Supplementary material
(Note S1-table S1-FigS1-S4)

A global analysis of soil acidification caused by nitrogen addition
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Notes S1. A list of 61 papers used for establishing the database of this meta-analysis

Aarnio T, Martikainen PJ (1994) MINERALIZATION OF CARBON AND NITROGEN IN ACID FOREST SOIL TREATED WITH FAST AND SLOW-RELEASE NUTRIENTS. Plant and Soil, 164, 187-193.

Aarnio T, Martikainen PJ (1995) MINERALIZATION OF C AND N AND NITRIFICATION IN SCOTS PINE FOREST SOIL TREATED WITH NITROGEN FERTILIZERS CONTAINING DIFFERENT PROPORTIONS OF UREA AND ITS SLOW-RELEASING DERIVATIVE, UREAFORMALDEHYDE. Soil Biology & Biochemistry, 27, 1325-1331.

Aarnio T, Raty M, Martikainen PJ (2003) Long-term availability of nutrients in forest soil derived from fast- and slow-release fertilizers. Plant and Soil, 252, 227-239.

Allison SD, Czimczik CI, Treseder KK (2008) Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. Global Change Biology, 14, 1156-1168.

Andersen KM, Corre MD, Turner BL, Dalling JW (2010) Plant-soil associations in a lower montane tropical forest: physiological acclimation and herbivore-mediated responses to nitrogen addition. Functional Ecology, 24, 1171-1180.

Bergkvist B, Folkeson L (1992) SOIL ACIDIFICATION AND ELEMENT FLUXES OF A FAGUS-SYLVATICA FOREST AS INFLUENCED BY SIMULATED NITROGEN DEPOSITION. Water Air and Soil Pollution, 65, 111-133.

Bowman WD, Cleveland CC, Halada L, Hresko J, Baron JS (2008) Negative impact of nitrogen deposition on soil buffering capacity. Nature Geoscience, 1, 767-770.

Bowman WD, Murgel J, Blett T, Porter E (2012) Nitrogen critical loads for alpine vegetation and soils in Rocky Mountain National Park. Journal of Environmental Management, 103, 165-171.

Bradley K, Drijber RA, Knops J (2006) Increased N availability in grassland soils modifies their microbial communities and decreases the abundance of arbuscular mycorrhizal fungi. Soil Biology & Biochemistry, 38, 1583-1595.

Brenner R, Boone RD, Ruess RW (2005) Nitrogen additions to pristine, high-latitude, forest ecosystems: consequences for soil nitrogen transformations and retention in mid and late succession. Biogeochemistry, 72, 257-282.

Chen CR, Xu ZH, Hughes JM (2002) Effects of nitrogen fertilization on soil nitrogen pools and microbial properties in a hoop pine (Araucaria cunninghamii) plantation in southeast Queensland,
Corre MD, Beese FO, Brumme R (2003) Soil nitrogen cycle in high nitrogen deposition forest: Changes under nitrogen saturation and liming. *Ecological Applications*, **13**, 287-298.

Demoling F, Nilsson LO, Baath E (2008) Bacterial and fungal response to nitrogen fertilization in three coniferous forest soils. *Soil Biology & Biochemistry*, **40**, 370-379.

Erickson H, Keller M, Davidson EA (2001) Nitrogen oxide fluxes and nitrogen cycling during postagricultural succession and forest fertilization in the humid tropics. *Ecosystems*, **4**, 67-84.

Fang Y, Xun F, Bai W, Zhang W, Li L (2012) Long-Term Nitrogen Addition Leads to Loss of Species Richness Due to Litter Accumulation and Soil Acidification in a Temperate Steppe. *Plos One*, **7**.

Foereid B, Barthram GT, Marriott CA (2007) The CENTURY model failed to simulate soil organic matter development in an acidic grassland. *Nutrient Cycling in Agroecosystems*, **78**, 143-153.

Fox TR (2004) Nitrogen mineralization following fertilization of Douglas-fir forests with urea in western Washington. *Soil Science Society of America Journal*, **68**, 1720-1728.

Gilliam FS, Adams MB, Yurish BM (1996) Ecosystem nutrient responses to chronic nitrogen inputs at Fernow Experimental Forest, West Virginia. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **26**, 196-205.

Gnankambary Z, Stedt U, Nyberg G, Hien V, Malmer A (2008) Nitrogen and phosphorus limitation of soil microbial respiration in two tropical agroforestry parklands in the south-Sudanese zone of Burkina Faso: The effects of tree canopy and fertilization. *Soil Biology & Biochemistry*, **40**, 350-359.

Gulledge J, Hrywna Y, Cavanaugh C, Steudler PA (2004) Effects of long-term nitrogen fertilization on the uptake kinetics of atmospheric methane in temperate forest soils. *Fems Microbiology Ecology*, **49**, 389-400.

Hogberg P, Fan HB, Quist M, Binkley D, Tamm CO (2006) Tree growth and soil acidification in response to 30 years of experimental nitrogen loading on boreal forest. *Global Change Biology*, **12**, 489-499.

Homann PS, Caldwell BA, Chappell HN, Sollins P, Swanston CW (2001) Douglas-fir soil C and N properties a decade after termination of urea fertilization. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **31**, 2225-2236.

