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Nitrogen loss from deserts in the southwestern United States

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Abstract. A lower limit for nitrogen loss from desert ecosystems in the southwestern United States was estimated by comparing nitrogen inputs to the amount of nitrogen stored in desert soils and vegetation. Atmospheric input of nitrogen for the last 10 000 years was conservatively estimated to be 2.99 kg N/m^2. The amount of nitrogen stored in desert soils was calculated to be 0.604 kg N/m^3 using extant data from 212 profiles located in Arizona, California, Nevada, and Utah. The average amount of nitrogen stored in desert vegetation is approximately 0.036 kg N/m^2.

Desert conditions have existed in the southwestern United States throughout the last 10 000 years. Under such conditions, vertical leaching of nitrogen below a depth of 1 m is small (ca. 0.028 kg N/m^2 over 10 000 years) and streamflow losses of nitrogen from the desert landscape are negligible. Thus, the discrepancy found between nitrogen input and storage represents the amount of nitrogen lost to the atmosphere during the last 10 000 years. Loss of nitrogen to the atmosphere was calculated to be 2.32 kg N/m^2, which is 77% of the atmospheric inputs.

Processes resulting in nitrogen loss to the atmosphere from desert ecosystems include wind erosion, ammonia volatilization, nitrification, and denitrification. Our analysis cannot assess the relative importance of these processes, but each is worthy of future research efforts.

Introduction

Losses of nitrogen from arid lands may be important to the global atmosphere and to native desert vegetation. In desert ecosystems volatile losses of nitrogen are considered to be especially significant (West & Skujins 1978; West & Skujins 1977; Bowden 1986; Skujins 1981). Volatile losses of nitrogen include nitric oxide (NO), nitrous oxide (N_2O), ammonia (NH_3), and dinitrogen (N_2) gas. Of these compounds nitric oxide, nitrous oxide, and ammonia are of particular consequence to the atmosphere. Nitric oxide has a short turnover time and is important in regulating atmospheric hydroxyl and ozone levels (Logan et al. 1981). Nitrous oxide has a long atmospheric lifetime and can undergo photochemical reactions in the stratosphere that are linked to the destruction of ozone (Cicerone 1987; Mooney et al. 1987). Nitrous oxide is also a 'greenhouse' gas that is contributing to the global warming of the Earth's surface (Dickinson & Cicerone 1986; Bolle et al. 1986; Ramanathan et al. 1985). Ammonia has a short atmospheric lifetime but is the only trace gas capable of increasing the alkalinity of precipitation (Warneck 1988; Charlson & Rodhe 1982; Quinn et al. 1987). Thus, ammonia is involved in the regulation of rainfall acidity.

In addition to its possible atmospheric effects, nitrogen loss in any form represents a loss of soil fertility to desert vegetation. Several studies have shown

that nitrogen limits plant growth in deserts (Ettershank et al. 1978; Fisher et al. 1988; Nobel et al. 1988; James & Jurinak 1978; Romney et al. 1978), and nitrogen is commonly thought to be second only to water as a major limiting factor in arid regions.

The magnitude of nitrogen loss from arid lands is poorly known despite its possible regional and global significance. Therefore, in this paper we use available data to estimate a lower limit for the magnitude of nitrogen loss from deserts in the southwestern USA.

Methods and results

Conceptual model

The conceptual model used to estimate nitrogen loss from deserts is a simple comparison between nitrogen inputs and the amount of nitrogen stored in the system. The difference between nitrogen inputs and storage represents the quantity of nitrogen lost from the ecosystem. To make this estimate conservative (i.e. a lower limit), whenever necessary the values used were weighted to either overestimate the storage component or underestimate the input component of the model. In either case, the amount of nitrogen lost from the ecosystem is underestimated. Each component of the conceptual model (time, input, storage, and deep seepage) will now be discussed and the methods used to quantify them described.

Time

The northward displacement of the jet stream at the end of the last glacial period has allowed desert conditions to exist in the southwestern United States throughout the last 10 000 years (COHMAP 1988). As a result evapotranspiration has greatly exceeded precipitation causing lakes to dry and resulting in the range expansion of xeric plant species (Street & Grove 1977; Thorne 1986; Van Devender & Spaulding 1979). Under arid conditions vertical leaching of nitrogen below a depth of 1 m, and streamflow losses of nitrogen from the desert landscape are negligible. Thus, by confining our calculation to the last 10 000 years any discrepancy between nitrogen input and storage should represent the amount of nitrogen lost to the atmosphere.

