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Nitrogen leaching from natural ecosystems under global change: a modelling study

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Text S1. Description of LPJ-GUESS

General description

LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator; Smith et al., 2001) simulates vegetation dynamics and biogeochemical fluxes of C and N in terrestrial ecosystems and employs generalized biome- or global-scale parameterizations of component ecosystem processes, allowing it to be employed without recalibration globally or for any large region. It is forced by climate variables, CO_2 concentration and N deposition and runs with a daily time step, except for C allocation, vegetation dynamics, and disturbances, which are resolved annually. Our simulations focused on natural vegetation, i.e. croplands were not considered. Eleven plant functional types (PFTs) were included, representing vegetation in temperate, tropical, boreal, and grassland biomes. The model predicts the occurrence of each PFT based on bioclimatic limits and competition with other PFTs for light and soil resources. Contrary to most global ecosystem models, LPJ-GUESS explicitly represents the age distribution of woody PFTs. The model simulates trees of different cohorts (age classes) which are each represented by an average individual for each age class of each of a number of co-occurring PFTs. Mortality and establishment of the individuals are implemented in a stochastic fashion, as are fire and other disturbances (see below). Sub-grid variability resulting from landscape heterogeneity and differences in disturbance history are accounted for by simulating a predefined number of replicate "patches" (area 0.1 ha) per grid cell. The conditions for all patches within a grid cell are identical but differences arise from the stochastic calculations.

Within each patch LPJ-GUESS simulates fluxes of C, water and N, in vegetation and soil based on descriptions of various processes, including photosynthesis, plant C allocation, autotrophic respiration, evapotranspiration, percolation, lateral runoff, and soil carbon cycling. Soil carbon cycling is simulated using a scheme based on the CENTURY model, as described by Smith et al. (2014) . Soil hydrology is represented using two soil layers of 0.5 and 1 m. Downward percolation is simulated with a leaky bucket scheme (Gerten et al., 2004). Available water capacity (AWC) and a hydraulic conductivity are derived from sand, silt and clay fraction, as described in Olin et al. (2015). Water in excess of the AWC in the first and second soil layer is exported as surface runoff and interflow, respectively.

Fire is modelled stochastically according to the scheme described in Thonicke et al. (2001). Fire can occur when a fuel (litter) load of 200 g m^{-2} or higher is present. When this is the case, the probability of a fire occurring on a given day is a non-linear function of the moisture content of the upper soil layer, serving as proxy for the litter layer. The actual occurrence of a fire is determined using a random number generator. If a fire occurs, a PFT dependent fraction of the biomass (50–90 %) is lost from the ecosystem. Additional disturbances, killing all vegetation, are modelled with a fixed expected return time of 100 years.

The simulation is initialized with a 500-year spin-up to accumulate vegetation and soil C pools in equilibrium with the initial forcing. During this phase, the model is forced by a trend-free time series (here 10 years; see below) of annually-varying inputs.

N cycling module

In LPJ-GUESS ecosystem N is present in vegetation biomass and in the soil in mineral and organic form. In the model version employed for our study, mineral soil N is represented by a single pool; i.e. different N species such as ammonium and nitrate, and transformation between these are not distinguished. Atmospheric N deposition is added to the soil mineral N pool. Biological N fixation (BNF) is calculated as a linear function of evapotranspiration (Cleveland et al., 1999) and added to the mineral N pool, up to a maximum pool capacity of 2 g N m^{-2}. Root uptake transfers N from the soil mineral N pool to vegetation on a daily time step. Plant N demand is driven by optimal leaf N content required for photosynthesis, computed based on the carboxylation capacity of Rubisco ($V_{\max}$) that maximizes canopy-level net photosynthesis (Haxeltine and Prentice, 1996), given current atmospheric CO_2 concentration, temperature, soil water, and leaf area index (LAI). In addition to leaves plants require N for sapwood, heartwood, and roots. Plants also maintain an N store pool with a maximum size defined by biomass, leaf C to N ratio, and PFT type. Following Meyerholt and Zaehle (2015), the C:N ratios of non-leaf pools are fixed, which represents a modification to the model version described in Smith et al. (2014), where C:N ratios of non-leaf tissue were scaled based on leaf C:N. Plants take up N from the mineral soil pool and the N store in order to maintain optimal leaf N. If insufficient N is available the plant experiences N stress and $V_{\max}$ is reduced. To this end the model calculates an "N limitation factor" equal to the ratio of the true $V_{\max}$ and the $V_{\max}$ in absence of N limitation (both without water limitation). Additionally, different PFT cohorts compete for N, where the competitive strength of an individual is determined by its root biomass, the combined C to N ratio of roots and leaves, and growth form, with grass PFTs being more competitive than tree PFTs.

N stored in vegetation is returned to the soil in organic form in conjunction with biomass turnover due to senescence, mortality, and disturbance. Retranslocation transfers 50 % of leaf and root N to the N store pool, up to a maximum capacity, prior to turnover. Litter and soil organic matter (SOM) dynamics follow the CENTURY model (Parton et al., 1993), which includes nine litter and SOM pools, and two microbial pools. The C to N ratio of the slowest SOM pool (passive) is fixed, while the other pools vary depending on litter N content and soil available N. During decomposition N is transferred to or from the mineral N in order to maintain the C to N ratio of the pools. If insufficient N is available decomposition rates are reduced. Additionally, 1 % of the daily N mineralization is lost, representing gaseous N loss during nitrification and denitrification. Organic N leaching occurs as a fraction of the soil microbial N pool, determined by the percolation rate and the sand fraction. Mineral N leaching is calculated as a fraction of the mineral N pool equal to the relative water loss by percolation and interflow. Surface runoff does not cause N loss. Finally, fire events cause loss of vegetation N which is assumed to be emitted in gaseous form.

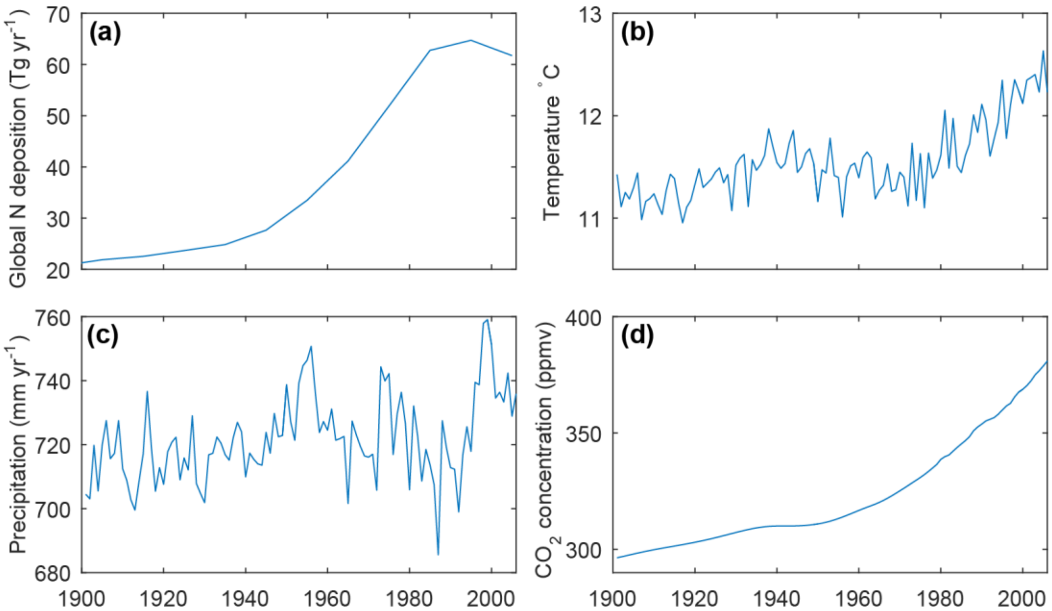

Figure S1. Change of model drivers during the simulation period. (a) global total atmospheric N deposition; (b) global mean temperature; (c) global mean precipitation rate; (d) global mean atmospheric CO_2 concentration.

