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SHORT COMMUNICATION

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Regional-scale drought increases potential soil fertility in semiarid grasslands

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Abstract Although drying of soil has increased fertility in laboratory-based experiments, a direct link between longer-scale weather conditions associated with drought and soil fertility has not been documented at the field scale. Soil from a semiarid grassland on the Sevilleta National Wildlife Refuge (NWR) that was collected over a 10-year period had the highest levels of potentially mineralizable nitrogen (PMN, a measure of potential soil fertility) during drought periods in 1989 and 1995. Whereas previous soil collections on the Sevilleta NWR were made for different reasons, soils were collected in June 2002 near the peak of a regional-scale drought to test the hypothesis that potential soil fertility increased with drought. Another semiarid grassland site, the Bernalillo Watershed, was sampled to extend the spatial extent of the analysis. The 2002 collections showed soil PMN near the highest at both sites, thereby supporting the hypothesis. Longer-term PMN data at both sites were correlated with the Palmer Drought Index (PDI), a regional-scale index with drier periods given negative values. Over a 13-year period, the Sevilleta soils had higher PMN during periods of drought (r =−0.533, P <0.05). Although not significant, a similar trend was shown over an 8-year record at the Bernalillo Watershed (r =−0.356, not significant). Also, PMN levels measured during a previous 3-year wet-to-drought period at another semiarid grassland site on the Sevilleta NWR were highly significantly correlated with the PDI (r = −0.723, P <0.01). Thus, drought can increase soil fertility, which can alter additional ecosystem processes.

Keywords Palmer Drought Index · Potentially mineralizable nitrogen · Soil fertility · Above-ground net primary production

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Introduction

The availability of water is well known to limit above-ground net primary production (ANPP) in semiarid and arid grasslands (Risser 1988), but there is evidence that ANPP may be co-limited by the availability of nitrogen (N; Hooper and Johnson 1999). Conceptually, the amount of N available for plant growth is the sum of soil inorganic N and the pool of organic N that can be decomposed within a year, i.e., readily mineralizable N. This readily mineralizable organic N pool is a very small portion of the soil total organic N and is much smaller than the slowly mineralizable or recalcitrant organic N pools.

The size of the inorganic N and readily mineralizable N pools varies over time in response to many factors. During periods of increased moisture, reductions in soil inorganic N can occur through immobilization in new microbial biomass, uptake by higher plants, or loss through denitrification (Westerman and Tucker 1978). Small volume rain events that stimulate microbial activity but not plant growth may increase soil inorganic N by mineralizing a portion of the readily mineralizable N pool. The mineralizable N pool can decrease during periods of extended moisture and can increase in response to microbial and plant root mortality during periods of drying.

Drying and rewetting of soil is known to stimulate mineralization of the portion of microbial biomass that died during desiccation or rewetting and to increase the availability of a portion of the slowly mineralizable organic N sources (Jenkinson and Powlson 1976; Kieft et al. 1987; Nishio and Fujimoto 1991; Van Gestel et al. 1993). However, the relationship between drying and rewetting of soil and mineralizable N has been tested in laboratory settings only and has not been directly tested in the field. Experiments conducted with desert soils suggest that N availability is lower during periods of unusually wet weather and is higher following periods of drought (Fisher et al. 1987). A drought period appeared to have a greater effect on soil fertility, as measured by potentially mineralizable N (PMN), which measures net N mineralization potential (Hart et al. 1994), in a semiarid grassland than concurrent application of a prescribed fire (White and Loftin 2000), but the relationship between drought and soil fertility was not directly tested.

Demonstration of the relationship between drought and potential soil fertility in the field requires long-term measurements of soil fertility and an index of relative drought severity. Although drought is difficult to define and to quantify, a number of drought indices have been developed (Heim 2002). One widely used index is the Palmer Drought Index (PDI, also known as the Palmer Drought Severity Index; Palmer 1965). The index uses a model that incorporates antecedent precipitation, moisture supply, and moisture demand (roughly equivalent to potential evapotranspiration) in an attempt to measure the duration and intensity of droughts. The index is calculated for defined regions over the entire United States. The dimensionless index is positive during wetter-than-normal periods, zero for normal periods, and negative for drier-than-normal periods. Drought conditions occur when the PDI reaches −2 or lower.