Inputs

Nitrogen input into desert ecosystems can occur by wetfall and dryfall deposition, and by nitrogen fixation. The annual deposition of nitrogen in wetfall was determined by averaging over 50 measurements made during a 4-year period in the western United States after excluding values identified as being influenced by pollution (Young et al. 1988). Nitrogen deposition measured in that study

showed little spatial or seasonal variability. Thus, we estimate the total deposition of nitrogen in wetfall to be 0.145 g N/m^2 yr or 1.45 kg N/m^2 for the last 10 000 years.

Few direct measurements of dry deposition have been made in the western United States, so estimates presented by Young et al. (1988) were used in conjunction with the measurements made by Schlesinger et al. (1982). The deposition rates used were 0.018, 0.0889, and 0.0068 g N/m^2 yr for NO_2–N, HNO_3–N, and NO_3–N, respectively (Young et al. 1988). The deposition rate used for NH_4^+–N was 0.040 g N/m^2 yr, which was the rate measured at a coastal, remote site in California (Schlesinger et al. 1982). Thus, we estimate the total deposition of nitrogen in dryfall to be 0.154 g N/m^2 yr or 1.54 kg N/m^2 for the last 10 000 years.

Nitrogen fixation is considered a major mechanism of nitrogen input in many deserts, with estimates ranging from 0.05 to 10.0 g N/m^2 yr (Rychert et al. 1978; Crawford & Gosz 1982; Boring et al. 1988). Both symbiotic and nonsymbiotic nitrogen fixation have been shown to occur in desert ecosystems (Rundel et al. 1982; MacGregor & Johnson 1971; Rychert & Skujins 1974; Mayland et al. 1966; Mayland & McIntosh 1966). Of these, nonsymbiotic fixation by blue-green algae in cryptogamic crusts has received the most attention. Unfortunately, annual nitrogen fixation rates for desert ecosystems are based primarily on extrapolations from lab measurements, leaving the *in situ* spatial and temporal variability of this process poorly understood. Given the limitations of existing data, a regional approximation of nitrogen fixation would be unreliable. Therefore, nitrogen inputs due to fixation will not be included in our calculation of the lower limit for nitrogen loss in desert ecosystems. The assumption that no nitrogen fixation occurs is certainly false, but it makes our calculation of nitrogen loss conservative by underestimating total nitrogen inputs.

Combining the estimates of nitrogen input for both wetfall and dryfall yields a total inorganic nitrogen input of 0.299 g N/m^2 yr or 2.99 kg/m^2 over the last 10 000 years. Our estimate of total nitrogen deposition is lower than recent estimates for a semiarid site in New Mexico (0.64 g N/m^2 yr; Gosz 1980) and a desert site in Utah (1.19 g N/m^2 yr; West 1978). It is also lower than the 1.0 g N/m^2 yr which is considered a realistic estimate for the total physical input of nitrogen into deserts by Crawford & Gosz (1982). In addition, our estimate for inorganic nitrogen inputs in wetfall (0.145 g N/m^2 yr) is lower than values for several sites in the southwestern USA which range from 0.17 to 0.596 g N/m^2 yr (West 1978).

Our model assumes that the value used for nitrogen deposition is not significantly affected by pollution and has remained relatively constant throughout the last 10 000 years. Air pollution in the western USA is substantially lower than in the eastern USA and, though it does have some influence on the chemistry of precipitation, its influence is restricted to distances less than 100 km from its source (Young et al. 1988). We feel the deposition value used in this study was not significantly affected by pollution for 3 reasons: first, all sites identified by Young et al. (1988) as having unusually high nitrogen concentrations and a

recognizable source area were eliminated from the data set; second, both the nitrate and ammonium concentrations reported by Young et al. (1988) were similar to historic values measured in 1956 (Junge 1958) which probably represent prepollution or close to prepollution levels; and finally, our value is similar to or less than values measured at remote locations (0.22 g N/m^2 yr, Schlesinger et al. 1982; 0.5 g N/m^2 yr, Vitousek et al. 1987; 0.241 g N/m^2 yr, Galloway 1985).

