Published July, 1987

DIVISION S-7—FOREST AND RANGE SOILS

Nitrogen Mineralization in a Desert Soil: Interacting Effects of Soil Moisture and Nitrogen Fertilizer[1]

F. M. FISHER, L. W. PARKER, J. P. ANDERSON, AND W. G. WHITFORD[2]

ABSTRACT

The responses of N mineralization to two patterns of supplemental water, N fertilizer, and a drying-wetting episode were examined in order to evaluate the effects of variation in timing and intensity of natural precipitation on N availability. Field plots received either 6 mm water/week or 25 mm water/month with or without 10 g N m^{-2}. Samples were collected three times from July 1984 to March 1985 and incubated in the lab for 28 d. The effects of drought were simulated by drying soil at 35°C for 28 d followed by 168-d leaching incubations. Supplemental water reduced 28-d mineralization by 22% in soils collected during dry and moderate soil moisture conditions (July 1984, October 1984) but had no effect on soils collected during a moist period (March 1985). Nitrogen fertilizer had no effect on 28-d mineralization in soils from July but increased 28-d mineralization by 58% in soils from October and March. Air-drying increased mineralization rates across all field treatments during the first 14 d of the 168-d leaching incubations. Mineralization rates were lower in soils from watered plots in both the air-dry and field-moist treatments. Air-drying interacted with both the water and N treatments by increasing watering effects and decreasing fertilizer N effects. The observed drying effects appear to be a net result of several processes that, on the whole, tend to increase N availability. Mineralization rates in both experiments were lower in 6 mm/week soils than in 25 mm/month soils which, in turn, were lower than unwatered controls. We hypothesize that increased moisture availability eventually leads to losses of mineralizable N as initially rapid mineralization converts organic N to inorganic forms that are readily lost from the soil.

Additional Index Words: **Chihuahuan Desert, *Larrea tridentata*, simulated rainfall, soil drying effects.**

Fisher, F.M., L.W. Parker, J.P. Anderson, and W.G. Whitford. 1987. Nitrogen mineralization in a desert soil: Interacting effects of soil moisture and nitrogen fertilizer. Soil Sci. Soc. Am. J. 51:1033-1041.

NITROGEN CAN BE AN IMPORTANT FACTOR limiting the growth of native plants in arid and semiarid ecosystems. In some cases, N amendments must be combined with water to produce significant growth responses (James and Jurinak, 1978; Romney et al., 1978). However, Ettershank et al. (1978) found in the northern Chihuahuan Desert of southern New Mexico, USA that perennial vegetation growth increased by >100% in response to N fertilizer. In the present study, we found similar responses for the growth of the dominant perennial shrub, creosotebush [*Larrea tridentata* (DC.) Cov.] (results to be reported elsewhere). Vegetation response to variation of N availability is not always evident in the northern Chihuahuan Desert: Lajtha and Schlesinger (1986) found no indication of increased growth of creosotebush or associated annual plants in areas of increased N availability adjacent to mesquite plants (*Prosopis glandulosa* Torr.).

Although water is often assumed to be the primary factor limiting plant growth in deserts, responses of native plants to irrigation in the northern Chihuahuan Desert have been variable. For example, the first year of irrigation produced marked increases in production of annual plants but responses were insignificant during the second year (Gutierrez and Whitford, 1987b). In the present study, adding 25 mm of water per month in a single application had no effect on creosotebush growth but adding the same amount in four weekly applications of 6 mm significantly increased growth (results to be reported elsewhere). The effects of variations of water and N availability on the annual plant community can be particularly complex: observed responses range from species responding only to water amendments to those that respond only to N amendments. Many species respond to both water and N alone and in combination (Gutierrez and Whitford, 1987a). Taken together, these observations suggest that a complex relationship between water and N availability is a major factor controlling plant production in the northern Chihuahuan Desert.

A significant proportion of the N necessary for plant growth is provided by the mineralization of organic matter. Factors that affect the quantities of mineralizable organic N or otherwise alter the rates of N mineralization should alter ecosystem function. Nitrogen availability in arid and semiarid ecosystems is highly variable in both space and time (West and Skujins, 1978). Charley and West (1977) and Parker et al. (1982) showed that N availability is greatest in the surface soil layers below the canopy of dominant shrubs where organic matter accumulates. The seasonal and variable nature of desert precipitation probably affects both the quantity of mineralizable N and rates of N mineralization. Increased annual plant production during unusually wet periods can produce large quantities of N-poor organic matter, the decomposition of which may immobilize significant quantities of N (Parker et al., 1984). Lowered oxygen tension and increased organic C availability during wet periods may favor N losses through denitrification (Westerman and Tucker, 1978; West and Skujins, 1978). In contrast, severe drying prior to a wet period may increase N availability by killing microbial biomass and making avail-

---

[1] Contribution from the Dep. of Biology and the Jornada LTER program, New Mexico State Univ., Las Cruces, NM 88003. Received 24 Oct. 1986.

[2] College Assistant Professor, former College Assistant Professor, Research Assistant, and Professor, respectively.

able previously protected nonbiomass soil organic matter (Marumoto et al., 1982; Bottner, 1985). Small rain events of insufficient magnitude to elicit plant response may cause N mineralization in surface soil layers leading to accumulation of inorganic N during drought (Charley, 1972).

The relationships described above may cause the periods of maximum water and N availability to be out of phase with each other. Periods of unusually wet weather could reduce N availability by immobilization and denitrification to such an extent that N might continue to limit production during a subsequent drier period. Similarly, drought could increase N availability with the result that in a subsequent wet period N might not be limiting regardless of above-average moisture availability. The high spatial heterogeneity is a further complication since unusual precipitation patterns may have different effects on woody vs. herbaceous plants so that the under- and between-shrub portions of the ecosystem may not respond identically.

The hypothesized relationships between climate, production, and N mineralization led us to design a field experiment to examine effects of soil moisture, seasonal climate, simulated drought, and N enrichment on plant productivity and N availability. Here we report the effects on N availability as indicated by measurements of potential N mineralization. We hypothesized that prolonged wet conditions (>2 yr) would reduce N availability and that simulated drought would increase N availability. We predicted that N fertilizer would have extended effects on N availability as a result of immobilization of fertilizer N by microorganisms followed by mineralization. Responses to watering and fertilizer application were examined with reference to patterns of spatial and seasonal variation.

