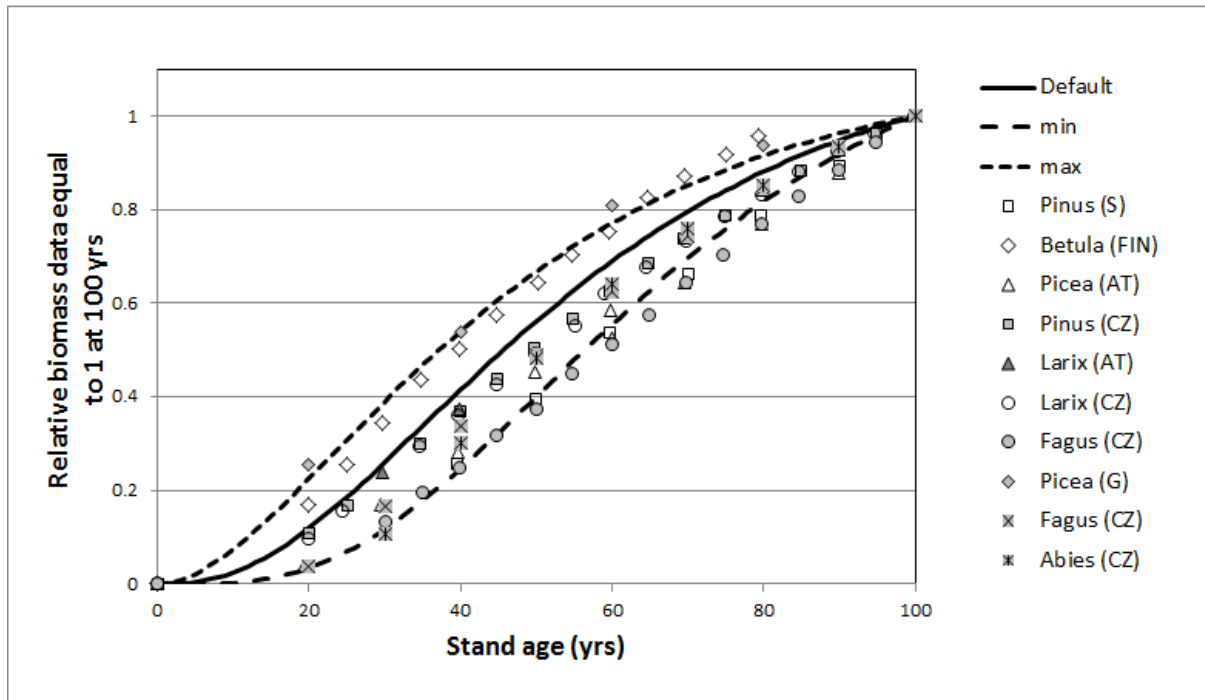



Figure S2. The spatial distribution of the estimated POD$_1$SPEC across Europe assuming no soil water stress (NSW), separately for coniferous and deciduous tree species for annual mean values for the period 2008-2012 (a, c) and as the difference in maximum and minimum POD$_1$SPEC values across the years 2008-2012 (b, d).

(a) (b)

(c) (d)

