Supplement of

Soil nitrous oxide emissions from global land ecosystems and their drivers within the LPJ-GUESS model (v4.1)

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Table S1. Literature-based natural vegetation sites used for model soil N_2O evaluation: Geographic location; Dominant species; Experimental period; Observed N_2O fluxes at the studied sites[a].

Geographic location	Lon	Lat	Vegetation types	Dominant species	Period of N_2O measurement	Observed N_2O fluxes (kg N ha^{-1} yr^{-1})[b]	Reference
Mooloolah (Australia)	152.93	-26.76	Subtropical rainforest	-	Mar.2007-Feb.2009	0.511±0.118 (2007/2008) 0.521±0.006 (2008/2009)	Rowlings et al. (2012)
Klausen-Leopoldsdorf (Austria)	16.05	48.12	Temperate deciduous broadleaf forest	Beech	May 2002-Apr.2004	0.538±0.031 (2002/2003) 0.671±0.021 (2003/2004)	Kitzler et al. (2006)
Achenkirch (Austria)	11.71	47.49	Temperate needleleaf forest	Spruce	Entire 2002-2003	0.402±0.036 (2002) 0.292±0.036 (2003)	Kesik et al. (2005)
Innsbruck (Austria)	11.45	-47.30	Temperate needleleaf forest	Spruce	Jul.1990-Jun.1991	0.081±0.008	Henrich and Haselwandter (1997)
Schottenwald (Austria)	16.25	48.23	Temperate deciduous broadleaf forest	Beech	May 2002-Apr.2004	0.76±0.003 (2002/2003) 0.82±0.005 (2003/2004)	Kitzler et al. (2006)
Manaus (Brazil)	-59.96	-2.89	Tropical rainforest	-	Apr.1987-Apr.1988	1.90	Luizão et al. (1989)
Tapajós National Forest (Brazil)	-54.95	-2.89	Tropical rainforest	-	Entire 2000-2004	2.10±0.70 (5-year average)	Davidson et al. (2008)
Paragominas (Brazil)	-47.52	-2.98	Tropical rainforest	-	Entire 1995-1996	2.43±0.22 (2-year average)	Verchot et al. (1999)
Ontario (Canada)	-80.67	49.05	Boreal needleleaf forest	Black spruce	Jun.1992-Aug.1992	0.044±0.067	Schiller and Hastie (1996)
Saskatchewan 1 (Canada)	-106.20	53.62	Boreal deciduous broadleaf forest	Trembling aspen	Apr.1994-Sep.1994	0.281±0.101	Simpson et al. (1997)
Saskatchewan 1 (Canada)	-106.20	53.62	Boreal deciduous broadleaf forest	Trembling aspen	May 2006-Oct.2006 May 2007-Oct.2007	0.12 (2006) 0.14 (2007)	Matson et al. (2009)
Saskatchewan 2 (Canada)	-105.12	53.99	Boreal needleleaf forest	Black spruce	May 2006-Oct.2006 May 2007-Oct.2007	0.13 (2006) -0.02 (2007)	Matson et al. (2009)
Saskatchewan 3 (Canada)	-104.69	53.92	Boreal needleleaf forest	Jack pine	May 2006-Oct.2006 May 2007-Oct.2007	0.05 (2006) 0.08 (2007)	Matson et al. (2009)

Mont St. Hilaire (Canada)	-73.13	45.52	Temperate deciduous broadleaf forest	American beech	May 2006- May 2008	0.307±0.081 (3-year average)	Ullah and Moore (2011)
Tibetan Plateau (China)	93.05	35.13	Alpine grassland	Stipa purpurea	Aug.2000-Jul.2001	0.044	Pei et al. (2004)
Changbai mountain (China)	126.92	41.38	Temperate mixed forest	Amur lime; Korean pine	Jun.1994-Oct.1995	0.557±0.483	Chen et al. (2000)
Inner Mongolia (China)	114.67	43.53	Temperate semi-arid grassland	Chinese rye grass	Entire 1995, 1998, 2001-2003	0.58±0.16 (1995) 0.25±0.12 (1998) 1.62±0.53 (2001) 0.61±0.53 (2002) 0.58±0.36 (2003)	Du et al. (2006)
Xishuangbanna (China)	101.26	21.93	Tropical seasonal rainforest	Pometia tomentosa	Entire 2003	2.59±0.29	Yan et al. (2008)
Sorø (Denmark)	11.59	55.39	Temperate deciduous broadleaf forest	Beech	Entire 2003	0.548±0.036	Kesik et al. (2005)
Bombuscaro (Ecuador)	-78.97	-4.10	Tropical rainforest	Moraceae	May 2008-May 2009	0.279±0.119	Wolf et al. (2011)
Reserva San Francisco (Ecuador)	-79.07	-3.97	Tropical rainforest	Lauraceae	May 2008-May 2009	0.566±0.148	Wolf et al. (2011)
Padasjoki (Finland)	24.97	61.32	Boreal needleleaf forest	Picea abies	Jun.-Aug. in 2000, 2001, 2003	0.197±0.056 (3-year average)	Maljanen et al. (2006)
Kiel (Germany)	10.12	54.26	Temperate deciduous broadleaf forest	European beech	Entire 1993	0.40	Mogge et al. (1998)
Wildmooswald (Germany)	8.12	47.12	Temperate needleleaf forest	Norway spruce	Entire 2001-2002	0.675±0.359 (2001) 0.475±0.457 (2002)	Jungkunst et al. (2004)
Höglwald (Germany)	11.28	48.83	Temperate needleleaf forest	Norway spruce	Entire 1994-1995, 1997, 2000-2005, 2007-2009	0.4 (1994), 0.8 (1995) 0.7 (1997), 0.5 (2000) 0.4 (2001), 0.7 (2002) 0.4 (2003), 0.2 (2004) 1.0 (2005), 0.6 (2007) 0.8 (2008), 1.0 (2009)	Luo et al. (2012)
Jambi (Indonesia)	102.11	-1.12	Tropical rainforest	-	Sep.1997-Aug.1998	0.259±0.204	Ishizuka et al. (2002)
Puncak Dingin (Indonesia)	120.30	-1.27	Tropical rainforest	-	Nov.2002-Oct.2003	1.01±0.16	Purbopuspito et al. (2006)