The relationship between soil fertility and regional drought in semiarid grasslands was the focus of this study. We used PMN as the indicator of soil fertility and the monthly PDI values calculated for Region 05 in New Mexico (Fig. 1) as the indicator of regional-scale drought. We hypothesized that drought increases soil fertility and thus that the PDI should be negatively correlated with PMN. This hypothesis was tested through the synthesis of three different research projects. First, soils were collected from two semiarid grasslands during a relatively strong drought period (June 2002, PDI of −2.7) to determine soil fertility during a defined drought period. The two grasslands, one on the Sevilleta National Wildlife Refuge (Sevilleta NWR) and the other within the Bernalillo Watershed, are within the same PDI region in New Mexico but are about 120 km apart. Second, the regional PDI values were correlated with the results of the June 2002 soil collections and additional extant data for each grassland to test the relationship with drought over longer time periods. Third, the PDI values for this region were correlated with extant data on soil fertility, microbial biomass carbon (C), and total organic C from an additional grassland site on the Sevilleta NWR where a higher frequency of sampling was done over a shorter time (Kieft et al. 1998). The relationship between regional-scale drought and soil fertility was assessed through the synthesis of these three projects.

Materials and methods

Site descriptions

Sevilleta sites

Two of the study sites are located on the Sevilleta National Wildlife Refuge (NWR) in central New Mexico (Fig. 1). The Sevilleta NWR, a 93,000-ha refuge established in 1973, is managed by the US Fish and Wildlife Service and is the focus of the Sevilleta Long-Term Ecological Research (LTER) project (http://sevilleta.unm.edu). Domesticated livestock were excluded from the refuge after 1973. The general area was selected in 1989 for intensive study because it appeared typical of the grassland-creosote bush ecotone in the northern Chihuahuan Desert, with creosote bush extending from the south into the fringes of the grasslands in which the two study sites lie. Annual precipitation averages about 200–250 mm.

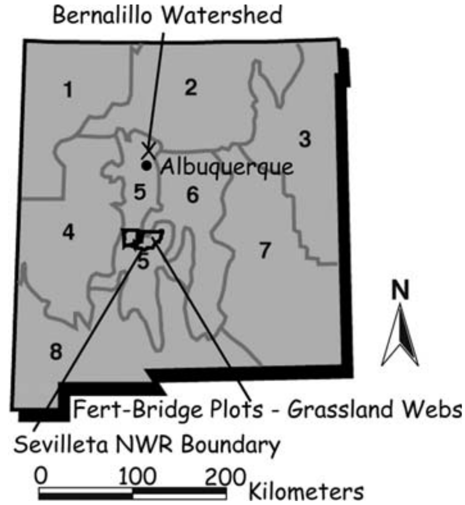

Fig. 1 Map indicating the Palmer Drought Index regions within New Mexico, the middle Rio Grande region (05), and the Sevilleta and Bernalillo Watersheds

Soil collections on the Sevilleta for measurement of field-available inorganic N and PMN began in association with a study to determine the effects of N fertilization on semiarid grassland ANPP as part of the Sevilleta LTER. The area was selected because of its high cover by black grama [*Bouteloua eriopoda* (Torr.) Torr.] and relatively uniform nature. The soils tend to be sandy loam with developing petrocalic horizons beginning at about 20 cm. The original study area, referred to as the "Fertilizer Plots", is a 300×300-m area containing 100 individual plots. Soil collections began at this site in 1989 (only results from unfertilized, control plots are reported here) and continued semi-annually until 1994. In 1994 measurements of soil fertility began at five locations (about 75 m apart) along the eastern edge of the Fertilizer Plots, that were instrumented with soil bridges (bridges described by White and Loftin 2000) to measure changes in soil microtopography and grass cover over time (referred to as "Bridge Plots"). A direct comparison of soils collected at the Fertilizer Plots with soils at the Bridge Plots, conducted in 1998, found a highly significant correlation between the same measurements at both sites (r =0.998, see details below). Thus, the combined soil data from the Fertilizer Plots and adjacent Bridge Plots, referred to as the "Fert-Bridge Plots", constitute the long-term measurements of soil fertility on the Sevilleta.