Although direct measurements of nitrogen deposition in the southwestern USA throughout the last 10 000 years do not exist, there is some evidence to suggest that both wetfall and dryfall deposition have remained relatively constant over long periods of time. The 2000-year record of nitrate concentrations measured in the Greenland ice core is relatively constant up until 1955 (Herron 1982; Mayewski et al. 1986) and has an inverse relationship with the snow accumulation rate (Herron 1982) which suggests a relatively constant rate of deposition. In addition, studies of calcium carbonate in desert soils of the southwestern USA show that the rate of formation is consistent with the assumption of a relatively constant rate of calcium input from dryfall throughout the Holocene (Schlesinger 1985).

The evidence presented above suggests that our estimate of nitrogen deposition is not significantly affected by pollution and that prior to anthropogenic pollution both wet and dryfall deposition were relatively constant over long periods of time. Therefore, we feel the estimate used in this study is likely to be less than or equal to the actual long-term nitrogen deposition value for arid lands in the southwestern USA.

Storage

To estimate the amount of nitrogen stored in desert soils of the southwestern USA, we compiled data from 212 profiles located in Arizona, California, Nevada, and Utah (Soil Conservation Service 1970, 1973, 1974, 1982). The number of profiles per state ranged from 34 in California to 71 in Arizona, and 29 counties in all were represented (Fig. 1). Only soils characteristic of arid regions, Aridisols (Argids and Orthids) and Entisols (Orthents and Fluvents), were used (Dregne 1976). We included some profiles in these classes from semi-arid grasslands in coastal and central California. All profiles had contiguous measurements of organic carbon to a depth of greater than 50 cm and at least one measurement of Kjeldahl nitrogen. The variables incorporated into our database were: % sand, silt, and clay; dry weight bulk density (g/cm^3); % organic carbon; % total Kjeldahl nitrogen; and the extractable calcium and sodium content (meq/100 g). All analyses were performed by the Soil Survey Laboratory in Riverside, California. The analytical methods used were the same for all profiles except for extractable calcium and sodium that underwent refinements through time. The analytical methods used were as follows: particle size was measured using the pipet method; bulk density using saran-coated clods or field moist cores; % organic carbon by an acid-dichromate digestion followed by titration with iron sulfate; % nitrogen by a Kjeldahl digestion followed by

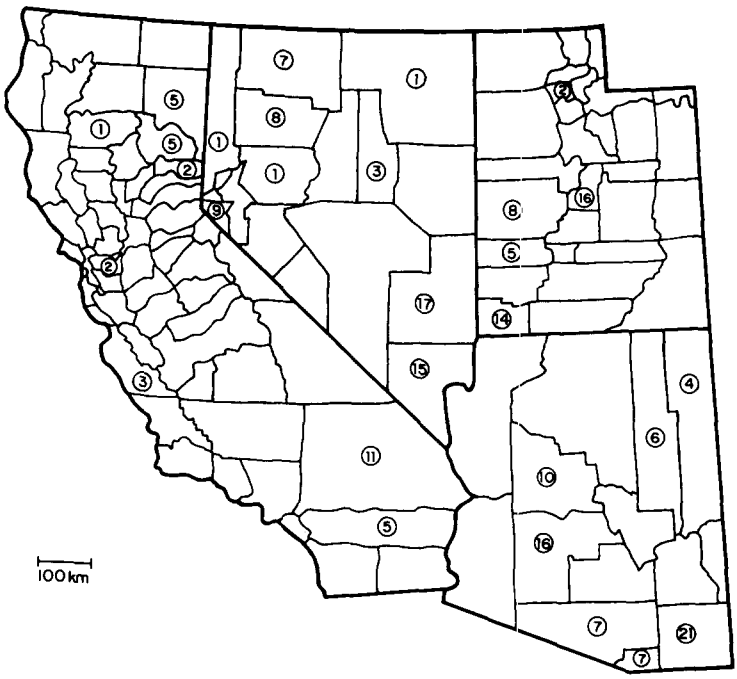

Fig. 1. Location in the southwestern USA of soil profiles used in this study. Values indicate the number of profiles in each county.

ammonia distillation; extractable calcium by an ammonium acetate extraction followed by either an oxalate-permanganate determination or measurement by atomic absorption spectrophotometry; and extractable sodium by an ammonium acetate extraction followed by flame photometry (Soil Conservation Service 1972). For the purposes of making a regional estimate, any differences due to the analytical methods were ignored.