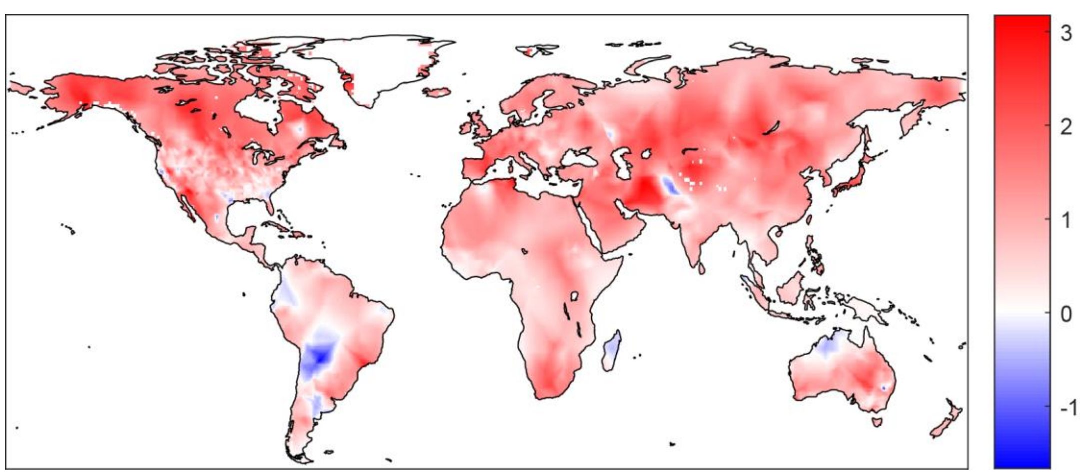

Figure S2. Mean temperature difference between 1997–2006 and 1901–1910 (°C).

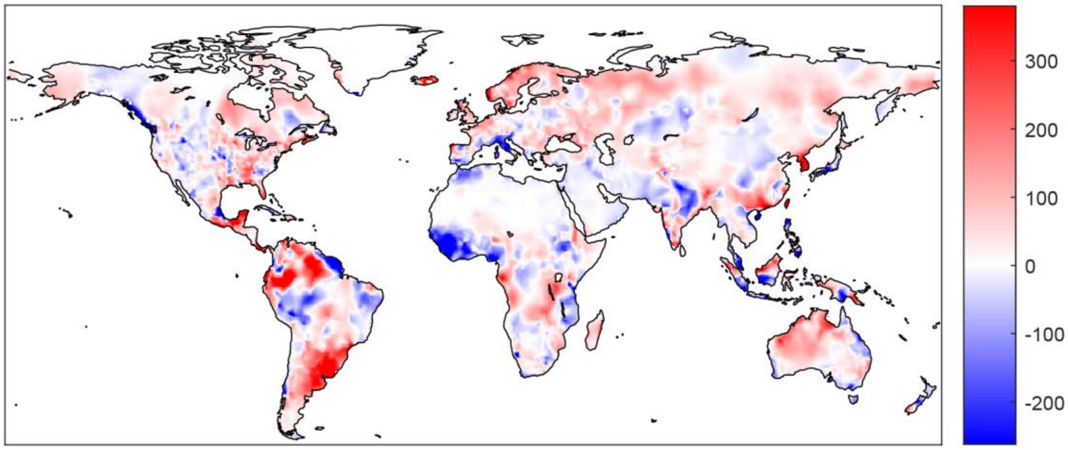

Figure S3. Mean precipitation difference between 1997–2006 and 1901–1910 (mm yr^{-1}).

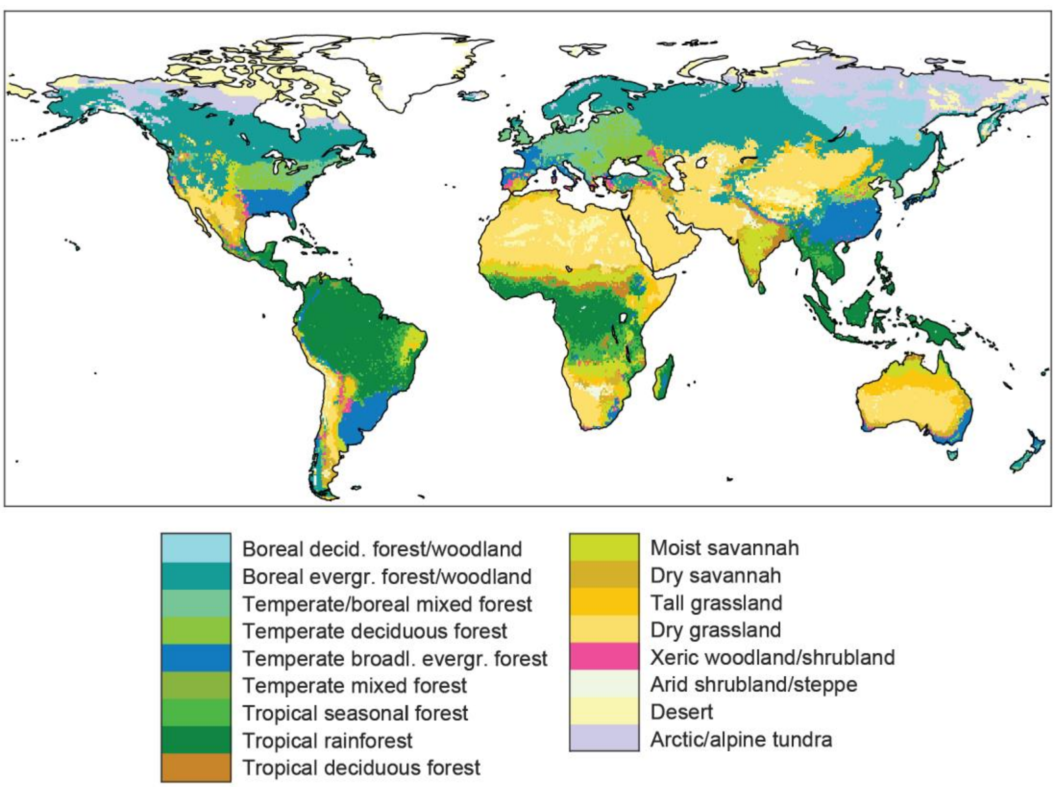

Figure S4. Biome distribution for the true historical simulation (+Ndep +clim +CO_2). Biome classes are derived from leaf area index of the PFTs averaged over the period 1997–2006 (Smith et al., 2014).

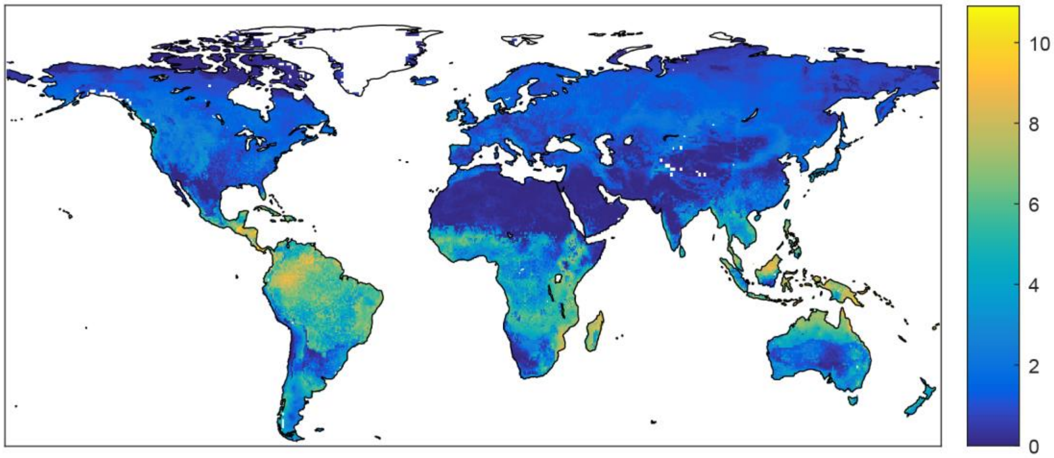

Figure S5. Biological N fixation (kg N ha^{-1} yr^{-1}) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006.