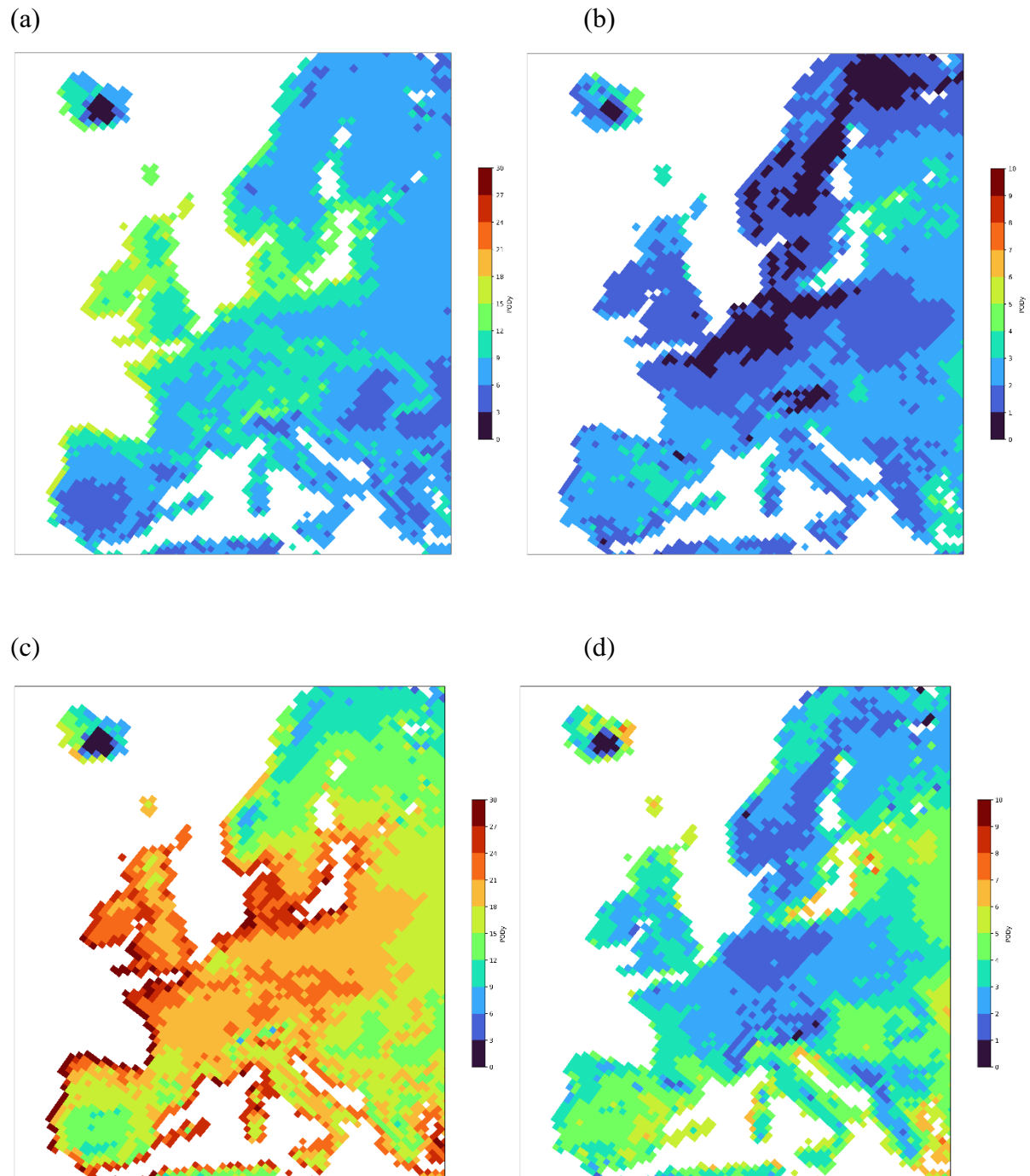



Figure S3. Dose-response relationships based on POD_1SPEC for assessments based on the estimated impacts on tree growth rates (Relative GAI) for other species and PFT dose-response relationships.