MATERIALS AND METHODS

The study was performed on the Jornada Long-Term Ecological Research (LTER) site located on the New Mexico State University College Ranch 40 km NNE of Las Cruces, NM. The LTER site is located on an east-facing alluvial piedmont and traverses seven vegetation types along a topographical gradient ranging from a rocky mountain slope to an ephemeral lake bed. Annual precipitation averages 213 mm, 55% falling during July through September as convectional thundershowers. Temperatures regularly exceed 40°C in summer and regularly drop below 0°C in December-February.

This research is part of a series of intensive experiments performed within a shrubland vegetation type dominated by creosotebush [*Larrea tridentata* (DC.) Cov.]. This vegetation type is located approximately mid-slope (3° gradient) on loamy sand soils with a $CaCO_3$ deposition layer (caliche) at ca. 40 cm. The soil is classified as a Typic Haplargid of the Dona Ana series (Wierenga et al., 1987). Total N at 0- to 10-cm averages 390 mg kg^{-1} under shrubs and 350 mg kg^{-1} between shrubs (see below for methods).

The experiment was arranged in a split-plot design with each plot receiving a single supplemental water treatment and split into fertilized and unfertilized halves. Nine watered plots (5 by 10 m) were established in spring of 1981 and fenced to prevent herbivory by rabbits. Three supplemental water treatments (+6.3 mm/week, +25 mm/month, unwatered control) were applied to each of three randomly chosen plots from June 1981 until March 1985 except after precipitation events of 25 mm or more. Buffer zones of at least 10 m prevented runoff from entering adjacent plots. Fertilizer (NH_4NO_3) was applied at the rate of 10 g N m^{-2} to the down-slope half of each supplemental water plot (to prevent runoff of added N onto unfertilized plots) on 23 Feb. 1983 and 19 June 1984. All treatment plots were lightly watered to dissolve the granular fertilizer and soak it into the soil. Precipitation during the study was measured using two rain gauges located at the site. Soil water potential was measured using soil psychrometers buried at 5 and 15 cm.

We employed two biological assays to evaluate net N mineralization (Stanford and Smith, 1972; Keeney, 1982; Stanford, 1982). An aerobic batch procedure, in which inorganic N is allowed to accumulate in the soil, was used to examine the treatment effects as they interacted with season and microsite. These incubations allow toxins and waste products to accumulate but are relatively simple to perform and are well-suited to experiments using relatively short-term incubations with a large number of samples. Leaching incubations (Stanford and Smith, 1972) were used to study the effects of soil drying and to characterize in greater detail the treatment effects at a particular time and location. Periodic leaching removes waste products and toxins and replenishes nutrients other than N allowing incubation for over 30 weeks. Although leaching may remove some of the mineralizable N, the empirical success of this technique at predicting mineralization rates in the field (Smith et al., 1977; Richter et al., 1980; Marion et al., 1981) suggests that leaching of mineralizable N is negligible.

Batch Mineralization Potentials

Soil samples were collected on 19 July 1984, 25 Oct. 1984, and 14 Mar. 1985. Each of these sampling dates falls at the end of one of the three climatically distinct seasons characteristic of the northern Chihuahuan Desert: (i) dry, warm spring-early summer (March–June), (ii) warm, wet summer-fall (July–October) during which 70% of the year's precipitation falls, and (iii) cool, dry winter (December–February) characterized by regular night-time freezing temperatures. Samples were collected from under and between shrubs at depths of 0 to 10 and 10 to 20 cm. Each sample consisted of five bulked 2.5-cm cores collected within a 0.1 m^2 area. A single sample was collected from each of the four depth-location combinations for each of the 18 water-N plots making a total of 72 samples. Sampled locations were marked with a flag to prevent future re-sampling of the same location. Under-canopy samples were collected from the northwest side of the shrub at 0.5 canopy radius to reduce variation resulting from soil patterns created by prevailing winds and differential snow melt under canopies (Whitford, unpublished).

Samples were collected in polyethylene bags and stored at 2 to 7°C to maintain soil moisture content at field levels until the start of the incubations, <96 h after collection. After sieving (2-mm mesh), 25-g soil samples were incubated at 35°C in 50-mL plastic vials covered with 0.5 mil (0.0125-mm thick) polyethylene film to permit aeration and reduce moisture loss (Bremner and Douglas, 1971; Westermann and Crothers, 1980). Moisture content was adjusted to field capacity (0.1 g/g) using a syringe to add water through a small hole in the polyethylene film. The hole in the polyethylene also improved aeration. Moisture content was adjusted every 7 d during the incubation and subsamples were removed for inorganic N determination at days 7, 14, and 28.

Inorganic N (NH_4-N and NO_3 + NO_2-N) was determined in 2.0 *M* KCl extracts with a 10:1 ratio of soil to KCl (Keeney and Nelson, 1982). Using an automated salicylate procedure (Wall and Gehrke, 1975; Nelson, 1983) NH_4-N was measured in the extracts, and NO_3 + NO_2-N was measured by an automated Cd reduction procedure (Henriksen and Selmer-Olsen, 1970). Total N (Nelson and Sommers, 1980) was determined from the samples collected in October 1984 and March 1985. Samples were air-dried and then ground with a motorized mortar and pestle to pass a 0.15-mm sieve before micro-Kjeldahl digestion using an Al block digestor (Nelson and Sommers, 1980). By using an automated salicylate procedure (Wall and Gehrke, 1975), NH_4-N in the digest was measured. The two salicylate procedures (NH14-N in KCl extracts, NH_4-N in Kjeldahl digests) were both modified from the original procedures to optimize the concentration of reactants and the pH of the reaction mixture (Nelson, 1983; F.M. Fisher, unpublished). All automated procedures were performed with a Scientific Instruments Continuous Flow Analyzer. (Orion Scientific Instruments, Pleasantville, NY).

Data from each of the three sample collections were analyzed using the general linear models procedure (PROC GLM) of SAS (SAS Institute, Inc., 1985). Mineralization was calculated as the net change in inorganic N occurring in each time interval during the incubation (days 0–7, days 7–14, and days 14–28). The ANOVA procedures followed Steel and Torrie's (1980) recommendations for a split-plot design except that the error term used to test the supplemental water treatments was modified to reflect the completely randomized arrangement of watered plots (as oppposed to a blocked arrangement). Planned orthogonal contrasts were used to indicate significant differences between watering treatments (Harris, 1975; Steel and Torrie, 1980). Single degree-of-freedom contrasts partitioned the sums of squares into two components attributable either to (i) differences between the unwatered control and the mean of the two watered treatments, or (ii) differences between the two watered treatments. In the case of significant interactions between treatments, simple treatment effects were examined as suggested by Steel and Torrie (1980). Residuals from all analyses were plotted against predicted values and tested for normality using the Kolmogorov D statistic as performed by PROC UNIVARIATE of SAS (SAS Institute, Inc., 1985).

