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Carbon–nitrogen interactions in European forests and semi-natural vegetation – Part 2: Untangling climatic, edaphic, management and nitrogen deposition effects on carbon sequestration potentials

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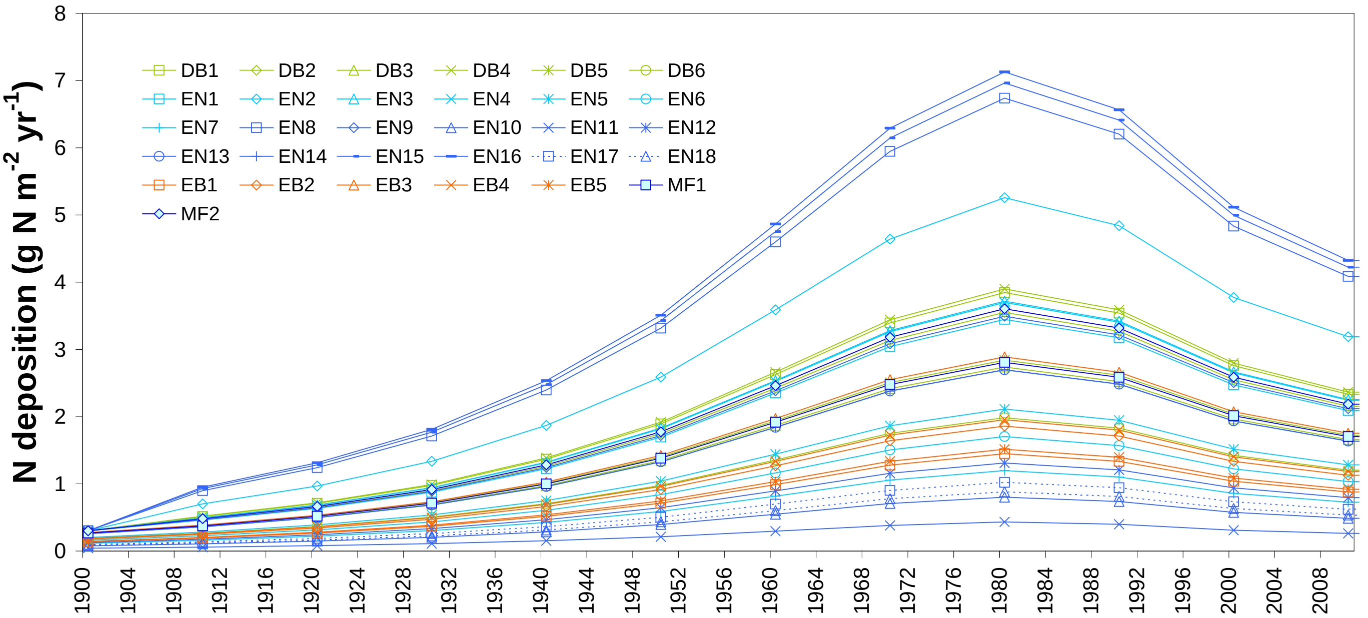

Figure S1. Historical N deposition over the 20th century used as inputs to the BASFOR model. The relative temporal evolution of N_{dep} was assumed to be identical for all sites and was derived from Fig.3, p72, in van Oijen et al. (2008).

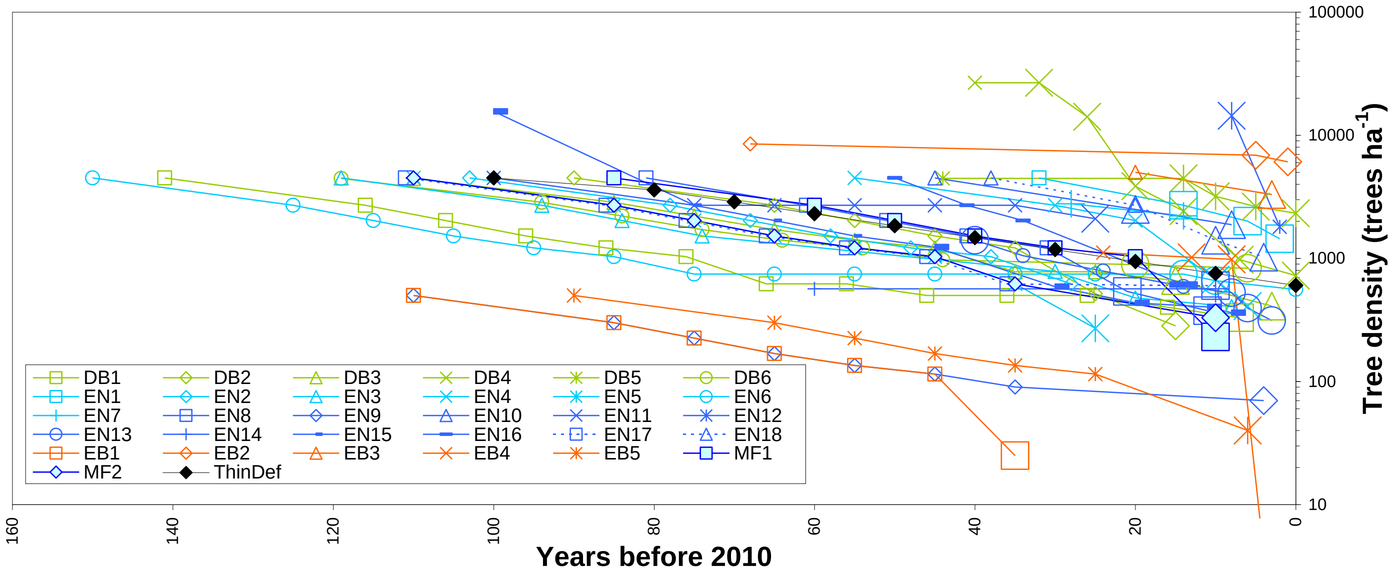

Figure S2. Reconstructed time courses of stand density, driven by thinning events over the lifetimes of CEIP/NEU forest monitoring sites, with DBF, ENF(1-7: spruce), ENF(8-18: pine), EBF and MF shown as different colours. Actual (observed and reported) tree density is shown by larger symbols on each time series, while small symbols indicate values reconstructed on the basis of the default density/thinning scheme ("ThinDef", black symbols, illustration for a 100-yr old forest in 2010) adopted from Cameron et al. (2013).