The Soil Conservation Service frequently did not measure nitrogen below the first several depth increments, and often bulk density measurements for a profile were incomplete. Therefore, 43% of the nitrogen and 49% of the bulk density values were estimated. To estimate the missing nitrogen values we used the organic carbon measurements, which were nearly complete, and the strong linear relationship that exists between organic carbon and Kjeldahl nitrogen ($r = 0.958$; Fig. 2). All missing bulk densities were estimated by using the value of 1.50 g/cm^3, which is the mean of the 581 bulk density measurements that were reported. The frequency distribution of the measured bulk densities is bell-shaped and very narrow, so the mean value should provide a reasonable and unbiased estimate (Fig. 3).

To calculate the amount of nitrogen stored in a cubic meter of desert soil, the

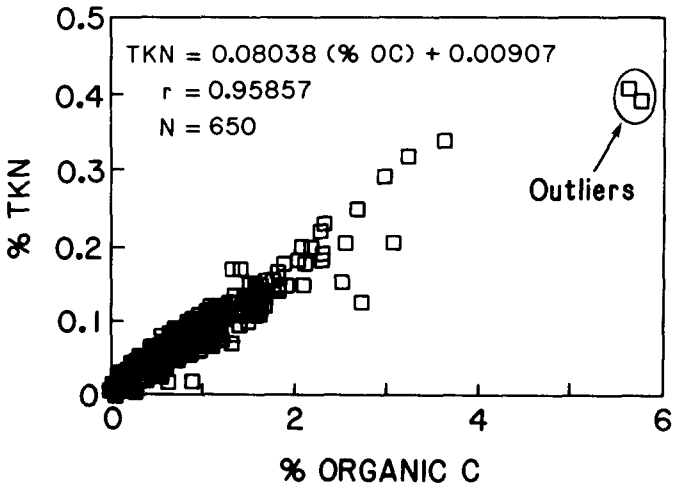

Fig. 2. Relationship between the % organic C and the % Kjeldahl N (TKN) in desert soils of the southwestern US.

following formula was summed for all depth increments in a given profile to 1 m:

$$\text{kg N in profile} = (\text{ID} \times \text{BD} \times \text{NC}) \times 10\,\text{kg N} \times \text{cm}^2/\text{g N} \times \text{m}^2$$

where: ID = increment depth (cm)
BD = bulk density (g soil/cm^3)
NC = nitrogen concentration (g N/g soil)

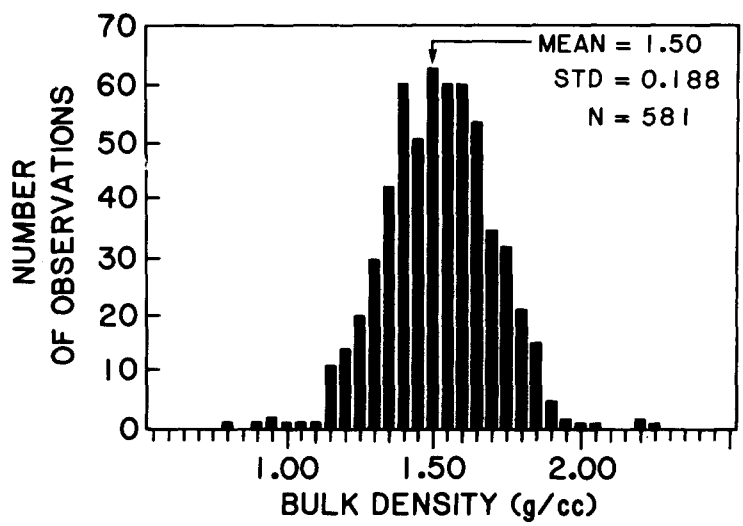

Fig. 3. Frequency distribution of bulk density measurements in desert soils of the southwestern US.