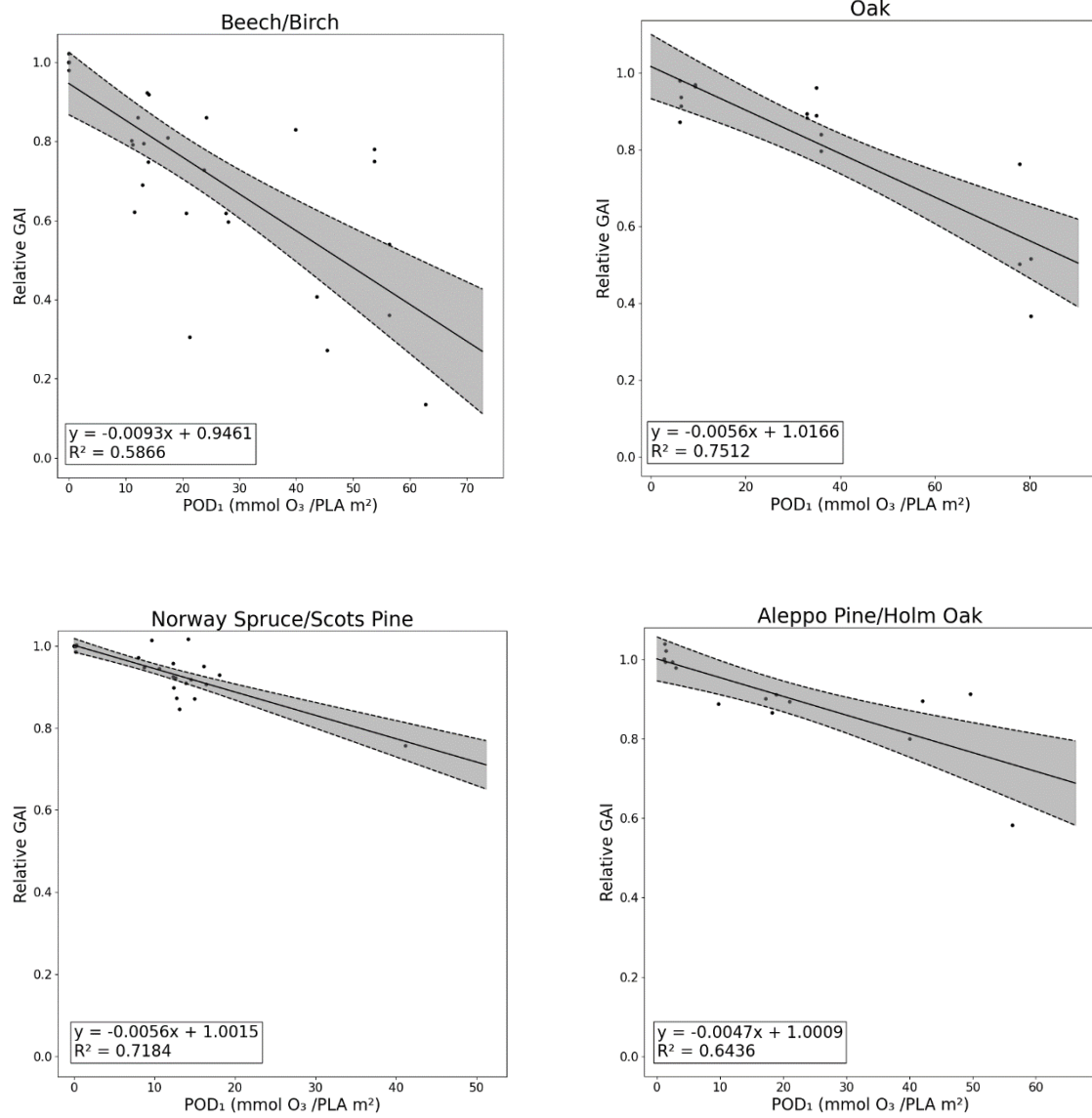



Figure S4a. The limits to POD$_1$SPEC from f_{temp} for individual species and all years (2008-2012) across Europe. Colour scale from red (1) to blue (0).