More frequent measurements of soil fertility occurred over a 3-year period at a grassland site approximately 2.5 km west of the Fert-Bridge Plots (Kieft et al. 1998). The grassland in this area is dominated by predominantly black grama [*B. eriopoda* (Torr.) Torr.] with some blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.] and other grasses present. Experimental plots used to quantify arthropod and rodent populations were established at this site in 1989. These circular plots, called "webs" (Anderson et al. 1983), have a 100-m radius and occupy over 3 ha. Five of these webs are in the grassland site (referred to as "Grassland Webs" in this paper). Each web comprised a sample unit and was at least 200 m from other webs. The Grassland Webs research site occupies about 30 ha of semiarid grassland.

Bernalillo Watershed

The Bernalillo Watershed is a shrub-invaded semiarid grassland where prescribed fire is being used in efforts to control shrub cover and to increase grass cover. A more detailed description of the Bernalillo Watershed is in White and Loftin (2000). The site lies north of Albuquerque within the Cibola National Forest. The soil is a clayey loam and the dominant perennial grasses are: black, blue, and sideoats grama [*B. eriopoda* (Torr.) Torr.; *B. gracilis* (Willd. ex Kunth) Lag. ex Griffiths; and *B. curtipendula* (Michx.) Torr.; respectively]; purple three awn (*Aristida purpurea* Nutt.); galleta [*Hilaria jamesii* (Torr.) Benth]; and dropseed (*Sporobolus* sp). Annual precipitation averages about 200–250 mm.

Soil sampling: all plots

All soils were sampled to 20-cm depth of mineral soil (when present, plant litter was removed from the mineral soil surface). All soil samples were placed into an ice chest and transported on ice to the Sevilleta Field Station or directly to the University of New Mexico (UNM), where they were sieved (<2 mm), mixed, live roots removed, and stored at 5°C. All soil N measurements were performed at UNM. Study-specific details of sampling at each of the three sites are detailed below.

Fertilizer Plots

Within the 300×300-m Fertilizer Plot site, four untreated 30×30-m plots were randomly selected on each sampling date. Three randomly selected 1×0.5-m quadrats within the northwest quarter of each plot were sampled by taking a 4-cm diameter by 20-cm deep core from the northwest and opposing corner of each quadrat. Both cores were composited to make one sample from each quadrat, resulting in three soil samples for each plot. Each soil sample was analyzed separately and the results were averaged to give a single value for each plot, resulting in four measures of PMN for the site. Collections began in 1989 and ended in October 1994 at this area, with the exception of the collection in July 1998 for comparison to the Bridge Plots.

Bridge Plots

Locations for five bridges were established in November 1994 at 75-m intervals about 50 m east of the Fertilizer Plots. Within 5 m of each bridge, soil cores (4-cm diameter by 20-cm deep) were taken from under two individual grasses and from two bare soil openings. The two cores were composited to give a single soil sample from under grass and bare soil at each bridge. The relative cover of grass and bare soil determined at the bridge was used to weight the respective soil N values, resulting in a weighted value for each bridge (n =5) for each collection. Thus, there were five values of PMN along the 300-m transect for each collection.

Fertilizer Plot-Bridge Plot comparison

In July 1998, soils were collected on the same day from the Fertilizer Plots and the Bridge Plots for direct comparison. Over the course of the 6-week incubation, inorganic N and PMN values in soils from both Plots were within 5% and were significantly correlated (r =0.998, values not presented in this report). Thus, the data used in this report to correlate with the PDI are the average N values from the four Fertilizer Plots for the collections from 1989 through to 1994 and the average from the five Bridge Plots from 1995 through to 2002. Specifically for this study, soils were collected during a drought period from the Bridge Plots on 19 June 2002, to determine PMN.