Rorekatimbu (Indonesia)	120.30	-1.32	Tropical rainforest	-	Nov.2002-Oct.2003	0.29±0.02	Purbopuspito et al. (2006)
Wuasa (Indonesia)	120.30	-1.42	Tropical rainforest	-	Nov.2002-Oct.2003	1.11±0.17	Purbopuspito et al. (2006)
Palangka Raya (Indonesia)	114.03	-2.35	Tropical deciduous forest	Tetramerista glabra	Jun.2002-May 2004	2.51 (2-year average)	Takakai et al. (2006)
Parco Ticino (Italy)	8.74	45.36	Temperate deciduous broadleaf forest	Hardwoods	Entire 2002-2003	0.511±0.109 (2002) 0.183±0.001 (2003)	Kesik et al. (2005)
Sarawak (Malaysia)	111.85	2.82	Tropical rainforest	Gonystylus bancanus	Aug.2002-Jul.2003	0.70	Melling et al. (2007)
Christchurch (New Zealand)	171.68	-43.13	Temperate evergreen broadleaf forest	Black beech	Jan.1998-Apr.1999	0.01	Price et al. (2004)
Åmli (Norway)	8.5	58.82	Temperate evergreen needleleaf forest	Scots pine	Jul.1992-Aug.1992	0.124±0.031	Sitaula et al. (1995)
Gigante Peninsula (Panama)	-79.83	9.10	Tropical evergreen forests	Oenocarpus mapora	Entire 2006-2007	1.35±0.09 (2006) 0.98±0.10 (2007)	Koehler et al. (2009)
Gårdsjön (Sweden)	12.02	58.07	Temperate needleleaf forest	Norway spruce	Entire 1993-1994	0.095±0.024 (2-year average)	Klemedtsson et al. (1997)
Northumberland (UK)	-2.05	55.17	Grassland	-	Entire 2001-2002	0.191±0.064 (2001) 0.191±0.064 (2002)	Ball et al. (2007)
Harvard forest (USA)	-72.19	42.53	Temperate deciduous broadleaf forest	Black oak	May 1988-Apr.1989	0.017±0.017	Bowden et al. (1990)
Ithaca, New York (USA)	-76.45	42.44	Grassland	Timothy weed	May 1980-Apr.1981	0.9	Duxbury et al. (1982)
White Mountain National Forest (USA)	-71.75	43.91	Temperate deciduous broadleaf forest	American beech; Sugar maple	Entire 1998-2000	1.25±0.13 (1998) 0.55±0.04 (1999) 0.67±0.24 (2000)	Groffman et al. (2006)
Mercury, Nevada (USA)	-115.92	36.82	Arid grassland	Pleuraphis rigida	Entire 1999-2000	0.091±0.066 (2-year average)	Billings et al. (2002)
Saratoga (USA)	-106.85	41.44	Temperate semi-arid grassland	Festuca idahoensis	Entire 1986-1987	0.255 (1986) 0.280 (1987)	Matson et al. (1991)
Whiteface Mt., New York (USA)	-73.90	44.40	Temperate needleleaf forest	Spruce-fir	May 1990-Sep.1990	0.185	Castro et al. (1993)

Mt. Mansfield, Vermont (USA)	-72.80	44.50	Temperate needleleaf forest	Spruce-fir	May 1990-Sep.1990	0.171	Castro et al. (1993)
Acadia, Maine (USA)	-68.40	44.30	Temperate needleleaf forest	Spruce-fir	May 1990-Sep.1990	0.032	Castro et al. (1993)
Fort Collins (USA)	-104.75	40.80	Grassland	Blue gramma	Entire 1991-1994	0.130±0.017 (1991) 0.118±0.019 (1992) 0.177±0.049 (1993) 0.127±0.035 (1994)	Mosier et al. (1996)
Baraboo (USA)	-89.67	43.44	Grassland	Little bluestem	Sep.1981-Mar.1982	0.028	Cates and Keeney (1987)
Santa Barbara (Venezuela)	-63.45	9.75	Tropical herbaceous savanna	Trachypogon	Apr.2000-Mar.2001	0.913±0.073	Simona et al. (2004)
Harare (Zimbabwe)	30.91	-17.68	Subtropical woody savanna	Julbernardia globiflora	Oct.2000-Sep.2001	0.497±0.223	Rees et al. (2006)
Ankasa Conservation Area (Ghana)	-2.68	5.27	Tropical rainforest	-	Entire 2009-2010	2.33±0.20 (2-year average)	Castaldi et al. (2013)
Kakamega Forest National Park (Kenya)	34.86	0.25	Tropical rainforest	-	Apr.2004-Jun.2004	2.60±1.20	Werner et al. (2007)
Fukushima (Japan)	140.33	37.35	Temperate evergreen needleleaf forest	Japanese cedar	Entire 2003-2004	0.872 (2003) 1.077 (2004)	Morishita et al. (2007)
Oita (Japan)	131.28	33.18	Temperate evergreen needleleaf forest	Japanese cedar	Entire 2003-2004	0.979 (2003) 1.128 (2004)	Morishita et al. (2007)

a–Additional data collected from the original literature are available at https://doi.org/10.5281/zenodo.14169306; b–Observations of N_2O fluxes are represented as annual cumulative values ± standard errors, derived from field trial replicates reported in the literature.

Table S2. Literature-based cropland sites used for model soil N_2O evaluation: Geographic location; Cropping system and its growth calendar; Field management practices (such as irrigation, N fertilizer, and tillage) at the studied sites[a].