Birch_NE

Norway spruce_NE

Scots pine

Norway spruce_CCE

Temperature Oak

Beech

Mediterranean Deciduous Oak

Mediterranean evergreen oak

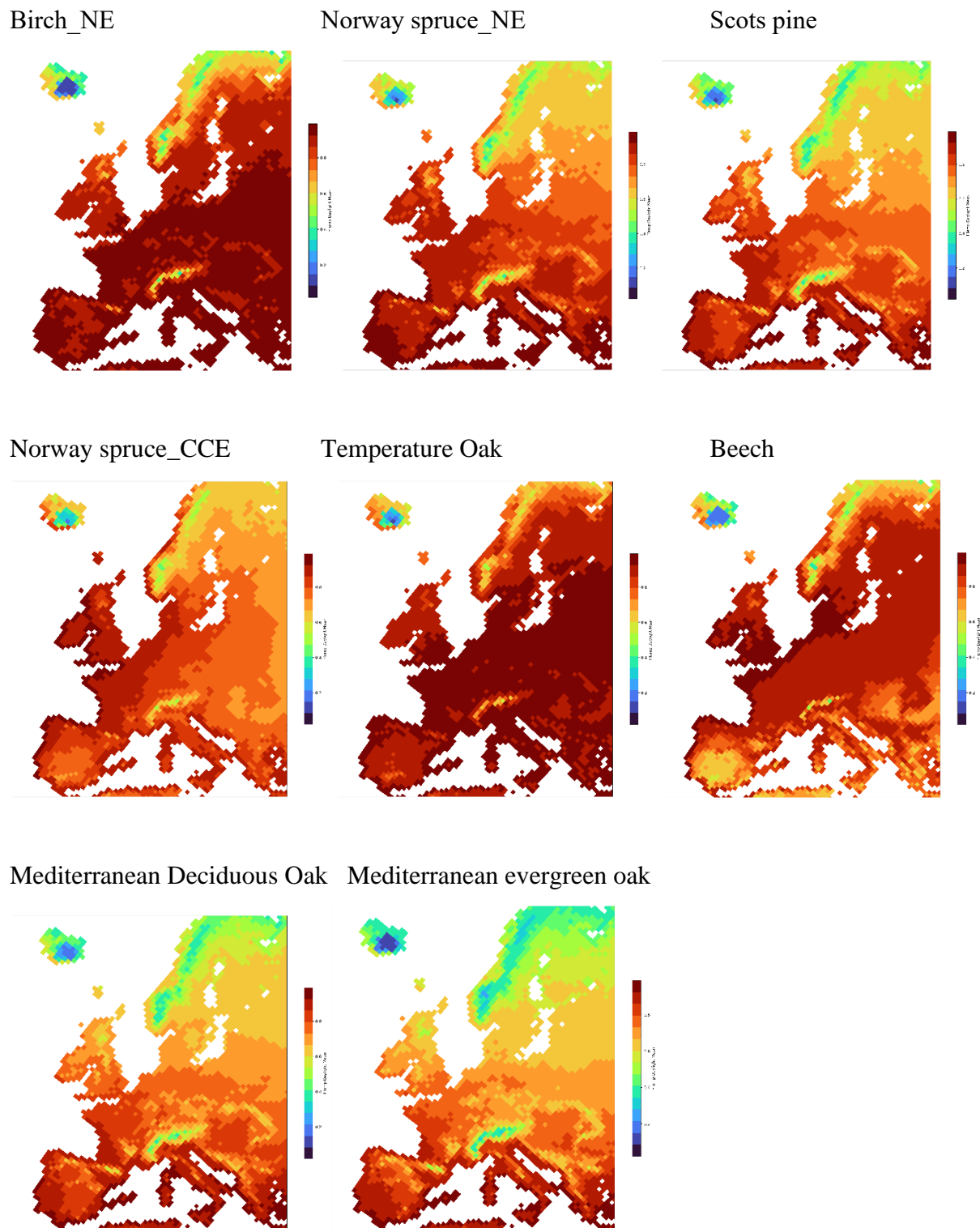
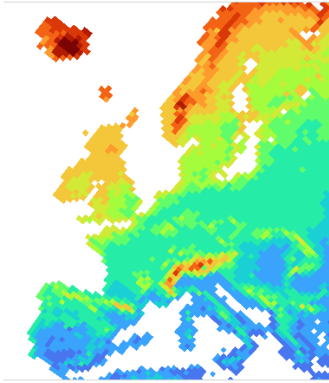
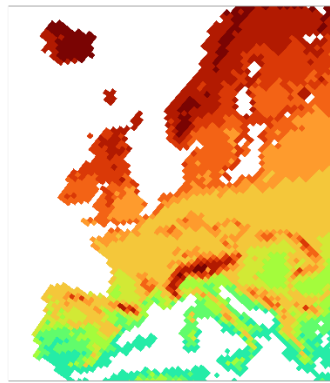
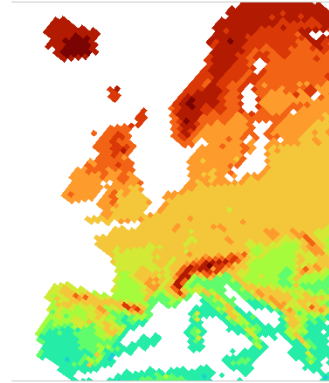
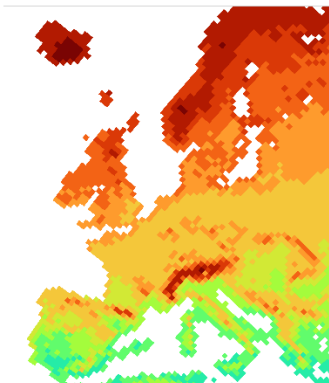
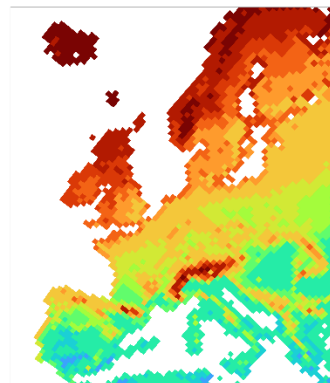
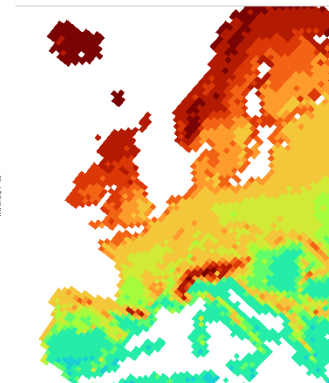



Figure S4b. The limits to POD₁SPEC from f_{VPD} for individual species and all years (2008-2012) across Europe. Colour scale from red (1) to blue (0).