Horswill P, O’sullivan O, Phoenix GK, Lee JA, Leake JR (2008) Base cation depletion, eutrophication and acidification of species-rich grasslands in response to long-term simulated nitrogen deposition. *Environmental Pollution*, **155**, 336-349.

Johnson D, Leake JR, Lee JA, Campbell CD (1998) Changes in soil microbial biomass and microbial activities in response to 7 years simulated pollutant nitrogen deposition on a heathland and two grasslands. *Environmental Pollution*, **103**, 239-250.

Johnson D, Leake JR, Read DJ (2005) Liming and nitrogen fertilization affects phosphatase activities, microbial biomass and mycorrhizal colonisation in upland grassland. *Plant and Soil*, **271**, 157-164.

Jung K, Chang SX (2012) Four years of simulated N and S depositions did not cause N saturation in a mixedwood boreal forest ecosystem in the oil sands region in northern Alberta, Canada. *Forest Ecology and Management*, **280**, 62-70.

Keeler BL, Hobbie SE, Kellogg LE (2009) Effects of Long-Term Nitrogen Addition on Microbial Enzyme Activity in Eight Forested and Grassland Sites: Implications for Litter and Soil Organic Matter Decomposition. *Ecosystmes*, **12**, 1-15.
Koehler B, Corre MD, Veldkamp E, Wullaert H, Wright SJ (2009) Immediate and long-term nitrogen oxide emissions from tropical forest soils exposed to elevated nitrogen input. *Global Change Biology, 15*, 2049-2066.

Kowaljow E, Mazzarino MJ (2007) Soil restoration in semiarid Patagonia: Chemical and biological response to different compost quality. *Soil Biology & Biochemistry, 39*, 1580-1588.

Kristensen HL, McCarty GW (1999) Mineralization and immobilization of nitrogen in heath soil under intact Calluna, after heather beetle infestation and nitrogen fertilization. *Applied Soil Ecology, 13*, 187-198.

Lee KH, Jose S (2003) Soil respiration, fine root production, and microbial biomass in cottonwood and loblolly pine plantations along a nitrogen fertilization gradient. *Forest Ecology and Management, 185*, 263-273.

Li LJ, Zeng DH, Mao R, Yu ZY (2012) Nitrogen and phosphorus resorption of Artemisia scoparia, Chenopodium acuminatum, Cannabis sativa, and Phragmites communis under nitrogen and phosphorus additions in a semiarid grassland, China. *Plant Soil and Environment, 58*, 446-451.

Li YQ, Xu M, Zou XM (2006) Effects of nutrient additions on ecosystem carbon cycle in a Puerto Rican tropical wet forest. *Global Change Biology, 12*, 284-293.

Lieb AM, Darrouzet-Nardi A, Bowman WD (2011) Nitrogen deposition decreases acid buffering capacity of alpine soils in the southern Rocky Mountains. *Geoderma, 164*, 220-224.

Liu Y, Xu R, Xu X, Wei D, Wang Y, Wang Y (2013) Plant and soil responses of an alpine steppe on the Tibetan Plateau to multi-level nitrogen addition. *Plant and Soil, 373*, 515-529.

Lu X-K, Mo J-M, Gundersern P, Zhu W-X, Zhou G-Y, Li D-J, Zhang X (2009) Effect of Simulated N Deposition on Soil Exchangeable Cations in Three Forest Types of Subtropical China. *Pedosphere, 19*, 189-198.

Maljanen M, Jokinen H, Saari A, Strommer R, Martikainen PJ (2006) Methane and nitrous oxide fluxes, and carbon dioxide production in boreal forest soil fertilized with wood ash and nitrogen. *Soil Use and Management, 22*, 151-157.

Malikonen E (1990) ESTIMATION OF NITROGEN SATURATION ON THE BASIS OF LONG-TERM FERTILIZATION EXPERIMENTS. *Plant and Soil, 128*, 75-82.

Meiwes KJ, Merino A, Beese FO (1998) Chemical composition of throughfall, soil water, leaves and leaf litter in a beech forest receiving long term application of ammonium sulphate. *Plant and Soil, 201*, 217-230.

Minocha R, Long S, Magill AH, Aber J, Mcdowell WH (2000) Foliar free polyamine and inorganic ion content in relation to soil and soil solution chemistry in two fertilized forest stands at the Harvard Forest, Massachusetts. *Plant and Soil, 222*, 119-137.

Moscatelli MC, Lagornarsino A, De Angelis P, Grego S (2008) Short- and medium-term contrasting effects of nitrogen fertilization on C and N cycling in a poplar plantation soil. *Forest Ecology and Management, 255*, 447-454.

Parker JL, Fernandez IJ, Rustad LE, Norton SA (2001) Effects of nitrogen enrichment, wildfire, and harvesting on forest-soil carbon and nitrogen. *Soil Science Society of America Journal, 65*, 1248-1255.

Pei G, Ma H, Gao R, Yin Y, Chen S (2013) Effects of simulated nitrogen deposition on available P and K in soils of subtropical forest. *Soil and Fertilizer Sciences in China, 16*-20,87.