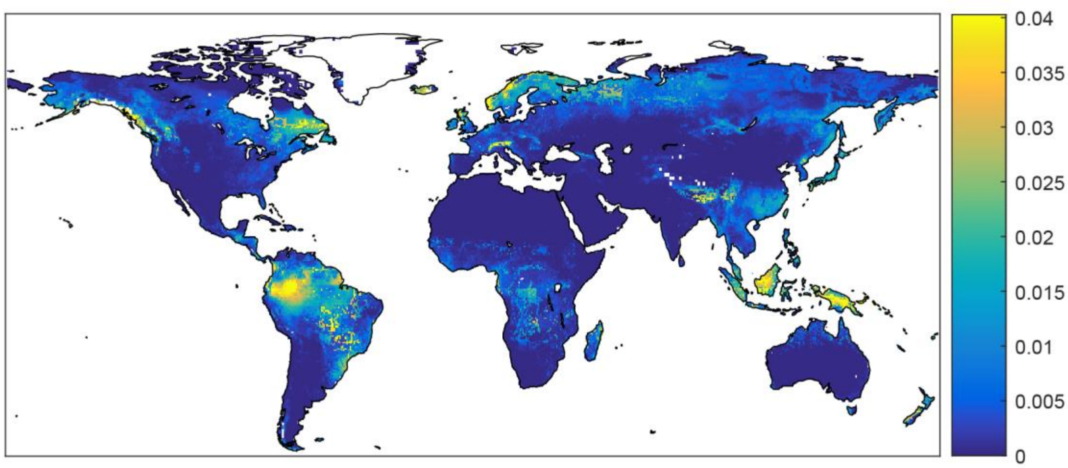

Figure S6. Organic N leaching (kg N ha^{-1} yr^{-1}) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006.

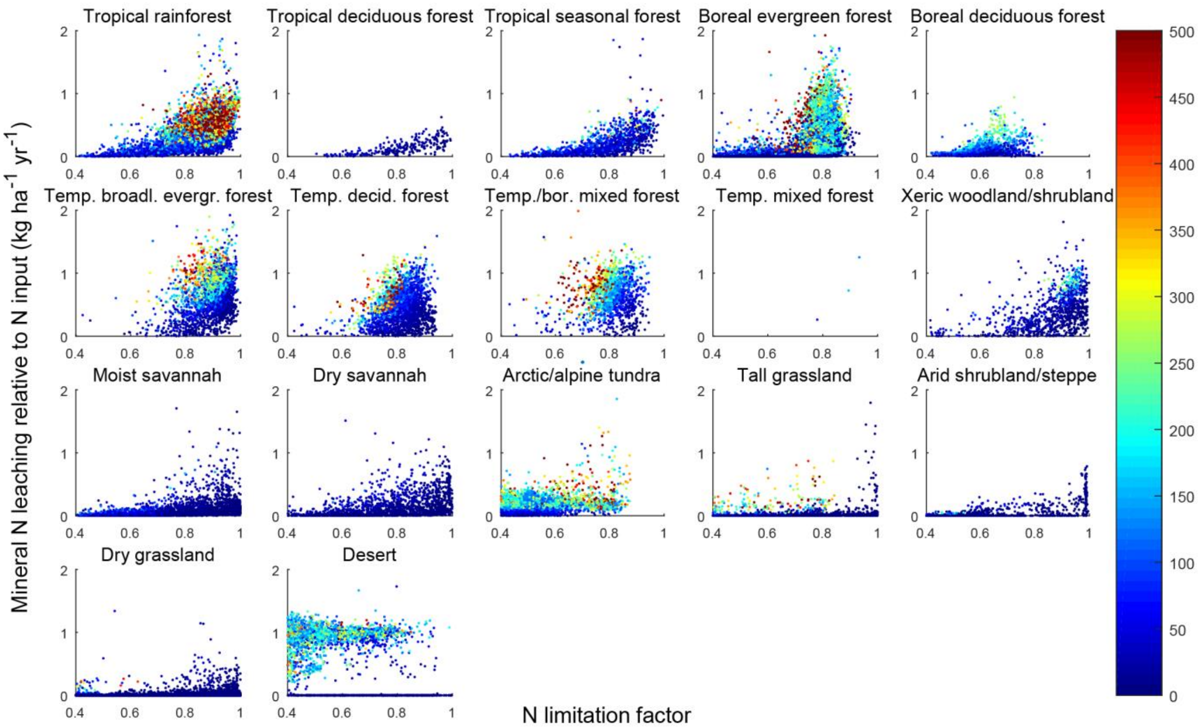

Figure S7. N leaching relative to N input vs N status for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006. Colours indicate the combined rate of interflow and percolation from the root zone (mm yr^{-1}; upper limit cut off to improve readability)

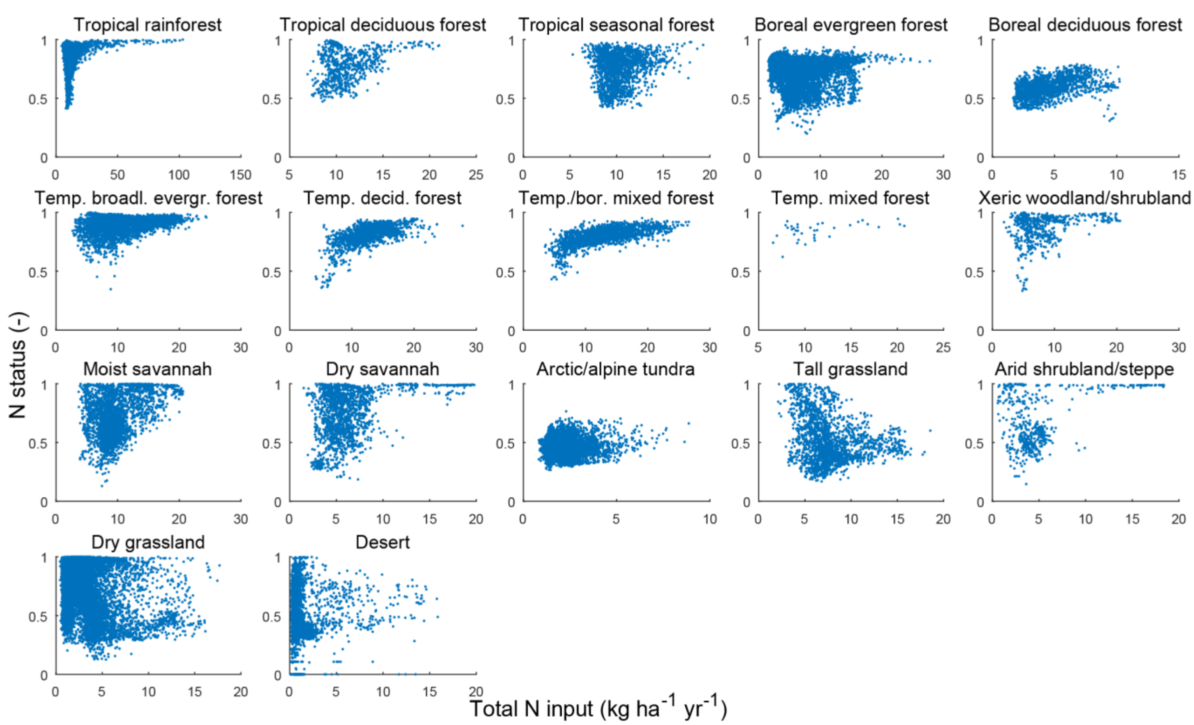

Figure S8. N status vs total N input (fixation + deposition) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006.