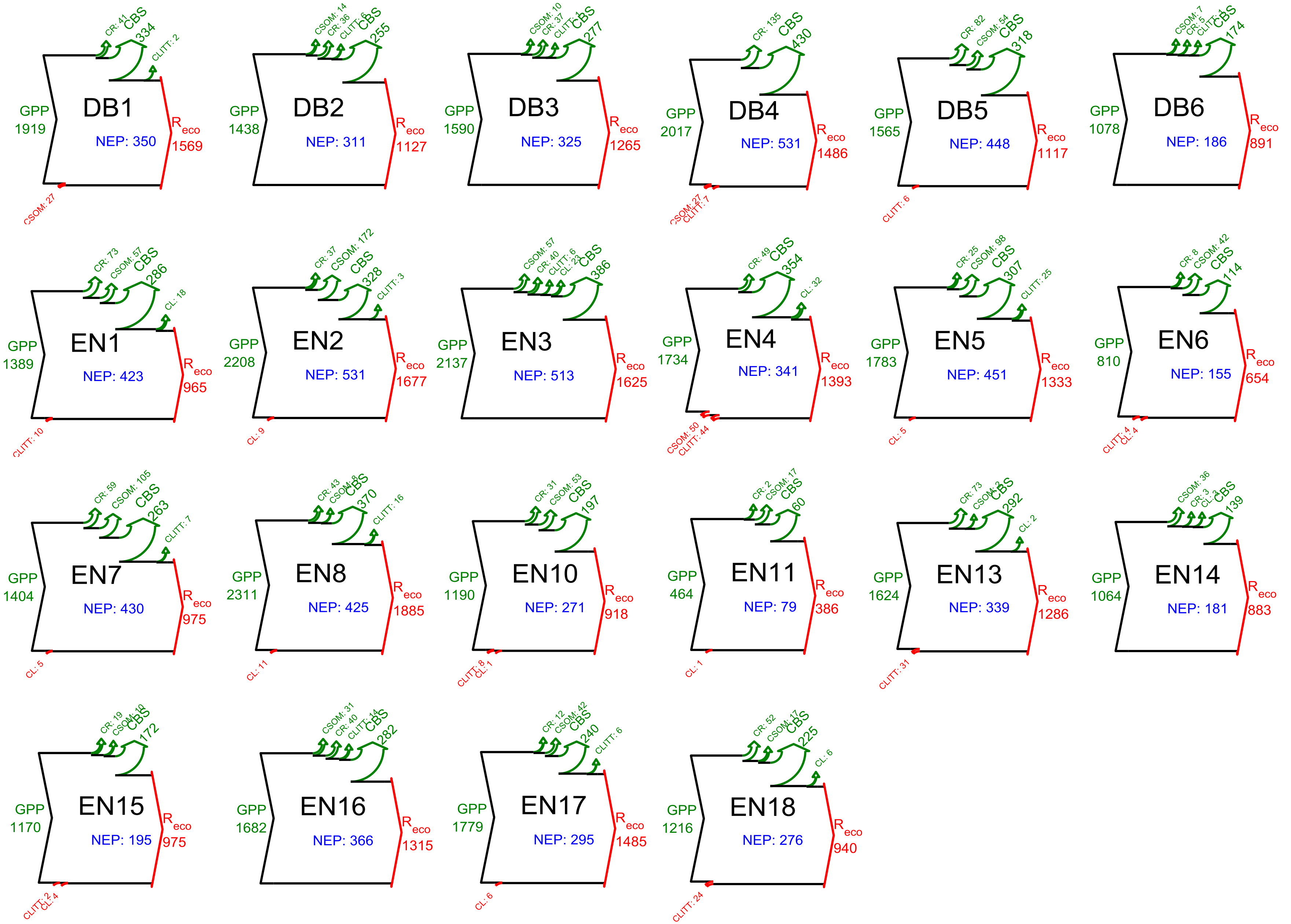

Figure S3. Modelled (BASFOR) partitioning of C fluxes at deciduous broadleaf (DB) and coniferous evergreen needleleaf (EN) forests, and associated changes in C pools in soil organic matter (CSOM), roots (CR), litter layers (CLITT), branches and stems (CBS) and leaves (CL) (units g (C) m^{-2} yr^{-1}). The simulations were run over the most recent 5-year period which did not include any thinning event ('5-yr' in the text). In this case (no disturbance, no export), NEP = NECB = d(CSOM+CR+CLITT+CBS+CL) / dt. Green indicates ecosystem C gain (photosynthesis and C pool increase), red denotes ecosystem C loss (respiration and C pool decrease). The sizes of the Sankey plots are not proportional to the C fluxes of the different study sites.

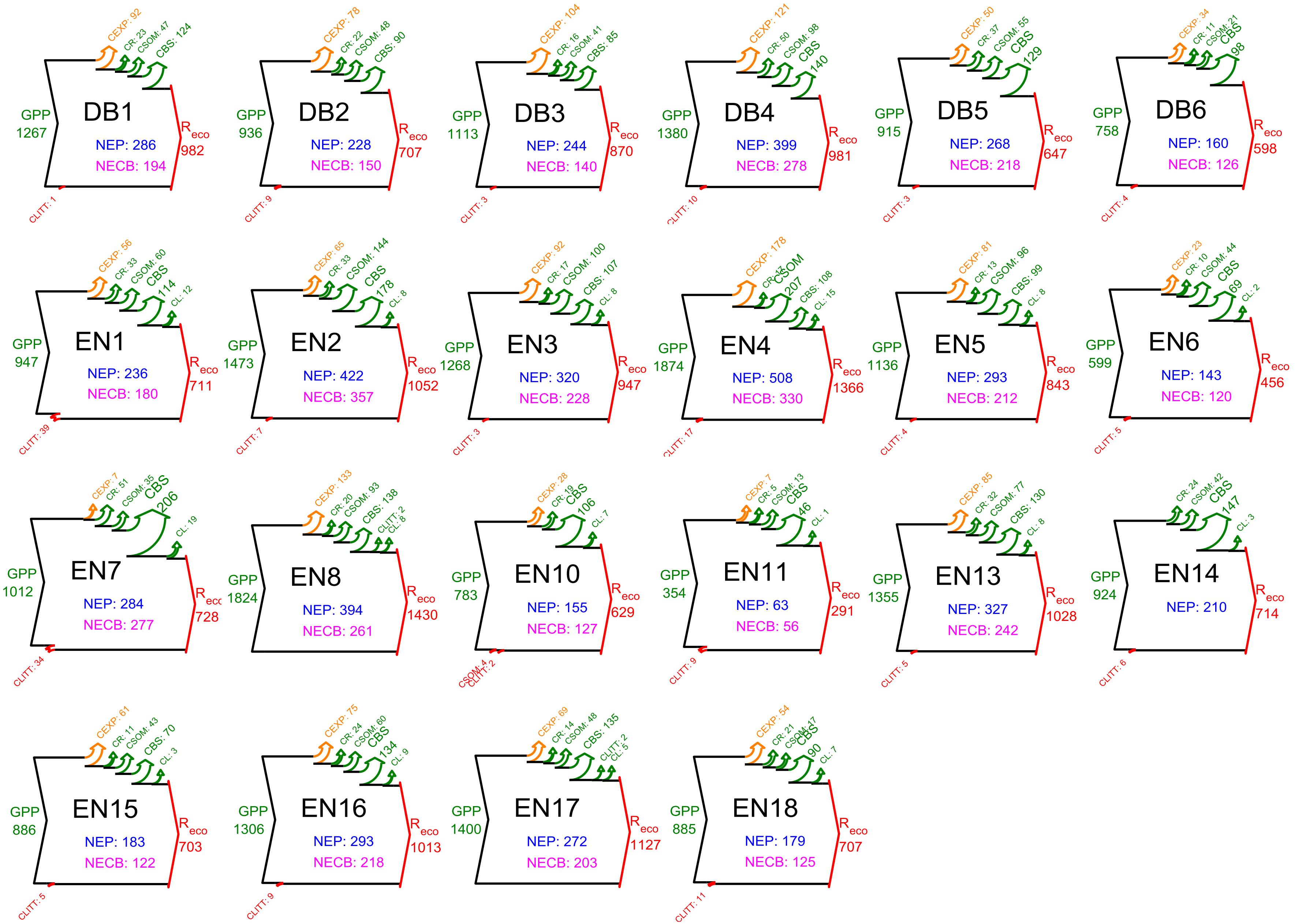

Figure S4. Same as Fig. S3, but simulated over the whole time period since the forest was established ('lifetime' in the text), i.e. including C exports (CEXP) through all thinning/management events (units g (C) m^{-2} yr^{-1}). In this case, NEP - CEXP = NECB = d(CSOM+CR+CLITT+CBS+CL) / dt. The sizes of the Sankey plots are not proportional to the C fluxes of the different study sites.