Geographic location	Lon	Lat	Cropping systems[b]	Sowing-harvest dates (DOY)[c]	Water and N fertilizer inputs[d]	Tillage, Residue Retention, Cover Crops	Period of N_2O measurement	Reference
Bretenierre (France)	5.11	47.23	SW	58-206	RF F: 131	NO, NO, YES	Mar.2012-Mar.2013	Vermue et al. (2016)
Reckenholz (Switzerland)	8.52	47.43	Maize	128-285	IRRI F: 160	YES, NO, NO	Mar.2014-Oct.2014	Hüppi et al. (2015)
DOK (Switzerland)	7.53	47.60	Maize	146-267	RF F: 0 | 170 | 183 | 335	YES, YES, YES	May 2013-Sep.2013	Skinner et al. (2019)
Aeschi (Switzerland)	7.66	47.17	Pea | Maize	112-183, 2019 (Pea) 129-259, 2020 (Maize)	RF F:0 (Pea) | 110 (Maize)	YES, NO, YES	May 2019-Jun.2019 May 2020-Sep.2020	Maier et al. (2022)
Jinzhou (China)	119.71	32.58	Rice	162-294	IRRI F: 0 | 150 | 250	YES, NO, NO	Jun.-Oct. in 2005, 2006, 2007	Yao et al. (2012)
Shuangqiao (China)	120.66	30.83	Rice	180-302	IRRI F: 0 | 90 | 180 | 270 | 360	YES, NO, NO	Jul.2007-Aug.2007	Iqbal (2009)
New Delhi (India)	77.20	28.67	Rice | WW	180-302 (Rice) 315-89 (WW)	IRRI F: 0 | 120	YES, NO, NO	Jul.2000-Mar. 2001	Bhatia et al. (2005)
Cuttack (India)	85.93	20.43	Rice	193-293	IRRI F: 100	YES, NO, NO	Jul.2011-Oct.2011	Bhattacharyya et al. (2013)
Los Baños (Philippines)	121.26	14.16	Maize	55-164	IRRI F: 0 | 130 | 190	YES, NO, NO	Mar.2012-Jun.2012	Weller et al. (2015)
Suzhou (China)	120.92	31.53	Rice | WW	174-292 (Rice) 323-139 (WW)	IRRI (Rice); RF (WW) F: 0 | 240	YES, NO, NO	Jul.2011-May 2014	Yang et al. (2015)
Changshu (China)	120.68	31.55	Rice	174-292	IRRI F: 0 | 225 | 270 | 300	YES, NO, NO	Jul.-Oct. in 2009, 2010	Ma et al. (2013)
Munich (Germany)	11.33	48.50	Maize | WW	115-292 (Maize) 297-226 (WW)	RF F: 0 | 65 | 130 (Maize) F: 0 | 90 | 180 (WW)	YES, NO, NO	Mar.1995-Feb.1997	Ruser et al. (2001)
Jurong (China)	119.30	31.97	WW	346-163	RF F: 0 | 100 | 200 | 270	YES, NO, NO	Dec.2008-Jun.2009 Dec.2009-Jun.2010	Ji et al. (2012)

Yongji (China)	110.72	34.93	WW | Maize	291-164 (WW) 166-288 (Maize)	IRRI F: 0 | 60 | 120 | 180 | 300 | 400 (WW) F: 0 | 75 | 150 | 250 | 350 | 450 (Maize)	YES, YES, NO	Nov.2009-Oct.2010	Liu et al. (2012)
Yanting (China)	105.28	31.16	WW | Maize	299-130 (WW) 144-258 (Maize)	RF F: 0 | 150 | 250	YES, NO, NO	Oct.2004-Sep.2007	Zhou et al. (2013)
New Delhi (India)	77.20	28.67	WW	324-97	IRRI F: 0 | 120	YES, NO, NO	Dec.1998-Mar.1999	Majumdar et al. (2002)
Mundare (Canada)	-112.0	53.0	SW	144-268	RF F: 60	NO, NO, NO	Jun.1996-Sep.1996	Izaurralde et al. (2004)
Swift Current (Canada)	-107.0	50.0	SW	144-272	RF F: 0 | 45 | 110	NO, NO, NO	Jun.1999-Sep.1999	Izaurralde et al. (2004)
Huantai (China)	117.98	36.97	WW | Maize	286-161 (WW) 173-270 (Maize)	IRRI F: 0 | 180 | 270 (WW) F: 0 | 220 | 330 (Maize)	YES, YES, NO	Oct.2008-Sep.2010	Yan et al. (2013)
Saint-Jean-sur-Richelieux (Canada)	-73.35	45.30	Maize | Soybean	131-301 (Maize) 144-275 (Soybean)	RF F: 0 | 80 | 160 (Maize) F: 0 (Soybean)	YES, NO, NO NO, NO, NO	May-Oct. in 2004, 2005	Larouche (2006)
Honghe Farm (China)	131.52	47.58	Maize	153-264	RF F: 0 | 150 | 250	YES, NO, NO	Jun.2005-Sep.2005	Song and Zhang (2009)
Fengqiu (China)	114.40	35.00	Maize | WW	158-262 (Maize) 282-156 (WW)	IRRI F: 0 | 150 | 250	YES, NO, NO	Jun.2004-May 2005	Ding et al. (2007)
Fort Collins (USA)	-104.98	40.65	Maize	124-287	IRRI F: 0 | 67 | 134 | 246	YES, NO, NO NO, YES, NO	May-Oct. in 2005, 2006	Halvorson et al. (2008)
Fort Collins (USA)	-104.98	40.65	Maize	116-290	IRRI F: 0 | 134 | 224	YES, NO, NO NO, YES, NO	May-Oct. in 2003, 2004	Liu et al. (2005)
Guelph (Canada)	-80.42	43.57	Maize	123-272 (2006) 129-268 (2007)	RF F: 0 | 60 | 90 | 150	YES, NO, NO	May and Jul. in 2006, 2007	Ma et al. (2010)
L'Île-Perrot (Canada)	-73.95	45.11	Maize | Soybean	126-287 (Maize) 143-291 (Soybean)	RF F: 0 | 90 | 180 (Maize) F: 0 | 20 | 40 (Soybean)	YES, NO, NO	May 1994-Oct.1994	MacKenzie et al. (1997)
Wageningen (Netherlands)	5.67	51.96	Maize	126-281	RF F: 0 | 75 | 113 | 150 | 188	YES, NO, NO	May 2001-Oct.2001	van Groenigen et al. (2004)
Leeuwarden (Netherlands)	5.78	53.17	Maize	131-281	RF F: 0 | 75 | 113 | 150 | 188	YES, NO, NO	May 2001-Oct.2001	van Groenigen et al. (2004)