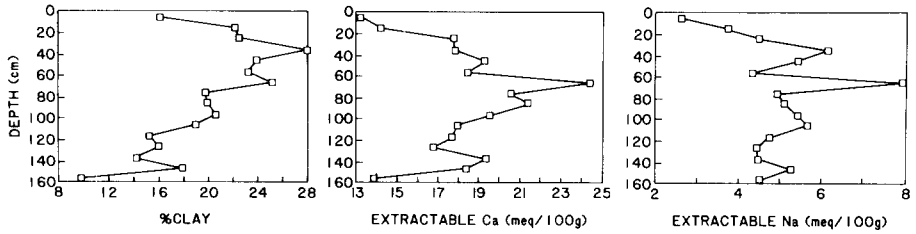

Fig. 4. Mean % clay, extractable Ca, and extractable Na vs. depth in desert soils of the southwestern US.

To adjust profiles that were less than 1 m deep, we prorated the calculated value of nitrogen storage by the actual depth sampled (i.e. (N in profile) × (1/depth of profile)).

The mean nitrogen content for the 212 soil profiles used in this study was 0.604 kg N/m^3 (S.D. = 0.376), which is our estimate of nitrogen storage in desert soils of the United States. This value for nitrogen storage compares favorably to previously reported values for desert soils, which range from 0.105 to 0.831 kg N/m^3 (West & Klemmedson 1978; Post et al. 1985).

The amount of nitrogen stored in desert vegetation was estimated to be 0.036 kg N/m^2. This value was determined by averaging the midpoints of the ranges reported for the Sonoran (0.064–0.083 kg N/m^2), Mojave (0.005–0.017 kg N/m^2), and Great Basin (0.019–0.028 kg N/m^2) deserts by Crawford & Gosz (1982). The amount of nitrogen in desert vegetation is very small and accounts for only 5.6% of the total nitrogen in the system (soil + vegetation). Therefore, any error in this estimate will be unlikely to have a significant effect on our calculation of nitrogen loss.

Deep seepage

In desert soils it is commonly thought that highly soluble products are deposited at the depth to which percolating rainwater normally penetrates (Cooke & Warren 1973). Indeed, Arkley (1963) found a strong, 1:1 relationship between the observed depth of the carbonate horizon and the calculated depth of leaching in 28 soils of moderate age from California and Nevada. Depth profiles for the various components in our database show that the peak clay content occurs at an average depth of about 35 cm, and the peak level of extractable calcium and sodium both occur at an average depth of approximately 65 cm (Fig. 4, Table 1). The position of the peaks in the clay and calcium concentration probably indicates the consistent occurrence of argillic horizons overlying calcic horizons, which is a common pattern in desert soils (Gile et al. 1981). The peaks in calcium and sodium concentration indicate that the normal maximum depth of percolating rainwater in these soils is about 65 cm. Therefore, the soil depth of 1 m used in our calculation of soil nitrogen storage ensures that nearly all vertically transported nitrogen is included. A recent paper, however, demonstrates that thermonuclear ^{36}Cl from a fallout peak in 1955 could be detected in

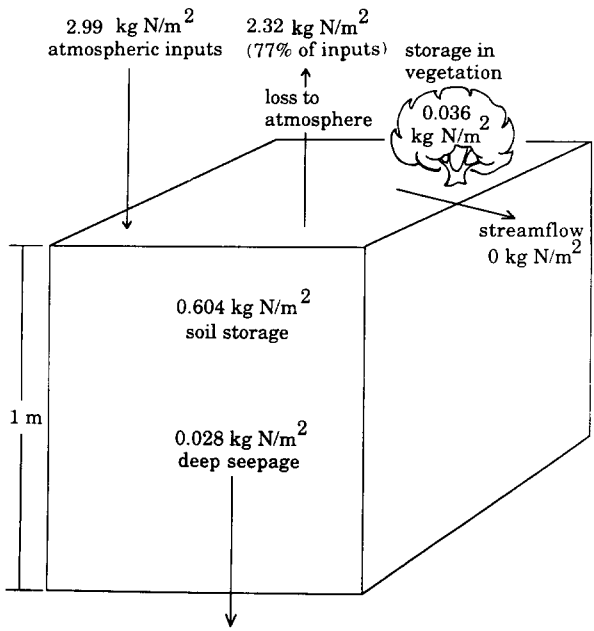

Fig. 5. Diagram summarizing the fluxes of N used to conservatively estimate N loss from the deserts in the southwestern US.