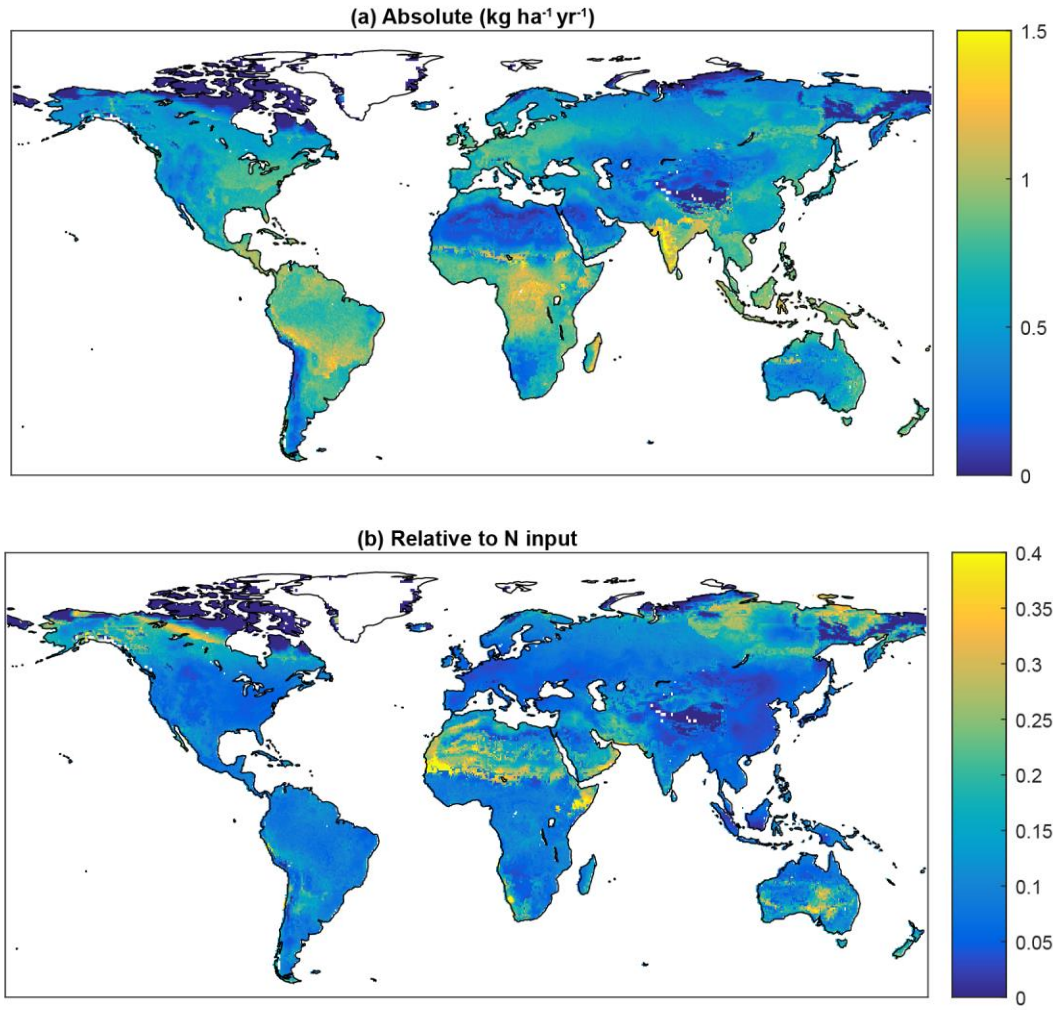

Figure S9. N loss due to denitrification (kg ha^{-1} yr^{-1}) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006. (a) Absolute; (b) Relative to total N input (deposition + fixation)

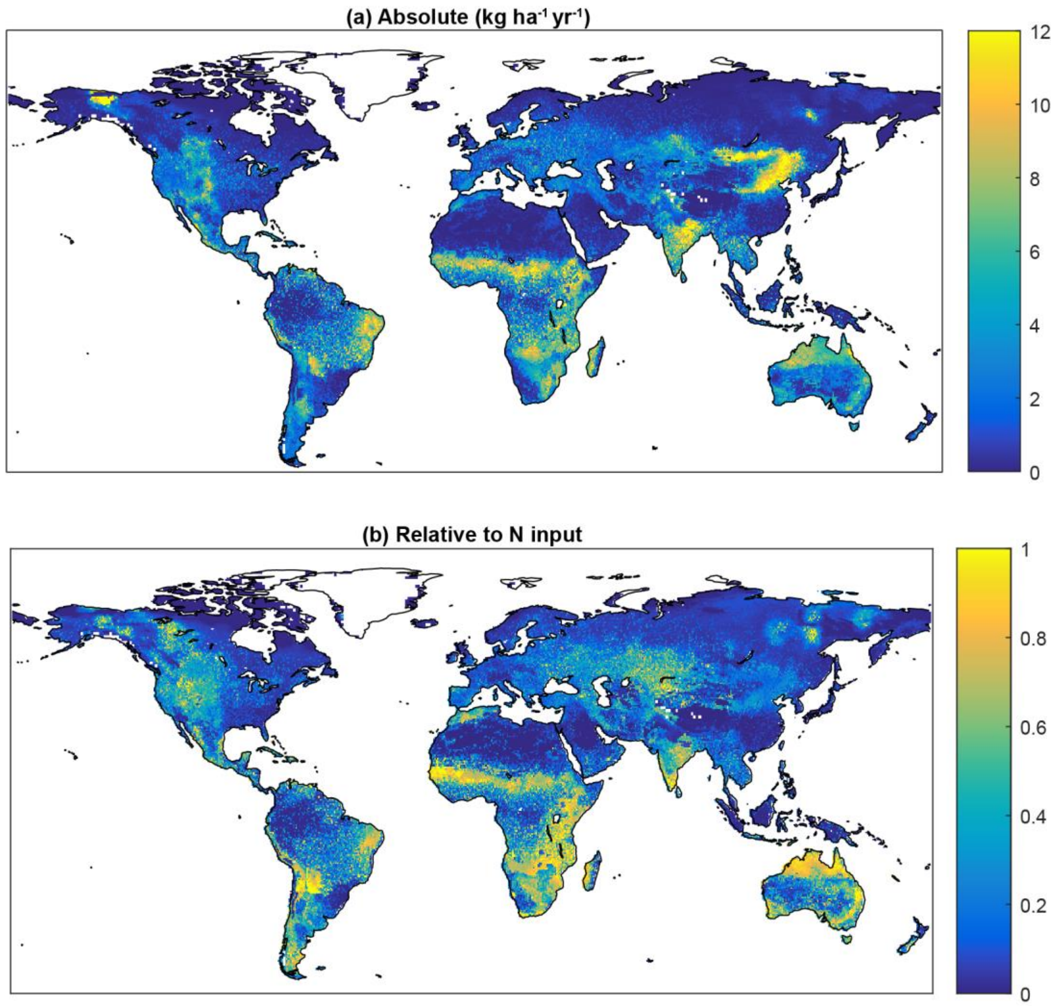

Figure S10. N loss due to fire (kg N ha^{-1} yr^{-1}) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006. (a) Absolute; (b) Relative to total N input (deposition + fixation)

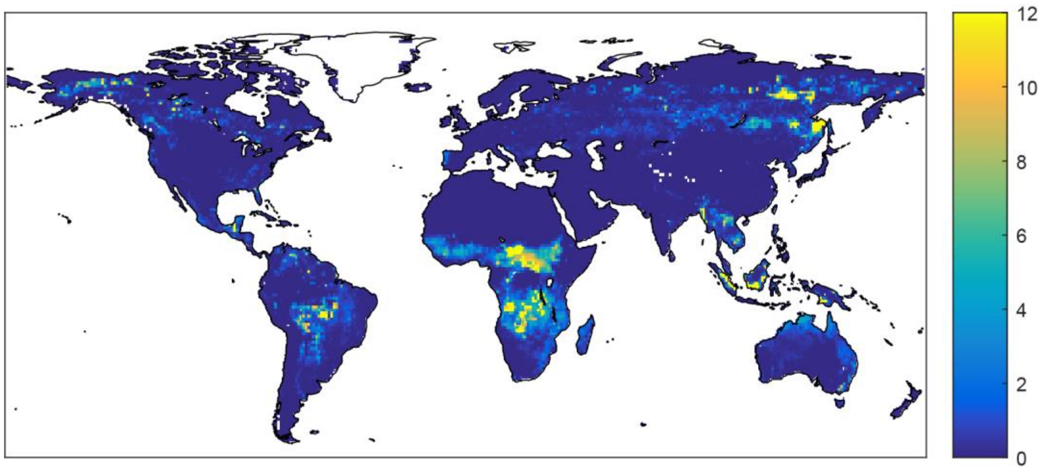

Figure S11. Fire N emissions (kg N ha^{-1} yr^{-1}) input in the atmospheric chemistry models that were used to derive the ACCMIP dataset of atmospheric N deposition. Note that the axis scale has been cut-off at 12 kg N ha^{-1} yr^{-1} for comparability with Figure S10a.