Grassland Webs

For each soil collection, a randomly located point on the circumference of each of five webs was selected and soils from that location and the opposite side of the web were collected (4-cm diameter by 20-cm deep cores, Kieft et al. 1998). Sample webs were collected 17 times during 1992–1994, beginning in April 1992 and ending in August 1994.

Bernalillo Watershed

The Bernalillo Watershed includes eight 1-ha plots, four control and four burned, arranged in a randomized block design (White and Loftin 2000). Each sample from the four control plots consisted of six soil cores taken beneath grass, two cores each along three 60-m permanent transects. Samples were collected on 20 June 2002, to specifically determine PMN during the drought period.

Sample analyses

After determining water-holding capacity (WHC; White and McDonnell 1988), fresh portions of each sample were adjusted to 50% of determined WHC and up to 11 subsamples were apportioned into plastic cups. Each cup contained approximately 30 g dry-weight mineral soil. One subsample of each sample was immediately extracted with 100 ml 2N KCl for NH_4^+-N and NO_3^--N analyses to determine "field-available" N. The remainder of the cups were covered with plastic wrap, sealed with a rubber band, and incubated in the dark at 20°C. The plastic wrap minimized water loss during incubation, yet exchange of CO_2 and O_2 was sufficient to keep the subsamples aerobic during incubation. Moisture content was monitored by mass loss and replenished as needed. At weekly intervals, one subsample of each sample was removed and extracted with KCl for 18–24 h. The clarified KCl was filtered through a Kimwipe and analyzed for NH_4^+-N and NO_3^--N + NO_2^--N on a Technicon AutoAnalyzer (Technicon, Terrytown, N.Y.) as described in White (1986). PMN was determined to be the maximum amount of extractable N during the incubation, which occurred at or before 6-week extraction in the Sevilleta soils (Kieft et al. 1998) and at or near the 10-week extraction for the Bernalillo Watershed soils (White and Loftin 2000). Other analyses performed on the soil samples are detailed in Kieft et al. (1998) and White and Loftin (2000).

Palmer Drought Index

The PDI (Palmer 1965) is a model that incorporates antecedent precipitation, moisture supply, and moisture demand (roughly potential evapotranspiration) in an attempt to measure the duration and intensity of droughts. The PDI is calculated on a monthly basis for geographic regions throughout the United States. Positive PDI values indicate wetter-than-normal periods, zero indicates normal periods, and negative values indicate drier-than-normal periods. Drought conditions exist when the PDI is at or lower than −2. The source of the monthly values used in this comparison was http://www.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html. The PDI monthly values for New Mexico Division 05, in which all the study sites lie (Fig. 1), from 1989 through to June 2002, corresponding to the months in which soils were collected, were used to correlate with soil PMN (Fig. 2). The PDI was −2.7 for the collections made in June 2002. From 1989 through to 2002, the highest PDI occurred in August 1992 (7.5) and the lowest in May