Eldorado do Sul (Brazil)	-51.07	-30.10	Maize	300-102	IRRI F: 0 | 180	NO, YES, YES	Oct.2004-Nov.2004	Bayer et al. (2015)
Beijing (China)	116.3	39.95	Maize	129-272	IRRI F: 0 | 150 | 300	YES, NO, NO	May 2002-Jun.2002	Liu et al. (2004)
KBS (USA)	-85.37	42.41	Maize	141-285 (2007) 135-297 (2008)	RF F: 0 | 45 | 90 | 135 | 180 | 225	YES, NO, NO	May-Oct. in 2007, 2008	Hoben et al. (2011)
Fairgrove (USA)	-83.64	43.52	Maize	111-281 (2007) 135-306 (2008)	RF F: 0 | 45 | 90 | 135 | 180 | 225	YES, NO, NO	Apr.-Oct. in 2007, 2008	Hoben et al. (2011)
Reese (USA)	-83.65	43.45	Maize	111-281 (2007) 135-306 (2008)	RF F: 0 | 45 | 90 | 135 | 180 | 225	YES, NO, NO	Apr.-Oct. in 2007, 2008	Hoben et al. (2011)
Mason (USA)	-84.51	42.47	Maize	127-295	RF F: 0 | 45 | 90 | 135 | 180 | 225	YES, NO, NO	May 2007-Oct.2007	Hoben et al. (2011)
Stockbridge (USA)	-84.27	42.48	Maize	143-287	RF F: 0 | 45 | 90 | 135 | 180 | 225	YES, NO, NO	May 2008-Sep.2008	Hoben et al. (2011)
Carlow (Ireland)	-6.92	52.85	SW	95-223 (2004) 92-217 (2005)	RF F: 0 | 70 | 140 (2004) F: 0 | 79 | 159 (2005)	YES, NO, NO NO, NO, NO	Apr.-Aug. in 2004, 2005	Abdalla et al. (2010)
Harlaka (Canada)	-71.32	46.77	Soybean	141-276 (2001) 141-258 (2002)	RF F: 0	YES, YES, NO	May -Oct. in 2001, 2002	Rochette et al. (2004)
Patancheru (India)	78.45	17.88	Sorghum	172-281	RF F: 0 | 90	YES, NO, NO	Jun.2010-Sep.2010	Ramu et al. (2012)
Dano (Burkina Faso)	-3.08	11.16	Sorghum	121-277	RF F: 0 | 52.5 | 140	YES, NO, NO	May 2006-Aug.2006	Brümmer et al. (2008)
Siribougou (Mali)	-6.43	13.27	Millet | Bean	190-300 (Millet) 190-275 (Bean)	RF F: 0 | 24 (Millet) F: 0 (Bean)	YES, NO, NO	Entire 2004	Dick et al. (2008)
Göttingen (Germany)	9.93	51.49	WW	323-219	RF F: 0 |180	YES, NO, NO	Mar.2016-Feb.2018	Wang et al. (2021)
Aranjuez (Spain)	-3.52	40.05	Maize	96-268	IRRI F: 140 |170 |190	YES, NO, NO YES, NO, YES	Oct.2013-Sep.2014	Guardia et al. (2016)
Willbriggie (Australia)	145.95	-34.48	Sorghum	356-119	IRRI F: 300	YES, NO, NO	Dec.2013-Apr.2014	Jamali et al. (2015)
Toowoomba (Australia)	151.78	-27.51	WW	161-298	IRRI F: 200	YES, NO, NO	Jun.2009-Oct.2009	Scheer et al. (2012)

St. Petersburg (Russia)	30.13	59.57	SW	132-242	RF F: 0 |65 |110	YES, NO, NO	May 2004-Aug.2004	Buchkina et al. (2010)
Ehime (Japan)	132.78	33.95	Rice	165-279	IRRI F: 80	YES, YES, NO	Jun.2012-Sep.2012	Toma et al. (2016)
Amir Temur Garden (Uzbekistan)	60.52	41.60	WW	282-171	IRRI F: 192	YES, NO, NO	Oct.2005-Jun.2006	Scheer et al. (2008)
Amir Temur Cum (Uzbekistan)	60.42	41.63	Rice	140-257 (2005) 143-252 (2006)	IRRI F: 270 (2005) |200 (2006)	YES, NO, NO	May-Oct. in 2005, 2006	Scheer et al. (2008)
Skierniewice (Poland)	20.17	51.95	SW	81-294	RF F: 0 |90	YES, NO, NO	Apr.2012-Oct.2012	Sosulski et al. (2015)
Naples (Italy)	14.97	40.62	Maize	125-231	IRRI F: 130	YES, NO, NO NO, NO, NO	May 2008-Sep.2008	Forte et al. (2017)
Santa Maria (Brazil)	-53.71	-29.72	Maize | WW	315-119 (Maize) 151-309 (WW)	IRRI F: 0 |135 (Maize) F: 0 |112 (WW)	YES, NO, YES YES, NO, NO	Nov.2010-Oct.2011	Aita et al. (2015)
Sinnamary (French Guiana)	-52.92	5.28	Maize	333-118	RF F: 169	YES, NO, YES NO, NO, YES	May 2010-Apr.2011	Petitjean et al. (2015)
Celaya (Mexico)	-101.32	20.73	Maize | WW	104-258 (Maize) 287-78 (WW)	IRRI F: 240 (Maize) F: 300 (WW)	YES, YES, NO	Apr.2007-Mar.2008	Grageda-Cabrera et al. (2011)
Maseno (Kenya)	34.58	0.00	Maize	80-220	RF F: 0 | 50 | 75 | 100 | 200	YES, NO, NO	Mar.2010-Jun.2010	Hickman et al. (2014)
Harare (Zimbabwe)	31.01	-17.70	Maize	292-79	RF F: 0 | 60 | 120	YES, NO, NO	Oct.2008-Mar.2009	Nyamadzawo et al. (2017)
Kolero (Tanzania)	37.80	-7.25	Maize	76-189	RF F: 0 | 100	YES, NO, NO (F0) NO, NO, NO (F100)	Mar.2013-May 2014	Kimaro et al. (2016)
Kairanga (New Zealand)	175.65	-40.35	Maize	296-137	RF F: 163 | 186	YES, NO, NO	Nov.1998-Sep.1999	Choudhary et al. (2001)