desert soils at depths greater than 1 m (Phillips et al. 1988). Thus, loss of nitrogen by deep seepage below a depth of 1 m cannot be totally dismissed. To determine the magnitude of nitrogen loss due to deep seepage below a depth of 1 m, we multiplied the estimate of recharge flux (0.25 cm/yr; Phillips et al. 1988) by the concentration of nitrate-N found in well water at the same site (1.13 mg N/L; Schlesinger unpubl.). Ammonium nitrogen in the same water was negligible. The resulting product was then multiplied by the time interval under consideration (10 000 years) to estimate that 0.028 kg N/m^2 has been lost to deep seepage. This value is smaller than the amount of nitrogen stored in vegetation and is a negligible amount for the purposes of our calculation of nitrogen loss.

Conclusions

When our estimate for nitrogen input for the last 10 000 years (2.99 kg N/m^2) is compared to the amount of nitrogen stored in the soil (0.604 kg N/m^2) and in vegetation (0.036 kg N/m^2) and to our estimate of vertical leaching (0.028 kg N/m^2), a discrepancy of 2.32 kg N/m^2 is found (Fig. 5). This value is about 77% of the estimated nitrogen inputs. Overland flow may redistribute soil nitrogen within a desert landscape but most basins in the southwestern USA are endorheic (Cooke & Warren 1973), and it is reasonable to assume that little of the

Table 1. Summary statistics by depth increment for Aridisols and Entisols in the southwestern US. Reconstructed bulk density and Kjeldahl N values are included. Multiple samples from a given profile can result in sample sizes > 212 for a particular depth increment.

Depth (cm)	% Clay			Bulk density (g/cm^3)			% Organic C			% Kjeldahl N			Extractable Ca (meq/100 g)			Extractable Na (meq/100 g)		
	X	SD	(*n*)	X	SD	(*n*)	X	SD	(*n*)	X	SD	(*n*)	X	SD	(*n*)	X	SD	(*n*)
0–10	16.15	11.89	(257)	1.50	0.09	(259)	0.72	0.72	(259)	0.064	0.054	(259)	13.27	9.93	(165)	2.68	6.56	(249)
10–20	22.20	13.11	(143)	1.48	0.11	(145)	0.58	0.53	(145)	0.056	0.047	(145)	14.24	9.26	(98)	3.78	8.73	(138)
20–30	22.52	13.69	(117)	1.49	0.12	(119)	0.47	0.36	(119)	0.048	0.032	(119)	17.77	12.04	(80)	4.53	9.96	(117)
30–40	27.98	16.37	(110)	1.50	0.13	(110)	0.42	0.38	(110)	0.045	0.034	(110)	17.83	10.66	(69)	6.18	10.73	(107)
40–50	23.96	16.13	(120)	1.50	0.15	(124)	0.35	0.27	(124)	0.038	0.024	(124)	19.29	13.71	(81)	5.46	9.21	(119)
50–60	23.28	13.66	(81)	1.52	0.13	(84)	0.30	0.22	(82)	0.033	0.018	(82)	18.45	8.51	(51)	4.36	7.28	(82)
60–70	25.23	15.30	(83)	1.49	0.12	(85)	0.27	0.19	(81)	0.030	0.015	(81)	24.36	16.50	(49)	7.95	11.49	(83)
70–80	19.82	13.63	(66)	1.52	0.13	(69)	0.25	0.23	(64)	0.029	0.020	(64)	20.57	14.43	(43)	4.96	7.57	(67)
80–90	19.98	12.75	(83)	1.48	0.16	(88)	0.24	0.25	(81)	0.029	0.024	(81)	21.39	14.47	(53)	5.13	8.35	(86)
90–100	20.63	13.74	(62)	1.51	0.12	(64)	0.22	0.21	(57)	0.027	0.017	(57)	19.52	10.23	(31)	5.45	6.81	(61)
100–110	19.02	14.91	(49)	1.50	0.12	(50)	0.18	0.13	(45)	0.023	0.011	(45)	17.93	10.95	(30)	5.69	7.70	(47)
110–120	15.31	12.80	(55)	1.51	0.11	(58)	0.18	0.34	(54)	0.022	0.020	(54)	17.67	10.78	(41)	4.77	5.69	(57)
120–130	16.05	11.42	(43)	1.54	0.99	(43)	0.13	0.10	(38)	0.020	0.009	(38)	16.77	7.67	(33)	4.46	5.60	(40)
130–140	14.24	14.16	(37)	1.51	0.10	(37)	0.13	0.15	(35)	0.019	0.013	(35)	19.31	18.82	(23)	4.47	5.89	(36)
140–150	17.97	14.47	(31)	1.51	0.08	(31)	0.10	0.09	(30)	0.017	0.007	(30)	18.36	11.33	(24)	5.27	6.51	(31)
150–160	9.84	7.32	(20)	1.49	0.08	(20)	0.12	0.11	(18)	0.019	0.009	(18)	13.87	10.38	(15)	4.51	6.00	(20)