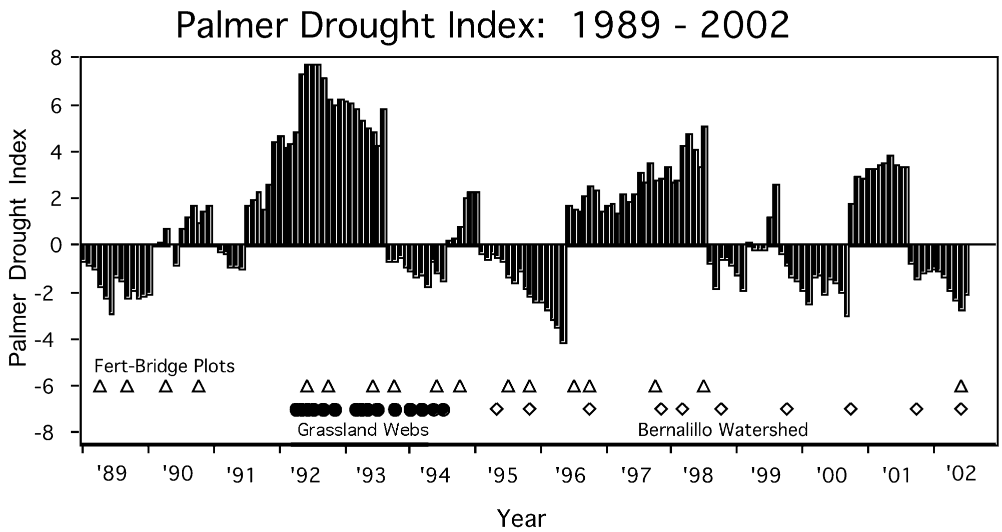

Fig. 2 Values for the Palmer Drought Index (PDI) for New Mexico Region 05 from 1989 through to 2002 and indication of the soil collection dates at the Sevilleta Fert-Bridge site (*open triangle*), Grassland Webs (*filled circle*), and the Bernalillo Watershed (*open diamond*)

1996 (−4.1; Fig. 2), but no soil collections were made during either of these periods.

Statistical analyses

The means of the measured PMN for each collection at the three sites (Fert-Bridges Plots, Bernalillo Watershed, and Grassland Webs) were correlated with the corresponding monthly PDI values. For the Grassland Webs, area-weighted means of microbial biomass C and total organic C were correlated with the corresponding PDI. Correlation analyses were performed on the paired data using StatView SE. Critical values for correlation coefficients were determined using n −2 degrees of freedom and assuming two independent variables. Unless otherwise indicated, we used a significance level of P <0.05 with "ns" used to indicate non-significant results.

Results

June 2002 soil collection

The PDI was −2.7 in June 2002, which was the most negative value for a month in which a soil was collected at all three grasslands. PMN was the second highest ever measured from the Fert-Bridge Plots (a collection in July 1989 had a higher mean value; Fig. 3) and the highest ever measured from the Bernalillo Watershed (Fig. 4). These results indicate that the regional-scale drought had a strong influence on increasing PMN.

Longer-term soil data and PDI relationship

Using the entire collection period from the Fert-Bridge Plots (15 collections from 1989 through to 2002), there was a significant negative correlation between PMN and the PDI (r =−0.533, P <0.05; Fig. 3), indicating higher potential soil fertility during drought and lower fertility during periods of higher moisture. The relationship was much stronger (P <0.01, r =−0.703) when a single collection (July 1995, lowest measured PMN) was omitted from the correlation. The relationship between soil fertility and PDI was not significant at the Bernalillo Watershed using the entire period of record (ten collections from 1995 through to 2002; Fig. 4), but there was a similar trend (negative correlation, r =−0.356). The relationship between soil fertility and PDI was highly significant (P <0.01, r =−0.723) using the extant data from the Grassland Webs (15 collections from 1992 through to 1994; Fig. 5).

Additional soil analyses for factors that may contribute to changes in PMN were available for collections made at the Grassland Webs. There was a significant positive correlation between PDI and microbial biomass C (r =0.593, P <0.05, n =16) and a negative trend between PDI and total organic C (r =−0.418, ns, n =16) at the Grassland Webs. Direct correlation between PMN and microbial biomass C was not significant (r =−0.306, ns, n =14) but showed a trend toward decreasing microbial biomass C

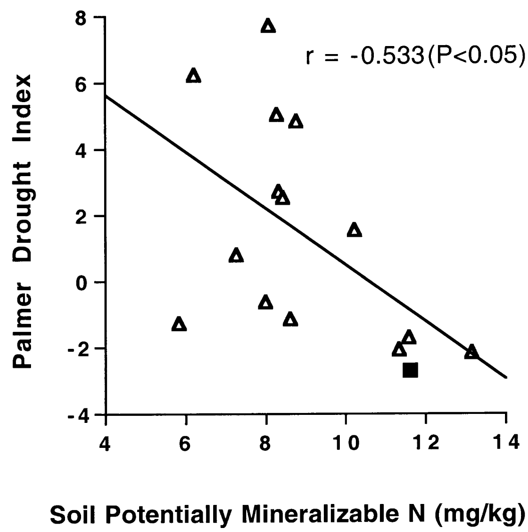

Fig. 3 Relationship between the Palmer Drought Index (PDI) and soil potentially mineralizable N for soil collections from the Sevilleta Fert-Bridge site in 2002 (*filled square*) and collections from 1989 through to 1998. *Line* indicates best-fit with correlation coefficient and probability level displayed *upper right*