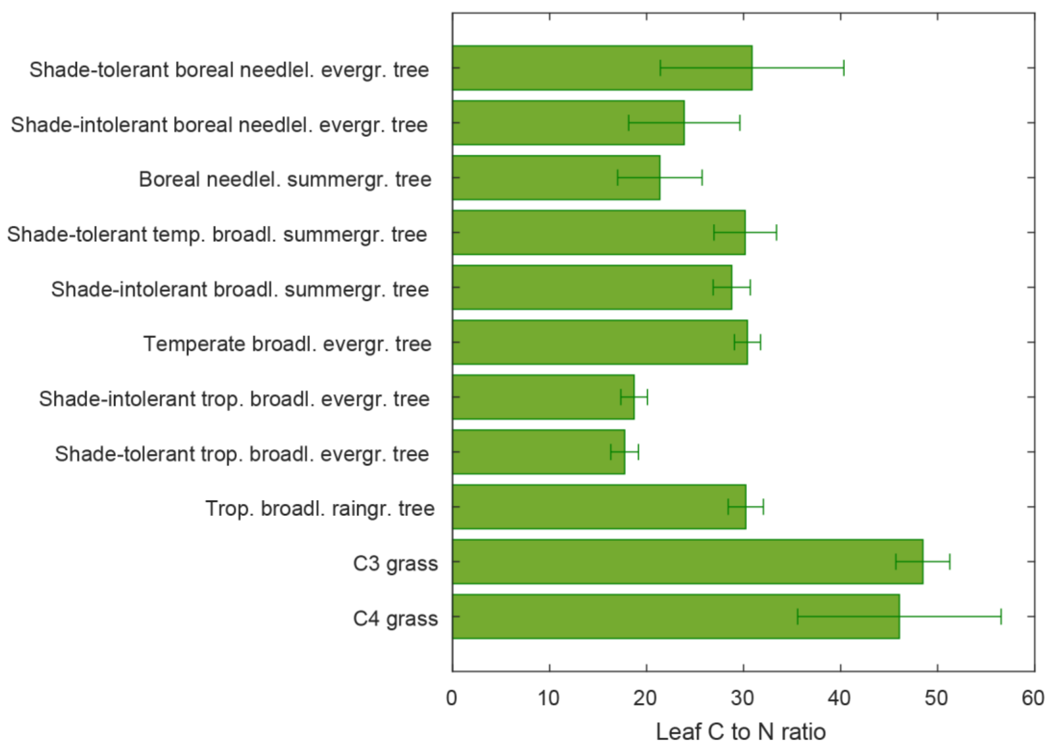

Figure S12. Predicted leaf C to N ratio of the plant functional types in LPJ-GUESS. The bars show means over the grid cells where the respective PFTs are dominant (have highest leaf area index). Error bars indicate 1 standard deviation.

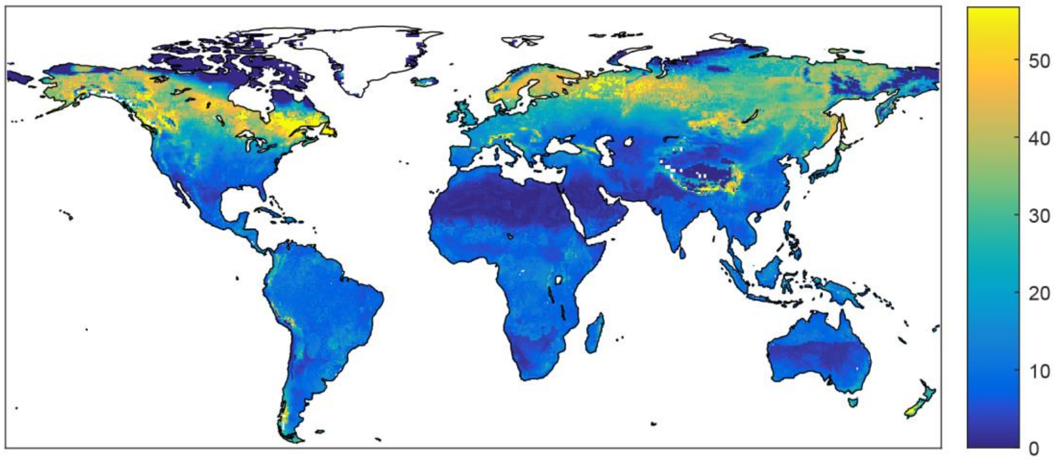

Figure S13. Soil organic carbon storage (kg C m^{-2}) for the true historical simulation (+Ndep +clim +CO_2) averaged over the period 1997–2006.

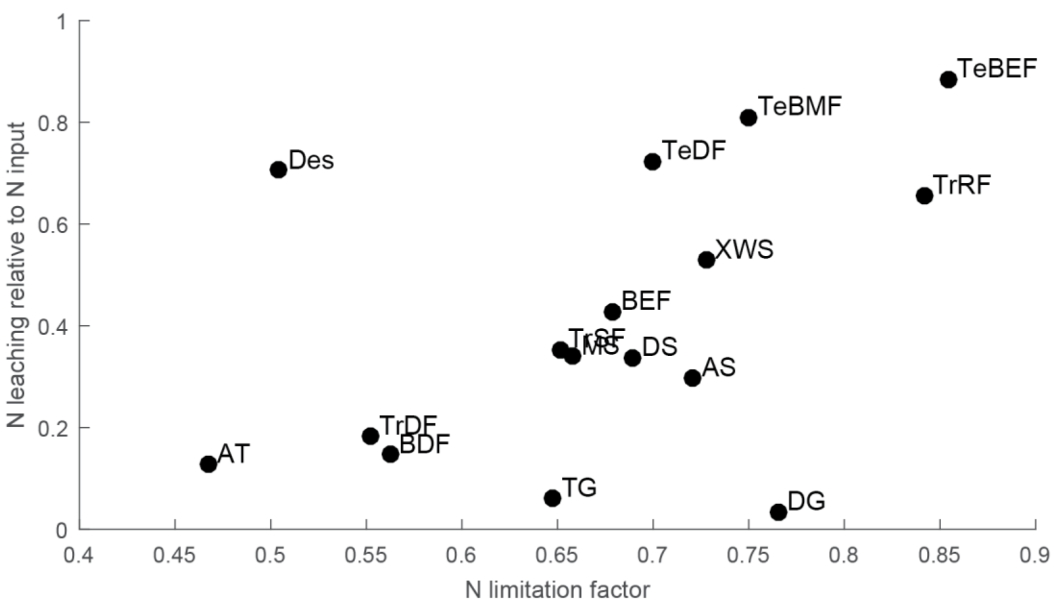

Figure S14. N leaching relative to total N input vs N status averaged over the period 1997–2006 for a simulation run with true drivers (+Ndep +clim +CO_2) but fire and other disturbances switched off. TrRF: Tropical rainforest, TrDF: Tropical deciduous forest, TrSF: Tropical seasonal forest, BEF: Boreal evergreen forest/woodland, BDF: Boreal deciduous forest/woodland, TeBEF: Temperate broadleaved evergreen forest, TeDF: Temperate deciduous forest, TeBMF: Temperate/boreal mixed forest, TeMF: Temperate mixed forest, XWS: Xeric woodland/shrubland, MS: Moist savannah, DS: Dry savannah, AT: Arctic/alpine tundra, TG: Tall grassland, AS: Arid shrubland/steppe, DG: Dry grassland, Des: Desert.

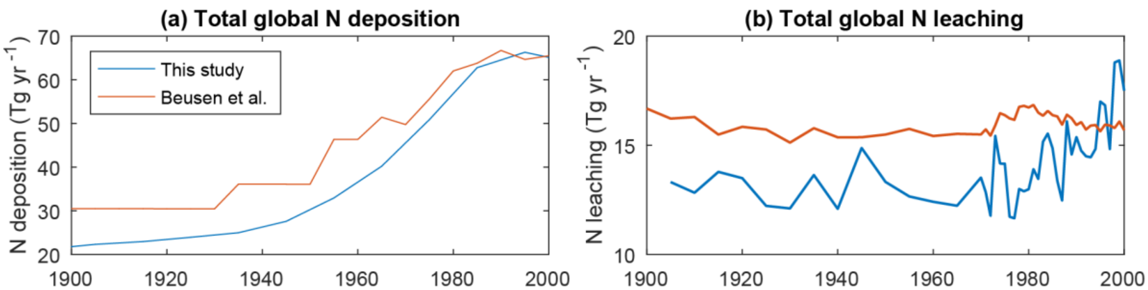

Figure S15. Comparison of N fluxes with results of Beusen et al., (2016). (a) Total global N deposition, including non-natural lands. (b) Total global N deposition from natural lands, corrected for changes in natural landcover based on the dataset used by Beusen et al. (2016).