We also conducted a post-hoc analysis of treatment means across all three sampling dates to (i) identify seasonal trends in the unwatered-unfertilized control soils and indicate their consistency for different locations and depths, and (ii) identify seasonal changes in the effects of water and N averaged across the treatments and locations. The post-hoc analysis of means was performed using Tukey pairwise comparisons (Steel and Torrie, 1980; SAS Institute, Inc., 1985).

Leaching Mineralization Potentials

The leaching incubation procedures were similar to those of Stanford and Smith (1972) and Marion et al. (1981). Soil (50 g) was placed in 55-mm diam Buchner funnel containing Whatman GF-A glass-fiber filter paper to prevent leaching of particulate matter. Leachings consisted of four 25-mL aliquots of 0.01 *M* $CaCl_2$ followed by 25 mL of -N nutrient solution containing 0.002 *M* $CaSO_4 \cdot 2H_2O$, 0.001 *M* $MgSO_4 \cdot 7H_2O$, 0.002 *M* $Ca(H_2PO_4)_2 \cdot H_2O$, and 0.0025 *M* K_2SO_4, plus 0.5 mL of 5 *N* H_2SO_4 to help dissolve the P salts. The solution was adjusted to pH 6 with 5 *M* KOH before use.

Soil samples (0–10 cm) were collected from all treatment plots on 19 Feb. 1985 under the northwest side of the shrub canopy at 0.5 canopy radius. The methods of sample collection were identical to those used for the batch mineralization potentials. The moisture content of all soil samples was at or near field capacity as indicated by psychrometer readings (Fig. 1). Leaching incubations were initiated immediately with one set of subsamples (field-moist treatment) while the other set was dried at 35°C for 28 d (air-dry treatment). Soils from both treatments were incubated at 35°C and leached at 0 time and days 7, 14, 28, 56, 84, 112, 140, and 168. The field-moist soils were also leached at day 196. Moisture content was set to −30 kPa by suction and funnels were covered with wax film during the incubation. A glass fiber filter disk was placed on top of the soil to reduce soil dispersion during leaching and evaporation during incubation. Aeration occurred through the neck of the funnel (Stanford and Smith, 1972).

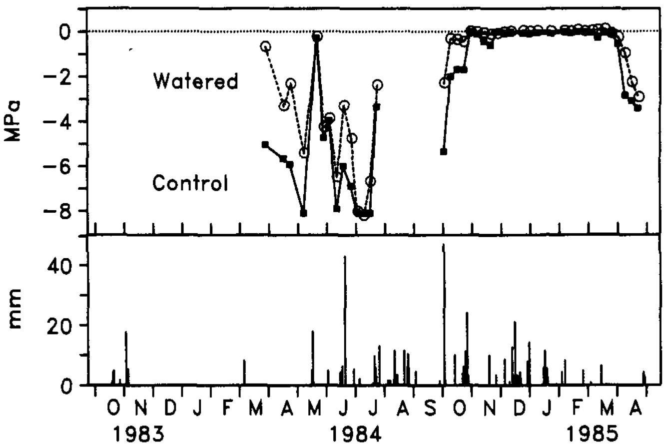

Fig. 1. Mean soil water potential at 5 and 15 cm in supplemental water and control plots and precipitation recorded at the study site.

Leachate was immediately preserved with 0.5 mg/L phenylmercuric acetate (PMA) and stored at 2 to 7°C until chemical analysis, usually <2 weeks. All leachate was analyzed for NO_3+NO_2-N. Leachate was also analyzed for NH_4-N from the start of the incubation until day 14, when negligible amounts were detected indicating further analysis of NH_4-N was unnecessary. Methods of chemical analysis are identical to those used in the batch incubations.

Double exponential equations (Jones, 1984; Deans et al., 1986) were fitted for each replicate of the experiment using the Marquardt option of the SAS nonlinear curve-fitting procedure, NLIN (SAS Institute, Inc., 1985). The fitted equations are of the form

$$N_t = N_1 - N_1 e^{-k_1 t} + N_2 - N_2 e^{-k_2 t}$$

where N_t is cumulative N mineralized (mg kg^{-1}) at time *t* (d), N_1 and k_1 are the pool size (mg kg^{-1}) and rate coefficient (d^{-1}), respectively, of the small, rapidly mineralizing pool (small-fast pool), and N_2 and k_2 are the pool size and rate coefficient, respectively, of the large, slowly mineralizing pool (large-slow pool). The curve fitting was performed in a two-step process because our attempts to fit all four parameters of a double exponential equation usually failed to converge. The first step of the analysis was identical to the procedure of Jones (1984). Parameters for the size and rate of the large-slow pool (N_2, k_2) and for the size of the small-fast pool (N_1) were estimated using a subset of the data from which the day 7 and 14 leachings had been removed. A number of trials established that this subset gave lower error mean squares than the complete data set or any other subset from which the day 7, 14, and 28 leachings were sequentially removed. In the second step, the parameters estimated in the first step were held constant and the complete data set was used to estimate the rate parameter of the small-fast pool (k_1).

ANOVA's were performed on the cumulative inorganic N mineralized and on the parameter estimates for the individual replicates for each of the four kinds of parameters (pool sizes and rate constants for large-slow and small-fast pools). The ANOVA's were performed using procedures similar to those used for the batch mineralization potentials.

Table 1. Effects of supplemental water pattern and annual application of 10 g N m^{-2} on net N mineralization in batch incubations of soils collected 19 July 1984.

