ABSTRACT

THE EFFECTS OF MICROARTHROPODS ON NITROGEN
AVAILABLITY WITHIN THE RHIZOSPHERE
OF ERIONEUROM PULCHELLUM
IN A NORTHERN CHIHUAHUAN DESERT ECOSYSTEM
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Doctor of Philosophy in Soil Ecology
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Las Cruces, New Mexico, 1989
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Recent studies suggest that rhizosphere soil microarthropods may have a major role in determining soil nitrogen availablity. Desert soil microarthropods are consumers of soil bacteria, fungi, and nematodes, thus they accelerate mineralization processes by causing turnover in immobilized nitrogen. Therefore, I hypothesized that changing densities of soil microarthropods would result in changes in nitrogen availability. In order to test this hypothesis, Erioneuron pulchellum rhizosphere soil samples were taken monthly from control plots, plots irrigated with 6 mm/ wk., plots soaked with chlordane (to remove

microarthropods), and plots treated with chlordane that were irrigated with 6 mm/ wk. These samples were analyzed for available inorganic nitrogen (NO_3 and NH_4), gravimetric soil moisture, plant shoot and root biomass, plant shoot and root total nitrogen, plant growth, microarthropod and nematode densities. Microarthropods and nematodes responded to water only after a long dry period in April 1987. Water seemed to deplete nitrogen from soils, enhancing turnover and rapid nitrogen mineralization in the first year. This resulted in nitrogen depletion in the second year. Nematodes increased density in response to elimination of microarthropods only during the unusual wet winter-spring 1986-87, when soil water potential was above -0.4 MPa most of the time. Biocide treatment used to eliminate microarthropods, led to an increase in soil available nitrogen, but a decrease in plant root nitrogen. There was no significant difference in plant shoot biomass among treatments, and root biomass was higher only in the irrigated plots with microarthopods. There was no correlation between microarthropods and plant shoot or root total nitrogen among treatments. Over all treatments and dates root biomass was very low, averaging only 0.23 g per kg dry soil. These data suggest that in the live rhizosphere of Erioneuron pulchellum, if water is available, then soil biota and nitrogen dynamics might be regulated by organic matter. Also, there were no significant differences in nitrogen mineralization potentials of soils from the various treatments. These data indicate that soil microarthropods are not essential for nitrogen mineralization or other aspects of the nitrogen cycle in the rhizosphere of fluff grass.

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INTRODUCTION

Desert soils are characterized by low concentrations of nitrogen, phosphorus, and organic matter (West 1981). Arid and semi-arid ecosystems are primarily water limited (Noy-Meir 1973); however, several studies have suggested that nutrients may be limiting production when water is not limiting (Cline and Rickard 1973, Ludwig and Flavill 1979, Floret et al. 1982, Penning de Vries and Djiteye 1982, Gutierrez and Whitford 1987b, Fisher et al. 1988). According to West and Skujins (1978) nitrogen is the most cited nutrient limiting primary productivity.

In nutrient cycles, the mineralization process is generally represented as the flow from a litter or soil organic matter component to an available soil nutrients component (Gosz 1981), or, additionally, through a soil microbe component (Mellilo 1981). Soil microfauna are important in nutrient cycling, primarily through facilitation of the mineralization of inorganic nutrients from their immobilized form in soil organic matter (Alexander 1977, Parker et al. 1984).

The functional roles of organisms have been emphasized by many ecosystem researchers (Chew 1974, Mattson and Addy 1975, Crossley 1987, Santos et al. 1981, Parker et al. 1984, Seastedt 1984, Coleman et al. 1984, Coleman 1985, Anderson et al. 1985, Ingham et al. 1985, Ingham et al. 1986a,b, Hunt et al. 1987, Zak and Whitford 1988). When interactions between species are considered in terms of functional roles, associations frequently appear to be of a synergistic rather than antagonistic nature.

Kitchell et al. (1979) suggested that terrestrial environmental consumer populations, (i.e., soil microarthropods) may be important in nutrient cycles,

affecting the equilibrium between immobilization and mineralization of plant nutrients. Anderson et al. (1981), Baath et al. (1981), and Coleman et al. (1984) reported that grazing of the rhizosphere microflora by nematodes and microarthropods increased mineralization of nitrogen and phosphorus in microcosms, even when bacterial populations were reduced. In the Chihuahuan Desert microarthropods affect rates of decomposition and mineralization (Santos et al. 1981, Whitford et al. 1982, Parker et al. 1984) by acting as regulators of microbial populations directly by dispersing microorganisms and grazing on fungi and/or indirectly by preying on microbivorous nematodes.

Skujins (1981) showed that the distribution of nitrogen in arid soils is directly related to the accumulation of litter and organic matter. When two consecutive wet seasons occur, Parker et al. (1984) found that primary production of shrubs and annuals was reduced in the Chihuahuan Desert. They proposed that in a wet year nitrogen from decomposing roots of the annual species Lepidium lasiocarpum was immobilized by fungi, thereby decreasing nitrogen availability to plants during the next wet year. Their data suggest that fungal grazing by nematodes and microarthropods enhanced the rate of mineralization of immobilized nitrogen. In the Chihuahuan Desert decomposition and nitrogen mineralization rates of roots and surface litter transfered belowground is regulated by trophic interactions between soil biota (Zak and Whitford 1988). In this system microarthropods, the top trophic group, prey on nematodes and also graze directly on bacteria and fungi, while nematodes feed on protozoans, bacteria, and fungi.

In the northern Chihuahuan Desert the response of microarthropods to water amendments is highly significant with an increase in population biomass

(Whitford et al. 1981, Whitford et al. 1986, Mackay et al. 1986). It has also been indicated that microarthropod population densities vary seasonally (Santos and Whitford 1981, Santos et al. 1981, Santos et al. 1984, Wallwork et al. 1984, Wallwork et al. 1985, Silva et al. 1985, Wallwork et al. 1986) achieving the highest population density during the hot and wet summer season from June to October.

In order to understand relationships and dynamics within actual communities, field experiments, give more realistic results than laboratory experiments (Diamond 1986). Field experiments, in contrast to laboratory experiments, are conducted outdoors and operate on natural rather than synthetic communities. A field experiment also incorporates the natural spatial heterogeneity which cannot be achieved in a laboratory experiment. This benefit comes at the cost of losses in regulation of independent variables and site matching. In a field experiment the researcher can manipulate one or few independent variables and also effectively select initial values of other independent variables through site selection, but can not hold them constant or regulate their trajectories, as can be done in a laboratory experiment.

Ingham et al. (1985) used a microcosm experiment to demonstrate that microbivorous nematodes have a potentially important role in ecosystems. However, nematodes are not the only organisms that regulate ecosystem nutrient cycling and primary productivity (Anderson et al. 1981, Coleman et al. 1983, Seastedt 1984). Although the biological processes observed in microcosm experiments also may occur in the field, in a native soil these biological processes may be mediated by other physical and/or biological interactions. Indeed the main disadvantage of a microcosm experiment is the difficulty of extrapolating results to

the field. To understand the functioning of an ecosystem it is important to consider all the interactions occurring within all biological processes. Based on a microcosm study, Ingham et al. (1985) suggested that nematodes regulate grassland primary productivity. However, field studies conducted by Santos et al. (1981), Whitford (1981), Whitford et al. (1982), and Parker et al. (1984) suggested that primary productivity within arid and semi-arid ecosystems may be regulated by predatory mites grazing upon nematodes, fungi, and bacteria, which ultimately regulates fluxes of nitrogen.

According to Whitford et al. (1986) nitrogen mineralization is water-pulsed; hence, it is more sporadic than is the mass loss from dead plant material. Whitford et al. (1986) showed that plants which received supplemented water had lower nitrogen present in leaves, stems and buds than plants which received no water. These results are inherent to the concept that in desert ecosystems nitrogen available to plant production is primarily generated through internal cycling, rather than through fixation (both free living and symbiotic) or atmospheric deposition. However, more research needs to be done on these potentially important inputs of nitrogen to desert ecosystems.

In the Chihuahuan Desert there is some evidence that water is not the only factor limiting primary production, but that nitrogen may also be an important limiting factor (Ludwig and Flavill 1979, Gutierrez and Whitford 1987a, Fisher et al. 1988). Fisher et al. (1988) found that creosotebush production was limited by both nitrogen availability and soil moisture. Fisher et al. (1988) also found that temporal rainfall patterns were as important as total rainfall amounts, confirming findings by Ludwig and Flavill (1979) that small, frequent rainfall events were

more effective in promoting creosotebush growth than large, infrequent rainfall events.

Ettershank et al. (1978) found that low nitrogen availability decreased biomass production of the shrub Larrea tridentata and the grass Erioneuron pulchellum during periods of adequate soil moisture. Fisher et al. (1988) studied the effects of supplemental water on Larrea tridentata growth, and Gutierrez and Whitford (1987a) on annual plant growth, and their results also showed that the availability of soil nitrogen can be the most limiting factor controlling plant growth during periods of suitable soil moisture.

I conducted this study in an area where Larrea tridentata, the dominant shrub, has a widely scattered spatial distribution, with an herb-grass layer predominated by clumps of the perennial grass Erioneuron pulchellum (H.B.K.) Takeoka (fluff grass). Erioneuron pulchellum is a tufted C4 perennial grass, usually not more than 15 cm high [description adapted from Hitchcock (1971) and Gould (1975)]. Culms are slender, scabrous or puberulent, consisting of one long internode, bearing at the top a fascicle of narrow leaves. The fascicle eventually bends over to the ground, taking root and producing the inflorescence. Sheaths often have a tuft of long hairs at the base. The flowering period is from June to November. Erioneuron pulchellum occurs on dry rocky slopes and desert flats of Utah, Nevada, Texas, Arizona, New Mexico and Northern Mexico. The small size of Erioneuron pulchellum makes easy to handle, facilitating growth measures. It also has a well defined shallow root system (most of the roots are within 20 cm depth, personal observation). The root system remains alive throughout the year, maintaining ongoing rhizosphere interactions. The

characteristics of Erioneuron pulchellum make it an ideal species for studying rhizosphere relations and biomass dynamics.