Birch_NE   Norway spruce_NE   Scots pine

Norway spruce_CCE   Temperature Oak   Beech

Mediterranean Deciduous Oak   Mediterranean evergreen oak

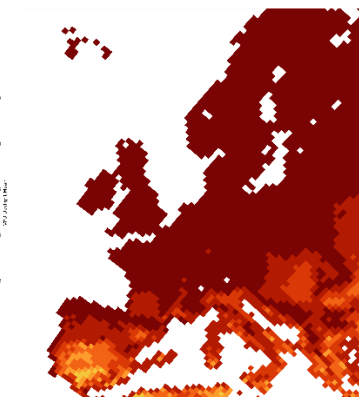
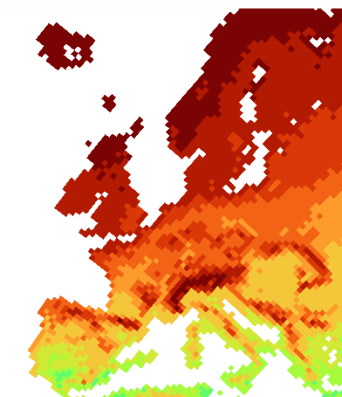
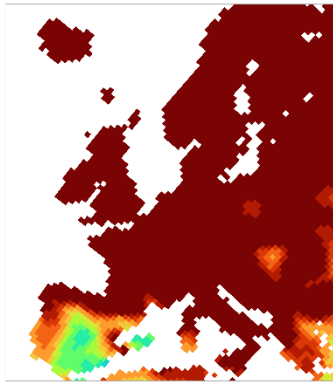
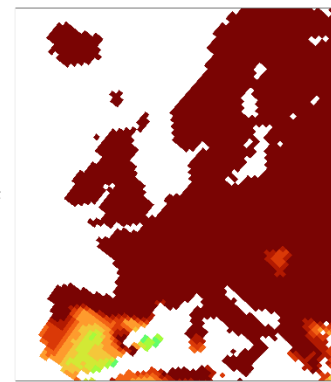
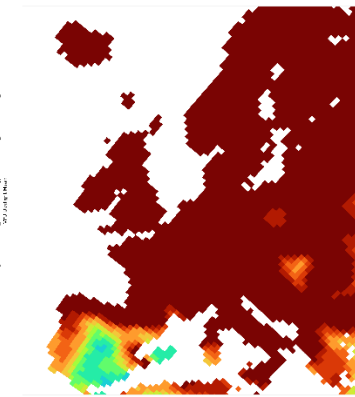
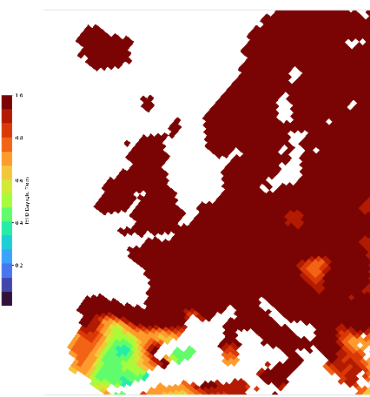



Figure S4c. The limits to POD$_1$SPEC from f_{PAW} (where g_{sto} reduces on exceedance of 75% of available soil water) for individual species and all years (2008-2012) across Europe. Colour scale from red (1) to blue (0).

Birch_NE   Norway spruce_NE   Scots pine

Norway spruce_CCE   Temperature Oak   Beech

Mediterranean Deciduous Oak   Mediterranean evergreen oak

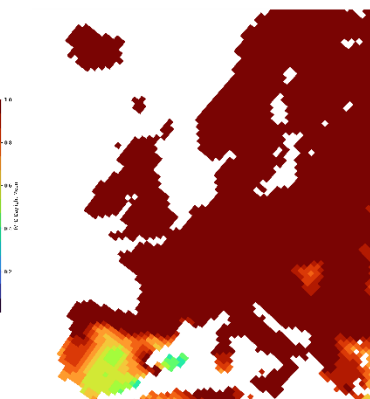



Figure S4d. The limits to POD$_1$SPEC from f_{PAW} with a more sensitive relationship where g_{sto} reduces on exceedance of 50% of available soil water for individual species and for the year 2012 only across Europe. Colour scale from red (1) to blue (0).

Birch_NE   Norway spruce_NE   Scots pine

Norway spruce_CCE   Temperature Oak   Beech

Mediterranean Deciduous Oak   Mediterranean evergreen oak