a–The measured N_2O fluxes collected from the original literature are available at https://doi.org/10.5281/zenodo.14169306; b–Cropping systems: SW-spring wheat; WW-winter wheat; c–Sowing and harvest dates of crops are represented as DOY (day-of-year calendar); d–Water and N fertilizer management: RF-rain-fed; IRRI-irrigated; F-mineral N fertilizer application rate in kg N ha^{-1}.

Table S3. Modelled continent-level total soil N_2O emissions from natural vegetation, pasture, and cropland in the decades of the 1960s and 2010s (i.e., S1 run in Table 1 in the main text). The simulated results are represented as 10-year mean ± 1 standard deviation. The division of the 10 continents used in this study was given in Fig. S4.

	Natural vegetation (Tg N yr^{-1})		**Pasture (Tg N yr^{-1})**		**Cropland (Tg N yr^{-1})**		**All (Tg N yr^{-1})**	
	1960s	2010s	1960s	2010s	1960s	2010s	1960s	2010s
North America	0.58±0.04	0.89±0.09	0.04±0.03	0.06±0.04	0.09±0.01	0.46±0.06	0.71±0.07	1.40±0.12
South America	1.09±0.06	0.94±0.09	0.05±0.01	0.05±0.01	0.08±0.01	0.18±0.01	1.22±0.06	1.17±0.09
Europe	0.29±0.02	0.71±0.04	0.01±0.00	0.02±0.00	0.17±0.06	0.49±0.04	0.47±0.08	1.21±0.07
Africa	1.34±0.09	1.30±0.09	0.10±0.02	0.12±0.01	0.07±0.01	0.19±0.01	1.52±0.09	1.61±0.10
Oceania	0.17±0.03	0.20±0.06	0.07±0.02	0.05±0.02	0.05±0.02	0.05±0.01	0.28±0.06	0.30±0.08
West Asia	0.13±0.02	0.19±0.03	0.01±0.00	0.01±0.00	0.01±0.00	0.09±0.01	0.15±0.02	0.29±0.03
Central Asia	0.03±0.00	0.07±0.02	0.01±0.00	0.02±0.00	0.03±0.02	0.11±0.03	0.07±0.02	0.19±0.05
East Asia	0.20±0.02	0.66±0.03	0.02±0.00	0.07±0.01	0.04±0.01	1.18±0.12	0.25±0.03	1.91±0.13
South Asia	0.22±0.02	0.40±0.03	0.01±0.00	0.01±0.00	0.16±0.01	0.79±0.06	0.39±0.03	1.20±0.08
Southeast Asia	0.45±0.02	0.50±0.08	0.00±0.00	0.01±0.00	0.03±0.00	0.14±0.02	0.48±0.02	0.65±0.09
Global	4.51±0.10	5.87±0.13	0.31±0.04	0.40±0.05	0.73±0.12	3.64±0.18	5.55±0.19	9.92±0.28

Table S4. Modelled relative contributions ($\Delta N_2O_{\%}$) of each factor to global soil N_2O emissions in the decades of the 1960s and 2010s. The modelled results are represented as a 10-year average (%). See S0–S6 runs in Table 1 in the main text for simulation setups and Eq. 24 for $\Delta N_2O_{\%}$ calculation.

	Natural vegetation (%)		**Pasture (%)**		**Cropland (%)**		**All (%)**	
	1960s	2010s	1960s	2010s	1960s	2010s	1960s	2010s
Climate change	68.6	75.1	69.6	61.4	1.3	0.2	30.9	23.7
Rising CO_2	-73.9	-87.3	-34.1	-97.9	-1.8	-6.3	-30.3	-31.9
N fertilization	0.0	0.0	0.0	0.0	52.2	87.3	25.9	58.1
N deposition	174.7	125.9	63.7	116.7	8.9	9.0	76.5	46.4
Land use change	-89.2	-35.6	2.6	-2.3	46.0	15.6	-6.6	1.0
Interactive effects[a]	19.8	21.9	-1.8	22.1	-6.6	-5.8	3.6	2.8

a–The total effect of the five environmental factors did not sum to 100% due to their interactive effects in the factorial experiments. See Sect. 2.3.2 in the main text for more details.