Prescott CE, Kishchuk BE, Weetman GF (1995) Long term effects of repeated N fertilization and straw
application in a jack pine forest. 3. Nitrogen availability in the forest floor. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **25**, 1991-1996.

Prietzel J, Rehfuess KE, Stetter U, Pretzsch H (2008) Changes of soil chemistry, stand nutrition, and stand growth at two Scots pine (*Pinus sylvestris* L.) sites in Central Europe during 40 years after fertilization, liming, and lupine introduction. *European Journal of Forest Research*, **127**, 43-61.

Prietzel J, Wagoner GL, Harrison RB (2004) Long-term effects of repeated urea fertilization in Douglas-fir stands on forest floor nitrogen pools and nitrogen mineralization. *Forest Ecology and Management*, **193**, 413-426.

Ring E (2004) Experimental N fertilization of Scots pine: effects on soil-solution chemistry 8 years after final felling. *Forest Ecology and Management*, **188**, 91-99.

Sirulnik AG, Allen EB, Meixner T, Fenn ME, Allen MF (2007) Changes in N cycling and microbial N with elevated N in exotic annual grasslands of southern California. *Applied Soil Ecology*, **36**, 1-9.

Smolander A, Barnette L, Kitunen V, Lumme I (2005) N and C transformations in long-term N-fertilized forest soils in response to seasonal drought. *Applied Soil Ecology*, **29**, 225-235.

Solis E, Campo J (2004) Soil N and P dynamics in two secondary tropical dry forests after fertilization. *Forest Ecology and Management*, **195**, 409-418.

Stroia C, Morel C, Jouany C (2011) Nitrogen Fertilization Effects on Grassland Soil Acidification: Consequences on Diffusive Phosphorus Ions. *Soil Science Society of America Journal*, **75**, 112-120.

Thirukkumaran CM, Parkinson D (2002) Microbial activity, nutrient dynamics and litter decomposition in a Canadian Rocky Mountain pine forest as affected by N and P fertilizers. *Forest Ecology and Management*, **159**, 187-201.

Tu L-H, Hu T-X, Zhang J, Li R-H, Dai H-Z, Luo S-H (2011) Response of soil organic carbon and nutrients to simulated nitrogen deposition in Pleioblastus amarus plantation, Rainy Area of West China. *Chinese Journal of Plant Ecology*, **35**, 125-136.

Turner BL, Yavitt JB, Harms KE, Garcia MN, Romero TE, Wright SJ (2013) Seasonal Changes and Treatment Effects on Soil Inorganic Nutrients Following a Decade of Fertilizer Addition in a Lowland Tropical Forest. *Soil Science Society of America Journal*, **77**, 1357-1369.

Van Miegroet H, Jandl R (2007) Are nitrogen-fertilized forest soils sinks or sources of carbon? *Environmental Monitoring and Assessment*, **128**, 121-131.

Wallenstein MD, McNulty S, Fernandez JJ, Boggs J, Schlesinger WH (2006) Nitrogen fertilization decreases forest soil fungal and bacterial biomass in three long-term experiments. *Forest Ecology and Management*, **222**, 459-468.

Weand MP, Arthur MA, Lovett GM, Sikora F, Weathers KC (2010) The phosphorus status of northern hardwoods differs by species but is unaffected by nitrogen fertilization. *Biogeochemistry*, **97**, 159-181.

Wei C, Yu Q, Bai E *et al.* (2013) Nitrogen deposition weakens plant-microbe interactions in grassland ecosystems. *Global Change Biology*, **19**, 3688-3697.

Zeglin LH, Stursova M, Sinsabaugh RL, Collins SL (2007) Microbial responses to nitrogen addition in three contrasting grassland ecosystems. *Oecologia*, **154**, 349-359.

Zhang G, Chen Z, Zhang A, Chen L, Wu Z (2014) Influence of climate warming and nitrogen deposition on soil phosphorus composition and phosphorus availability in a temperate grassland, China. *Journal of Arid Land*, **6**, 156-163.
Zhu F, Yoh M, Gilliam FS, Lu X, Mo J (2013) Nutrient Limitation in Three Lowland Tropical Forests in Southern China Receiving High Nitrogen Deposition: Insights from Fine Root Responses to Nutrient Additions. Plos One, 8.
Table S1. Response ratios (R) of seven variables extracted from each study