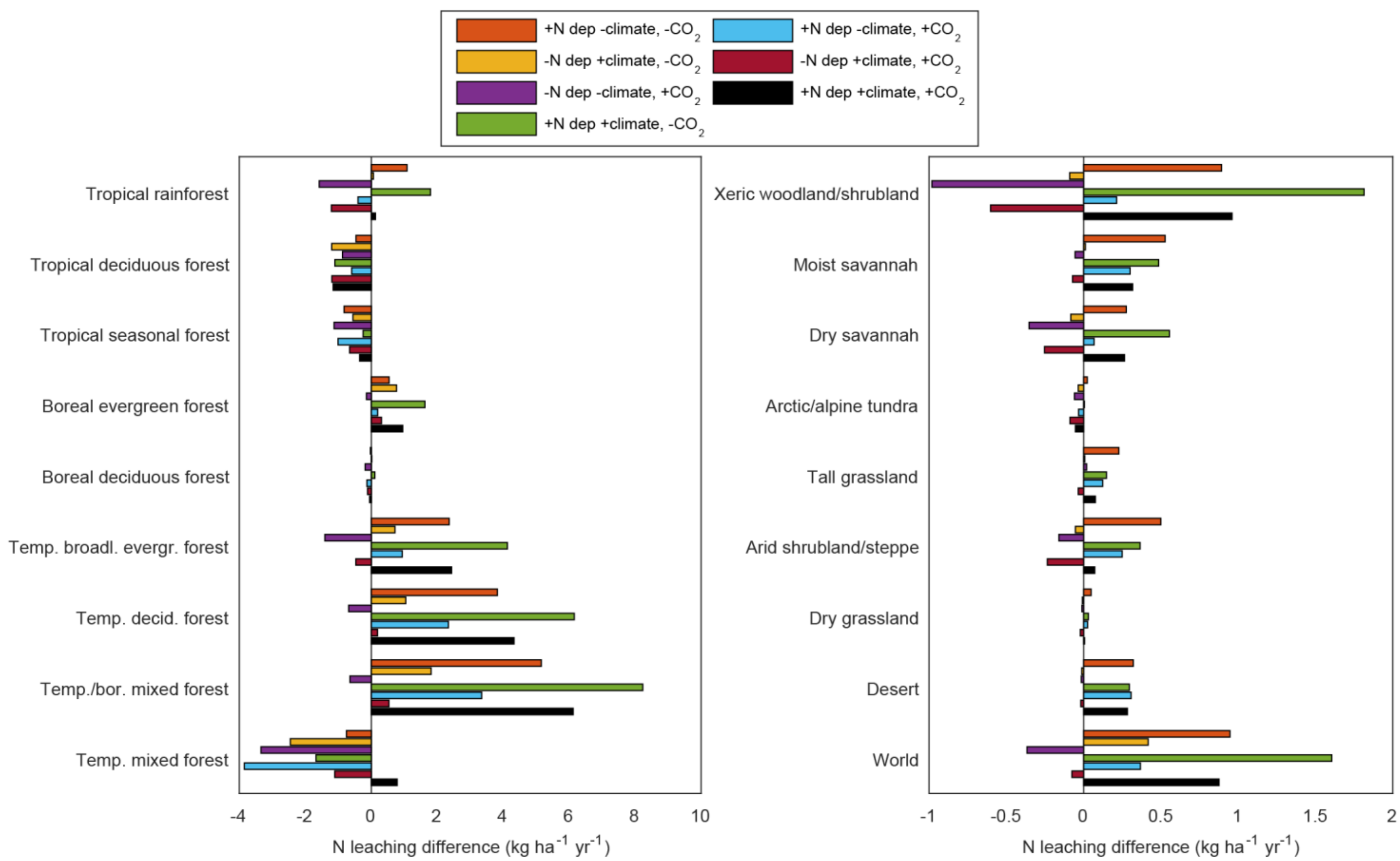

Figure S16. N leaching difference with control simulation (-Ndep -clim -CO_2) for the eight simulations averaged over the period 1997–2006.

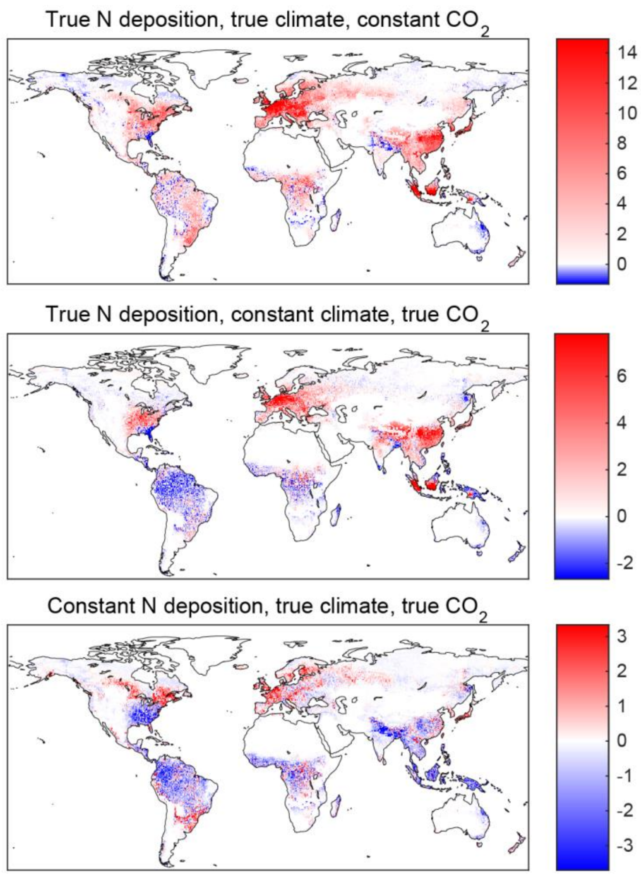

Figure S17. Mineral N leaching difference with the control simulation (-Ndep -clim -CO_2) for the two-factor simulations. For readability, the colour axis has been cut off at approximately the 1% and 99% quantile.

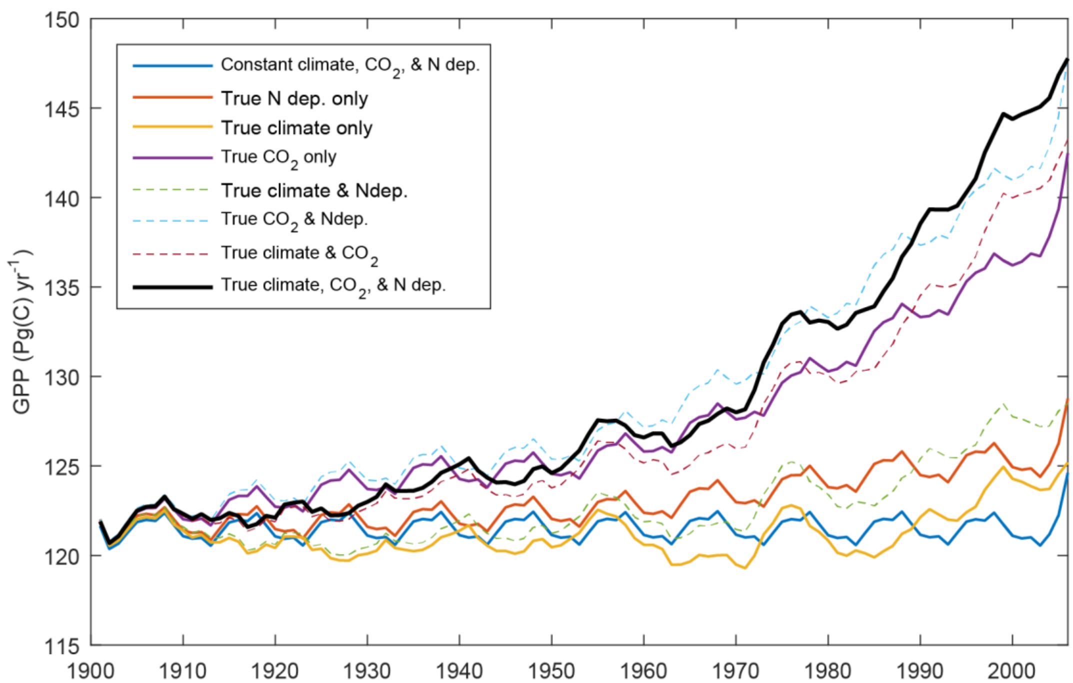

Figure S18. Global total GPP vs time for the eight simulations. For readability, the time series have been smoothed with a 5-year moving window