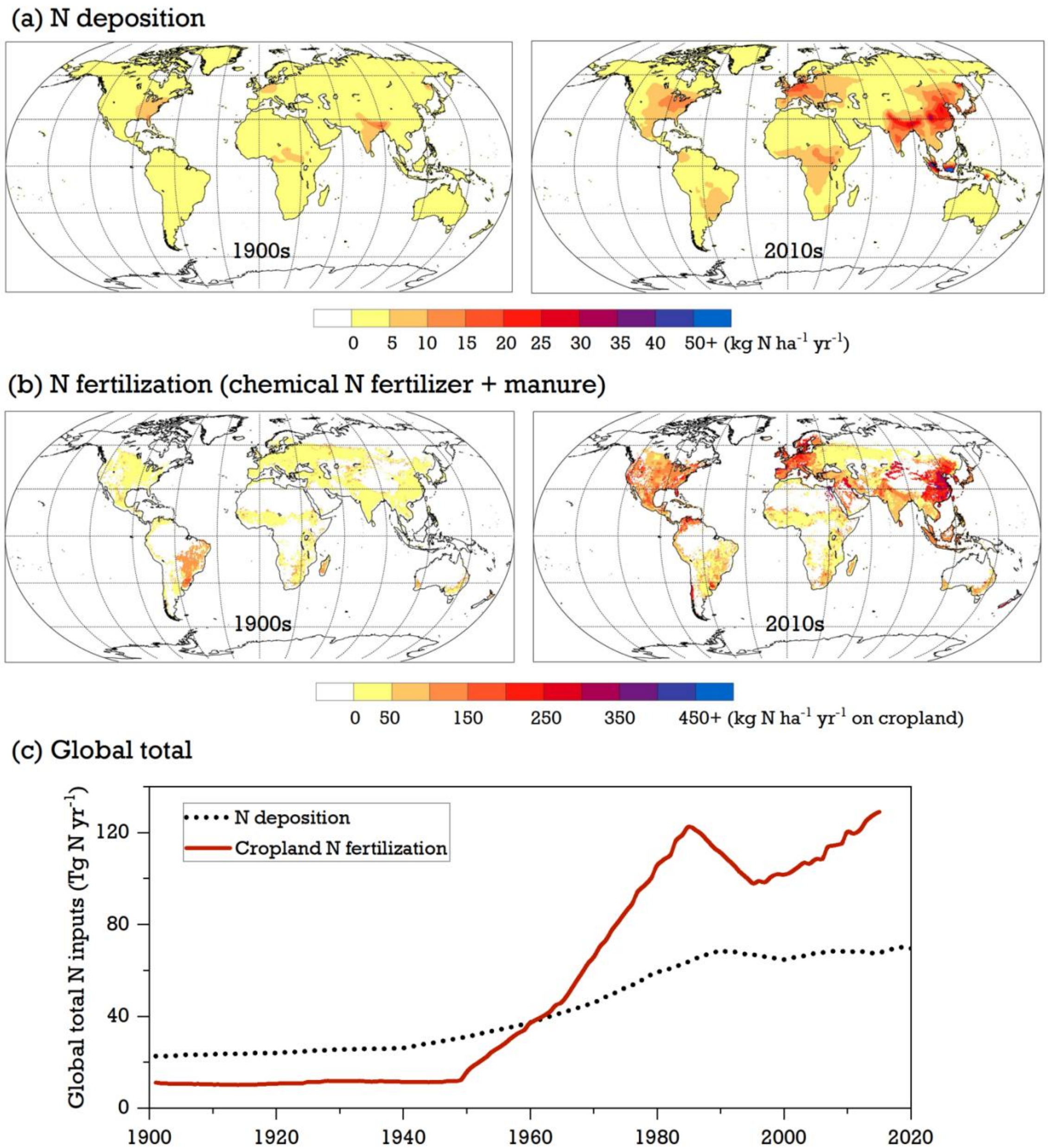

Figure S1. Maps of (a) N deposition and (b) cropland N fertilization (chemical N fertilizer + manure) in the decades of the 1900s and the 2010s. Global total N inputs of deposition and cropland fertilization between 1901-2020 is shown in (c). N deposition data on global lands are taken from Tian et al. (2018). Mineral N fertilizer and manure application rate on croplands (1901-2015) are derived from Ag-GRID (Elliott et al., 2015) and Zhang et al. (2017), respectively.