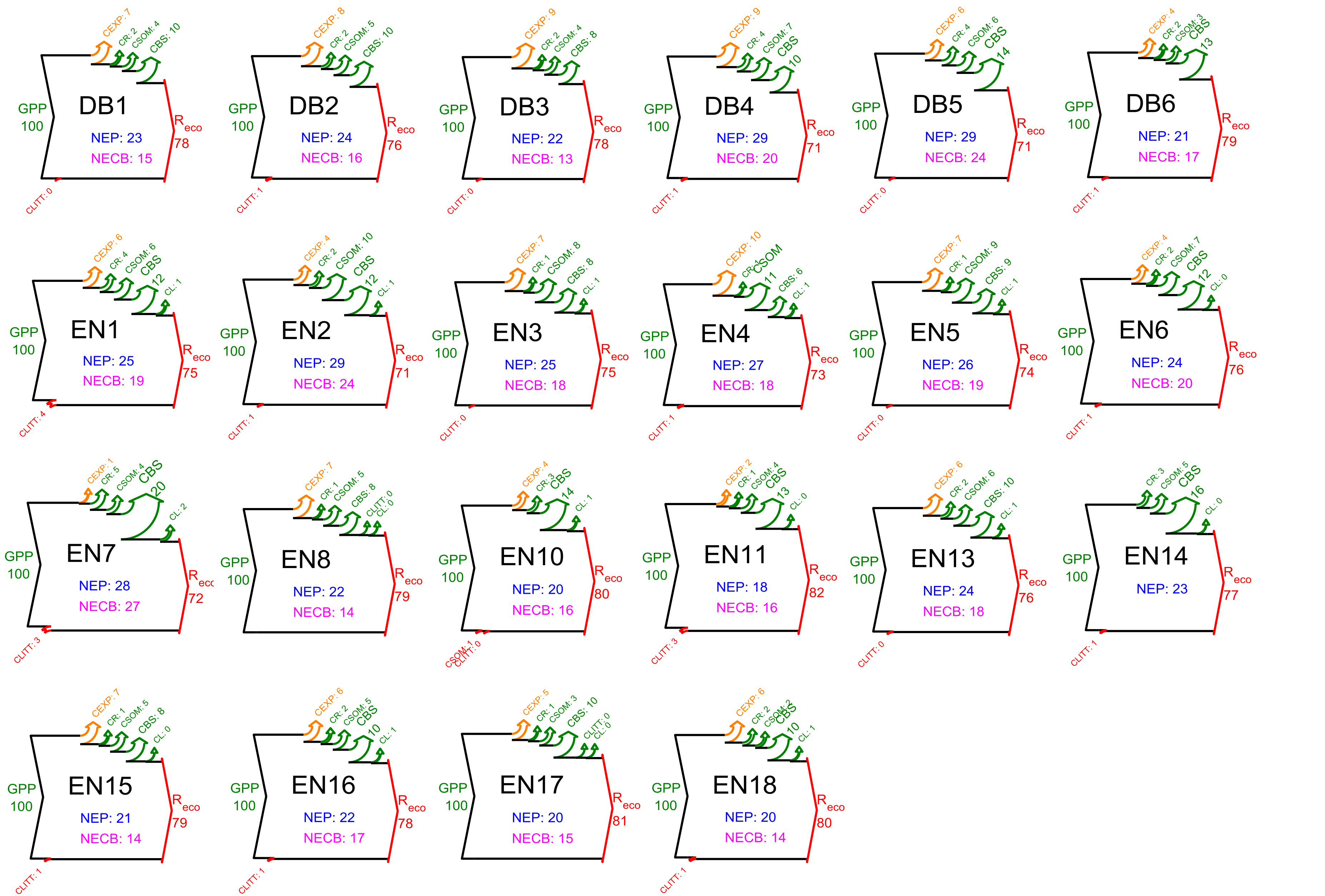

Figure S5. Same as Fig. S4, but normalized to the mean lifetime GPP of each site (units % GPP). The NECB percentage value corresponds to the lifetime carbon sequestration efficiency (CSE). The sizes of the Sankey plots are not proportional to the C fluxes of the different study sites.

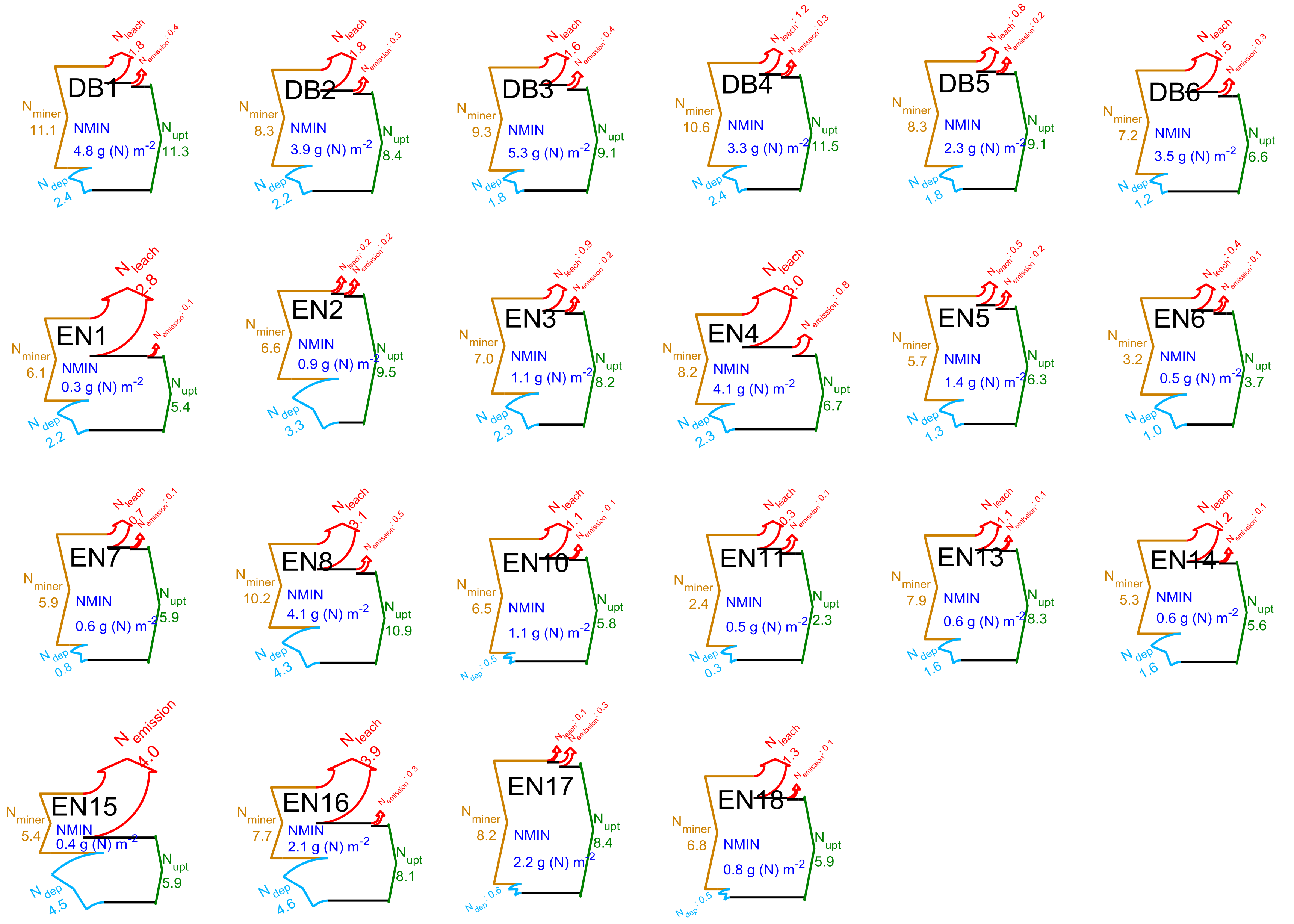

Figure S6. Modelled (BASFOR) nitrogen budgets at deciduous broadleaf (DB) and coniferous evergreen needleleaf (EN) forests. The simulations were run over the most recent 5-year period which did not include any thinning event ('5-yr' in the text). The data show ecosystem SOM mineralisation (N_{miner}) and atmospheric Nr deposition (N_{dep}) (together making up N_{supply}), balanced by vegetation uptake (N_{upt}) and the sum of losses as dissolved N (N_{leach}) and gaseous NO + N_2O ($N_{emission}$) (units: g (N) m^{-2} yr^{-1}). NMIN indicates the mean size of the soil inorganic N pool (g (N) m^{-2}) over the modelling period. The sizes of the Sankey plots are not proportional to the N fluxes of the different study sites.