			Incubation period, d				
Depth	Location	Treatment	0-7	7-14	14-28	0-14	0-28
cm			mg mineralized N kg^{-1}				
			Supplemental water effects†				
0-20	Both	Control	5.7a	−5.6a	16.1a	0.1	16.2a
		+6 mm/week	4.1b	−3.7b	9.5b	0.4	9.9bc
		+25 mm/month	3.1b	−0.9b	12.3b	2.3	14.6bd
0-10	Canopy	Control	6.7	−5.8	20.7	0.9	21.6
		+6 mm/week	7.1	−2.0	19.7	5.1	24.8
		+25 mm/month	4.4	3.0	21.4	7.4	28.8
	Open	Control	6.2	−3.8	11.0	2.4	13.4
		+6 mm/week	8.0	−5.9	7.9	2.1	10.0
		+25 mm/month	3.0	−1.2	12.4	1.8	14.1
10-20	Canopy	Control	4.4a	−4.9	19.9a	−0.5	19.4a
		+6 mm/week	2.5b	−4.1	7.7b	−1.6	6.0b
		+25 mm/month	2.2b	−3.7	10.6b	−1.6	9.0b
	Open	Control	5.6a	−7.9a	12.9a	−2.3	10.6a
		+6 mm/week	−1.0b	−3.0b	2.8b	−4.1c	−1.3bc
		+25 mm/month	3.1b	−1.5b	5.1b	1.5d	6.6bd
			Nitrogen fertilizer effects (10 g N m^{-2} yr^{-1})				
0-20	Both	Control	2.4a	0.9a	10.4a	3.3a	13.4
		+ N	6.3b	−7.8b	14.9b	−1.5b	13.8
0-10	Canopy	Control	3.2a	−2.5	16.2	5.7	21.8
		+ N	8.9b	−5.6	25.0	3.2	28.3
	Open	Control	2.3a	1.0a	11.1	3.3a	14.4
		+ N	9.1b	−8.3b	9.8	0.8b	10.6
10-20	Canopy	Control	1.9a	1.4a	7.1a	3.3	10.4
		+ N	4.1b	−9.9b	18.3b	−5.8	12.5
	Open	Control	2.0	−1.2a	7.5	0.9a	8.4
		+ N	3.1	−7.2b	6.4	−4.1b	2.3

† Significant differences for planned contrasts between the unwatered control and the mean of the watered treatments, and between the two watered treatments are indicated by the letters a and b and the letters c and d, respectively. Letters indicate significant differences ($P < 0.10$) for each combination of incubation period, depth, and location.

We also performed a multivariate analysis of variance (MANOVA) to examine treatment effects on all four rate/pool-size parameters at the same time. This approach may reveal effects on combinations of the four parameters that may not be evident from analyzing each parameter individually (Harris, 1975). The data for the four rate/pool-size parameters were transformed to *z*-scores (standard deviations) so that the weightings of the discriminant function directly indicate the relative importance of each parameter (Harris, 1975).

RESULTS AND DISCUSSION

Batch Mineralization Potentials

The initial soil samples were collected in July 1984 4 weeks after fertilizer application following a long period of predominantly dry weather (Fig. 1). The soils exhibited an overall pattern of net mineralization during days 0 to 7, net immobilization during days 7 to 14, followed by rapid net mineralization during days 14 to 28 (Table 1). The initial phase of mineralization probably resulted from the activity of organisms capable of surviving adverse conditions. The intermediate stage of net immobilization probably resulted from rapid population growth of microorganisms capable of exploiting the near optimal environmental conditions of the incubations. Sufficient populations of these organisms were apparently present after day 14 to result in rapid mineralization.

The watering treatments, especially the 6 mm/week treatment, significantly reduced grand means across depth and location in the July 1984 collection (0–20, both; Table 1). However, significant interactions were found involving the water treatments, N fertilizer treatments, and depth. Examination of the effects of water for each depth (Table 1) show that water clearly reduced mineralizable N in the 10 to 20 cm soils but had no consistent effect on the 0 to 10 cm soils. Examination of the effects of water in 0 to 10 cm soils within fertilizer treatments (Table 2) indicates that water tended to decrease mineralization in the unfertilized plots but either had no effect or increased it in the N-fertilized plots. To summarize, water consistently reduced N mineralization except in the fertilized 0 to 10 cm soils as reflected by the grand means (0–20, Both; Table 1). The low net mineralization rates in the unwatered, 0 to 10 cm, fertilized soils may have resulted from high initial levels of inorganic N that had not yet been immobilized by plants or microorganisms in the dry conditions in the field. The increased moisture availability in the incubations may have caused rapid immobilization and low net mineralization. With the exception of the fertilized 0 to 10 cm soils, these data support our hypothesis that high moisture availability reduces N availability.

The N fertilizer tended to increase mineralization in the July 1984 samples during days 0 to 7 and days 14 to 28 but net immobilization during days 7 to 14 tended to cancel the increases (Table 1). Therefore this data collection provides little support for our hypothesis that fertilizer N increases N mineralization.

The October 1984 sample collection occurred at the end of the warm moist summer season (Fig. 1) and

Table 2. Effects of supplemental water pattern (Water treatment), with and without annual application of 10 g N m^{-2}, on net N mineralization in batch incubations of soils collected from 0–10 cm on 19 July 1984.†

Location	Fertilizer treatment	Water treatment	Incubation period, d				
			0–7	7–14	14–28	0–14	0–28
			mg mineralized N kg^{-1}				
Canopy	Control	Control	3.2	0.4	20.7	3.6	24.3
		+6 mm/week	2.9	1.6	15.2	4.5	19.7
		+25 mm/month	3.6	5.5	12.6	9.0	21.6
	+ N	Control	10.1	−11.9	20.7	−1.8	18.9
		+6 mm/week	11.3	−5.5	24.2	5.8	30.0
		+25 mm/month	5.1	0.6	30.2	5.8	36.0
Open	Control	Control	2.1	4.0	13.4	6.2a	19.5a
		+6 mm/week	2.4	−0.5	8.8	2.0b	10.8b
		+25 mm/month	2.3	−0.4	11.0	1.9b	12.9b
	+ N	Control	10.2	−11.6	8.6	−1.4	7.2
		+6 mm/week	13.5	−11.3	7.0	2.2	9.2
		+25 mm/month	3.6	−2.0	13.8	1.6	15.4

† Letters indicate significant differences ($P < 0.10$) for each combination of incubation period, location, and N fertilizer treatment.