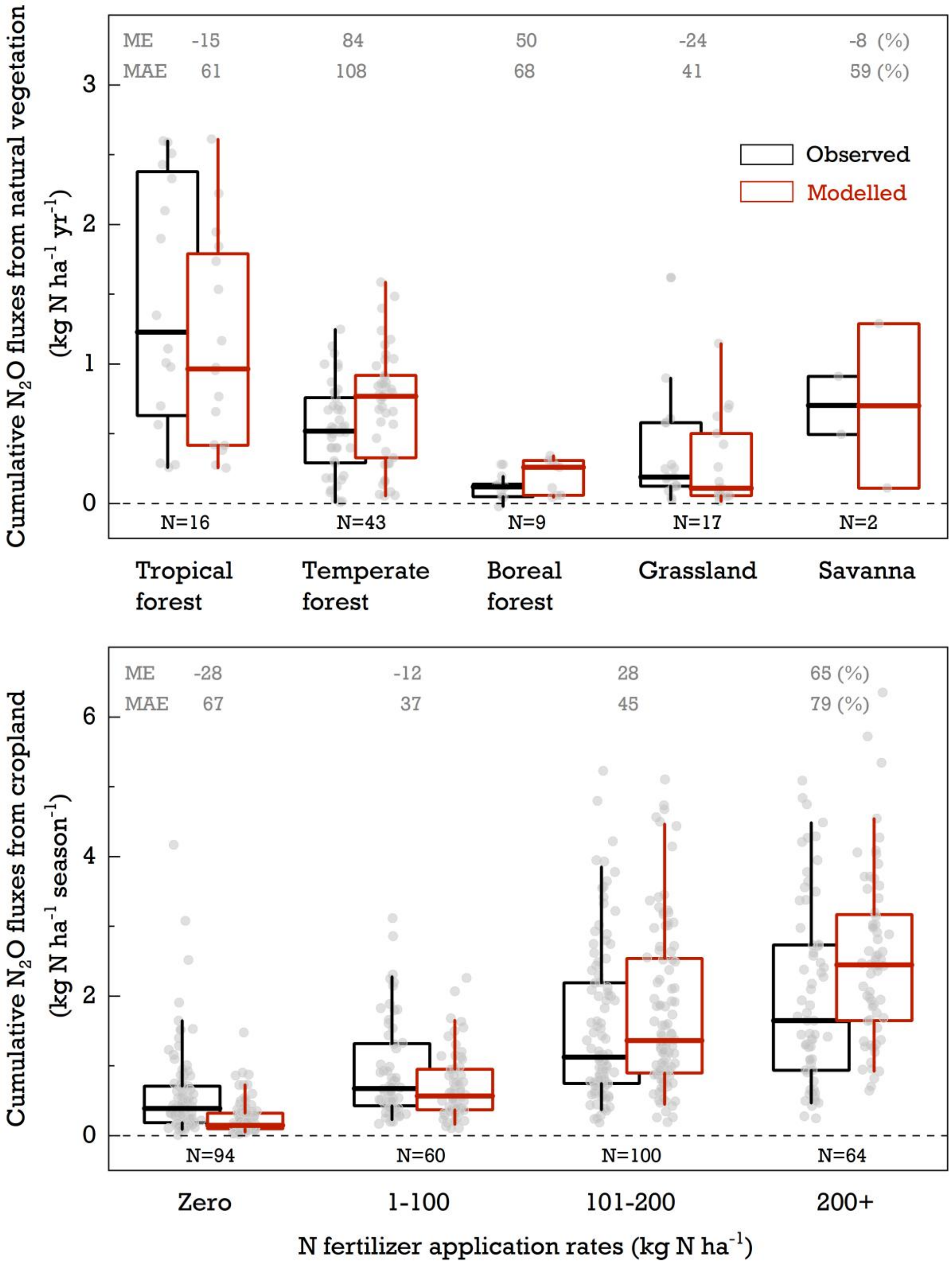

Figure S2. Comparison of modelled and observed cumulative N_2O emissions on natural lands (top) and cropping systems (bottom) across all evaluated sites. Box plots denote the 5th and 95th percentiles by the whiskers, median and interquartile range are the box lines. ME (mean error) and MAE (mean absolute error) are shown as percentages.

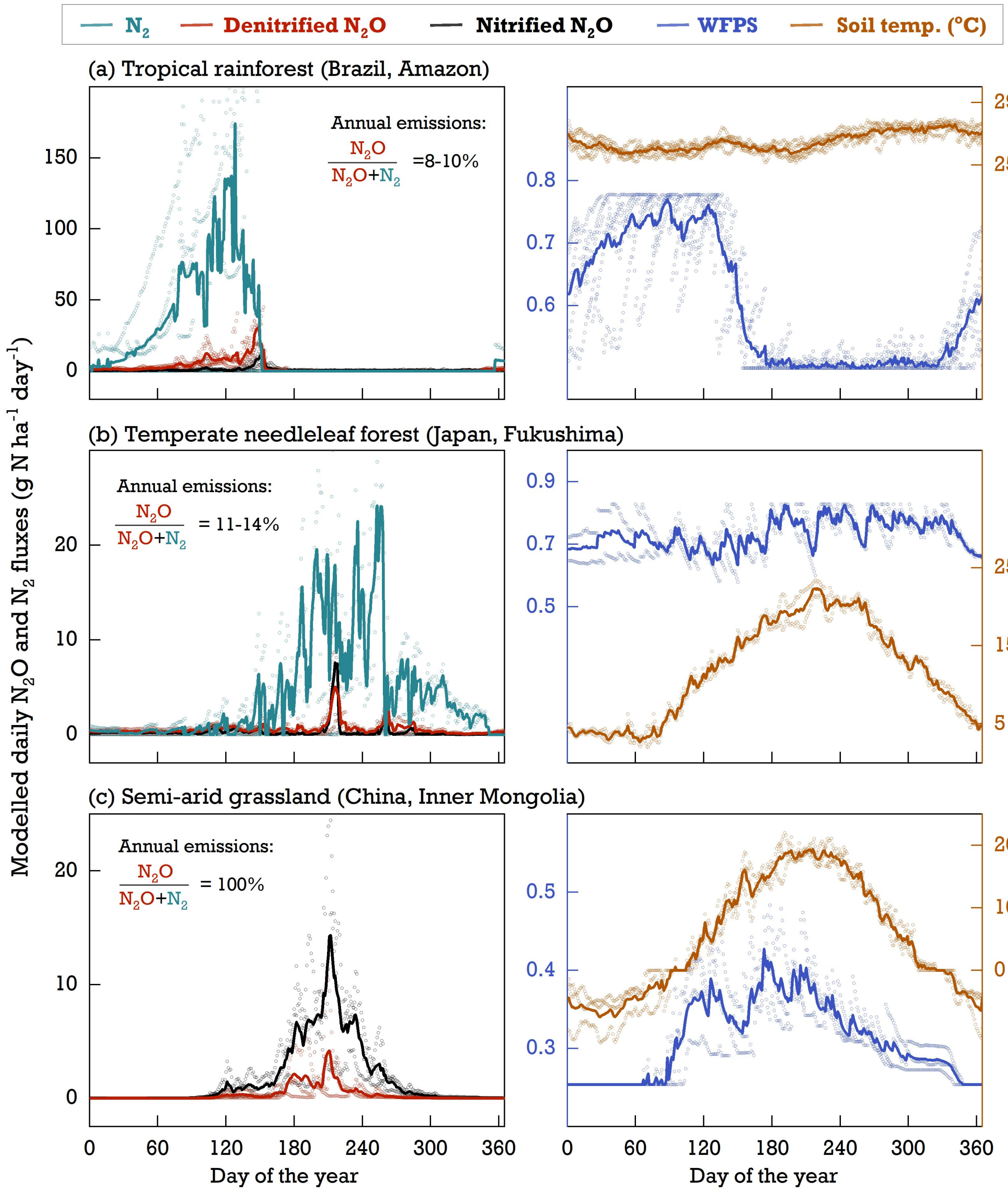

Figure S3. Modelled daily fluxes of N_2, nitrified N_2O, denitrified N_2O, and soil WFPS and temperature in the top layer (0–50 cm) for three different sites: (a) the Tapajós National Forest in Brazil (54.9°W, 2.9°S; 2000–2004), (b) a temperate cedrus forest in Fukushima, Japan (140.3°E, 37.4°N; 2003–2004), and (c) a semi-arid grassland in Inner Mongolia, China (114.7°E, 43.5°N; 2001–2003). The thick lines represent the multi-year average of simulations, while open circles indicate the simulations for individual years.