Ettershank et al. (1978) demonstrated that Erioneuron pulchellum (fluff grass) is nitrogen-limited in the northern Chihuahuan Desert. They observed that nitrogen added to fluff grass produced a highly significant increasing in plant biomass. They suggested that the shallow-rooted perennial grass and probably the soil microflora and others plant species extract a portion of the nitrogen added as it moves down through the soil horizon.

In summary, microcosm studies (Coleman et al. 1984, Ingham et al. 1985, Ingham et al. 1986a,b, Hunt et al. 1987) have suggested that soil biota are important in nitrogen mineralization, and field studies conducted within the northern Chihuahuan Desert have shown that microarthropods have no effect on decomposition of surface litter material (Silva et al. 1985, Mackay et al. 1986, Whitford et al. 1986, and Zak and Whitford 1988). However, microarthropods are very important in the decomposition and nitrogen mineralization of buried litter and roots (Santos and Whitford 1981, Santos et al. 1981, Elkins and Whitford 1982, Whitford et al. 1982, and Parker et al. 1984, Zak and Whitford 1988, Whitford et al. 1988a). These studies suggest that microarthropods should be important in affecting decomposition and nitrogen mineralization within a living rhizosphere system. Therefore, it can be hypothesized that elimination of microarthropods from a living rhizosphere system decrease nitrogen mineralization,and inorganic N, and thus, plant growth. Other studies have demonstrated that plant biomass increased with water supplement, and that if water is not limiting growth then nitrogen can become limiting (Gutierrez and Whitford 1987a, Fisher et al. 1988). Studies have also shown that supplemental

water increased microarthropod densities (Whitford et al. 1981, MacKay et al. 1986, Whitford et al. 1988b). Thus, I also hypothesized that water supplement would increase microarthropod densities and consequently enhance nitrogen mineralization and increase inorganic N in the rhizosphere, leading to increased above and belowground biomass of Erioneuron pulchellum.

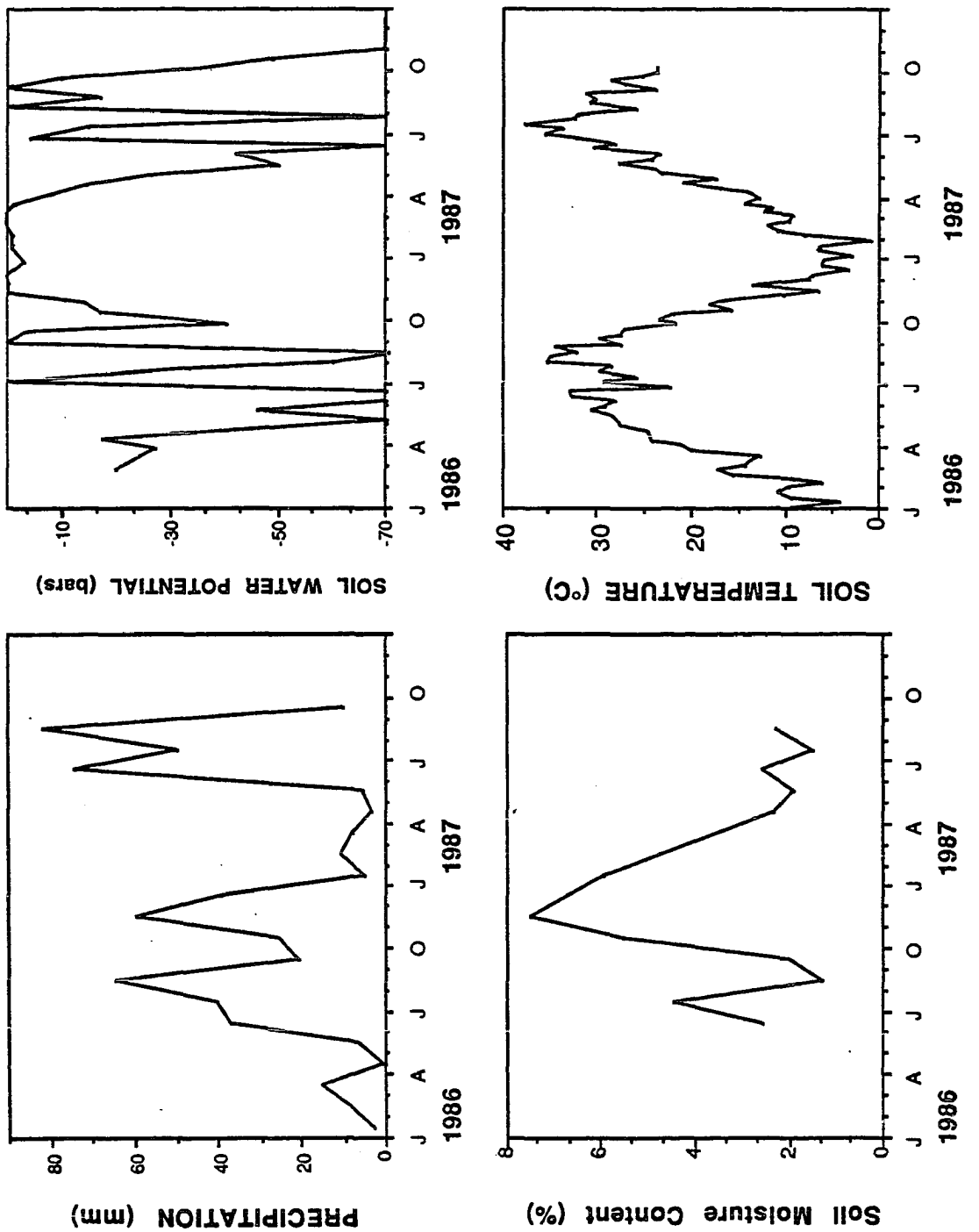
METHODS

Study Site

This study was conducted in the Jornada del Muerto Basin on the NSF Long-Term Ecological Research (LTER) site, located on the New Mexico State University College Ranch 40 km NNE of Las Cruces, Dona Ana County, New Mexico. The site is near the northern limits of the Chihuahuan Desert. The elevation of the site varies from 1200 to 2000 m. Summer maximum air temperatures reach 40°C while freezing temperatures have been recorded from October to mid-April (data from the Jornada Validation Site Weather Station). The study region has three well-defined seasons during the year: The hot and wet summer from July to October, the cool and dry winter from November to March, and the hot and dry spring from April to June. The 100-year mean annual precipitation is 211 mm (Houghton 1972), most of which is late summer rainfall from convectional storms. Climatic and soil environment conditions for the sampling period of June 1986 to August 1987 are shown in Figure 1.

The site lies on an alluvial piedmont (bajada) sloping from west to the east and north. The soils are Dona Ana series (Typic Haplargid, coarse loamy) (Wierenga et al. 1987). A caliche layer generally exists 0.8 to 1.0 m below the surface. The differentiation between soils and drainages produces distinct assemblages of vegetation (Whitford and Bryant 1979, Ludwig and Whitford 1981).

Figure 1. Environmental and climatic data for the time the study was conducted. a) Precipitation data from a rain gauge located 100 m from the study site. b) Mean average gravimetric soil moisture (15 cm depth) at each sample time from the control plots. c) Soil water potential (15 cm depth) from the Jornada-LTER transect located 1 km from the study area. d) Soil temperature (20 cm depth) from the Jornada-LTER weather station located 1 km from the study area.



The non-arroyo areas of the upper bajada where this study was conducted have an essentially monospecific shrub cover of creosotebush (Larrea tridentata) (Ludwig and Whitford 1981) and support a variety of annuals and the small perennial grass Erioneuron pulchellum (fluff grass) (H.B.K) Takeoka.

Experimental Design

I established twenty 6 x 6 m plots with a 3 m buffer between plots. Five plots each were randomly assigned to one of four treatments: (1) chlordane amendment (100ml AI (Active Ingredients) per 10,000 ml) to exclude microarthropods, (2) sprinkler irrigation (6 mm per week), (3) sprinkler irrigation (6 mm per week) plus chlordane amendment (100 ml AI (Active Ingredients) per 10,000 ml) and (4) no treatment. At approximately monthly intervals from May 1986 to August 1987 I took three randomly located subsamples from within each plot. Samples consisted of a fluff grass plant and a soil core 10 cm in diameter and 15 cm deep centered on each plant. This volume of soil contained 95% of the plant roots. This soil core volume is referred to as the rhizosphere throughout the remainder of this paper.

There was no sprinkler irrigation from November 1986 to March 1987 which was during the non-growing season of Erioneuron pulchelum.

Field Procedures

For each sample a plant was measured (two diameters and height) then clipped at ground level, collected in a paper bag and transported to the laboratory for chemical analysis. After a plant was collected, a rhizosphere soil sample was taken using a soil core (10 cm diameter, 15 cm depth). The soil sample was placed in a plastic bag, stored in a cooler and immediately transported to the laboratory.

Soil Analysis

For each soil sample, subsamples were taken for extraction of microarthropods and nematodes. Microarthropods were extracted in modified Tullgren funnels into water (Santos et al. 1978), then counted and identified to species (Krantz 1978). After microarthropod extraction the soil was sieved through a 2-mm screen mesh and roots were collected. On subsamples for nematode extraction, roots were carefully separated by hand, then nematodes were extracted by a modified sugar flotation technique (Freckman et al. 1977). Remaining soil was sieved through a 2-mm screen mesh, then roots were collected and added to roots collected from other subsamples. Soil subsamples were then taken for the following chemical analyses: nitrogen mineralization potential, soil total N, and inorganic N (NH_4-N and NO_3+NO_2-N).

Inorganic N

Inorganic N (NH_4 -N and NO_3 +NO_2 -N) was extracted by placing 10 g sub-sample of each soil sample in polyethylene bottles containing 100 ml of 2.0 Molar KCL + PMA (to prevent growth by bacteria and fungi) (Keeney and Nelson 1982). Sub-samples were shaken 30 times and filtered after setting overnight. NH_4 -N was measured in the extracts by an automated salicylate procedure (Wall and Gehrke 1975, Nelson 1983). NO_3 + NO_2 -N was measured using an automated cadmium reduction procedure (Henriksen and Selmer-Olsen 1970). Automated measurements were made on a Scientific Instruments Continuous Flow Analyzer.