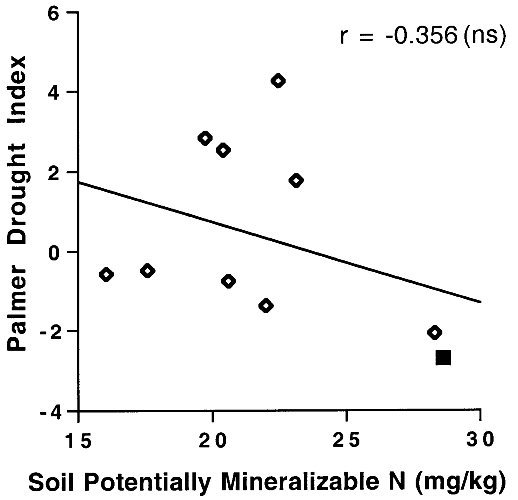

Fig. 4 Relationship between the Palmer Drought Index (PDI) and soil potentially mineralizable N for soil collections from the Bernalillo Watershed in 2002 (*filled square*) and collections from 1995 through to 2001. *Line* indicates best-fit with correlation coefficient and probability level displayed *upper right*

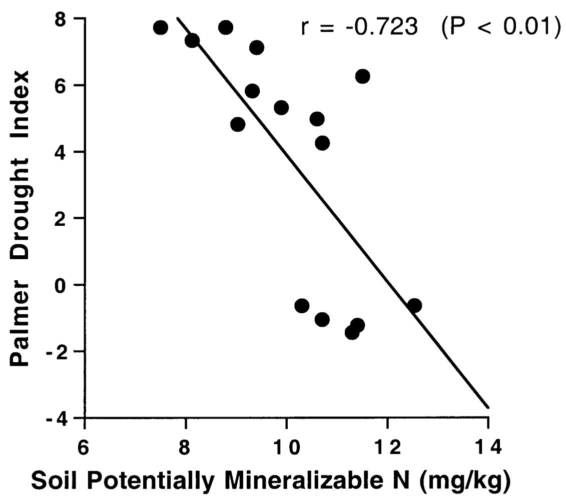

Fig. 5 Relationship between the Palmer Drought Index (PDI) and soil potentially mineralizable N for soil collections from the Sevilleta Grassland Webs from 1992 through to 1994. *Line* indicates best-fit with correlation coefficient and probability level displayed *upper right*

with increasing PMN. PMN and total organic C were positively correlated, although the trend was not significant (r =0.302, ns, n =14). Thus, drought was associated with increasing PMN, increasing total organic C, and decreasing microbial biomass C at the Grassland Webs.

Discussion

Our hypothesis was supported by statistical analysis of two of the three datasets and by the collections from two sites during the recent drought. Data from the Sevilleta NWR Fert-Bridge plots and the Grassland Webs showed statistically significant, negative correlations between PMN and PDI. This indicates that periods of extended drought correspond with periods of greatest potential soil fertility and wetter-than-average periods have lower potential soil fertility. The soil collections in June 2002 occurred near the peak of the drought period (PDI of −2.7), which was the most negative PDI of all collections at the Sevilleta and the Bernalillo Watershed. In these soils, PMN was near the highest of all collections at the Sevilleta and was the highest at the Bernalillo Watershed. These results support a strong relationship between regional-scale drought and higher potential soil fertility in semiarid grasslands.

Inherent in all the soil collections is the variation associated with the effects of multiple factors that influence PMN and function at smaller spatial scales (i.e., between plot, within site variability) or temporal scales within the monthly averaged PDI. Such variables may include the effects of diurnal and weekly temperature fluctuations, including heating and drying in the summer and freeze-thaw in the winter (DeLuca et al. 1992). There is large variation in local-scale precipitation frequency, amount, and duration. Within all of these sites, there is local variation in soil texture and depth of soil horizons (Treadwell 1996; Buxbaum 2003), and there may be variations due to grass species-level influence on soil fertility that were not controlled at time of collection. Even with the multitude of factors that could contribute to variation in PMN, the correlation of the regional PDI with PMN was significant in two of the three comparisons in this study, both studies on the Sevilleta, with evidence of the general relationship at the Bernalillo Watershed. It is possible that variation in PMN may correlate with larger-scale phenomenon such as the El Niño-Southern Oscillation Index, but that was not investigated by this effort.