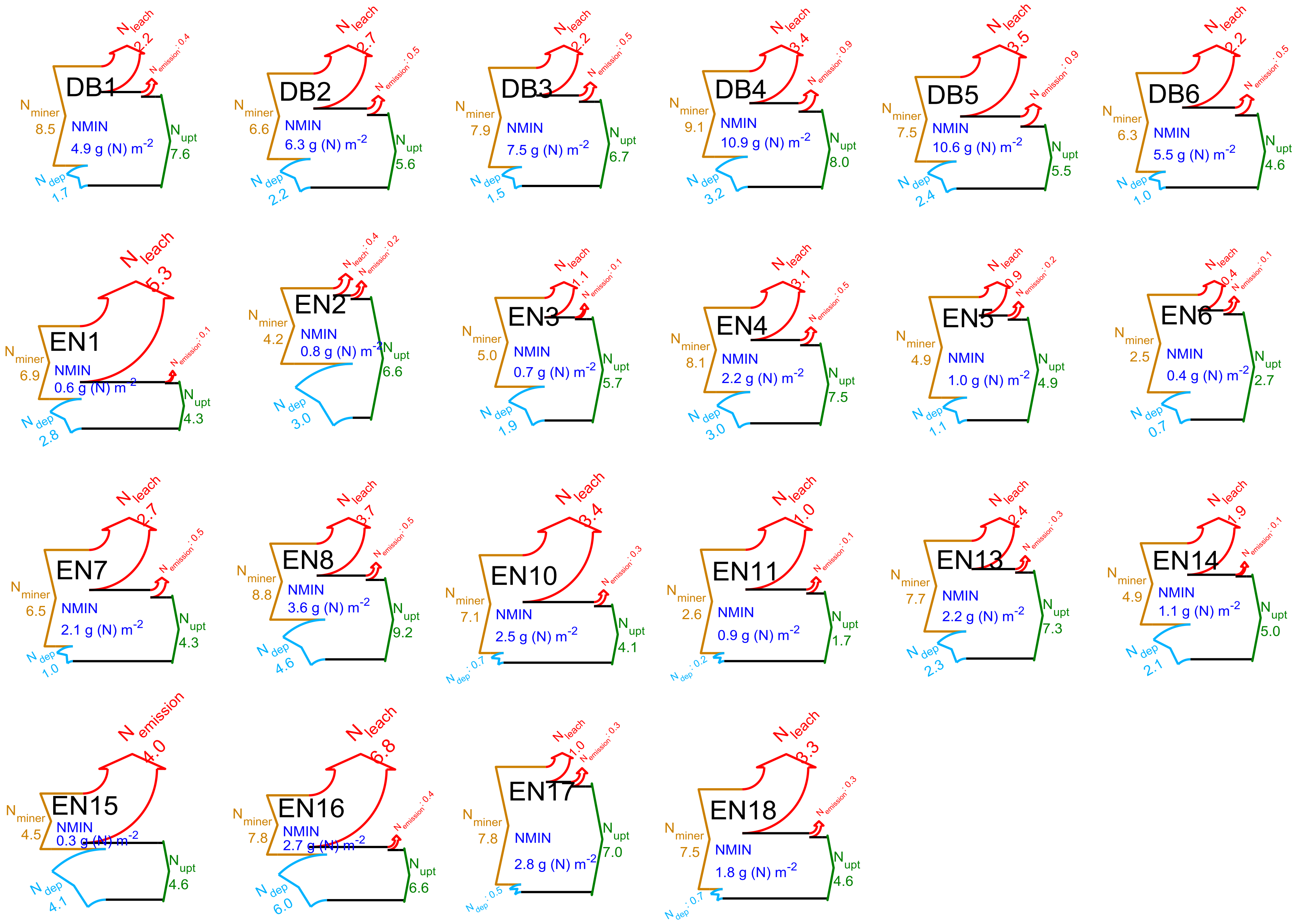

Figure S7. Same as Fig. S6, but simulated over the whole time period since the forest was established ('lifetime' in the text) (units: g (N) m^{-2} yr^{-1}, except for NMIN). The sizes of the Sankey plots are not proportional to the N fluxes of the different study sites.