Nitrogen Mineralization Potential

Net mineralizable N was estimated using a batch incubation procedure (Stanford and Smith 1972; Keeney 1982; Stanford 1982; Fisher et. al. 1987). Soil sub-samples (25 g) were incubated at 35 ^{o}C in 50-ml plastic vials covered with 0.0125 mm polyethylene film and sealed with rubber bands to reduce moisture loss. Moisture content was adjusted to 10% water content by weight at weekly intervals by injecting deionized water through a small hole in the polyethylene film using a syringe. Sub-samples were removed for inorganic N (NH_4 -N and NO_3 + NO_2 -N) determination following 2,4,8,and 12-week incubation periods. Inorganic N was extracted by placing 10 g of soil into polyethylene bottles containing 100 ml of 2.0 Molar KCL + PMA (to prevent growth by bacteria and fungi) (Keeney and Nelson, 1982). Samples were shaken 30 times, and let set for 24 hours, and then filtered. NH_4 -N was measured by an automated salicylate procedure (Wall and Gehrke 1975) an NO_3 + NO_2-N by an automated cadmium

reduction procedure (Henriksen and Selmer-Olsen 1970). Net N mineralization was calculated as the net change in N occurring from the beginning to the end of each incubation period

Soil Moisture

Gravimetric soil moisture was determined for all the samples used for inorganic N and nitrogen mineralization potential. Ten grams of well-mixed soil from each sample were oven-dried for 48 hours at 105 C, and reweighed. Weekly rainfall amounts were recorded from a rain gauge located less than 100 meters away from the study site. Soil temperature measurements were taken from the LTER Jornada site permanent weather station, located approximately 1 km from the study area. Soil water potential measurements were taken from 15 cm depth soil psychrometers located on the permanent LTER control transect (Wierenga et al. 1987) approximately 1 km from the study site.

Field Resin Bags

An ion exchange resin bag technique (Binkley 1984, Lajtha 1988) was used to determine N availability in the rhizosphere of Erioneuron pulchellum. A 50 cm^2 area of undyed nylon stocking material was sewn into a bag containing 10 g (wet weight) of either Dowex 1-X8 anion exchange resin or Dowex 50 W- X8 cation exchange resin, both 20-50 mesh. Anion resins were placed in three successive rinses of 0.5 M $NaHCO_3$, converting resins to the bicarbonate form. Cation resin bags, already in the H^+ form, were rinsed three successive times with dilute HCl. All bags were rinsed with deionized water and spun dry in a open-basket hand centrifuge before being taken to the field. Ten bags of anion and two

and two bags of cation exchange resin were placed in each plot (total of 20 plots), directly in the rhizosphere of a plant (12 Erioneuron pulchellum plants per plot) at approximately 10 cm depth. Bags were replaced every 12 weeks for 9 months. Bags were rinsed thoroughly in deionized water and spun dry upon collection from the field. Anion and cation bags were desorbed in 2.0 M KCl + PMA (to avoid bacterial and fungal growth). Samples were shaken 30 times, let set overnight, and filtered. The solution was analyzed for NH_4 -N using an automated salicylate procedure (Wall and Gehrke, 1975; Nelson 1983) and NO_3 + NO_2-N using an automated cadmium reduction procedure (Henriksen and Selmer-Olsen 1970). Standards containing anion or cation exchange resin bags were extracted the same as field exchange resin bags.

Plant Analysis

Biomass and Total Nitrogen

Roots were separated from the soil using a 2 mm sieve, picked up from debris with forceps and cleaned up by hand. Root and shoot material was oven-dried for 96 hours at 50^{0}C, weighed, and ground in a Wiley Mill for chemical analysis. The ground plant and root were prepared for nitrogen analysis by a micro Kjeldahl digestion using an aluminum block digestor (Keeney and Nelson 1982). Nitrogen analyses were performed on the digest using automated procedures (Keeney and Nelson 1982) on a Scientific Instruments Continuous Flow Analyzer.

Size-Biomass Relationships

Aboveground biomass estimates of plants were obtained at irregular spaced intervals, but size measurements (i.e., diameter and height) were made on each sample date. In order to predict biomass of plants for all sample dates, linear regressions were conducted with size characteristics (i.e., cover and volume) as independent variables and biomass (g dry weight) as dependent variable using SAS Proc GLM (SAS Institute, Incoporated 1985). A stepwise regression conducted with cover, Log(cover), cover^2, volume, Log(volume), and volume^2 as possible independent variables resulted in selection of the following regression equation ($R^2 = 0.9517$):

$$\text{Biomass (g)} = 0.122088 \times \text{Cover} - 0.000312 \times \text{Cover}^2$$

Growth

I permanently tagged 15 plants in each of the 20 plots and followed growth through the 1986 growing season. Measurements were taken in March, July, and September. Shoot biomass estimates were obtained from the regression equations given above. In order to remove initial size differences from plants selected for growth measurements, biomass estimates were converted to Relative Growth, calculated by the following equation:

$$\text{Relative Growth} = [\text{Biomass}_t - \text{Biomass}_0] / \text{Biomass}_0$$

where Biomass_t is Biomass at time t and Biomass_0 is initial biomass (time 0). Biomass was estimated by the regression equation described in the previous section.

Nitrogen Budgets

A whole plant system nitrogen budget was estimated for the plant growth data using information from sample dates. Regressions of shoot and root biomass versus plant size were made for each treatment (see Size-Biomass Relationships above and appendix B), and biomass was estimated for each growth measurement. These biomass estimates were multiplied by overall treatment means of shoot total nitrogen (C=7.615, CH=7.619, CHW=7.615, W=6.941 mg N g^{-1}dry weight) and root total nitrogen (C=5.812, CH=6.094, CHW=5.837, W-5.472 mg N g^{-1} dry weight) to obtain the absolute amount of nitrogen (mg per plant) within shoots and roots. Plot averages of soil inorganic nitrogen were taken from the field sample data for dates closest to the dates growth measurements were made. In this study rhizosphere core samples (10 cm diameter, 15 cm depth) had a volume of 1177 cm^{-3}. Assuming a typical soil bulk density of approximately 1 g cm^{-3}, soil rhizosphere volumes contained approximately 1.2 kg of soil. Soil inorganic nitrogen values (mg N kg^{-1} dry soil were multiplied by the (1.2 kg) (rhizosphere volume)$^{-1}$ to obtain estimates of the absolute amount of soil rhizosphere inorganic nitrogen [mg N (rhizosphere volume)$^{-1}$]. Total rhizosphere nitrogen was calculated as the sum of soil inorganic and root nitrogen. Plant whole system nitrogen was calculated as the sum of soil inorganic, root and shoot nitrogen. Net changes in system nitrogen between dates were calculated as the difference from March.

Statistical Analysis

All variables with subsamples within plots were averaged to give plot mean values for use in statistical analysis. All variables were log-transformed to normalize data prior to analysis. Data consisted of repeated measures on permanent plots through time, thus split plot in time, full factorial analysis of variance models were used to test for differences between treatments and sample dates (PROC GLM, SAS Institute, Inc., 85). Main factors and factor levels included in the analysis were CHLORDANE (plots with and without chlordane treatment to remove microarthropods) and WATER (plots with and without water supplement). Planned means comparisons of variables with significant ANOVA's were made using least-square- means pairwise comparisons. The ANOVA tables are in Appendix A.

RESULTS

Soil Biota

Chlordane-treated plots consistently had lower microarthropod densities than untreated plots (Tables 1,2,3,4). Overall , water had a significant effect on soil moisture ($p < 0.05$; Appendix Table A20) and on total microarthropods ($p < 0.05$; Appendix Table A1). However, water treatment effects were not constant through time; microarthropods seem to respond to water supplement only after a dry period, such as August 1986 and April 1987. Also, Table 15 shows higher soil moisture on watered plots for the same sample dates. Control plots had higher microarthropod densities after rainfall events in October and November 1986. Mites of the order Prostigmata seem to follow the same pattern (Table 2), increasing in density in response to water supplement in August 1986 and April 1987, after a dry period. In control plots higher densities followed a rainfall event at the beginning and end of the growing season. Mites of the order Cryptostigmata responded to water supplement with increased densities in August 1986, and January and April 1987. In control plots higher densities were found in July and October 1986, and June 1987 after rainfall events (Table 3). Densities of mesostigmatid mites were also related to water supplement, increasing in densities after a dry period, but only in the second year in April 1987 (Table 4). In control plots mesostigmatid mites occurred at higher densities only in the first year after a rainfall event in June 1986. Densities of mites of the order Astigmata were very low in the rhizosphere of fluff grass (Table 5) with no clear treatment effects over all sampling dates.

Table 1. Comparisons of mean total microarthropod densities between treatments by sampling date.

Total Microarthropod Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	50.16 ^{a}	4.29 ^{b}	8.51 ^{b}	45.19 ^{a}
JUNE	121.16 ^{a}	0.82 ^{c}	4.39 ^{b}	70.22 ^{a}
JUNE	21.97 ^{a}	1.51 ^{b}	2.18 ^{b}	23.50 ^{a}
JULY	84.79 ^{a}	1.65 ^{c}	8.55 ^{b}	63.88 ^{a}
AUGUST	20.79 ^{b}	1.21 ^{d}	3.39 ^{c}	50.99 ^{a}
SEPTEMBER	48.13 ^{a}	0.85 ^{c}	3.92 ^{b}	30.40 ^{a}
OCTOBER	56.35 ^{a}	7.16 ^{c}	8.89 ^{c}	27.68 ^{b}
NOVEMBER	28.44 ^{a}	2.20 ^{c}	3.32 ^{c}	12.56 ^{b}
JANUARY - 1987	56.94 ^{a}	3.12 ^{b}	4.96 ^{b}	67.47 ^{a}
APRIL	57.48 ^{b}	0.00 ^{c}	0.00 ^{c}	206.09 ^{a}
MAY	28.85 ^{a}	1.03 ^{b}	0.90 ^{b}	38.92 ^{a}
JUNE	82.19 ^{a}	1.15 ^{b}	2.56 ^{b}	60.02 ^{a}
JULY	12.01 ^{a}	2.83 ^{b}	0.87 ^{b}	21.78 ^{a}
AUGUST	15.29 ^{a}	1.62 ^{c}	5.40 ^{b}	24.68 ^{a}

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 2. Comparisons of mean densities of mites of the order Prostigmata between treatments by sampling date.