| studies | ecosystems     | latitude | longitude | $R_{Si}$ | $R_{Ca}$ | $R_{Mg}$ | $R_{K}$ | $R_{Na}$ | $R_{Al}$ | $R_{Mn}$ | $N$ addition rate | soil depth | Reference        |
|---------|----------------|----------|-----------|----------|----------|----------|---------|----------|----------|----------|------------------|------------|------------------|
| 1       | boreal forest  | 61.00    | 26.00     | 1.03     | 1.41     | 1.58     | 1.48    | 0.90     | 20.00    | 3.0      | 20.00            | 3.0        | Aarnio_1994      |
| 2       | boreal forest  | 61.18    | 25.17     | 0.95     |          |          |         |          |          |          | 15.00            | 5.0        | Aarnio_1995      |
| 3       | boreal forest  | 61.18    | 25.17     | 1.00     |          |          |         |          |          |          | 15.00            | 5.0        | Aarnio_1995      |
| 4       | boreal forest  | 61.18    | 25.17     | 1.11     |          |          |         |          |          |          | 15.00            | 5.0        | Aarnio_1995      |
| 5       | tropical forest | 61.23    | 26.53     | 0.96     |          |          |         |          |          |          | 2.00             | 2.5        | Aarnio_2003      |
| 6       | temperate forest | 63.92    | -145.73   | 0.89     |          |          |         |          |          |          | 10.00            | 2.5        | ALLISON_2008     |
| 7       | grassland      | 8.75     | -82.23    | 0.98     |          |          |         |          |          |          | 12.50            |            | Andersen_2010    |
| 8       | temperate forest | 55.58    | 14.12     | 1.00     |          |          |         |          |          |          | 6.60             | 5.0        | Bergkvist_1992   |
| 9       | temperate forest | 55.58    | 14.12     | 0.97     |          |          |         |          |          |          | 19.80            | 15.0       | Bergkvist_1992   |
| 10      | temperate forest | 55.58    | 14.12     | 0.99     |          |          |         |          |          |          | 6.60             | 30.0       | Bergkvist_1992   |
| 11      | temperate forest | 55.58    | 14.12     | 0.98     |          |          |         |          |          |          | 19.80            | 30.0       | Bergkvist_1992   |
| 12      | grassland      | 49.17    | 19.96     | 0.98     | 0.69     | 0.72     | 0.72    | 0.80     | 0.70     | 2.00    | 15.00            | 7.5        | BOWMAN_2008      |
| 13      | grassland      | 49.17    | 19.96     | 0.96     | 0.63     | 0.74     | 0.61    | 0.84     | 0.74     | 6.00    | 15.00            | 0.75       | BOWMAN_2008      |
| 14      | grassland      | 49.17    | 19.96     | 0.95     | 0.54     | 0.64     | 0.62    | 0.80     | 0.60     | 15.00  | 15.00            | 10.00      | BOWMAN_2008      |
| 15      | grassland      | 40.43    | -105.72   | 1.00     | 1.07     | 1.02     | 0.97    | 2.87     | 1.12     | 0.50   | 10.00            |            | Bowman_2012     |
| 16      | grassland      | 40.43    | -105.72   | 1.02     | 1.10     | 1.04     | 0.97    | 1.97     | 1.15     | 1.00   | 10.00            |            | Bowman_2012     |
| 17      | grassland      | 40.43    | -105.72   | 0.75     | 0.78     | 0.75     | 0.42    | 2.87     | 0.69     | 3.00   | 10.00            |            | Bowman_2012     |
| 18      | grassland      | 45.18    | -93.27    | 0.93     |          |          |         |          |          | 5.44    | 7.5              |            | Bradley_2006    |
| 19      | grassland      | 45.18    | -93.27    | 0.81     |          |          |         |          |          | 27.20  | 7.5              |            | Bradley_2006    |
| 20      | boreal forest  | 64.75    | -148.30   | 0.96     |          |          |         |          |          | 10.00  | 10.00            |            | BRENNER_2005    |
| 21      | boreal forest  | 64.75    | -148.30   | 0.91     |          |          |         |          |          | 10.00  | 25.0             |            | BRENNER_2005    |
| 22      | boreal forest  | 64.75    | -148.30   | 0.93     |          |          |         |          |          | 10.00  | 10.00            |            | BRENNER_2005    |
| 23      | boreal forest  | 64.75    | -148.30   | 1.00     |          |          |         |          |          | 10.00  | 25.0             |            | BRENNER_2005    |
| 24      | temperate forest | -26.47   | 152.62    | 0.95     |          |          |         |          |          | 6.00   | 15.00            |            | Chen_2002       |
| 25      | temperate forest | -26.47   | 152.62    | 1.02     |          |          |         |          |          | 12.00  | 15.00            |            | Chen_2002       |
| 26      | temperate forest | -26.47   | 152.62    | 0.92     |          |          |         |          |          | 6.00   | 5.0              |            | Chen_2002       |
| 27      | temperate forest | -26.47   | 152.62    | 0.94     |          |          |         |          |          | 12.00  | 5.0              |            | Chen_2002       |
| 28      | temperate forest | 51.15    | -10.45    | 0.97     | 0.67     | 1.00     | 1.08    |          |          | 14.00  | 5.0              |            | Corre_2003      |
| 29      | boreal forest  | 64.12    | 19.45     | 1.01     |          |          |         |          |          | 10.00  | 5.0              |            | Demoling_2008   |
| 30      | boreal forest  | 57.13    | 14.75     | 0.89     |          |          |         |          |          | 10.00  | 5.0              |            | Demoling_2008   |
| 31      | boreal forest  | 56.55    | 13.22     | 0.89     |          |          |         |          |          | 10.00  | 5.0              |            | Demoling_2008   |