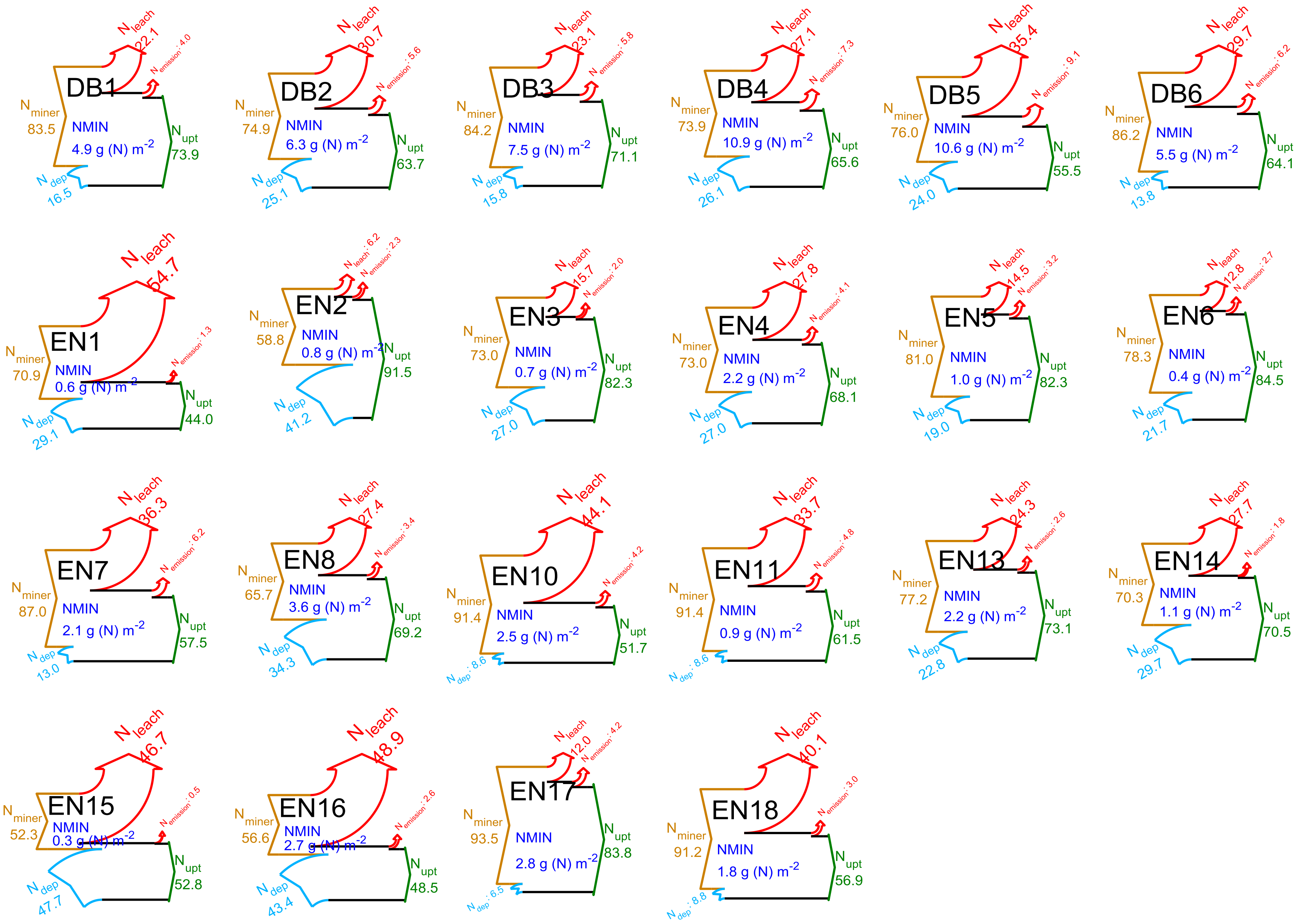

Figure S8. Same as Fig. S7, but fluxes are normalized and expressed as % of total N_{supply} (= N_{miner} + N_{dep} = 100). The N uptake percentage value corresponds to the lifetime nitrogen uptake efficiency (NUPE). The sizes of the Sankey plots are not proportional to the N fluxes of the different study sites.

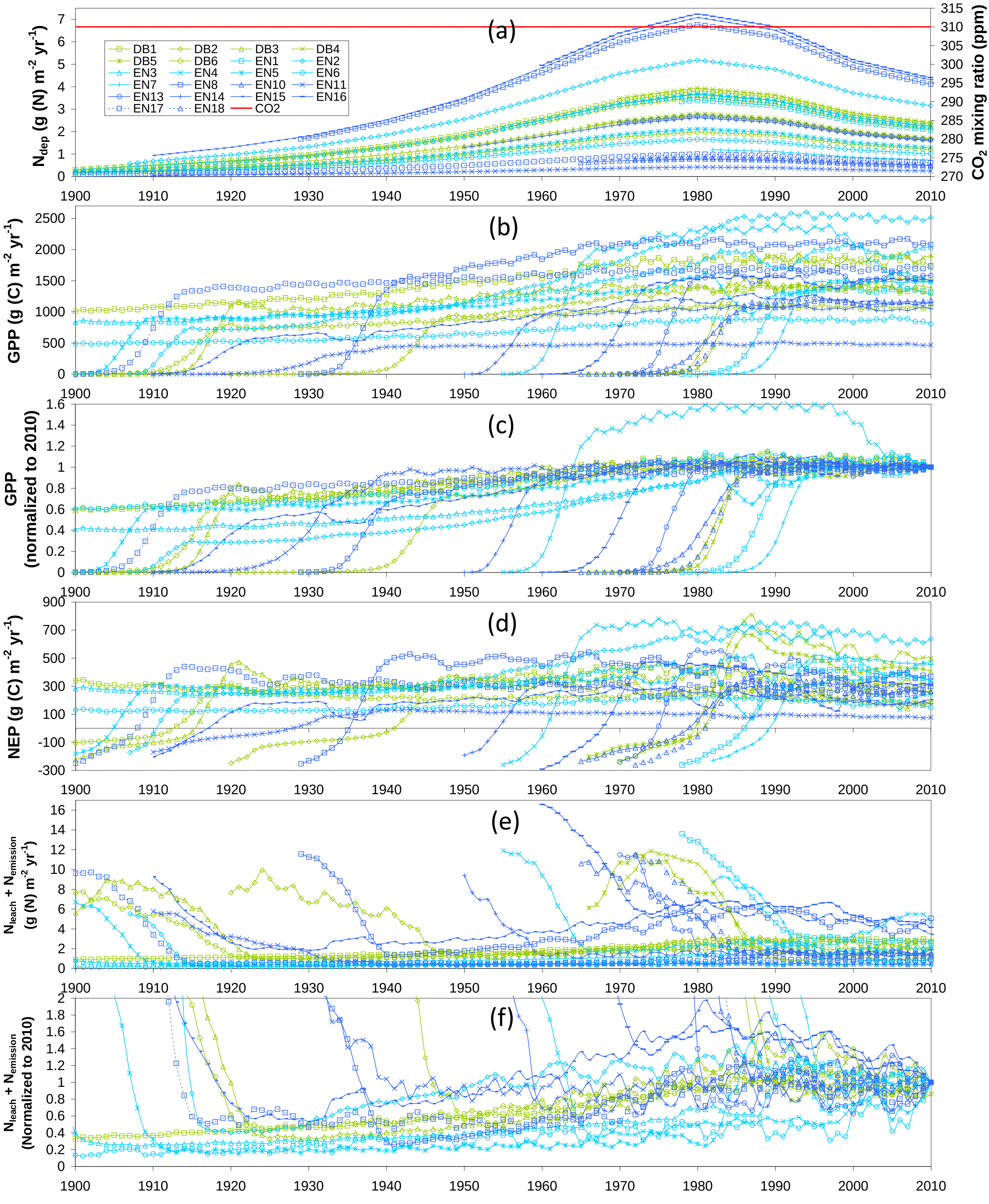

Figure S9. Alternative BASFOR model scenario using a constant CO_2 mixing ratio of 310 ppm through the entire modelling period (a), showing simulations of (b) gross primary productivity (GPP), (c) GPP normalized to the 2010 value, (d) net ecosystem productivity (NEP), (e) total N losses by leaching and gaseous emissions, and (f) total N losses normalized to 2010.