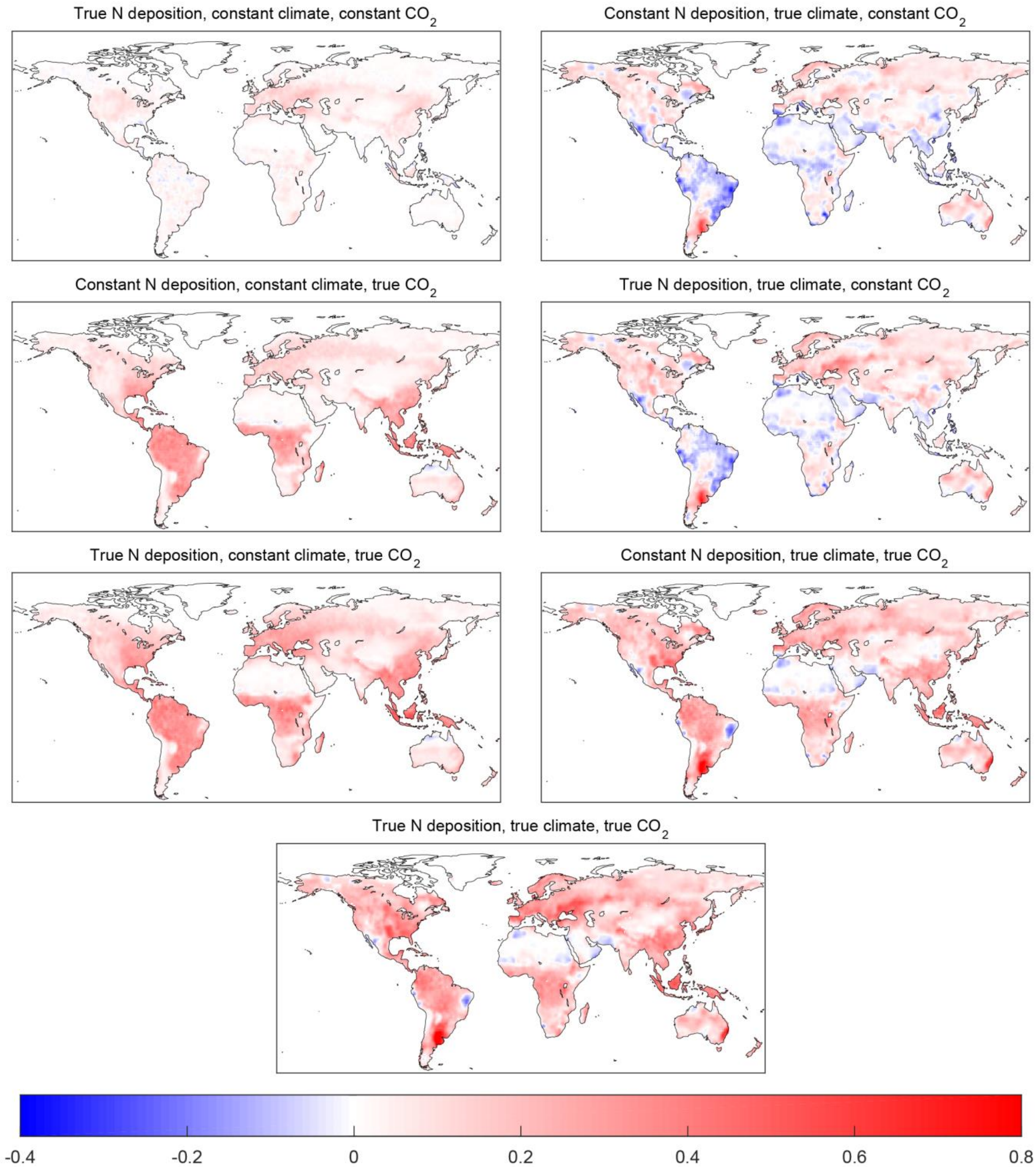

Figure S19. GPP difference (kg C m^{-2} yr^{-1}) with control simulation (-Ndep -clim -CO_2) for the other simulations averaged over the period 1997–2006.

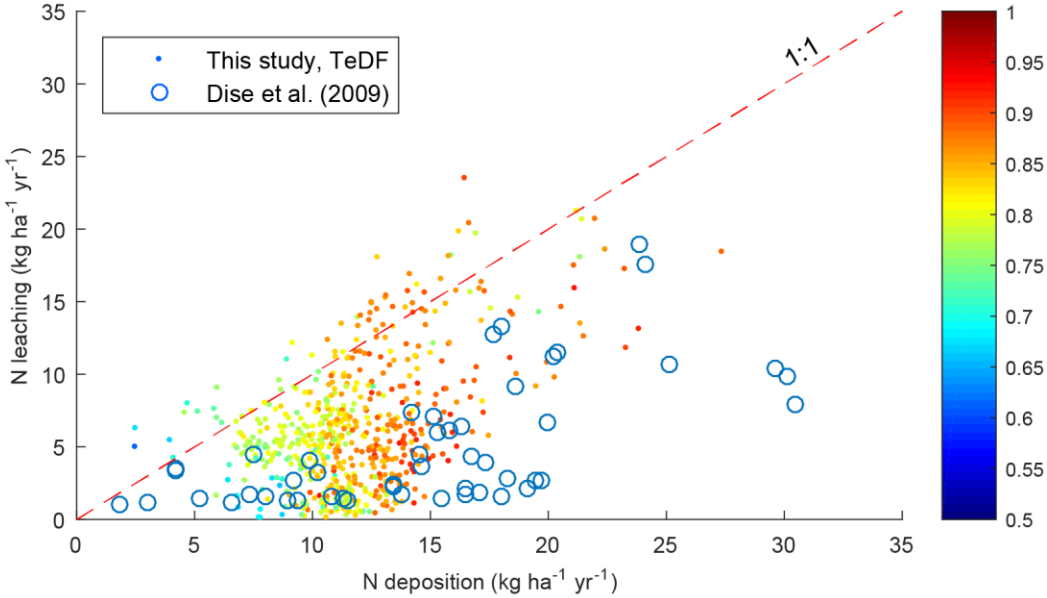

Figure S20. N leaching vs N deposition in European temperate deciduous forests for the true historical simulation (+Ndep +clim +CO_2) (averaged over the period 1997–2006) and Level II sites of the UN-ECE/EC Intensive Monitoring Programme (Dise et al., 2009). colours indicate ecosystem N status.

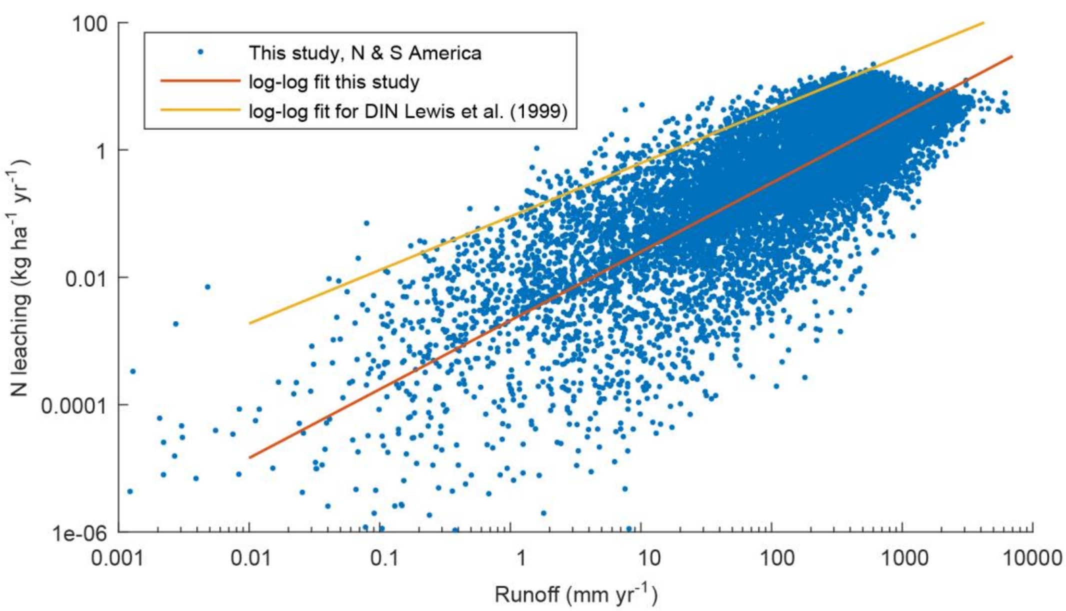

Figure S21. Mineral N leaching vs runoff for North and South America. The linear fit on log-log scale is compared to a fit for dissolved inorganic nitrogen (DIN) losses vs runoff published by Lewis et al. (1999).