Order Prostigmata Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	39.78 ^{a}	3.43 ^{b}	7.70 ^{b}	36.95 ^{a}
JUNE	82.38 ^{a}	0.48 ^{c}	2.94 ^{c}	43.50 ^{b}
JUNE	14.71 ^{a}	0.96 ^{a}	1.73 ^{a}	15.34 ^{a}
JULY	51.89 ^{a}	0.88 ^{c}	6.57 ^{c}	34.30 ^{b}
AUGUST	17.74 ^{b}	1.21 ^{c}	3.39 ^{bc}	35.65 ^{a}
SEPTEMBER	37.25 ^{a}	0.62 ^{b}	3.26 ^{b}	23.53 ^{a}
OCTOBER	36.66 ^{a}	4.12 ^{b}	6.84 ^{b}	14.38 ^{b}
NOVEMBER	18.52 ^{a}	1.97 ^{b}	2.57 ^{b}	6.31 ^{ab}
JANUARY - 1987	41.49 ^{a}	2.46 ^{b}	4.37 ^{b}	36.40 ^{a}
APRIL	47.42 ^{b}	0.00 ^{c}	0.00 ^{c}	181.59 ^{a}
MAY	23.10 ^{a}	0.84 ^{b}	0.84 ^{b}	30.03 ^{a}
JUNE	67.78 ^{a}	1.07 ^{b}	2.42 ^{b}	54.50 ^{a}
JULY	10.74 ^{ab}	2.83 ^{b}	0.74 ^{b}	19.46 ^{a}
AUGUST	13.73 ^{ab}	1.62 ^{b}	5.40 ^{ab}	20.79 ^{a}

* C= control, CH= chlordane, CHW=chlordane + water, W=water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 3. Comparisons of mean densities of mites of the order Cryptostigmata between treatments by sampling date.

Order Cryptostigmata Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	9.05 ^{a}	0.76 ^{b}	0.65 ^{b}	7.97 ^{a}
JUNE	24.97 ^{a}	0.34 ^{c}	1.35 ^{c}	14.60 ^{b}
JUNE	5.81 ^{a}	0.30 ^{b}	0.45 ^{b}	6.49 ^{a}
JULY	14.07 ^{b}	0.34 ^{c}	1.75 ^{c}	19.29 ^{a}
AUGUST	1.99 ^{b}	0.00 ^{b}	0.00 ^{b}	11.34 ^{a}
SEPTEMBER	10.16 ^{a}	0.14 ^{b}	0.22 ^{b}	6.74 ^{a}
OCTOBER	16.20 ^{a}	2.12 ^{c}	1.42 ^{c}	11.53 ^{b}
NOVEMBER	7.93 ^{a}	0.23 ^{c}	0.57 ^{bc}	4.47 ^{ab}
JANUARY - 1987	10.30 ^{b}	0.08 ^{c}	0.59 ^{c}	26.96 ^{a}
APRIL	5.77 ^{b}	0.00 ^{c}	0.00 ^{c}	13.62 ^{a}
MAY	4.26 ^{a}	0.05 ^{b}	0.00 ^{b}	6.43 ^{a}
JUNE	9.59 ^{a}	0.00 ^{c}	0.00 ^{c}	4.14 ^{b}
JULY	0.90 ^{a}	0.00 ^{a}	0.13 ^{a}	2.12 ^{a}
AUGUST	1.50 ^{a}	0.00 ^{a}	0.00 ^{a}	2.88 ^{a}

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 4. Comparisons of mean densities of mites of the order Mesostigmata between treatments by sampling date.

Order Mesostigmata Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	1.33 a	0.00 a	0.00 a	0.22 a
JUNE	6.42 a	0.00 c	0.00 c	2.62 b
JUNE	1.35 a	0.17 a	0.00 a	0.14 a
JULY	2.98 a	0.23 b	0.23 b	3.05 a
AUGUST	0.94 ab	0.00 b	0.00 b	2.72 a
SEPTEMBER	0.52 a	0.00 a	0.44 a	0.00 a
OCTOBER	2.09 a	0.30 a	0.00 a	0.46 a
NOVEMBER	1.55 a	0.00 a	0.18 a	0.88 a
JANUARY - 1987	3.92 a	0.22 b	0.00 b	3.50 a
APRIL	3.62 b	0.00 c	0.00 c	10.43 a
MAY	1.26 a	0.13 a	0.00 a	2.15 a
JUNE	3.48 a	0.08 b	0.14 b	1.34 ab
JULY	0.24 a	0.00 a	0.00 a	0.20 a
AUGUST	0.07 a	0.00 a	0.00 a	0.10 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 5. Comparisons of mean densities of mites of the order Astigmata between treatments by sampling date.

Order Astigmata Densities kg^{-1} dry soil				
	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	0.00 a	0.00 a	0.00 a	0.00 a
JUNE	0.37 a	0.00 b	0.00 b	0.00 b
JUNE	0.09 a	0.09 a	0.00 a	1.14 a
JULY	0.00 a	0.00 a	0.00 a	0.00 a
AUGUST	0.00 a	0.00 a	0.00 a	0.00 a
SEPTEMBER	0.19 a	0.08 a	0.00 a	0.14 a
OCTOBER	0.00 a	0.00 a	0.04 a	0.00 a
NOVEMBER	0.00 a	0.00 a	0.00 a	0.00 a
JANUARY - 1987	0.00 a	0.00 a	0.00 a	0.00 a
APRIL	0.00 a	0.00 a	0.00 a	0.00 a
MAY	0.00 a	0.00 a	0.00 a	0.05 a
JUNE	0.90 a	0.00 b	0.00 b	0.00 b
JULY	0.00 a	0.00 a	0.00 a	0.00 a
AUGUST	0.00 a	0.00 a	0.00 a	0.00 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Order Collembola did not show a consistent pattern throughout the sampling time (Table 6); the only significant increase in densities occurred in control plots in July 1986 after a small rainfall event (Figure 1). Densities of other microarthropod taxonomic groups, such as diplurans and psocopterans, are very low in the Chihuahuan Desert and these arthropods appeared to increase in density in response to a rainfall events rather than weekly water supplements (Table 7).

Trophic groups such as grazers, omnivores and predators exhibited increased densities in response to a water supplement after a dry period in April 1987 (Tables 8, 9, and 10, respectively). Omnivores had higher densities in the water plots at this time than did any other trophic group. In control plots grazers and predators occurred at higher densities in June 1986 and 1987. The remaining microarthropods were classified as an unknown trophic group and not analyzed further.

Nematode densities increased in response to water supplement at all sampling dates during the 1987 growing season, except for July. (Table 11). There were greater nematode densities in chlordane treated plots in November 1986 and January 1987. However no patterns were seen during the 1987 growing season.

Table 6. Comparisons of mean densities of Collembola between treatments by sampling date.

Order Collembola Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	0.00 a	0.05 a	0.16 a	0.00 a
JUNE	4.40 b	0.00 c	0.10 c	7.46 a
JUNE	0.00 a	0.00 a	0.00 a	1.14 a
JULY	13.17 a	0.00 c	0.00 c	5.89 b
AUGUST	0.00 a	0.00 a	0.00 a	1.18 a
SEPTEMBER	0.00 a	0.00 a	0.00 a	0.00 a
OCTOBER	0.56 a	0.62 a	0.59 a	1.11 a
NOVEMBER	0.44 a	0.00 a	0.00 a	0.89 a
JANUARY - 1987	1.23 a	0.36 a	0.00 a	0.60 a
APRIL	0.18 a	0.00 a	0.00 a	0.21 a
MAY	0.12 a	0.00 a	0.00 a	0.05 a
JUNE	0.00 a	0.00 a	0.00 a	0.05 a
JULY	0.13 a	0.00 a	0.00 a	0.00 a
AUGUST	0.00 b	0.00 a	0.00 a	0.62 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 7. Comparisons of mean densities of other microarthropod taxonomic groups between treatments by sampling date.

Other Microarthropod Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	0.00 [a]	0.06 [a]	0.00 [a]	0.05 [a]
JUNE	2.62 [a]	0.00 [c]	0.00 [c]	2.04 [b]
JUNE	0.00 [b]	0.00 [b]	0.00 [b]	0.39 [a]
JULY	2.68 [a]	0.20 [c]	0.00 [c]	1.35 [b]
AUGUST	0.13 [a]	0.00 [a]	0.00 [a]	0.10 [a]
SEPTEMBER	0.00 [a]	0.00 [a]	0.00 [a]	0.00 [a]
OCTOBER	0.84 [a]	0.00 [b]	0.00 [b]	0.20 [b]
NOVEMBER	0.00 [a]	0.00 [a]	0.00 [a]	0.00 [a]
JANUARY - 1987	0.00 [a]	0.00 [a]	0.00 [a]	0.00 [a]
APRIL	0.49 [a]	0.00 [b]	0.00 [b]	0.24 [ab]
MAY	0.11 [a]	0.00 [a]	0.06 [a]	0.21 [a]
JUNE	0.45 [a]	0.00 [b]	0.00 [b]	0.00 [b]
JULY	0.00 [a]	0.00 [a]	0.00 [a]	0.00 [a]
AUGUST	0.00 [a]	0.00 [a]	0.09 [a]	0.30 [a]

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 8. Comparisons of mean densities of the microarthropod grazer trophic group between treatments by sampling date.

Microarthropod Grazer Trophic Group Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	17.20 a	0.79 c	2.90 b	16.43 a
JUNE	36.23 a	0.12 d	2.29 c	18.09 b
JUNE	10.01 a	0.00 b	0.67 b	6.48 a
JULY	22.18 a	0.21 c	3.38 b	17.45 a
AUGUST	4.93 b	0.70 d	1.99 c	12.93 a
SEPTEMBER	11.56 a	0.23 c	0.37 c	6.78 b
OCTOBER	12.69 a	0.19 d	1.45 c	6.18 b
NOVEMBER	10.28 a	0.28 c	0.00 c	4.75 b
JANUARY - 1987	20.23 a	1.09 b	1.32 b	21.83 a
APRIL	22.56 b	0.00 c	0.00 c	71.75 a
MAY	10.02 b	0.53 c	0.14 c	17.72 a
JUNE	34.39 a	0.06 b	0.38 b	29.68 a
JULY	2.22 b	0.00 c	0.00 c	5.93 a
AUGUST	3.68 a	0.20 b	0.10 b	6.25 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 9. Comparisons of mean densities of the microarthropod omnivore trophic group between treatments by sampling date.