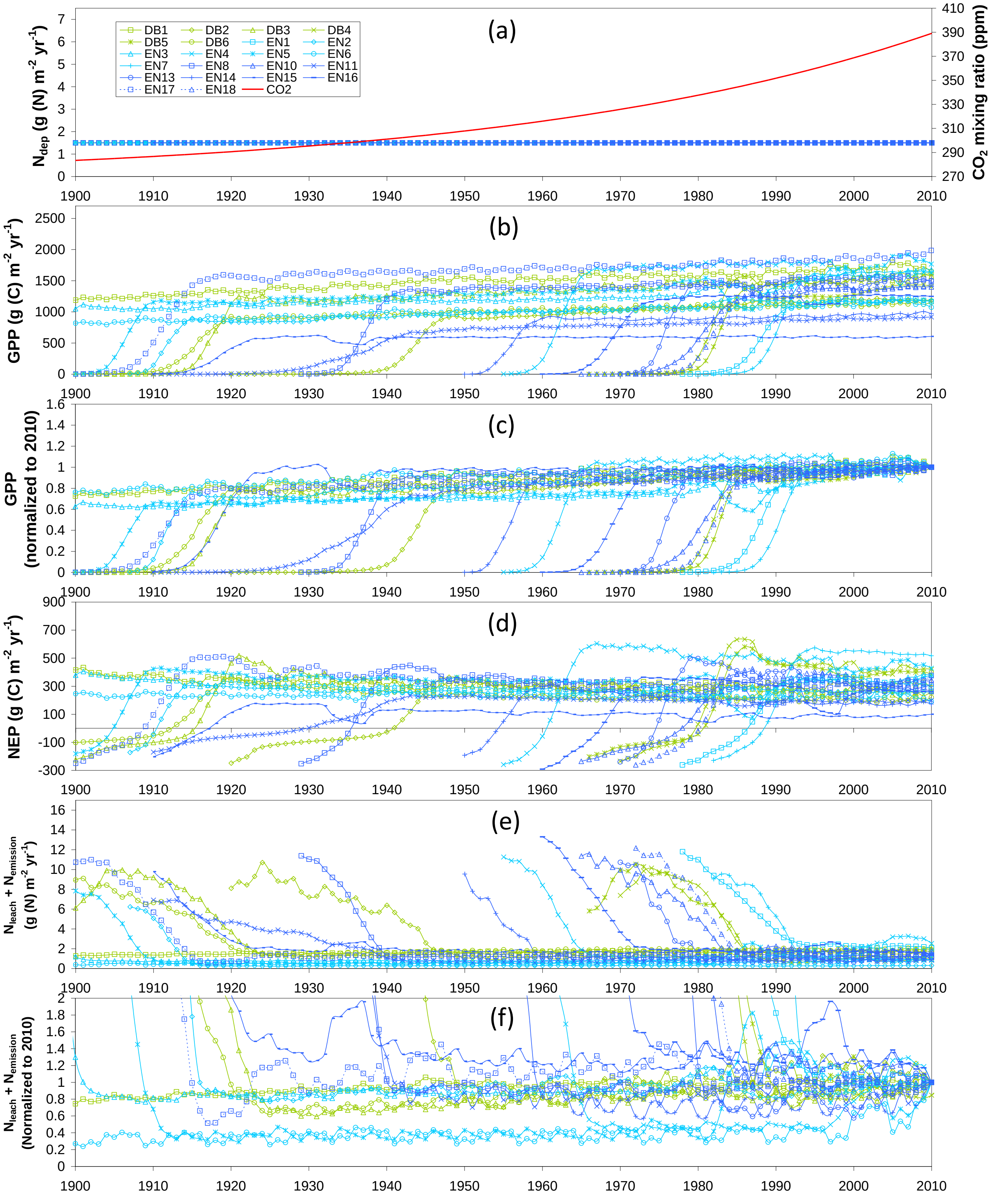

Figure S10. Alternative model scenario using a constant N_{dep} level of 1.5 g (N) m^{-2} yr^{-1} at all sites through the entire modelling period (a), showing simulations of (b) gross primary productivity (GPP), (c) GPP normalized to the 2010 value, (d) net ecosystem productivity (NEP), (e) total N losses by leaching and gaseous emissions, and (f) total N losses normalized to 2010.

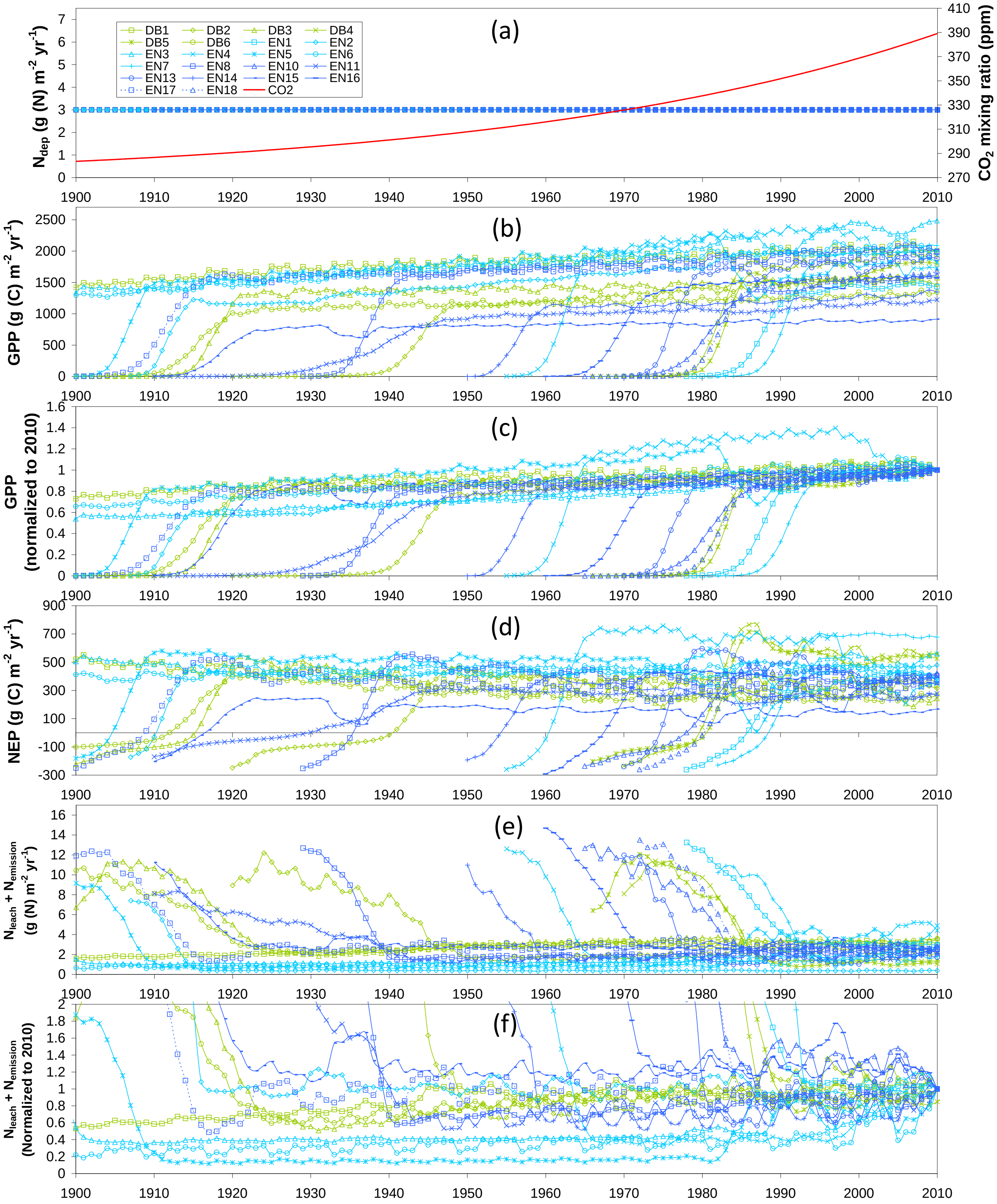

Figure S11. Alternative model scenario using a constant N_{dep} level of 3.0 g (N) m^{-2} yr^{-1} at all sites through the entire modelling period (a), showing simulations of (b) gross primary productivity (GPP), (c) GPP normalized to the 2010 value, (d) net ecosystem productivity (NEP), (e) total N losses by leaching and gaseous emissions, and (f) total N losses normalized to 2010.