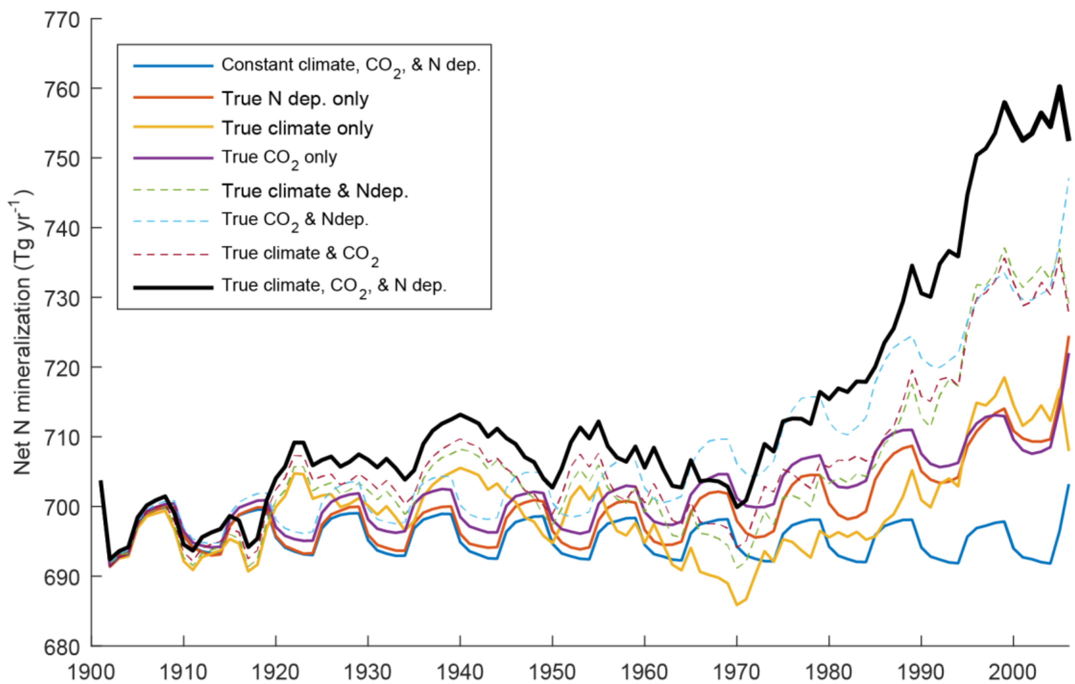

Figure S22. Global total net N mineralization vs time for the eight simulations. For readability, the time series have been smoothed with a 5-year moving window.

	TrRF	TrDF	TrSF	BEF	BDF	TeBEF	TeDF	TeBMF	TeMF	XWS	MS	DS	AT	TG	AS	DG	Des
TrRF	-	0.655	0.000	0.000	0.000	0.063	0.000	0.000	0.728	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TrDF	0.655	-	0.000	0.000	0.000	0.040	0.000	0.000	0.557	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TrSF	0.000	0.000	-	0.000	0.000	0.001	0.000	0.000	0.142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BEF	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BDF	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeBEF	0.063	0.040	0.001	0.000	0.000	-	0.000	0.000	0.384	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeDF	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeBMF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.043	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeMF	0.728	0.557	0.142	0.000	0.000	0.384	0.047	0.043	-	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
XWS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.001	0.000	0.000	0.000
MS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000
DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000
AT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000
TG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	-	0.000	0.000	0.000
AS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000
DG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000
Des	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-

Table S1. Test statistic of Welch's t-test for determining differences between biomes in total ecosystem N input (mean 1997–2006) between biomes (c.f. Fig. 2, main text). Welch's t-test is used for comparing populations with different variances with different and samples sizes. Significant differences ($\alpha \leq 0.05$) are printed in red. TrRF: Tropical rainforest, TrDF: Tropical deciduous forest, TrSF: Tropical seasonal forest, BEF: Boreal evergreen forest/woodland, BDF: Boreal deciduous forest/woodland, TeBEF: Temperate broadleaved evergreen forest, TeDF: Temperate deciduous forest, TeBMF: Temperate/boreal mixed forest, TeMF: Temperate mixed forest, XWS: Xeric woodland/shrubland, MS: Moist savannah, DS: Dry savannah, AT: Arctic/alpine tundra, TG: Tall grassland, AS: Arid shrubland/steppe, DG: Dry grassland, Des: Desert.

	TrRF	TrDF	TrSF	BEF	BDF	TeBEF	TeDF	TeBMF	TeMF	XWS	MS	DS	AT	TG	AS	DG	Des
TrRF	-	0.830	0.005	0.000	0.000	0.027	0.000	0.000	0.018	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
TrDF	0.830	-	0.027	0.000	0.000	0.082	0.001	0.000	0.000	0.000	0.019	0.000	0.000	0.000	0.000	0.000	0.000
TrSF	0.005	0.027	-	0.000	0.000	0.000	0.192	0.000	0.000	0.000	0.442	0.000	0.000	0.000	0.000	0.000	0.000
BEF	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BDF	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeBEF	0.027	0.082	0.000	0.000	0.000	-	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeDF	0.000	0.001	0.192	0.000	0.000	0.000	-	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000	0.000
TeBMF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.476	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeMF	0.018	0.000	0.000	0.000	0.000	0.004	0.000	0.476	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
XWS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MS	0.002	0.019	0.442	0.000	0.000	0.000	0.011	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000
DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000
AT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000
TG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000
AS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000
DG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000
Des	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-

Table S2. Test statistic of Welch's t-test for determining differences between biomes in total ecosystem N loss (mean 1997–2006) between biomes (c.f. Fig. 2, main text). Welch's t-test is used for comparing populations with different variances with different and samples sizes. Significant differences ($\alpha \leq 0.05$) are printed in red. TrRF: Tropical rainforest, TrDF: Tropical deciduous forest, TrSF: Tropical seasonal forest, BEF: Boreal evergreen forest/woodland, BDF: Boreal deciduous forest/woodland, TeBEF: Temperate broadleaved evergreen forest, TeDF: Temperate deciduous forest, TeBMF: Temperate/boreal mixed forest, TeMF: Temperate mixed forest, XWS: Xeric woodland/shrubland, MS: Moist savannah, DS: Dry savannah, AT: Arctic/alpine tundra, TG: Tall grassland, AS: Arid shrubland/steppe, DG: Dry grassland, Des: Desert.

	TrRF	TrDF	TrSF	BEF	BDF	TeBEF	TeDF	TeBMF	TeMF	XWS	MS	DS	AT	TG	AS	DG	Des
TrRF	-	0.231	0.106	0.000	0.374	0.000	0.000	0.383	0.000	0.950	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TrDF	0.231	-	0.034	0.889	0.012	0.000	0.000	0.127	0.000	0.331	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TrSF	0.106	0.034	-	0.000	0.329	0.001	0.000	0.528	0.000	0.378	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BEF	0.000	0.889	0.000	-	0.000	0.000	0.000	0.000	0.000	0.130	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BDF	0.374	0.012	0.329	0.000	-	0.000	0.000	0.932	0.000	0.543	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeBEF	0.000	0.000	0.001	0.000	0.000	-	0.000	0.000	0.006	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeDF	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeBMF	0.383	0.127	0.528	0.000	0.932	0.000	0.000	-	0.001	0.693	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TeMF	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.001	-	0.000	0.026	0.006	0.099	0.025	0.059	0.001	0.951
XWS	0.950	0.331	0.378	0.130	0.543	0.002	0.000	0.693	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.000	-	0.058	0.000	0.396	0.190	0.001	0.000
DS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.058	-	0.000	0.009	0.010	0.000	0.000
AT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.099	0.000	0.000	0.000	-	0.000	0.002	0.000	0.000
TG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.396	0.009	0.000	-	0.404	0.114	0.000
AS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.000	0.190	0.010	0.002	0.404	-	0.615	0.000
DG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.114	0.615	-	0.000
Des	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.951	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-

Table S3. Test statistic of Welch's t-test for determining differences between biomes in N net ecosystem exchange (mean 1997–2006) between biomes (c.f. Fig. 2, main text). Welch's t-test is used for comparing populations with different variances with different and samples sizes. Significant differences ($\alpha \leq 0.05$) are printed in red. TrRF: Tropical rainforest, TrDF: Tropical deciduous forest, TrSF: Tropical seasonal forest, BEF: Boreal evergreen forest/woodland, BDF: Boreal deciduous forest/woodland, TeBEF: Temperate broadleaved evergreen forest, TeDF: Temperate deciduous forest, TeBMF: Temperate/boreal mixed forest, TeMF: Temperate mixed forest, XWS: Xeric woodland/shrubland, MS: Moist savannah, DS: Dry savannah, AT: Arctic/alpine tundra, TG: Tall grassland, AS: Arid shrubland/steppe, DG: Dry grassland, Des: Desert.

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