Microarthropod Omnivore Trophic Group Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	17.00 a	1.39 b	1.16 b	11.60 a
JUNE	21.74 a	0.20 c	0.20 c	10.57 b
JUNE	0.87 ab	0.17 ab	0.00 b	1.63 a
JULY	22.36 a	0.25 b	1.83 b	14.02 a
AUGUST	7.97 a	0.51 b	0.84 b	8.80 a
SEPTEMBER	13.19 a	0.21 c	2.27 b	8.32 a
OCTOBER	8.86 a	0.00 d	1.18 c	2.84 b
NOVEMBER	8.38 a	0.00 c	0.38 c	1.67 b
JANUARY - 1987	16.64 a	0.33 b	0.09 b	19.09 a
APRIL	23.77 b	0.00 c	0.00 c	102.84 a
MAY	9.32 a	0.17 b	0.05 b	10.65 a
JUNE	21.36 a	0.50 b	1.13 b	19.53 a
JULY	4.94 b	1.02 c	0.39 c	9.34 a
AUGUST	6.15 a	0.46 b	0.97 b	9.84 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 10. Comparisons of mean densities of the microarthropod predator trophic group between treatments by sampling date.

Microarthropod Predator Trophic Group Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	4.31 a	0.69 b	0.62 b	4.36 a
JUNE	20.14 a	0.28 c	0.41 c	8.31 b
JUNE	5.36 a	0.61 c	0.07 c	1.93 b
JULY	14.32 a	0.23 c	0.78 c	4.06 b
AUGUST	4.55 a	0.00 b	0.15 b	7.03 a
SEPTEMBER	1.85 a	0.00 c	0.61 bc	1.02 ab
OCTOBER	6.94 a	0.63 c	0.22 c	2.10 b
NOVEMBER	4.18 a	0.10 b	0.18 b	0.99 b
JANUARY - 1987	14.32 a	0.22 b	0.10 b	11.63 a
APRIL	4.43 b	0.00 c	0.00 c	16.01 a
MAY	4.92 a	0.27 b	0.00 b	4.14 a
JUNE	16.49 a	0.29 c	0.91 c	5.90 b
JULY	2.59 a	1.16 b	0.29 b	3.61 a
AUGUST	2.04 a	0.95 b	0.38 b	4.40 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 11. Comparisons of mean densities of soil nematodes between treatments by sampling date.

Total Nematode Densities kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986				
JUNE				
JUNE	1408 a	1502 a	1700 a	1634 a
JULY	1834 a	1878 a	2095 a	2051 a
AUGUST	2784 a	1618 b	3376 a	3274 a
SEPTEMBER	1428 a	578 b	965 ab	1304 a
OCTOBER	1162 a	1291 a	1593 a	1695 a
NOVEMBER	1335 b	1706 ab	2402 a	1530 ab
JANUARY - 1987	1128 b	2549 a	2158 a	1216 b
APRIL	405 c	582 bc	798 b	1400 a
MAY	567 bc	377 c	987 ab	1150 a
JUNE	611 b	766 ab	824 ab	1134 a
JULY	847 a	605 a	728 a	762 a
AUGUST	91 b	108 ab	127 ab	163 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Inorganic Nitrogen

Over all sample dates water had no significant effect on inorganic nitrogen, but chlordane had a significant effect on inorganic N ($p < 0.05$; Appendix Table A19). Inorganic N appears to be higher in chlordane treated plots than control or water plots, however, this pattern was not consistent throughout the experiment (Table 12). Over all sample dates water or chlordane had no significant effect on nitrate (Appendix Table A18). Also, water had no significant effect on ammonium, but chlordane had a significant effect on ammonium ($p < 0.05$; Appendix Table A17). During the experiment treatment effects that were observed in inorganic N were not always caused by changes in the same nitrogen species; for example, the increased inorganic nitrogen in chlordane plus water plots in June 1986, chlordane and chlordane plus water plots in September 1986, and chlordane plots in January and May of 1987 were due to increases in ammonium nitrogen (Table 13), while the increased inorganic nitrogen in control plots in October 1986, chlordane and chlordane plus water plots in May 1987 were due to increases in nitrate nitrogen (Table 14). Gravimetric soil moisture was higher in watered plots than unwatered plots most of the growing season, when plots were being irrigated (Table 15).

Table 12. Comparisons of mean total inorganic nitrogen between treatments by sampling date.

Total Inorganic Nitrogen mg kg^{-1} dry soil in the rhizosphere

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986				
JUNE	1.33 ^{ab}	2.58 ^{c}	1.69 ^{bc}	0.91 ^{a}
JUNE	1.81 ^{a}	1.40 ^{a}	3.37 ^{b}	1.98 ^{a}
JULY	1.66 ^{a}	2.17 ^{a}	2.08 ^{a}	1.71 ^{a}
AUGUST	2.60 ^{a}	2.49 ^{a}	2.31 ^{a}	3.06 ^{a}
SEPTEMBER	0.61 ^{a}	2.72 ^{b}	2.87 ^{b}	1.01 ^{a}
OCTOBER	2.44 ^{a}	1.47 ^{a}	1.23 ^{a}	1.23 ^{a}
NOVEMBER	1.07 ^{a}	1.57 ^{a}	1.10 ^{a}	1.67 ^{a}
JANUARY - 1987	1.83 ^{a}	3.52 ^{b}	2.06 ^{a}	1.70 ^{a}
APRIL	1.31 ^{a}	1.92 ^{a}	1.49 ^{a}	1.16 ^{a}
MAY	1.20 ^{ab}	2.83 ^{c}	1.84 ^{bc}	0.94 ^{a}
JUNE	1.39 ^{a}	1.41 ^{a}	0.79 ^{a}	0.99 ^{a}
JULY	2.33 ^{a}	1.96 ^{a}	1.88 ^{a}	1.99 ^{a}
AUGUST	1.42 ^{a}	1.52 ^{a}	1.03 ^{a}	1.32 ^{a}

* C= control, CH= chlordane, CHW=chlordane + water, W=water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 13. Comparisons of mean soil NH_4^--N between treatments by sampling date.

NH_4^+-N mg kg^{-1} dry soil in the rhizosphere

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986				
JUNE	0.50 [a]	1.94 [b]	1.25 [b]	0.44 [a]
JUNE	0.78 [a]	0.88 [a]	2.80 [b]	0.95 [a]
JULY	1.20 [a]	1.48 [a]	1.26 [a]	1.12 [a]
AUGUST	2.09 [a]	2.01 [a]	1.74 [a]	2.62 [a]
SEPTEMBER	0.32 [a]	2.31 [b]	2.40 [b]	0.68 [a]
OCTOBER	1.16 [a]	1.16 [a]	0.91 [a]	0.94 [a]
NOVEMBER	0.91 [a]	1.42 [a]	0.96 [a]	1.56 [a]
JANUARY - 1987	1.63 [a]	3.25 [a]	1.76 [a]	1.57 [a]
APRIL	0.75 [a]	1.07 [a]	0.76 [a]	0.72 [a]
MAY	0.44 [a]	1.19 [b]	0.10 [a]	0.10 [a]
JUNE	0.77 [a]	0.74 [a]	0.43 [a]	0.57 [a]
JULY	1.51 [a]	1.37 [a]	0.94 [a]	1.11 [a]
AUGUST	0.94 [a]	0.89 [a]	0.58 [a]	0.77 [a]

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 14. Comparisons of mean soil NO_3^--N between treatments by sampling date.

NO_3^--N mg kg^{-1} dry soil in the rhizosphere

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986				
JUNE	0.83 a	0.65 ab	0.43 b	0.48 b
JUNE	1.03 a	0.52 b	0.57 b	1.03 a
JULY	0.46 b	0.69 ab	0.82 a	0.59 ab
AUGUST	0.51 a	0.47 a	0.57 a	0.44 a
SEPTEMBER	0.29 a	0.42 a	0.47 a	0.33 a
OCTOBER	1.28 a	0.31 b	0.32 b	0.30 b
NOVEMBER	0.16 a	0.14 a	0.15 a	0.11 a
JANUARY - 1987	0.21 a	0.27 a	0.30 a	0.13 a
APRIL	0.56 ab	0.84 a	0.73 a	0.43 b
MAY	0.77 b	1.64 a	1.74 a	0.84 b
JUNE	0.62 ab	0.67 a	0.37 b	0.42 ab
JULY	0.81 ab	0.59 b	0.93 a	0.87 ab
AUGUST	0.48 a	0.63 a	0.44 a	0.55 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 15. Comparisons of mean gravimetric soil moisture between treatments by sampling date.