Table 3. Effects of supplemental water pattern and annual application of 10 g N m^{-2} on net N mineralization in batch incubations of soils collected 25 Oct. 1984.†

Depth	Location	Treatment	Incubation period, d				
			0–7	7–14	14–28	0–14	0–28
cm			mg mineralized N kg^{-1}				
			Supplemental water effects†				
0–20	Both	Control	3.4	4.0	2.7	7.4a	10.1
		+6 mm/week	3.4	1.9	2.7	5.3b	8.0
		+25 mm/month	2.1	2.8	4.0	4.9b	8.8
0–10	Canopy	Control	8.2	8.5	7.8	16.7	24.5
		+6 mm/week	5.7	7.3	5.3	13.0	18.3
		+25 mm/month	4.5	7.1	9.2	11.6	20.8
	Open	Control	3.7	6.8a	−0.2	10.6	10.4
		+6 mm/week	4.8	0.8b	2.3	5.6	7.9
		+25 mm/month	3.5	2.7b	1.6	6.2	7.8
10–20	Canopy	Control	−0.5	0.1	3.5	−0.4	3.1
		+6 mm/week	0.3	0.4	2.9	0.7	3.6
		+25 mm/month	0.5	0.8	4.1	1.4	5.5
	Open	Control	2.1	0.5	−0.1	2.6	2.5
		+6 mm/week	2.9c	−1.1c	0.3	1.8	2.1
		+25 mm/month	−0.2d	0.7d	0.9	0.4	1.3
			Nitrogen fertilizer effects (10 g N m^{-2} yr^{-1})				
0–20	Both	Control	2.2	1.4a	2.7	3.7a	6.4a
		+ N	3.7	4.3b	3.5	8.0b	11.6b
0–10	Canopy	Control	3.9	4.3a	6.7	8.2a	14.9a
		+ N	8.4	11.0b	8.2	19.4b	27.5b
	Open	Control	2.8a	1.9	0.7	4.7a	5.4a
		+ N	5.3b	5.0	1.7	10.2b	12.0b
10–20	Canopy	Control	0.1	0.0	3.4	0.1	3.5
		+ N	0.1	0.9	3.6	1.0	4.6
	Open	Control	2.1	−0.5	0.1	1.6	1.7
		+ N	1.1	0.5	0.6	1.6	2.2

† See Table 1 supplementary notes on interpretation of watering effects.

the resulting patterns of net N mineralization were much different from those for the July 1984 samples (Tables 1, 3). The overall pattern of the October 1984 samples is one of gradually accumulating inorganic N (Table 3) suggesting the presence of well-established microbial populations that were altered little by the incubation procedures. Differences between soil depths were much larger than for the July sample (Tables 1, 3). Water had few significant effects on mineralization although there were trends towards reduced mineralization in the grand means and the 0 to 10 cm soils (Table 3). Nitrogen significantly increased mineralization rates in the 0 to 10 cm soils but had less effect on 10 to 20 cm soils. However, mineralization rates were so low in the 10 to 20 cm soils that they would contribute little to total N availability for 0 to 20 cm. Mineralization rates in canopy soils were approximately double those from between shrubs but responses to treatments were similar. Overall, this collection (Oct. 1984) supports our hypothesis concerning N fertilizer effects, but provides only weak support for our hypothesis about prolonged watering effects.

The March 1985 samples were collected at the end of an unusually wet winter (Fig. 1), and there was no evidence of a consistent water treatment effect (Table 4). Overall mineralization rates were lower than those for the July and October 1984 samples. Nitrogen fertilization continued to increase net mineralization rates

Table 4. Effects of supplemental water pattern and annual application of 10 g N m^{-2} on net N mineralization in batch incubations of soils collected 14 Mar 1984.†

			Incubation period, d				
Depth	Location	Treatment	0-7	7-14	14-28	0-14	0-28
cm			mg mineralized N kg^{-1}				
			Supplemental water effects†				
0-20	Both	Control	3.9a	−0.0a	1.5	3.8	5.3
		+6 mm/week	1.9b	2.1b	2.1	4.0	6.2
		+25 mm/month	2.1b	1.1b	2.4	3.3	5.7
0-10	Canopy	Control	5.2	2.6	3.5a	7.8	11.3
		+6 mm/week	6.4	2.7	5.8b	9.1	14.8
		+25 mm/month	6.0	0.7	6.1b	6.7	12.8
	Open	Control	4.2a	−2.0a	1.7	2.1	3.8
		+6 mm/week	0.7b	3.1b	1.1	3.8	5.0
		+25 mm/month	0.1b	2.7b	0.6	2.8	3.4
10-20	Canopy	Control	2.6	0.9	0.9a	3.5a	4.3
		+6 mm/week	1.9	0.5	2.9b	2.4b	5.3
		+25 mm/month	2.2	−0.5	3.2b	1.7b	5.0
	Open	Control	3.5a	−1.6a	−0.2	1.9	1.8
		+6 mm/week	−1.2b	2.0b	−1.2	0.8	−0.4c
		+25 mm/month	−0.2b	2.1b	−0.6	1.9	1.3d
			Nitrogen fertilizer effects (10 g N m^{-2} yr^{-1})				
0-20	Both	Control	1.9a	1.0	1.7	3.0a	4.6a
		+ N	3.4b	1.1	2.4	4.5b	6.9b
0-10	Canopy	Control	4.2a	2.0	4.5	6.2	10.8a
		+ N	7.5b	2.0	5.7	9.5	15.2b
	Open	Control	0.7a	1.1	0.3a	1.9a	2.2a
		+ N	2.9b	1.2	2.1b	4.1b	6.3b
10-20	Canopy	Control	2.0	0.4	2.5	2.3	4.8
		+ N	2.5	0.3	2.2	2.8	4.9
	Open	Control	0.7	0.7	−0.7	1.4	0.7
		+ N	0.7	1.0	−0.6	1.7	1.1

† See Table 1 supplementary notes on interpretation of watering effects.

in the 0 to 10 cm soils but not in the 10 to 20 cm soils (Table 4). This data collection provides some support for our N-fertilizer hypothesis but none for the prolonged watering effects hypothesis.

The post-hoc examination of pooled data from the three collections indicates that the validity of our initial hypotheses (prolonged high moisture availability reduces N availability; N fertilizer application increases N mineralization) is dependent upon seasonal fluctuations of natural moisture and N availability. The seasonal trends of cumulative 28-d mineralization for unwatered-unfertilized control soils are summarized by Fig. 2. This figure emphasizes the general decline in N availability (75% average decline) as environmental conditions gradually changed from dry, in spring of 1984, to unusually wet, in the spring of 1985. Table 5 shows that an overall change in the effectiveness of the water and N treatments occurred in parallel with the declining N availability. During July and October 1984, water reduced potential mineralization by 22% (averaged across depth, location, and month) but had no effect in March (Table 5). The 6 mm/week treatment was notably lower than the 25 mm/month treatment. In contrast, N fertilizer had no effect on potential mineralization in the dry July sam-

Table 5. Effects of water and N amendments ($P < 0.10$) on net N mineralization (28-d incubation) averaged across depth and location.