'missing' nitrogen was removed from the desert landscape by riverflow. Therefore, we conclude that at least 2.32 kg N/m^2 (77% of inputs) were lost to the atmosphere by various mechanisms including wind erosion and gaseous emissions. We believe this estimate is a lower limit because inputs were underestimated by not including nitrogen fixation and organic nitrogen deposition in our calculation, and because storage was overestimated by not correcting for nitrogen in the soil that was greater than 10 000 years old. Interestingly, the value we calculated for the percentage of nitrogen inputs that are lost (77%) is similar to the experimental results of Westerman & Tucker (1978) who found that in desert soils about 70% of added NH_4–N and about 95% of added NO_3–N were lost to the atmosphere after 1 year under field conditions.

The actual magnitude of nitrogen loss to the atmosphere from desert ecosystems is poorly known, but it can be estimated by adding estimates of nitrogen loss due to wind erosion to estimates of the volatile losses of nitrogen. An estimate for the long-range transport of desert dust is 1×10^{15} g/yr (Schutz 1980). Assuming all this dust is derived from the upper 10 cm of desert soils with an average nitrogen content of 0.064% (Table 1), the nitrogen loss from deserts due to wind erosion would be 6.40×10^{11} g N/yr. The annual output of volatile nitrogen ($NH_3 + N_2O + N_2 + NO_x$) from desert ecosystems has been reported to range from 0.1 to 2.0 g N/m^2 yr, which corresponds to a global emission rate of between 4.2 to 84.0×10^{12} g N/yr (Bowden 1986). By adding the estimate for nitrogen loss by deflation weathering from deserts (6.40×10^{11} g N/yr) to the upper and lower limits for volatile nitrogen loss from arid lands (4.2×10^{12} and 84.0×10^{12} g N/yr), the total nitrogen loss from the world's deserts can be estimated to be between 4.84×10^{12} and 84.6×10^{12} g N/yr. From this study, the lower limit for nitrogen loss to the atmosphere from deserts is 0.232 g N/m^2 yr which extrapolates to a global flux of 9.74×10^{12} g N/yr. This value is twice the lower limit obtained by adding estimates of dust and volatile nitrogen loss, and suggests that wind erosion (6.40×10^{11} g N/yr) comprises only 6.6% of the total nitrogen lost from the world's deserts. The loss of dust from deserts is poorly known and may be substantially greater than 1×10^{15} g/yr (Schutz 1980).

Although the independently derived lower limits were within a factor of 2 (4.84×10^{12} and 9.74×10^{12} g N/yr), the tentative nature of all these estimates must be emphasized. Both this study and Bowden (1986) rely on data from arid lands in the United States, which may not be representative of the Sahara, Australian, and Arabian deserts that are the largest in the world. In addition, only a few direct measurements of nitrogen loss from deserts, by any pathway, have been made. Clearly more direct measurements and field experiments along with process-level modelling are needed if we wish to assess more accurately the magnitude of nitrogen loss from desert ecosystems and the factors that control it.

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