Gravimetric Soil Moisture (%)

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986				
JUNE	2.53 a	3.61 b	4.78 c	4.85 c
JUNE	0.84 a	1.13 b	2.04 c	2.17 c
JULY	4.45 a	4.35 a	4.31 a	4.71 a
AUGUST	1.27 a	1.33 a	1.74 b	1.70 b
SEPTEMBER	2.01 a	2.04 a	2.23 a	2.09 a
OCTOBER	5.47 a	5.49 a	5.82 a	5.80 a
NOVEMBER	7.46 a	7.43 a	7.70 a	7.50 a
JANUARY - 1987	5.93 a	6.38 a	6.65 a	5.92 a
APRIL	2.28 a	3.46 b	4.70 c	4.24 c
MAY	1.89 a	1.90 a	2.48 b	2.69 b
JUNE	2.53 a	2.63 a	2.37 a	2.58 a
JULY	1.51 a	1.53 a	1.57 a	1.76 a
AUGUST	2.22 a	2.37 a	3.46 b	3.65 b

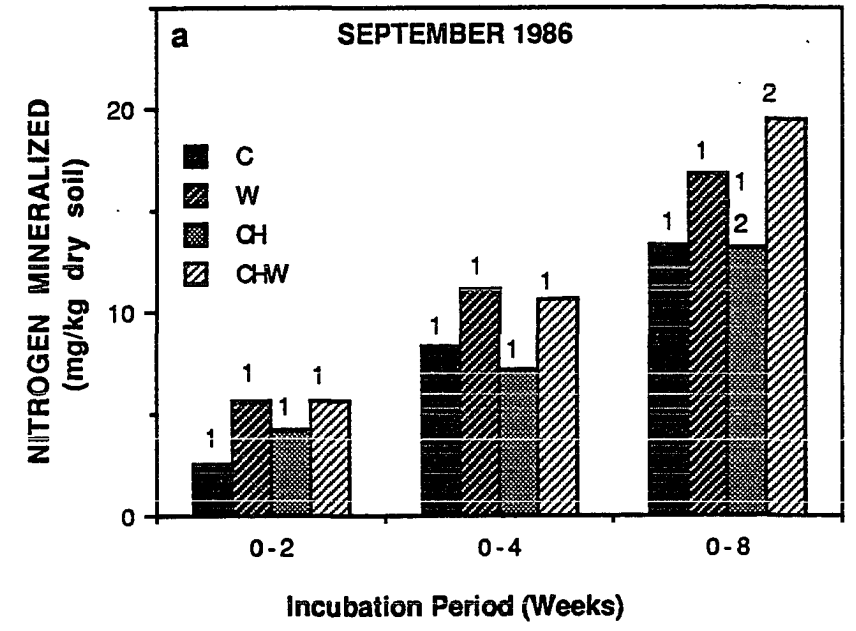
* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Net Nitrogen Mineralization and Resin Bags

Over all sample dates there were no significant water or chlordane effects on nitrogen mineralization (Appendix Table A23). However, there were significant treatment effects on net nitrogen mineralization in September 1986 samples following 8 weeks incubation, with chlordane plus water plots greater than control and water plots (Figure 2a). But, there were no treatment effects in August 1987 samples (Figure 2b). Furthermore, there were significant differences in net nitrogen mineralization between September 1986 and August 1987 only within control plots (Table 16).

Ammonium captured in the cation exchange resin bags was not affected by treatment on any sample date (Appendix Table A21, and Figure 3A). However, there were significant differences between samples dates, with capture of ammonium in spring 1987 greater than in summer and fall 1986 for all treatments (Table 17). Over all sample dates water or chlordane had no significant effect on nitrate captured in anion exchange resin bags (Appendix Table A22). The only treatment differences in capture of nitrate in anion exchange resin bags occurred in summer 1986, with chlordane plus water plots greater than both control and water plots (Figure 3b). All treatments had the same differences in capture of nitrate between sample dates, with capture in spring 1987 greater than summer and fall 1986, and capture in summer 1986 greater than in fall 1986 (Table 18).

Figure 2. Mean nitrogen mineralization potential in laboratory incubations of soil samples at 15 cm depth from each of the treatment. a) September 1986 samples; b) August 1987 samples. C=control, CH=chlordane, CHW=chlordane plus water, W=water same numbers above bars, indicate non significant differences, different numbers above bars, indicate significant differences.



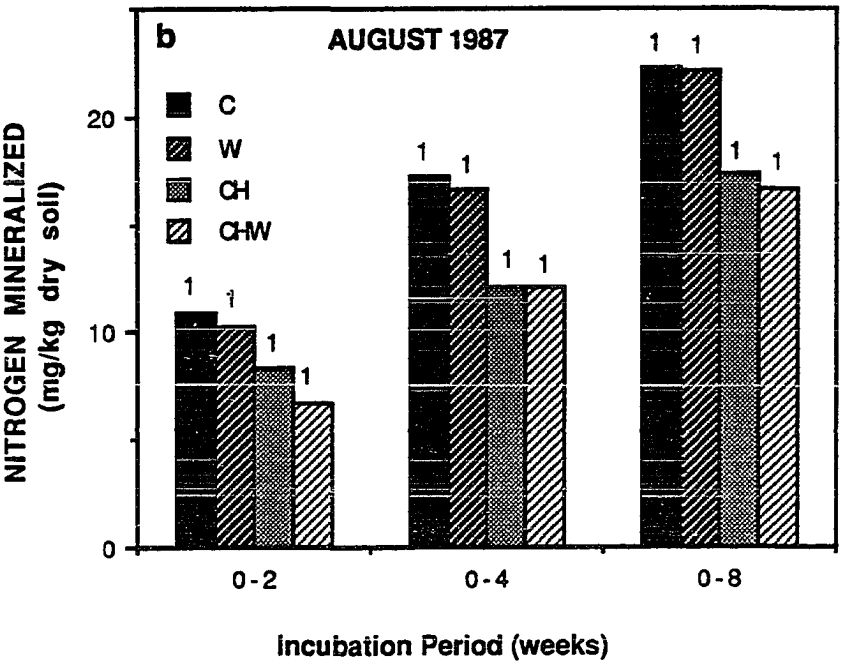


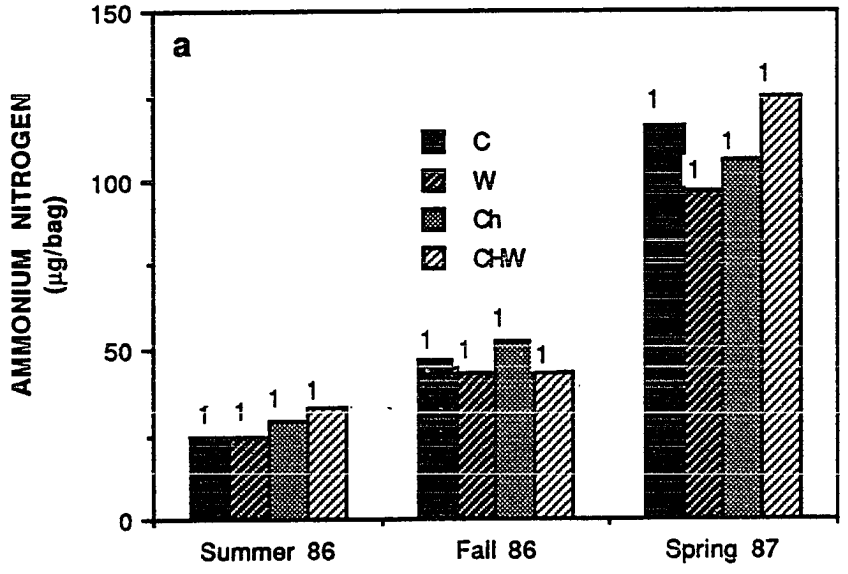
Table 16. Contrasts of means of nitrogen mineralization between September 1986 and August 1987 by treatment.

Nitrogen Mineralization (1986 and 1987)

	TREATMENT#			
Incubation Time@	C	CH	CHW	W
2	**	ns	ns	ns
4	**	ns	ns	ns
8	**	ns	ns	ns

C= control, CH= chlordane, CHW=chlordane + water, W=water.
* < 0.05, ** < 0.01, *** < 0.001
@ Incubation Time in weeks

Figure 3. Mean accumulation of NO_3 (a), and NH_4 (b) in field-placed resin bags during Summer (hot-wet season), Fall (hot-wet to cool-dry season), and Spring (hot-dry season) of 1986 and 1987. C=control, CH=chlordane, CHW=chlordane plus water, W=water same numbers above bars, indicate non significant differences, different numbers above bars, indicate significant differences.



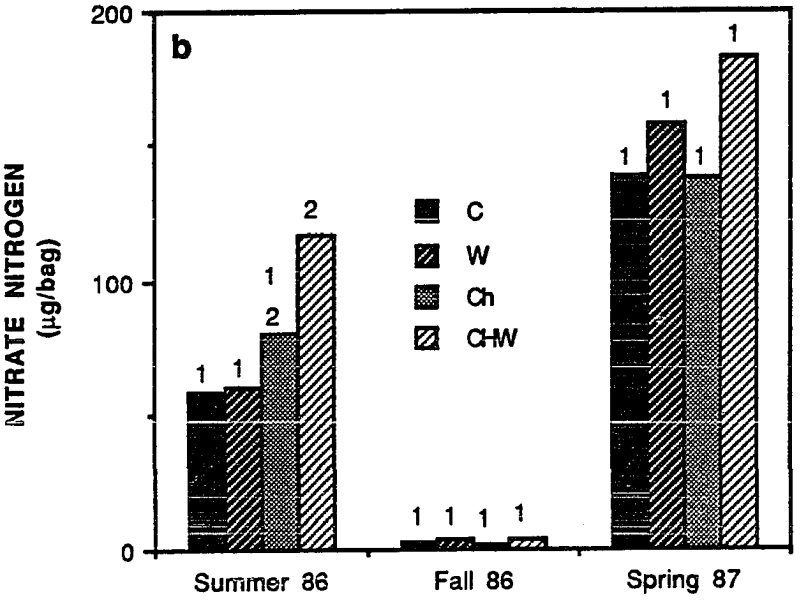


Table 17. Contrasts of means of cation exchange resin bag NH_4^+-N between seasons by treatment.

	NH_4^+-N (µg per resin bag)			
	TREATMENT#			
SEASON@	C	CH	CHW	W
Summer-Fall	ns	ns	ns	ns
Summer-Spring	***	**	**	***
Fall-Spring	**	*	*	**

C= control, CH= chlordane, CHW=chlordane + water, W=water.
* < 0.05, ** < 0.01, *** < 0.001
@ Summer 1986 , Fall 1986, Spring 1987

Table 18. Contrasts of means of anion exchange resin bag NO_3^--N between seasons by treatment.