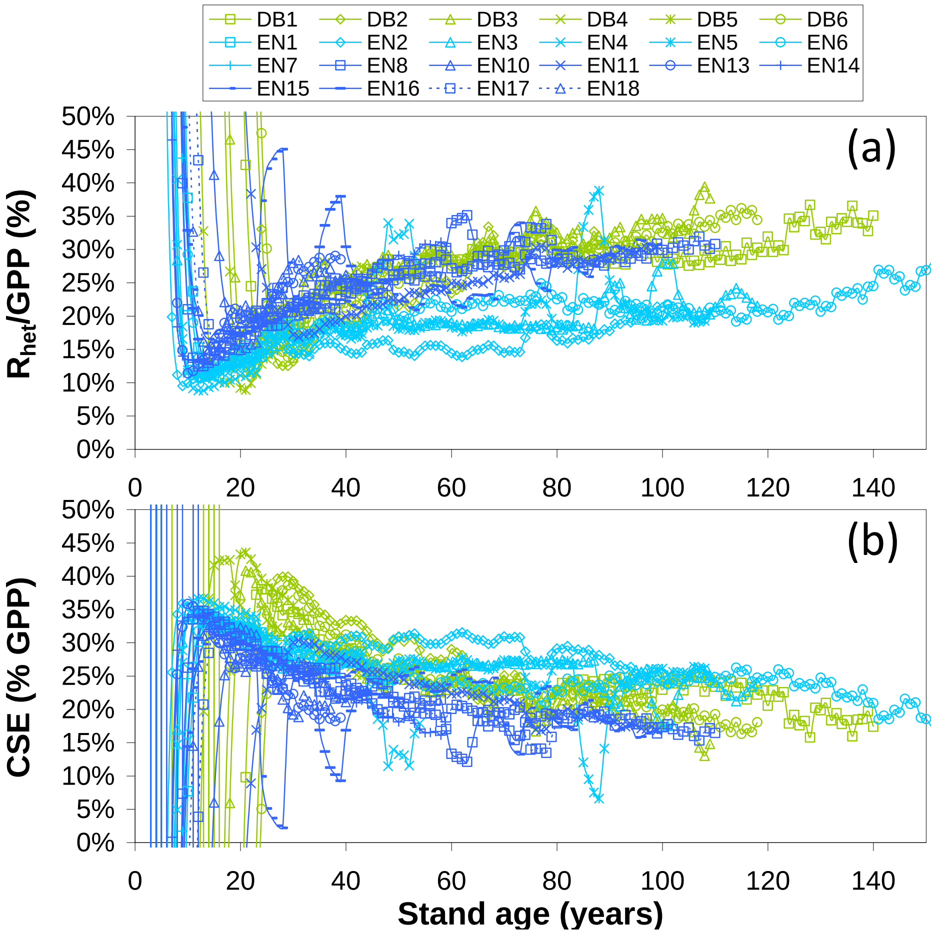

Figure S12. Modelled time courses for all forests of the study of (a) the ratio of heterotrophic respiration (R_{het}) to gross primary productivity (GPP) and (b) the carbon sequestration efficiency (CSE = NEP/GPP). Short term excursions are related to thinning events.

Table S1. Overview of ecosystem and climatic characteristics and inter-annual mean ecosystem/atmosphere exchange fluxes for forest and semi-natural short vegetation sites in the CEIP-NEU network. Only the 22 sites highligthed in blue were included in the meta-modelling study (see text for details).

Site Name	Location, Country	PFT [(1)] Short name	Dominant vegetation	Forest age (2010)	H_{max}[(2)] m	LAI_{max}[(3)] $m^2\ m^{-2}$	Lat. °N	Long. °E	Elevation m amsl[(4)]	MAT[(5)] °C	MAP[(6)] mm	N_{dep}[(7)] $g\ N\ m^{-2}\ yr^{-1}$	GPP[(8)] $g\ C\ m^{-2}\ yr^{-1}$	R_{eco}[(9)] $g\ C\ m^{-2}\ yr^{-1}$	NEP[(10)] $g\ C\ m^{-2}\ yr^{-1}$
DE-Hai	Hainich, Germany	DB1	*Fagus sylvatica*	142	23	4.0	51.079	10.452	430	8.4	775	2.3	1553	1074	479
DK-Sor	Sorø, Denmark	DB2	*Fagus sylvatica*	91	31	4.6	55.487	11.646	40	8.9	730	2.2	1883	1581	301
FR-Fon	Fontainebleau-Barbeau, France	DB3	*Quercus petraea*	111	28	5.1	48.476	2.780	92	11.0	690	1.7	1850	1185	665
FR-Fgs	Fougères, France	DB4	*Fagus sylvatica*	41	20	6.0	48.383	-1.185	140	10.3	900	2.4	1725	1316	409
FR-Hes	Hesse, France	DB5	*Fagus sylvatica*	45	16	6.7	48.674	7.066	300	10.2	975	1.7	1634	1187	446
IT-Col	Collelongo, Italy	DB6	*Fagus sylvatica*	120	22	5.7	41.849	13.588	1560	7.2	1140	1.2	1425	776	650
CZ-BK1	Bily Kriz, Czech Rep.	EN1	*Picea abies*	33	13	9.8	49.503	18.538	908	7.8	1200	2.1	1548	767	781
DE-Hoe	Höglwald, Germany	EN2	*Picea abies*	104	35	6.3	48.300	11.100	540	8.9	870	3.2	1856	1229	627
DE-Tha	Tharandt, Germany	EN3	*Picea abies*	120	27	6.7	50.964	13.567	380	8.8	820	2.3	1997	1396	601
DE-Wet	Wetzstein, Germany	EN4	*Picea abies*	56	22	7.1	50.453	11.458	785	6.6	950	2.2	1809	1767	43
IT-Ren	Renon, Italy	EN5	*Picea abies*	111	29	5.1	46.588	11.435	1730	4.6	1010	1.3	1353	528	826
RU-Fyo	Fyodorovskoye, Russia	EN6	*Picea abies*	190	21	2.8	56.462	32.922	265	5.3	711	1.0	1488	1559	-70
UK-Gri	Griffin, UK	EN7	*Picea sitchensis*	29	12	6.5	56.617	-3.800	340	7.7	1200	0.7	989	677	311
BE-Bra	Brasschaat, Belgium	EN8	*Pinus sylvestris*	82	21	1.9	51.309	4.521	16	10.8	850	4.1	1272	1149	123
ES-ES1	El Saler, Spain	EN9	*Pinus halepensis*	111	10	2.6	39.346	-0.319	5	17.6	551	2.1	1552	960	593
FI-Hyy	Hyytiälä, Finland	EN10	*Pinus sylvestris*	48	18	3.4	61.848	24.295	181	3.8	709	0.5	1114	845	268
FI-Sod	Sodankylä, Finland	EN11	*Pinus sylvestris*	100	13	1.2	67.362	26.638	180	-0.4	527	0.3	551	598	-47
FR-Bil	Bilos, France	EN12	*Pinus pinaster*	9	4	0.5	44.522	-0.896	50	12.4	930	0.8	1178	989	189
FR-LBr	Le Bray, France	EN13	*Pinus pinaster*	41	22	1.9	44.717	-0.769	61	12.9	972	1.6	1906	1479	427
IT-SRo	San Rossore, Italy	EN14	*Pinus pinaster*	61	18	4.0	43.728	10.284	4	14.9	920	1.6	2256	1702	554
NL-Loo	Loobos, Netherlands	EN15	*Pinus sylvestris*	101	18	1.5	52.168	5.744	25	10.0	786	4.2	1617	1141	476
NL-Spe	Speulderbos, Netherlands	EN16	*Pseudotsuga menziesii*	51	32	7.5	52.252	5.691	52	10.0	834	4.3	1416	1015	401
SE-Nor	Norunda, Sweden	EN17	*Pinus sylvestris*	112	28	4.6	60.083	17.467	45	6.8	527	0.6	1414	1356	58
SE-Sk2	Skyttorp, Sweden	EN18	*Pinus sylvestris*	39	16	3.2	60.129	17.840	55	7.4	527	0.5	1235	953	282
ES-LMa	Las Majadas, Spain	EB1	*Quercus ilex*	111	8	0.6	39.941	-5.773	258	16.1	528	0.9	1091	958	133
FR-Pue	Puechabon, France	EB2	*Quercus ilex*	69	6	2.9	43.741	3.596	270	13.7	872	1.1	1309	1030	279
IT-Ro2	Roccarespampani, Italy	EB3	*Quercus cerris*	21	16	3.8	42.390	11.921	224	15.7	876	1.8	1707	886	821
PT-Esp	Espirra, Portugal	EB4	*Eucalyptus globulus*	25	20	2.7	38.639	-8.602	95	16.1	709	1.2	1473	1163	311
PT-Mi1	Mitra, Portugal	EB5	*Quercus ilex, Quercus suber*	91	8	3.4	38.541	-8.000	264	14.5	665	0.9	870	817	53
BE-Vie	Vielsalm, Belgium	MF1	*Fagus sylvatica, Pseudotsuga menziesii*	86	30	5.1	50.305	5.997	450	8.1	1000	1.7	1792	1247	545
CH-Lae	Lägeren, Switzerland	MF2	*Fagus sylvatica, Picea abies*	111	30	3.6	47.478	8.365	689	7.7	1100	2.2	1448	757	692
DE-Meh	Mehrstedt, Germany	SN1	Afforestated grassland	n.a.	0.5	2.9	51.276	10.657	293	9.1	547	1.5	1171	1175	-4
ES-VDA	Vall d'Alinya, Spain	SN2	Upland grassland	n.a.	0.1	1.4	42.152	1.448	1765	6.4	1064	1.2	669	528	140
FI-Lom	Lompolojänkkä, Finland	SN3	Peatland	n.a.	0.4	1.0	67.998	24.209	269	-1.0	521	0.1	377	345	32
HU-Bug	Bugac, Hungary	SN4	Semi-arid grassland	n.a.	0.5	4.7	46.692	19.602	111	10.7	500	1.4	1044	918	126
IT-Amp	Amplero, Italy	SN5	Upland grassland	n.a.	0.4	2.5	41.904	13.605	884	9.8	1365	0.9	1241	1028	213
IT-MBo	Monte Bondone, Italy	SN6	Upland grassland	n.a.	0.3	2.5	46.029	11.083	1550	5.1	1189	1.7	1435	1347	89
NL-Hor	Horstemeer, Netherlands	SN7	Peatland	n.a.	2.5	6.9	52.029	5.068	-2	10.8	800	3.1	1584	1224	361
PL-wet	POLWET/Rzecin, Poland	SN8	Wetland (reeds, sedges, mosses)	n.a.	2.1	4.9	52.762	16.309	54	8.5	550	1.4	937	642	295
UK-AMo	Auchencorth Moss, UK	SN9	Peatland	n.a.	0.6	2.1	55.792	-3.239	270	7.6	1165	0.8	786	705	81