| 32      | tropical forest | 18.30    | -65.83    | 0.87     |          |          |         |          |          | 30.00  | 5.0              |            | Erickson_2001   |
| 33      | grassland      | 42.03    | 16.28     | 0.97     |          |          |         |          |          | 2.00   | 10.00            |            | Fang_2012       |
| 34      | grassland      | 42.03    | 16.28     | 0.91     |          |          |         |          |          | 8.00   | 10.00            |            | Fang_2012       |
| 35      | grassland      | 42.03    | 16.28     | 0.88     |          |          |         |          |          | 16.00  | 10.00            |            | Fang_2012       |
| 36      | grassland      | 42.03    | 16.28     | 0.82     |          |          |         |          |          | 32.00  | 10.00            |            | Fang_2012       |
| 37      | grassland      | 55.82    | -3.85     | 1.02     |          |          |         |          |          | 14.00  | 7.5              |            | Foereid_2007    |
|     |          |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|-----|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 20  | grassland | 55.48| -2.23| 0.97 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 21  | grassland | 56.87| -2.60| 0.98 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 22  | temperate forest | 46.22| -122.50| 0.98 | 14.00| 7.5  | Foereid_2007 |
| 22  | temperate forest | 46.22| -122.50| 0.99 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 22  | temperate forest | 46.22| -122.50| 0.90 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 22  | temperate forest | 46.22| -122.50| 0.96 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 23  | temperate forest | 39.05| -79.81| 0.91  | 0.69 | 0.86 | 0.92 |      |      |      |      |      |      |      |      |      |      |      |
| 24  | tropical forest | 11.50| -3.30| 0.97 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 25  | tropical forest | 11.50| -3.32| 0.97 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 26  | tropical forest | 11.50| -3.28| 0.90 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 27  | tropical forest | 11.50| -3.28| 0.92 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 28  | temperate forest | 42.20| -71.90| 1.00 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 29  | boreal forest | 64.50| 19.87| 0.41 | 0.64 | 0.43 | 1.09 | 3.40 | 5.0  |      |      |      |      |      |      |      |      |      |
| 29  | boreal forest | 64.50| 19.87| 0.20 | 0.38 | 0.29 | 0.97 | 6.80 | 5.0  |      |      |      |      |      |      |      |      |      |
| 29  | boreal forest | 64.50| 19.87| 1.31 | 1.84 | 1.01 | 1.16 | 3.40 | 15.0 |      |      |      |      |      |      |      |      |      |
| 29  | boreal forest | 64.50| 19.87| 0.97 | 1.89 | 1.08 | 1.63 | 6.80 | 15.0 |      |      |      |      |      |      |      |      |      |
| 30  | temperate forest | 47.41| -121.82| 0.96 |      |      |      | 8.60 | 2.5  |      |      |      |      |      |      |      |      |      |
| 31  | grassland | 53.26| 1.73 | 0.96 |      |      |      | 3.50 | 10.0 |     |      |      |      |      |      |      |      |      |
| 32  | grassland | 53.26| 1.73 | 0.96 |      |      |      | 3.50 | 20.0 |     |      |      |      |      |      |      |      |      |
| 32  | grassland | 53.26| 1.73 | 0.98 |      |      |      | 3.50 | 15.0 |     |      |      |      |      |      |      |      |      |
| 33  | grassland | 54.12| -2.58| 0.97 |      |      |      | 3.50 | 7.0  |     |      |      |      |      |      |      |      |      |
| 33  | grassland | 54.12| -2.58| 0.93 |      |      |      | 7.00 | 7.0  |     |      |      |      |      |      |      |      |      |
| 33  | grassland | 54.12| -2.58| 0.90 |      |      |      | 14.00| 20.0 |     |      |      |      |      |      |      |      |      |
| 34  | grassland | 55.47| 2.23 | 1.08 |      |      |      | 4.20 | A-horizon | Johnson_2005 |
| 35  | boreal forest | 56.10| -110.90| 0.90 | 0.71 | 0.82 | 1.00 | 1.00 | 1.65 | 3.00 | 0-15 |      |      |      |      |      |      |
| 36  | grassland | 45.40| -93.20| 0.94 | 0.92 | 0.76 | 0.98 | 0.75 | 1.41 | 10.00| 10.0 | Keeler_2009 |
| 37  | grassland | 45.40| -93.20| 0.89 | 0.68 | 0.60 | 0.85 | 0.79 | 1.68 | 10.00| 10.0 | Keeler_2009 |
| 38  | temperate forest | 45.40| -93.20| 0.93 | 0.93 | 0.94 | 0.97 | 1.61 | 0.81 | 10.00| 10.0 | Keeler_2009 |
| 39  | temperate forest | 45.40| -93.20| 1.01 | 0.51 | 0.56 | 0.94 | 0.77 | 1.15 | 10.00| 10.0 | Keeler_2009 |
| 40  | temperate forest | 45.40| -93.20| 0.97 | 0.71 | 0.67 | 0.98 | 1.00 | 1.09 | 10.00| 10.0 | Keeler_2009 |
| 41  | temperate forest | 45.40| -93.20| 0.97 | 1.16 | 0.88 | 1.20 | 0.42 | 1.36 | 10.00| 10.0 | Keeler_2009 |
| 42  | temperate forest | 45.40| -93.20| 0.94 | 0.76 | 0.68 | 0.97 | 2.38 | 1.62 | 10.00| 10.0 | Keeler_2009 |
| 43  | temperate forest | 45.40| -93.20| 1.02 | 1.48 | 1.17 | 1.03 | 1.00 | 1.06 | 10.00| 10.0 | Keeler_2009 |
| 44  | tropical forest | 9.10 | -79.83| 0.85 |      |      |      | 12.50| 5.0  |      |      |      |      |      |      |      |      |
| 45  | grassland | 40.57| -70.83| 0.94 |      |      |      | 10.00| 5.0  |      |      |      |      |      |      |      |      |
| 46  | grassland | 56.48| 8.92 | 1.05 |      |      |      | 1.50 | 3.0  |      |      |      |      |      |      |      |      |
| 47  | temperate forest | 30.83| -87.18| 1.05 |      |      |      | 5.60 | 7.5  |      |      |      |      |      |      |      |      |
| Site | Ecoregion          | Latitude | Longitude | z-value | r-value | s-value | p-value | F-value | AIC | AICc | BIC | Year   |
|------|--------------------|----------|-----------|---------|---------|---------|---------|---------|-----|------|------|--------|
| 47   | temperate forest   | 30.83    | -87.18    | 1.14    |         |         |         |         |     |      |      | Lee_2003 |