Sample	Treatment	Inorganic N†
		mg kg^{-1}
	Supplemental water effects	
July 84 and Oct. 84 pooled	0 mm	13.2a
	6 mm/week	8.9b
	25 mm/month	11.7ab
Mar. 85	0 mm	5.3
	6 mm/week	6.2
	25 mm/month	5.7
	Nitrogen fertilizer effects (10 g N m^{-2} yr^{-1})	
July 84	− N	13.8
	+ N	13.4
Oct. 84 and Mar. 85 pooled	− N	5.7a
	+ N	9.0b

† Letters indicate significant differences at $P < 0.10$.

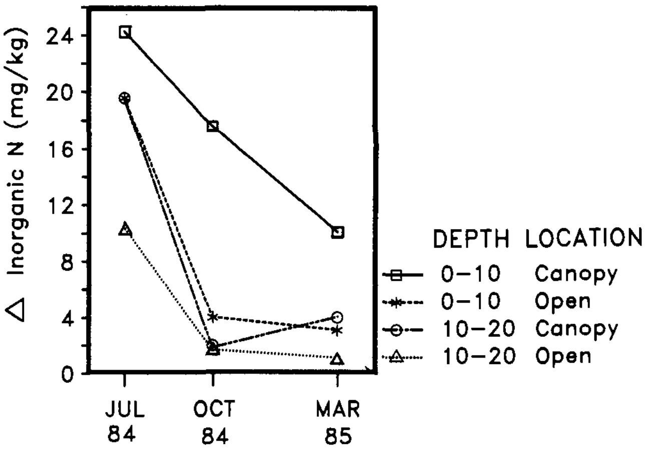

Fig. 2. Seasonal comparison of net N mineralization in 28-d incubations of soil collected from unwatered unfertilized plots. Mean July 1984 mineralization (averaged across depth and location) is significantly greater than October 1984 and March 1985 ($P < 0.10$; Student-Newman-Keuls Test).

Table 6. Effects of drying at 35 °C and amendments of water and N on N mineralized during leaching incubations.†, ‡

Amendment type	Treatment	Days 0	7	14	28	56	84	112	140	168	192
		mg mineralized N kg^{-1}									
		Field-moist soils									
Water†	None	1.2	10	20a	36a	52a	64a	69a	73a	79	83
	+6 mm/week	0.8	6	12b	22b	32b	39b	43b	47b	53	57
	+25 mm/month	0.9	7	15b	27b	39b	49b	55b	59b	64	67
N	None	0.8a	7	14	26	36	45	50	54	62	65
	+ N	1.1b	8	17	30	44	55	59	64	68	72
		Air-dry soils									
Water†	None	2.1a	12	23a	37a	54a	67a	72a	79a	86a	
	+6 mm/week	1.5b	9	15b	22b	30b	35b	37bc	41bc	45bc	
	+25 mm/month	1.5b	10	17b	27b	43b	50b	55bd	61bd	67bd	
N	None	1.6	9	16	27	40	48	53	58	63	
	+ N	1.8	11	20	30	42	51	55	60	66	
		Effects of air drying									
All	Field-moist	1.0a	7a	15a	28	40	50	55	59	65	69
	Air-dry	1.7b	10b	18b	28	41	50	54	59	65	

† See Table 1 supplementary notes on interpretation of watering effects.

‡ Letters indicate significant differences at — <0.10. Water-nitrogen interactions were not significant.

ples but increased potential mineralization in the October 1984 and March 1985 samples.

Spatial variation of mineralizable N in this Chihuahuan Desert shrubland was similar to that found by Charley and West (1977) in semiarid shrublands in Utah. The spatial pattern of mineralizable N is similar to patterns of other soil properties in shrub-dominated arid and semiarid ecosystems (Charley and West, 1975; Parker et al., 1982; Virginia and Jarrell, 1983). This study shows that N mineralization potential varies significantly through time and that the responses of mineralization potential to perturbations also may vary in time and space (treatment × time, treatment × depth, or treatment × location interactions). In this case, averaging across depth and location appears to have provided a valid indication of overall mineralization. However, because of the spatial and temporal variability of this environment, generalizations based on averages across microsites or seasons should only be made after careful study of the variation.

Leaching Mineralization Potentials

Supplemental water decreased inorganic N production during the intermediate stages (days 14–112) of the incubation of field-moist soils (Table 6). This is reflected by significantly lower rate constants for the large-slow pool (k_2) of the watered treatments (Table 7). Significant differences were present throughout the incubations of air-dry soils (Table 6) and corresponding differences were present in the pool-size parameter of the large-slow pool (N_2: Table 7). MANOVA confirmed that watering effects in the field-moist soils were restricted to the rate parameter of the large-slow pool (k_2). However, MANOVA suggested that all four parameters of the air-dry soils were affected to some extent. Overall, these data suggest that drying widened the differences between soils from the three watering treatments. This parallels results from the batch mineralization potentials in that watering effects were more detectable in drier soils (July 1984, October 1984) than in wet soils (March 1985).

No significant differences in mineralized N were found for the N fertilizer treatment in either the field-moist soils or the air-dry soils although fertilization significantly increased the inorganic N level of the field-moist soils (Table 6). However, significantly different parameter values were found for the field-moist soils: higher k_2 values suggest that N fertilizer increased the quality of the large-slow pool (Table 7). The greater sensitivity of wet soils to N effects parallels results from the batch mineralization potentials where relatively moist soils (October 1984, March 1985) responded to N fertilizer but dry soils did not (July 1984).

Air-drying consistently increased inorganic N and mineralized N during the first 14 d of incubation across all treatments (Table 6). A corresponding increase in

Table 7. Effects of drying at 35 °C and amendments of water and N on leaching incubation parameters for the double exponential equation ($N_t = N_1 - N_1e^{-k_1t} + N_2 - N_2e^{-k_2t}$).†, ‡

Amendment type	Treatment	Parameters N_1	k_1	N_2	k_2
		mg kg^{-1}	d^{-1}	mg kg^{-1}	d^{-1}
		Field-moist soils			
Water†	None	13	0.067	74	0.0129a
	+6 mm/week	9	0.058	52	0.0100b
	+25 mm/month	11	0.065	67	0.0093b
N	None	12	0.061	61	0.0091a
	+ N	10	0.066	67	0.0123b
		Air-dry soils			
Water†§	None	13	0.111	85a	0.0117
	+6 mm/week	11	0.148	42bc	0.0108
	+25 mm/month	10	0.114	68bd	0.0109
N	None	10	0.108	65	0.0111
	+ N	12	0.140	65	0.0112
		Effects of air drying			
All§	Field-moist	11	0.063a	64	0.0107
	Air-dry	11	0.124b	65	0.0111

† See Table 1 supplementary notes on interpretation of watering effects.