[(1)] PFT (plant functional types): DB: deciduous broadleaf forest; EN: evergreen needleleaf coniferous forest; EB: evergreen broadleaf Mediterranean forest; MF: mixed deciduous/coniferous forest; SN: short semi-natural, including moorland, peatland, shrubland and unimproved/upland grassland; [(2)] maximum canopy height; [(3)] maximum leaf area index, defined as 1-sided or half of total; [(4)] above mean sea level; [(5)] mean annual temperature; [(6)] mean annual precipitation; [(7)] nitrogen deposition; [(8)] gross primary productivity; [(9)] ecosystem respiration; [(10)] net ecosystem productivity; n.a.: not available/ not applicable.

Table S2. Procedure for the calculation of climate / soil standardization factors (f_{CLIM} or f_{SOIL}) through BASFOR meta-modelling for the n=22 forest sites. The indices i and j stand for the site being modelled (i = 1..n), and for the scenarios being applied for climate data or for soil parameters (j=1..n), respectively. See main text and Eqs (10-15) for details.

GPP(i,j)	Site modelled i=1	i=2	i=3	i=…	i=n-1	i=n
Scenario j=1	GPP(1,1) = GPP_{base}(1)	GPP(2,1)	GPP(3,1)	…	GPP(n-1,1)	GPP(n,1)
j=2	GPP(1,2)	GPP(2,2) = GPP_{base}(2)	GPP(3,2)	…	GPP(n-1,2)	GPP(n,2)
j=3	GPP(1,3)	GPP(2,3)	GPP(3,3) = GPP_{base}(3)	…	GPP(n-1,3)	GPP(n,3)
j=…	…	…	…	GPP(i=j) = GPP_{base}(i)	…	…
j=n-1	GPP(1,n-1)	GPP(2,n-1)	GPP(3,n-1)	…	GPP(n-1,n-1) = GPP_{base}(n-1)	GPP(n,n-1)
j=n	GPP(1,n)	GPP(2,n)	GPP(3,n)	…	GPP(n-1,n)	GPP(n,n) = GPP_{base}(n)

X(i,j) = GPP(i,j) / GPP_{base}(i)	Site modelled i=1	i=2	i=3	i=…	i=n-1	i=n	**Mean $\overline{X(j)}$**
Scenario j=1	1	GPP(2,1) / GPP_{base}(2)	GPP(3,1) / GPP_{base}(3)	…	GPP(n-1,1) / GPP_{base}(n-1)	GPP(n,1) / GPP_{base}(n)	$\overline{X(1)}$
j=2	GPP(1,2) / GPP_{base}(1)	1	GPP(3,2) / GPP_{base}(3)	…	GPP(n-1,2) / GPP_{base}(n-1)	GPP(n,2) / GPP_{base}(n)	$\overline{X(2)}$
j=3	GPP(1,3) / GPP_{base}(1)	GPP(2,3) / GPP_{base}(2)	1	…	GPP(n-1,3) / GPP_{base}(n-1)	GPP(n,3) / GPP_{base}(n)	$\overline{X(3)}$
j=…	…	…	…	1	…	…	**…**
j=n-1	GPP(1,n-1) / GPP_{base}(1)	GPP(2,n-1) / GPP_{base}(2)	GPP(3,n-1) / GPP_{base}(3)	…	1	GPP(n,n-1) / GPP_{base}(n)	$\overline{X(n-1)}$
j=n	GPP(1,n) / GPP_{base}(1)	GPP(2,n) / GPP_{base}(2)	GPP(3,n) / GPP_{base}(3)	…	GPP(n-1,n) / GPP_{base}(n-1)	1	$\overline{X(n)}$

X_{norm}(i,j) = X(i,j) / $\overline{X(j)}$	Site modelled i=1	i=2	i=3	i=…	i=n-1	i=n
Scenario j=1	X(1,1) / X(1)	X(2,1) / X(1)	X(3,1) / X(1)	...	X(n-1,1) / X(1)	X(n,1) / X(1)
j=2	X(1,2) / X(2)	X(2,2) / X(2)	X(3,2) / X(2)	...	X(n-1,2) / X(2)	X(n,2) / X(2)
j=3	X(1,3) / X(3)	X(2,3) / X(3)	X(3,3) / X(3)	...	X(n-1,3) / X(3)	X(n,3) / X(3)
j=…	...	...	...	X(i,j) / X(j)	...	...
j=n-1	X(1,n-1) / X(n-1)	X(2,n-1) / X(n-1)	X(3,n-1) / X(n-1)	...	X(n-1,n-1) / X(n-1)	X(n,n-1) / X(n-1)
j=n	X(1,n) / X(n)	X(2,n) / X(n)	X(3,n) / X(n)	...	X(n-1,n) / X(n)	X(n,n) / X(n)
f(i) = mean $\overline{X_{norm}(i)}$	**f(1) = $\overline{X_{norm}(1)}$**	**f(2) = $\overline{X_{norm}(2)}$**	**f(3) = $\overline{X_{norm}(3)}$**	**…**	**f(n-1) = $\overline{X_{norm}(n-1)}$**	**f(n) = $\overline{X_{norm}(n)}$**

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