The Bernalillo Watershed differs from the Sevilleta in a number of ways. The Bernalillo Watershed lies on the northern end of the New Mexico PDI Region 05 whereas the Sevilleta is more centrally located (Fig. 1). The Bernalillo Watershed has undergone much more recent and intensive management than the Sevilleta, which has not been subjected to anthropogenic disturbance since the removal of livestock in 1979. Extensive erosion and loss of topsoil at the Bernalillo Watershed during the 1950s led to rehabilitation efforts that included construction of erosion control dams at frequent intervals in all drainages, contour furrowing, the digging of small water catchments or pits (soil "chipping") throughout the watershed, and seeding of grasses followed by rodent control. Soil collections to a 20-cm depth included portions of the clay-rich argillic horizon, contributing to the higher clay content of Bernalillo Watershed soils relative to that of soils from the Sevilleta [a clay loam at the Bernalillo Watershed (White and Loftin 2000) and a sandy loam at the Sevilleta (Kieft et al. 1998)]. Current management efforts to continue restoration of the Bernalillo Watershed include the use of prescribed fire for woody-shrub control. The control plots are surrounded by an area treated with two prescribed fires since 1995, and ash from the burned areas was trapped by vegetation in the control plots. The combination of all these treatment variables along with the inherent short-term contributors to variation may have masked or dampened the effects of regional-scale drought at this site. Nonetheless, the overall relationship was evident in the negative correlation coefficient and the June 2002 drought collection having the highest potential soil fertility of all collections.

Increases in PMN can result from contributions to the readily mineralizable organic N pool by recently killed microbial biomass and fine roots, in addition to other factors. Mortality of microbial biomass and fine roots should result in a small increase in the soil total organic C pool, although it may not be detectable given the variability in soil total organic C. Thus, PMN should be negatively correlated with live microbial biomass C, which decreases during drought, and positively correlated with soil total organic C, which increases during drought. Similarly, PDI should be negatively correlated with soil total organic C and positively correlated with microbial biomass C given the assumptions stated above. The results show that the strongest relationship occurred between the PDI and the microbial biomass C and total organic C, but the direction of the relationships were shown by the correlations between PMN and these soil analyses.

The Sevilleta Web collections (Kieft et al. 1998) began during a much wetter-than-normal period, continued through a drying period, and ended during a moderate drought period (Fig. 2). The results from this study show two important relationships. First, the highest PMN (12.54 mg N kg^{-1}) occurred in October 1993 with the first negative PDI value indicating the onset of a significant regional-scale drought. This may indicate that the magnitude of change in soil fertility is greatest at the time of the first extended drying period than during later periods. Second, during the period of positive but declining PDI values (late 1992 and early 1993), PMN increased in some collections although the PDI remained positive. Increases in soil fertility during decreasing PDI periods probably reflect the influence of local-scale and shorter-term phenomena, including freeze-thaw and surface soil drying and rewetting. Thus, these results indicate that increases in soil fertility are not entirely dependent upon extended drought, but can occur during shorter periods of changing weather or moderate drought.

The suspected patterns of soil fertility and their variation with weather fluctuations (Fisher et al. 1987) were demonstrated in the field over two time periods: one spanning a 13-year period that included three moderate-to-strong drought periods, and the second covering a 3-year period that changed from a strongly wetter-than-normal period to a moderate drought. The potential for N co-limitation of ANPP in semiarid grasslands is thus lowest following drought periods and increases during extended wet periods. Plants that can survive periods of extended drought and that can respond rapidly to rewetting periods will have higher N resources available for growth and reproduction. Which plant species take advantage of this pulse of higher fertility will depend in part upon the timing of the drought and of the subsequent duration of rewetting.

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