‡ Letters indicate significant differences at $P < 0.10$. Water-nitrogen interactions were not significant.

§ MANOVA significant at $P < 0.01$.

the rate constant of the small-fast pool (k_1) suggests that drying increased organic N quality (Table 7) probably as result of enhanced turnover of microbial biomass and soil organic matter (Marumoto et al., 1982; Bottner, 1985).

The interactions of air-drying with the water and N fertilizer treatments indicate that drying effects are the net result of several processes tending to decrease or increase N availability. The overall tendency appears to be to increase N availability, which supports our original hypothesis. However, the process is more complicated than we had anticipated. For example, mineralization rates in dried N-fertilized soils and dried 6 mm/week soils tended to be lower than their field-moist counterparts indicating potential for net losses under certain circumstances. The net effect of drying seems to be dependent on the history of the soil. It is interesting that the direction of the drying effect was the inverse of the drying-episode frequency experienced by the soils in the field: drying tended to increase mineralizable N in the unwatered controls (infrequent drying episodes) and decreased it in the 6 mm/week (frequent episodes). Possibly the frequent episodes in the 6 mm/week plots depleted the fraction of organic matter made available by soil drying.

It should be noted that the conditions of the air-drying experiment were quite mild compared to field conditions where surface soil temperatures daily exceed 45°C in June and 6 months can pass without precipitation. The field conditions are actually more similar to conditions of oven-drying experiments which show dramatic increases in N turnover (Marumoto et al., 1982). Such conditions existed when the July 1984 soils were collected for the batch mineralization potentials and can explain the observed high mineralization rates. The effects of the experimental water treatments provide an explanation for the declining mineralization potential during the following months of wet weather.

Water-N Availability Relationships

The results of both the batch and leaching procedures indicate that supplemental water reduced potential mineralization rates supporting our original hypothesis. There are also indications that the mineralization potentials of the 6 mm/week soils were lower than those of the 25 mm/month soils. The loss of mineralizable N from watered plots was probably initiated by increased mineralization rates occurring early in the experiment prior to soil sample collection in 1984. Two factors probably contributed to faster mineralization rates in watered plots during the initial stages of the experiment: (i) greater overall moisture availability, and (ii) more frequent wetting and drying episodes. The 6 mm/week treatment is more effective than the 25 mm/month treatment in both respects. These results appear to conflict with those of Schimel and Parton (1986), who found greater mineralization associated with a single simulated monthly precipitation event than with simulated weekly or biweekly events delivering the same monthly total of moisture. However, their experiment excluded roots so that drying and wetting cycles did not occur in the small frequent event treatments but did occur in the single monthly event treatment. They suggested that the occurrence of drying/wetting cycles associated with small frequent events could increase mineralization rates to levels higher than observed in their single monthly event treatment.

Once N is mineralized, several mechanisms can remove it from the soil and the rates of these processes may be increased by wetter conditions. Some of these processes cause temporary losses, but their association with wetter conditions may significantly reduce potential productivity. These include increased N uptake by plants and immobilization of N by microbes during decomposition. The decomposition of N-poor roots of annual plants responding to wetter conditions may be a particularly important temporary N sink (Parker et al., 1984). Denitrification is increased by moist conditions and has been shown to be important in other desert ecosystems (Westerman and Tucker, 1978; West and Skujins, 1978). Ammonia (NH_3) volatilization is favored in soils of the type most common on the Jornada LTER site (high pH, coarse texture, and low cation exchange capacity), especially during the drying phase (Nelson, 1982). Leaching is an important loss in many ecosystems but it seems unlikely in the Chihuahuan Desert since creosotebush roots extend far below the 40-cm caliche layer that indicates the normal depth to which water penetrates. However, recent findings at this site of elevated NO_3^- concentrations (20–50 mg N kg^{-1}) at 1- to 3-m depth indicate that leaching cannot be eliminated as a possible N loss mechanism (R.A. Virginia, unpublished). There are insufficient data available at present to ascertain if any or all of these processes are important in these soils.

The results of the leaching experiments can be used to estimate changes of mineralizable N due to the treatment effects. We performed these calculations using the mean of the field-moist and air-dry soils to provide the most general estimates. Estimated mineralizable N ($N_1 + N_2$) for the unwatered control, 25 mm/month, and 6 mm/week treatments were 93, 78, and 57 mg kg^{-1}, respectively. This suggests that the water treatments caused an average loss of 25 mg kg^{-1} N which equals 27% of the mineralizable N and 6% of the total N. No significant differences in total N values were found for water treatments but this is not surprising because the least significant difference ($P <$ 0.10) for the effects of water treatments on the 0 to 10 cm, under-canopy soils is 51 mg kg^{-1}.

CONCLUSIONS

(1) Increased N mineralization resulting from the N fertilizer treatments indicates that N immobilization by soil microbes is a significant process in this desert soil.

(2) Decreased N mineralization resulting from the supplemental water treatments suggests that unusually wet weather can reduce N availability. Reduced N availability probably results from initially faster N mineralization accompanied by increased N losses.

(3) Small-frequent precipitation events (6 mm/week) caused greater N losses than did large-infrequent events (25 mm/week), probably be-

cause the greater frequency of drying-wetting episodes associated with the former.

(4) Increased mineralization from air-dried soils suggests that drought can increase N availability under subsequent wetter conditions.

(5) Significant interactions between air-drying and water and N treatments indicate that drying effects are the net result of several processes, and that specific effects are dependent upon both the past and current status of the soil.

ACKNOWLEDGMENT

R. Prevosto, H. Fischer, W.P. MacKay, and numerous others contributed to this research by performing chemical analyses, assisting in sample collection, and by setting up, watering, and fertilizing the experimental plots. D. Bachelet, G.M. Marion, D.L. Moorhead, O.E. Sala, and R.A. Virginia read and commented on drafts of this manuscript. This research was supported by National Science Foundation grant BSR 821539 to W.G. Whitford and by the Jornada Long Term Ecological Research Program (National Science Foundation grant BSR 814466).