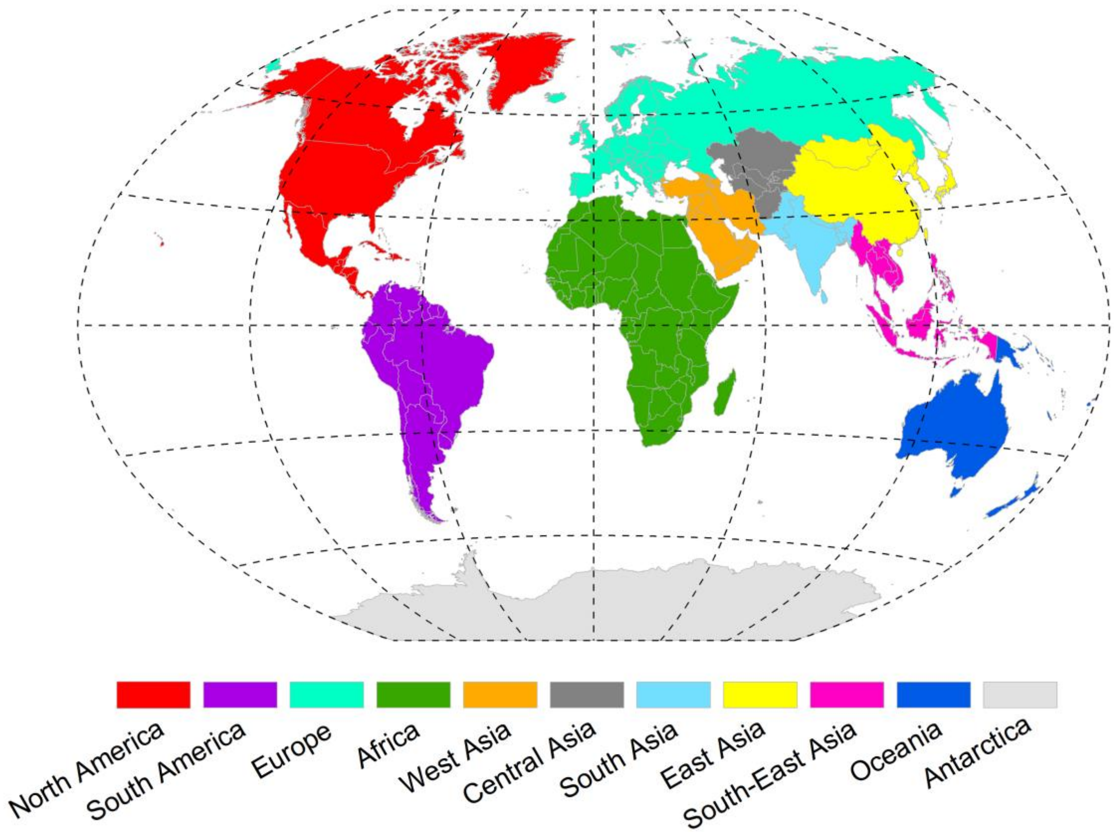

Figure S4. A global division of geographical regions to analyze soil N_2O emissions at a continental level.

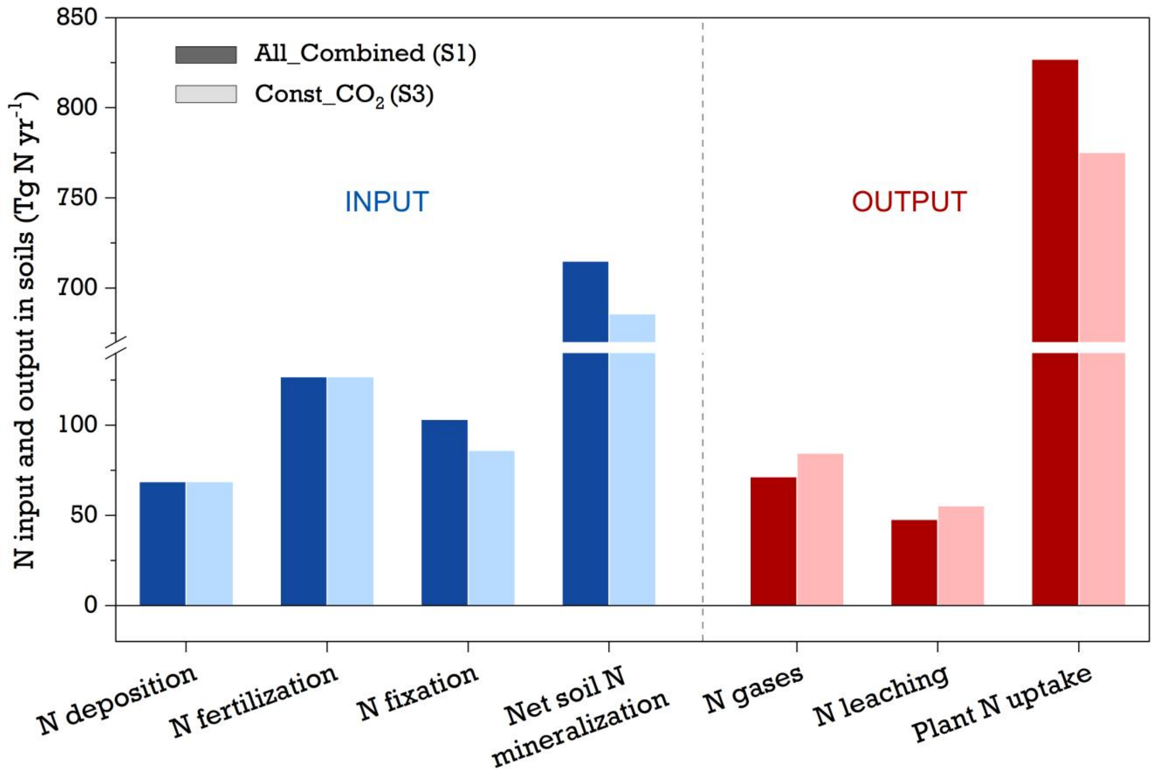

Figure S5. Modelled total N input and output in soils (Tg N yr^{-1}) across global terrestrial ecosystems in "All_Combined" and "Const_CO_2" runs in the 2010s. See Table 1 in the main text for simulation setups.

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