| 47   | temperate forest   | 30.83    | -87.18    | 1.11    |         |         |         |         |     |      |      | Lee_2003 |
| 48   | temperate forest   | 30.83    | -87.18    | 1.07    |         |         |         |         |     |      |      | Lee_2003 |
| 48   | temperate forest   | 30.83    | -87.18    | 1.04    |         |         |         |         |     |      |      | Lee_2003 |
| 49   | tropical forest    | 18.30    | -65.83    | 0.84    |         |         |         |         |     |      |      | Lee_2003 |
| 50   | grassland          | 42.97    | 122.35    | 0.80    |         |         |         |         |     |      |      | Li_2013 |
| 51   | tropical forest    | 49.00    | -105.58   | 0.95    | 0.83    | 0.73    | 0.79    | 0.64    | 0.85 | 2.14 | 3.77 | Lieb_2011 |
| 51   | tropical forest    | 49.00    | -105.58   | 0.89    | 0.84    | 0.73    | 0.88    | 0.91    | 1.90 | 2.17 | 4.00 | Lieb_2011 |
| 51   | tropical forest    | 49.00    | -105.58   | 0.93    | 0.81    | 0.56    | 0.81    | 0.45    | 2.77 | 3.20 | 6.00 | Lieb_2011 |
| 52   | grassland          | 30.78    | 90.96     | 0.96    |         |         |         |         |     |      |      | Liu_2013 |
| 52   | grassland          | 30.78    | 90.96     | 0.96    |         |         |         |         |     |      |      | Liu_2013 |
| 52   | grassland          | 30.78    | 90.96     | 0.96    |         |         |         |         |     |      |      | Liu_2013 |
| 52   | grassland          | 30.78    | 90.96     | 0.96    |         |         |         |         |     |      |      | Liu_2013 |
| 53   | tropical forest    | 23.16    | 112.16    | 0.98    | 0.99    | 0.84    | 0.74    | 0.88    | 1.05 | 1.17 | 5.00 | Lu_2009 |
| 53   | tropical forest    | 23.16    | 112.16    | 0.98    | 0.92    | 0.91    | 0.89    | 0.89    | 1.05 | 1.22 | 10.00| Lu_2009 |
| 53   | tropical forest    | 23.16    | 112.16    | 0.98    | 0.90    | 0.76    | 0.87    | 0.78    | 1.12 | 1.33 | 15.00| Lu_2009 |
| 54   | tropical forest    | 23.16    | 112.16    | 0.98    | 1.13    | 1.11    | 1.16    | 1.18    | 1.10 | 1.18 | 5.00 | Lu_2009 |
| 54   | tropical forest    | 23.16    | 112.16    | 0.98    | 1.53    | 1.09    | 1.06    | 1.16    | 1.09 | 1.45 | 10.00| Lu_2009 |
| 55   | tropical forest    | 23.16    | 112.16    | 0.97    | 1.17    | 1.14    | 1.01    | 1.25    | 1.05 | 0.90 | 5.00 | Lu_2009 |
| 55   | tropical forest    | 23.16    | 112.16    | 0.98    | 1.14    | 1.23    | 0.94    | 1.02    | 0.94 | 1.10 | 10.00| Lu_2009 |
| 56   | boreal forest      | 61.19    | 24.97     | 0.97    |         |         |         |         |     |      |      | Mina_2009 |
| 57   | boreal forest      | 62.00    | 26.22     | 1.00    |         |         |         |         |     |      |      | Maljonen_2006 |
| 57   | boreal forest      | 62.00    | 26.22     | 1.02    |         |         |         |         |     |      |      | Maljonen_2006 |
| 58   | boreal forest      | 62.00    | 26.22     | 0.98    |         |         |         |         |     |      |      | Maljonen_2006 |
| 58   | boreal forest      | 62.00    | 26.22     | 1.00    |         |         |         |         |     |      |      | Maljonen_2006 |
| 58   | boreal forest      | 62.00    | 26.22     | 0.98    |         |         |         |         |     |      |      | Maljonen_2006 |
| 59   | temperate forest   | 51.72    | 9.62      | 0.74    | 0.79    | 0.86    | 0.89    | 1.31    | 5.00 |      |      | Minocha_2000 |
| 59   | temperate forest   | 51.72    | 9.62      | 14.69   |         |         |         |         |     |      |      | Minocha_2000 |
| 60   | temperate forest   | 42.50    | -72.17    | 1.04    | 0.81    | 0.85    | 0.93    | 0.96    | 5.00 |      |      | Minocha_2000 |
| 60   | temperate forest   | 42.50    | -72.17    | 0.82    | 0.81    | 0.80    | 0.84    | 0.73    | 15.00|      |      | Minocha_2000 |
| 60   | temperate forest   | 42.50    | -72.17    | 1.06    | 0.84    | 0.81    | 0.63    | 0.49    | 5.00 |      |      | Minocha_2000 |
| 60   | temperate forest   | 42.50    | -72.17    | 0.99    | 0.67    | 0.46    | 0.90    | 0.46    | 15.00|      |      | Minocha_2000 |
| 61   | temperate forest   | 42.50    | -72.17    | 0.74    | 0.79    | 0.86    | 0.89    | 1.31    | 5.00 |      |      | Minocha_2000 |
| 61   | temperate forest   | 42.50    | -72.17    | 0.85    | 0.96    | 0.79    | 0.90    | 1.06    | 15.00|      |      | Minocha_2000 |
| 61   | temperate forest   | 42.50    | -72.17    | 0.76    | 0.60    | 0.75    | 1.08    | 0.62    | 5.00 |      |      | Minocha_2000 |
| 61   | temperate forest   | 42.50    | -72.17    | 0.77    | 0.65    | 0.63    | 0.93    | 0.67    | 15.00|      |      | Minocha_2000 |
| 62   | temperate forest   | 42.37    | 11.80     | 0.97    |         |         |         |         |     |      |      | Moscatelli_2008 |
| 63   | temperate forest   | 44.87    | -67.28    | 1.05    |         |         |         |         |     |      |      | Parker_2001 |
| 64   | temperate forest   | 44.87    | -67.28    | 1.00    |         |         |         |         |     |      |      | Parker_2001 |
| No. | Type          | Long  | Lat   | Value1 | Value2 | Value3 | Value4 | Value5 | Value6 | Value7 | Value8 | Value9 | Year       |
|-----|---------------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------------|
| 65  | tropical forest | 27.05 | 118.15| 0.97   |        |        |        |        |        |        |        |        | Pei_2013  |
| 66  | tropical forest | 27.05 | 118.15| 0.95   |        |        |        |        |        |        |        |        | Pei_2013  |
| 67  | tropical forest | 27.05 | 118.15| 1.02   |        |        |        |        |        |        |        |        | Pei_2013  |
| 68  | boreal forest  | 49.00 | -73.00| 1.06   |        |        |        |        |        |        |        |        | Prescott_1995 |