REFERENCES

Bottner, P. 1985. Response of microbial biomass to alternate moist and dry conditions in a soil incubated with ^{14}C- and ^{15}N-labelled plant material. Soil Biol. Biochem. 17:329–337.

Bremner, J.M., and L.A. Douglas. 1971. Use of plastic films for aeration in soil incubation experiments. Soil Biol. Biochem. 3:289–296.

Charley, J.L. 1972. The role of shrubs in nutrient cycling. p. 182–203. *In* C.M. McKell et al. (ed.) Wildland shrubs—Their biology and utilization. USDA Forest Service Gen. Tech. Rep. INT-1, Washington, DC.

Charley, J.L., and N.E. West. 1975. Plant induced soil chemical patterns in some shrub-dominated semi-desert ecosystems of Utah. J. Ecol. 63:945–964.

Charley, J.L., and N.E. West. 1977. Micro-patterns of nitrogen mineralization activity in soils of some shrub-dominated semi-desert ecosystems of Utah. Soil Biol. Biochem. 9:357–365.

Deans, J.R., J.A.E. Molina, and C.E. Clapp. 1986. Models for predicting potentially mineralizable nitrogen and decomposition rate constants. Soil Sci. Soc. Am. J. 50:323–326.

Ettershank, G., J.A. Ettershank, M. Bryant, and W.G. Whitford. 1978. Effects of nitrogen fertilization on primary production in a Chihuahuan Desert ecosystem. J. Arid Environm. 1:135–139.

Gutierrez, J.R., and W.G. Whitford. 1987a. Chihuahuan desert annuals: Importance of water and nitrogen. Ecology (in press).

Gutierrez, J.R., and W.G. Whitford. 1987b. Responses of Chihuahuan desert herbaceous annuals to rainfall augmentation. J. Arid Environ. 12:127–139.

Harris, R.J. 1975. A primer of multivariate statistics. Academic Press, New York.

Henriksen, A., and A.R. Selmer-Olsen. 1970. Automatic methods for determining nitrate and nitrite in water and soil extracts. Analyst (London) 95:514–518.

James, D.W., and J.J. Jurinak. 1978. Nitrogen fertilization of dominant plants in the northeastern Great Basin Desert. p. 219–231. *In* N.E. West and J. Skujins (ed.) Nitrogen in desert ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

Jones, C.A. 1984. Estimation of an active fraction of soil nitrogen. Commun. Soil Sci. Plant Anal. 15:23–32.

Keeney, D.R. 1982. Nitrogen—Availability indices. *In* A.L. Page et al. (ed.) Methods of soil analysis, Part 2. 2nd ed. Agronomy 9:711–735.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—Inorganic forms. *In* A.L. Page et al. (ed) Methods of soil analysis, Part 2. 2nd ed. Agronomy 9:643–698.

Lajtha, K., and W.H. Schlesinger. 1986. Plant response to variations in nitrogen availability in a desert shrubland community. Biogeochemistry 2:29–37.

Marion, G.M., J. Kummerow, and P.C. Miller. 1981. Predicting nitrogen mineralization in chaparral soils. Soil Sci. Soc. Am. J. 45:956–961.

Marumoto, T., J.P.E. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469–475.

Nelson, D.W. 1982. Gaseous losses of nitrogen other than through denitrification. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agronomy 22:327–363.

Nelson, D.W. 1983. Determination of ammonium in KCl extracts of soils by the salicylate method. Commun. Soil Sci. Plant Anal. 14:1051–1062.

Nelson, D.W., and L.E. Sommers. 1980. Total nitrogen analysis of soil and plant tissues. J. Assoc. Off. Anal. Chem. 63:770–778.

Parker, L.W., H.G. Fowler, G. Ettershank, and W.G. Whitford. 1982. The effects of subterranean termite removal on desert soil nitrogen and ephemeral flora. J. Arid Environm. 5:53–59.

Parker, L.W., P.F. Santos, J. Phillips, and W.G. Whitford. 1984. Carbon and nitrogen dynamics during the decomposition of litter and roots of a Chihuahuan Desert annual, *Lepidium lasiocarpum*. Ecol. Monogr. 54:339–360.

Richter, J., A. Nuske, U. Bohmer, and J. Wehrmann. 1980. Simulation of nitrogen mineralization and transport in loess-parabrownearthes: plot experiments. Plant Soil 54:329–337.

Romney, E.M., A. Wallace, and R.B. Hunter. 1978. Plant response to nitrogen fertilization in the northern Mohave Desert and its relationship to water manipulation. p. 232–243. *In* N.E. West and J. Skujins (ed.) Nitrogen in desert ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

SAS Institute, Inc. 1985. SAS user's guide: Statistics, version 5 ed. SAS Institute, Inc., Cary, NC.

Schimel, D.S., and W.J. Parton. 1986. Microclimate controls of nitrogen mineralization and nitrification in shortgrass steppe soils. Plant Soil 93:347–357.

Smith, S.J., L.B. Young, and G.E. Miller. 1977. Evaluation of soil nitrogen mineralization potentials under modified field conditions. Soil Sci. Soc. Am. J. 41:74–76.

Stanford, G. 1982. Assessment of soil nitrogen availability. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. Agronomy 22:651–688.

Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465–472.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics. 2nd ed. McGraw-Hill Book Co., New York.

Virginia, R.A., and W.M. Jarrell. 1983. Soil properties in a mesquite-dominated Sonoran Desert ecosystem. Soil Sci. Soc. Am. J. 47:138–144.

Wall, L.L., and C.W. Gehrke. 1975. An automated total protein nitrogen method. J. Assoc. Off. Anal. Chem. 58:1221–1226.

West, N.E., and J. Skujins. 1978. Summary, conclusions, and suggestions for further research. p. 244–253. *In* N.E. West and J. Skujins (ed.) Nitrogen in desert ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

Westerman, R.L., and T.C. Tucker. 1978. Denitrification in desert soils. p. 75–106. *In* N.E. West and J. Skujins (ed.) Nitrogen in desert ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

Westermann, D.T., and S.E. Crothers. 1980. Measuring soil nitrogen mineralization under field conditions. Agron. J. 72:1009–1012.

Wierenga, P.J., J.M.H. Hendrickx, M.H. Nash, J. Ludwig, and L. Daugherty. 1987. Variation of soil and vegetation with distance along a transect in the Chihuahuan Desert. J. Arid Environ. 12:(in press).