	NO_3^--N (μg per resin bag)			
	TREATMENT#			
SEASON@	C	CH	CHW	W
Summer-Fall	***	***	***	***
Summer-Spring	***	**	***	*
Fall-Spring	***	***	***	***

C= control, CH= chlordane, CHW=chlordane + water, W=water.
* < 0.05, ** < 0.01, *** < 0.001
@ Summer 1986 , Fall 1986, Spring 1987

Below and Aboveground Biomass and Total Nitrogen

Over all sample dates water had a significant effect on root biomass ($p < 0.05$; Appendix Table A16). However, over all sample dates chlordane had no significant effect on root biomass (Appendix Table A16). No consistent treatment effect patterns were found in root biomass of rhizosphere samples (Table 19). When there were any differences in root biomass it was significantly higher in water plots throughout the study, except in June 1986 and 1987. Root total nitrogen over all sample dates was affected by water and chlordane treatments ($p < 0.05$; Appendix Table A13). Root total nitrogen (Table 20) was generally higher in plots with microarthropods excluded (chlordane and chlordane plus water plots).

Overall main effects of water, chlordane and water * chlordane on plant biomass were all significant (Appendix Table A33). However, the only differences among sample dates were control plots having higher biomass than all other treatments in July 1986 and June 1987 (Table 21).

Table 19. Comparisons of mean root biomass between treatments by sampling date.

Root Biomass g kg^{-1} dry soil

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	0.25 a	0.19 a	0.20 a	0.22 a
JUNE	0.32 a	0.32 a	0.26 a	0.31 a
JUNE	0.48 a	0.34 bc	0.27 c	0.38 b
JULY	0.36 a	0.25 b	0.26 b	0.44 a
AUGUST	0.41 a	0.27 b	0.38 ab	0.48 ab
SEPTEMBER	0.29 ab	0.22 b	0.27 ab	0.31 a
OCTOBER	0.25 a	0.26 a	0.19 a	0.18 a
NOVEMBER	0.17 a	0.18 a	0.13 a	0.19 a
JANUARY - 1987	0.27 ab	0.20 b	0.24 ab	0.30 a
APRIL	0.19 ab	0.16 ab	0.14 b	0.22 a
MAY	0.25 ab	0.23 ab	0.20 b	0.28 a
JUNE	0.39 a	0.25 b	0.26 b	0.30 b
JULY	0.35 a	0.21 c	0.24 bc	0.31 ab
AUGUST	0.38 a	0.15 b	0.22 b	0.41 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 20. Comparisons of mean plant root total nitrogen between treatments by sampling date.

Plant Root Total Nitrogen mg g^{-1} root

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	4.92 a	4.92 a	5.47 a	5.11 a
JUNE	5.94 a	5.54 a	5.43 a	5.52 a
JUNE	5.57 b	6.57 a	6.24 a	5.86 ab
JULY	5.93 a	5.37 a	5.42 a	5.37 a
AUGUST	5.66 a	6.16 a	6.17 a	5.44 a
SEPTEMBER	6.19 ab	5.97 ab	6.32 a	5.56 b
OCTOBER	5.85 b	6.64 a	6.42 ab	5.89 ab
NOVEMBER	6.23 ab	6.74 a	5.82 ab	5.57 b
JANUARY - 1987	5.66 b	6.54 a	6.31 ab	6.03 ab
APRIL	5.92 b	6.76 a	5.97 b	5.40 b
MAY	6.13 a	6.75 a	6.61 a	6.15 a
JUNE	5.95 a	5.98 a	4.97 b	4.88 b
JULY	6.44 a	6.21 ab	5.69 bc	5.12 c
AUGUST	4.99 a	5.16 a	4.88 a	4.69 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 21. Comparisons of mean plant biomass between treatments by sampling date.

Plant biomass (g dry wt)				
	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	8.70 a	8.11 a	9.23 a	8.61 a
JUNE	8.92 a	7.35 c	7.35 cb	8.33 ab
JUNE	8.35 a	7.03 a	7.00 a	7.77 a
JULY	10.06 a	8.18 b	8.04 c	8.89 b
AUGUST	9.16 a	7.40 b	9.29 a	9.07 a
SEPTEMBER	8.13 a	7.22 ab	6.81 bc	6.13 c
OCTOBER	6.90 a	7.77 a	6.65 ab	5.08 b
NOVEMBER	6.84 a	6.05 ab	5.59 b	5.42 b
JANUARY - 1987	7.04 a	7.07 a	7.50 a	6.55 a
APRIL	6.43 a	6.23 a	5.92 a	6.40 a
MAY	6.29 b	7.15 b	7.50 a	6.76 b
JUNE	7.16 a	5.90 b	5.86 b	5.78 b
JULY	6.73 a	6.97 a	7.04 a	6.20 a
AUGUST	7.39 a	4.85 b	5.64 b	7.50 a

* C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 22. Comparisons of mean plant shoot total nitrogen between treatments by sampling date.

PLANT SHOOT TOTAL NITROGEN mg g^{-1} dry wt.

	TREATMENT*			
DATE	C	CH	CHW	W
MAY - 1986	6.55 ^{a}	6.01 ^{a}	6.39 ^{a}	6.23 ^{a}
JUNE				
JUNE	5.57 ^{b}	6.32 ^{ab}	7.12 ^{a}	6.05 ^{b}
JULY	7.51 ^{b}	9.21 ^{a}	9.91 ^{a}	10.63 ^{a}
AUGUST				
SEPTEMBER				
OCTOBER				
NOVEMBER	9.53 ^{a}		6.52 ^{b}	6.07 ^{b}
JANUARY - 1987				
APRIL	7.12 ^{a}	7.51 ^{a}	7.03 ^{a}	6.08 ^{b}
MAY				
JUNE				
JULY				
AUGUST	9.03 ^{a}	9.04 ^{a}	8.07 ^{a}	7.16 ^{b}

* C= control; CH= chlordane; CHW= chlordane + water, W= water. Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Plant Growth and Nitrogen Budget

Treatments had no effect on plant shoot growth and root growth over all sample dates (Appendix Tables A26 and A27). There were also no differences among treatments in relative plant shoot growth in the 1986 growing season (Table 23). The lower growth at the end of the growing season was due to loss of reproductive biomass. Relative plant root growth in the 1986 growing season was higher in the control treatment throughout the season (Table 24).

Plant root nitrogen was significantly affected by chlordane, water, and chlordane*water treatments over all sample dates ($p < 0.05$; Appendix Table A28). Control plots had higher levels of plant root nitrogen than any other plots during the 1986 growing season (Table 25). Plant shoot nitrogen was not significantly affected by treatments over all sample dates (Appendix Table A29). However, during the 1986 growing season control plots had higher plant shoot nitrogen levels than any other treatment (Table 26). Over all sample dates chlordane treatment significantly affected soil inorganic nitrogen ($p< 0.05$; Appendix Table A30). During the growing season inorganic nitrogen seems to be higher in chlordane treated plots (Table 27). Over all sample dates rhizosphere nitrogen (defined as soil inorganic nitrogen plus root nitrogen) was not significantly affected by treatments (Appendix Table A31). The highest level of rhizosphere. nitrogen occurred in microarthropods-free plots (Table 28). In the rhizosphere, values for soil inorganic nitrogen were almost double the values for root nitrogen especially in microarthropods-free plots (Tables 27, and 25, respectively). Over all sample dates whole plant system nitrogen was not significantly affected by treatments (Appendix Table A32). And there were no consistent patterns in whole

plant system nitrogen during the 1986 growing season (Table 29).

Net changes in root total nitrogen did not vary much throughout the sampling time, except in water and microarthropods free plots exhibiting high levels of nitrogen (Table 30). Aboveground nitrogen showed high net changes in nitrogen in control plots, with changes in watered plots much lower (Table 31). Net changes in soil inorganic nitrogen were low in control plots and high in water and microarthropods free plots at the end of growing season (Table 32). Belowground (rhizosphere) net changes in nitrogen were very small with a slightly increase in values of nitrogen in water and microarthropods-free plots throughout the 1986 growing season (Table 33). Overall water plots without microarthropods and control plots showed higher values of net change in whole system nitrogen than plots just without microarthropods, and plots that received just water supplements (Table 34).

Table 23. Comparisons of mean 1986 plant shoot growth (relative change in biomass from March) between treatments by sampling date.

RELATIVE PLANT SHOOT GROWTH

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	7.91[a]	11.85[a]	11.69[a]	8.60[a]
SEPTEMBER	5.77[a]	4.96[a]	8.57[a]	4.89[a]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 24. Comparisons of mean 1986 plant root growth (relative change in biomass from March) between treatments by sampling date.

RELATIVE PLANT ROOT GROWTH

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	0.33^{a}	0.25^{bc}	0.26^{b}	0.22^{c}
SEPTEMBER	0.22^{a}	0.11^{c}	0.18^{b}	0.12^{c}

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 25. Comparisons of mean plant root nitrogen during the 1986 growing season between treatments by sampling date.

PLANT ROOT NITROGEN (mg N/rhizosphere volume)

	TREATMENT#			
DATE	C	CH	CHW	W
MARCH	1.23[a]	0.85[c]	0.78[d]	0.97[b]
JULY	1.45[a]	1.07[c]	1.04[d]	1.26[b]
SEPTEMBER	1.35[a]	0.97[c]	0.96[c]	1.13[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 26. Comparisons of mean plant shoot nitrogen during the 1986 growing season between treatments by sampling date.

PLANT SHOOT NITROGEN (mg N/aboveground plant)

	TREATMENT#			
DATE	C	CH	CHW	W
MARCH	3.18[a]	1.68[b]	1.75[b]	1.73[b]
JULY	26.95[a]	20.0[b]	21.64[b]	19.99[b]
SEPTEMBER	16.31[a]	11.37[b]	16.11[a]	11.96[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 27. Comparisons of mean soil inorganic nitrogen during the 1986 growing season between treatments by sampling date.

SOIL INORGANIC NITROGEN (mg N/rhizosphere volume)

	TREATMENT#			
DATE	C	CH	CHW	W
MARCH	1.60[a]	3.10[a]	2.02[a]	1.10[b]
JULY	1.99[a]	2.60[a]	2.49[a]	2.05[a]
SEPTEMBER	0.73[b]	3.27[a]	3.44[a]	1.21[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 28. Comparisons of mean rhizosphere nitrogen during 1986 growing season between treatments by sampling date.