| 69  | boreal forest  | 48.73 | -122.75| 0.98  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 70  | boreal forest  | 47.37 | -121.90| 0.93  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 71  | boreal forest  | 47.30 | -123.27| 1.02  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 72  | boreal forest  | 47.25 | 123.58 | 1.00  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 73  | boreal forest  | 47.23 | -123.25| 1.00  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 74  | boreal forest  | 46.83 | -122.17| 1.02  |        |        |        |        |        |        |        |        | O-horizon Prietzel_2004 |
| 75  | boreal forest  | 48.98 | 11.38 | 1.06   |        |        |        |        |        |        |        |        | O-horizon Prietzel_2008 |
| 76  | boreal forest  | 48.98 | 11.38 | 1.03   |        |        |        |        |        |        |        |        | O-horizon Prietzel_2008 |
| 77  | boreal forest  | 62.15 | 62.15 | 0.98   |        |        |        |        |        |        |        |        | Ring_2004  |
| 78  | grassland      | 33.97 | -117.33| 1.00  |        |        |        |        |        |        |        |        | Siralknik_2007 |
| 79  | boreal forest  | 61.43 | 24.40 | 0.93   |        |        |        |        |        |        |        |        | Smolander_2005  |
| 80  | boreal forest  | 61.22 | 26.00 | 0.96   |        |        |        |        |        |        |        |        | Smolander_2005  |
| 81  | tropical forest | 21.10 | -89.28| 0.98   |        |        |        |        |        |        |        |        | Solis_2004  |
| 82  | tropical forest | 21.10 | -89.28| 0.96   |        |        |        |        |        |        |        |        | Solis_2004  |
| 83  | grassland      | 43.00 | 0.00 | 0.88   | 0.66   | 0.63   | 0.60   | 0.69   | 6.54   | 5.25   | 19.00  | 5.0     | Stroia_2011 |
| 84  | boreal forest  | 52.03 | -115.05| 1.02  |        |        |        |        |        |        |        |        | Thirukumaran_2002 |
| 85  | tropical forest | 30.59 | 103.63| 1.05   |        |        |        |        |        |        |        |        | Tu_2011    |
| 86  | tropical forest | 30.59 | 103.63| 1.00   |        |        |        |        |        |        |        |        | Tu_2011    |
| 87  | tropical forest | 30.59 | 103.63| 1.02   |        |        |        |        |        |        |        |        | Tu_2011    |
| 88  | temperate forest| 47.20 | 14.87 | 0.96   |        |        |        |        |        |        |        |        | Van-Miegroet_2007 |
| 89  | temperate forest| 43.43 | -72.45| 1.02   |        |        |        |        |        |        |        |        | Wallenstein_2006 |
| 90  | temperate forest| 43.43 | -72.45| 1.05   |        |        |        |        |        |        |        |        | Wallenstein_2006 |
| 91  | temperate forest| 42.50 | -72.17| 0.92   |        |        |        |        |        |        |        |        | Wallenstein_2006 |
| 92  | temperate forest| 42.50 | -72.17| 0.95   |        |        |        |        |        |        |        |        | Wallenstein_2006 |
| 93  | temperate forest| 42.50 | -72.17| 0.93   |        |        |        |        |        |        |        |        | Wallenstein_2006 |
| 94  | temperate forest| 42.21 | 74.50 | 1.00   |        |        |        |        |        |        |        |        | Weand_2010 |
| 95  | temperate forest| 42.21 | 74.50 | 0.98   |        |        |        |        |        |        |        |        | Weand_2010 |
| 96  | temperate forest| 42.21 | 74.50 | 0.96   |        |        |        |        |        |        |        |        | Weand_2010 |
| 97  | temperate forest| 42.21 | 74.50 | 0.99   |        |        |        |        |        |        |        |        | Weand_2010 |
| 98  | temperate forest| 42.21 | 74.50 | 0.96   |        |        |        |        |        |        |        |        | Weand_2010 |
| 99  | grassland      | 43.63 | 116.70| 0.93   |        |        |        |        |        |        |        |        | Wei_2013   |
|   | Type          | Latitude | Longitude | NDVI  | RelHum | Reference  |
|---|---------------|----------|-----------|-------|--------|------------|
| 99 | grassland     | 43.63    | 116.70    | 0.90  | 11.20  | 15.0       | Wei_2013   |
| 99 | grassland     | 43.63    | 116.70    | 0.83  | 22.40  | 15.0       | Wei_2013   |
| 99 | grassland     | 43.63    | 116.70    | 0.77  | 39.20  | 15.0       | Wei_2013   |
| 99 | grassland     | 43.63    | 116.70    | 0.77  | 56.00  | 15.0       | Wei_2013   |
| 100| grassland     | -30.40   | 29.40     | 0.98  | 7.10   | 10.0       | Zeglin_2007|
| 100| grassland     | -30.40   | 29.40     | 0.88  | 14.20  | 10.0       | Zeglin_2007|
| 101| grassland     | 39.08    | -96.58    | 0.96  | 10.00  | 10.0       | Zeglin_2007|
| 102| grassland     | 34.40    | -106.68   | 0.97  | 10.00  | 10.0       | Zeglin_2007|
| 103| grassland     | 42.33    | 116.28    | 0.93  | 10.00  | 15.0       | Zhang_2014 |
| 104| tropical forest| 23.17    | 112.55    | 0.98  | 15.00  | 10.0       | Zhu_2013   |
| 105| tropical forest| 23.17    | 112.55    | 1.00  | 15.00  | 10.0       | Zhu_2013   |
| 106| tropical forest| 23.17    | 112.55    | 1.01  | 15.00  | 10.0       | Zhu_2013   |
Figure S1. Distribution of the included studies across global land
Figure S2. Soil pH unit changes in the forest ecosystems dominated by conifer or non-conifer species to N addition at global scale. Dots represent soil pH unit changes with 95% confidence intervals (CI). If the 95% CI does not overlap 0, they are significantly affected by N addition at $\alpha = 0.05$. The dash vertical line is drawn indicating soil pH unit change= 0. The number next to the dots is the sample size of each variable. The calculation was based on the formula of

$$\log_{10}(H^+_{\text{treatment}}/H^+_{\text{control}})=\log_{10}(H^+_{\text{treatment}})-\log_{10}(H^+_{\text{control}}),$$

which indicates pH unit change ($pH_{\text{control}}-pH_{\text{treatment}}$) impacted by N addition. Notably, the data in the graph is presented by $pH_{\text{treatment}}-pH_{\text{control}}$. 

![Graph showing pH unit changes with confidence intervals](image-url)
Figure S3. Relationships between N addition rate and pH response ratio at global scale and across ecosystems (tropical forest, temperate forest, boreal forest and grassland)
Figure S4. Soil pH unit changes with different initial soil pH, rainfall, temperature and ambient N deposition at global scale. Dots represent soil pH unit changes with 95% confidence intervals (CI). If the 95% CI does not overlap 0, they are significantly affected by N addition at $\alpha = 0.05$. The dash vertical line is drawn indicating soil pH unit change= 0. The number next to the dots is the sample size of each variable. The calculation was based on the formula of $\log_{10}(H^+_{\text{treatment}}/H^+_{\text{control}})=\log_{10}(H^+_{\text{treatment}})-\log_{10}(H^+_{\text{control}})$, which indicates pH unit change ($pH_{\text{control}}-pH_{\text{treatment}}$) impacted by N addition. Notably, the data in the graph is presented by $pH_{\text{treatment}}-pH_{\text{control}}$. 