RHIZOSPHERE NITROGEN (mg N/rhizosphere volume)

	TREATMENT#			
DATE	C	CH	CHW	W
MARCH	2.61[b]	4.45[a]	2.30[b]	2.0[b]
JULY	3.44[a]	3.68[a]	3.53[a]	3.31[a]
SEPTEMBER	2.08[b]	4.24[a]	4.40[a]	2.34[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 29. Comparisons of mean whole plant system nitrogen during 1986 growing season between treatments by sampling date.

WHOLE PLANT SYSTEM NITROGEN (mg N/whole plant)

	TREATMENT#			
DATE	C	CH	CHW	W
MARCH	5.79^{ab}	6.13^{a}	4.05^{b}	3.73^{b}
JULY	30.39^{a}	23.68^{b}	25.17^{b}	23.31^{b}
SEPTEMBER	18.39^{a}	15.61^{b}	20.51^{a}	14.30^{b}

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 30. Comparisons of mean net change in plant root nitrogen from March between treatments by sampling date.

NET CHANGE IN PLANT ROOT NITROGEN

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	0.20^{b}	0.20^{b}	0.25^{a}	0.23^{ab}
SEPTEMBER	0.12^{b}	0.09^{c}	0.18^{a}	0.13^{b}

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 31. Comparisons of mean net change in plant shoot nitrogen from March between treatments by sampling date.

NET CHANGE IN PLANT SHOOT NITROGEN

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	22.33[a]	17.06[b]	18.90[a]	14.28[c]
SEPTEMBER	13.26[a]	7.19[b]	13.48[a]	8.32[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 32. Comparisons of mean net change in soil inorganic nitrogen from March between treatments by sampling date.

NET CHANGE IN SOIL INORGANIC NITROGEN

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	0.39[a]	-0.50[a]	0.47[a]	0.95[a]
SEPTEMBER	-0.87[a]	0.17[b]	1.42[b]	0.11[ab]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 33. Comparisons of mean net change in rhizosphere nitrogen from March between treatments by sampling date.

NET CHANGE IN RHIZOSPHERE NITROGEN

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	0.89[a]	-0.77[a]	1.24[a]	1.08[a]
SEPTEMBER	-0.55[b]	-0.76[a]	1.09[a]	-0.20[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

Table 34. Comparisons of mean net change in whole plant system nitrogen from March between treatments by sampling date.

NET CHANGE IN WHOLE PLANT SYSTEM NITROGEN

	TREATMENT#			
DATE	C	CH	CHW	W
JULY	23.22[a]	16.29[a]	20.15[a]	15.37[a]
SEPTEMBER	12.71[a]	6.44[b]	14.57[a]	8.12[b]

C= control, CH= chlordane, CHW=chlordane + water, W=water.
Estimates within the same row with different right superscript letters are significantly different from each other ($p < 0.05$).

DISCUSSION

Microcosm studies by Coleman et al. (1977), Coleman et al. (1978a,b), Woods et al. (1982) and Coleman et al. (1984) suggested that the presence of microarthropods in the system enhanced nitrogen mineralization. Field studies of Santos and Whitford (1981), Santos et al. (1981), and Elkins and Whitford (1982) on leaf litter bag decomposition showed that microarthropods enhanced litter decomposition, carbon dioxide evolution and nitrogen and phosphorus mineralization. Parker et al. (1984) found that microarthropods enhanced mineralization of nitrogen from decomposing roots. However, the present study, designed to examine the role of microarthropods within a "living" plant rhizosphere system, failed to show a significant positive relationship between microarthropod abundance and nitrogen availability or plant growth.

Nitrogen availability using field-placed resin bags was significantly different among seasons. This could be related to plant growth. Erioneuron pulchellum begins growth during late spring to early summer, and reaches maximum growth during the fall. Erioneuron pulchellum is senscent during winter and early spring. During the spring resin bags adsorbed the highest quantity of nitrate-nitrogen, possibly because plants were senescent, and there was no root competition for nitrogen.

Nutrient availability, measured by field-placed resin bags and by laboratory mineralization potential experiments, showed similar patterns. Both indices showed significant differences during the 1986 growing season.

The combination of water and absence of microarthropods resulted in an increase in nitrogen adsorbed.

Lajtha (1986) conducted a study in the same area, in which she measured nitrogen availability also using field-placed resin bags and nitrogen mineralization potential. Her resin bags produced slightly higher nitrogen values in the hot-wet season (summer in this study) than the results in this study, for all plots, except irrigated, and microarthropod absent plots. In this particular season (hot-wet) differences between these results and Lajtha's results might be attributed in part to the different plant species used in each study. It also could be attributed to the lower rainfall in 1986, resulting in less microbial activity, fewer nematodes, fewer microarthropods and less nitrogen mineralization and accumulation. Differences may also be a result of natural low organic substrate in the rhizosphere of fluff grass. In addition to the above, Freckman et al. (1987) reported that nematodes entered anhydrobiosis when soil water potential reached -0.4 MPa, corresponding to approximately 4.7% soil moisture (Schlesinger et al. 1987). This type of soil condition was very common during the entire year of this study, except during the wet winter and spring.

During the hot-dry season (spring 87) my soil nitrate concentrations were higher than those reported by Lajtha (1988) in all treatments. This could be due to high soil water availability during an unusual wet winter and spring, and also because there was no plant uptake during the non-growing season of fluff grass. Ammonium concentrations reported here were lower than the values reported by Lajtha (1988), and were not statistically different among treatments. However, ammonium was significantly different between

seasons, with higher values during the spring. This result is consistent with Binkley's (1984) observation that resin bags were not able to capture NH_4 or NO_3 through diffusion in dry soils because transport by water was critical. According to Lajtha (1988) the soils where this study was conducted had lower values of nitrogen availability than any other location on the Jornada-LTER site. Therefore, she suggested that plant production is significantly lower in these soils, yielding a lower rate of nutrient turnover and lower nutrient availability.

In this study nitrogen mineralization potential following 8 weeks incubation showed significant differences between years, but not among treatments. The combination of irrigation and no microarthropods plots had greater nitrogen mineralization than control or irrigated plots. Fisher et al. (1987) reported that small events (6 mm/wk) of simulated rainfall resulted in faster nitrogen mineralization, but greater nitrogen losses than large (25 mm/mo.) events. They attributed this to small events providing greater overall moisture availability, and more frequent wet and dry periods. Rhizosphere nitrogen mineralization index among all treatments in this study was approximately 12 mg of mineralized nitrogen after 28 days incubation. This result was equivalent to Lajtha (1988) and Fisher et al. (1987) nitrogen values in non-rhizosphere soils during the hot-wet (summer) season. These comparisons demonstrated that soils from the rhizosphere of fluff grass and non-rhizosphere soils had equivalent rates of nitrogen mineralization. Nash (1985) reported 0.4% of organic carbon in non-rhizosphere soil of similar vegetation. I estimated an average root biomass of 0.23 g per kg dry soil, which indicates that organic substrate within the rhizosphere is low. Fisher et

et al. (1987) reported 24.8 mg of mineralized nitrogen after 28 days incubation, in the soil under the canopy of Larrea tridentata (creosote bush), where the amount of organic matter should be much higher than in soil from the rhizosphere of fluff grass.

There were no correlations between microarthropods and plant root or shoot total nitrogen overall among treatments. Plant root biomass increased in response to water amendments, and the presence of microarthropods. In addition, within irrigation treatments plant shoot biomass exhibited a positive correlation with plant shoot total nitrogen ($r=0.82$, $p< 0.0001$). However, there was no correlation between plant shoot biomass and available nitrogen. This result differs from that of the Ettershank et al. (1978) study on growth response of Erioneuron pulchellum to nitrogen fertilization. They reported a marked increase in plant biomass in response to nitrogen amendments.

Despite all the variations among treatments, there were no differences in plant growth among treatments during the 1986 growing season. However, plant shoot and root total nitrogen was higher in water than control treatments at the beginning of the growing season. By the end of the growing season there was higher available nitrogen in control than water treatments. These results suggest a rapid turnover of organic matter and N mineralization in the first year, yielding lower nitrogen availability the second year. In the second year there was a higher level of nitrogen in the control than water treatment. This supports the hypothesis of Gutierrez and Whitford (1987a) that marked reduction in annual plant abundance and biomass on plots during the second year of 6mm /wk water addition was due to lack of available nitrogen.

Whitford et al. (1988a) reported that mass loss from roots via microbes and soil microfauna are insignificant. Their data confirms that termites are very important in the decomposition and mineralization of belowground plant material. However, in this study high levels of nitrogen mineralized occurred in treatments free of microarthropods and termites, suggesting that in a living system with low organic matter input microbial flora might be more important than termites, or microarthropods.

There were higher levels of soil inorganic nitrogen and lower levels of root nitrogen in the absence of microarthropods during the 1986 growing season (March-September). These results suggest that microbial immobilization occurred. Water amendments decreased soil inorganic nitrogen, and plant root and shoot nitrogen. This suggests a rapid turnover of organic matter and nitrogen mineralization at the beginning of the growing season, with nitrogen depletion occurring at the end of the growing season. Parker et al. (1984) in a study of litter and root decomposition reported that microarthropods are very important as regulators of decomposition and nitrogen fluxes in deserts. They suggested that predation by microarthropods on nematodes, protozoa, bacteria and fungi contributes to rate regulation. When studying live rhizosphere processes with low amounts of organic matter, results are quite different. Between July and September of the 1986 growing season there was a decrease in net nitrogen in the whole plant system among all treatments. This corresponded to a decrease in plant and root nitrogen. However, at the same time soil inorganic nitrogen increased, but only in the absence of microarthropods. In the absence of microarthropods,

nematode density was low, contrary to what was expected, suggesting that nitrogen mineralization was probably performed by microbial fauna.

Overall in the entire rhizosphere water irrigation enhanced nitrogen mineralization. A number of workers have demonstrated in laboratory experiments that protozoa and nematodes are able to regulate growth dynamics of bacteria, and hence the turnover and mineralization of nitrogen and phosphorus (Baath et al. 1978, Cole et al. 1978, Anderson et al. 1981, Clarholm et al. 1981 and Coleman et al. 1984). This experiment was not designed to manipulate nematode populations. However, when mites were excluded, I expected that the nematode population would increase markedly. Results from my study showed no nematode responses when microarthropods were eliminated except during November 1986 and January 1987. These sample dates were the only time during this study when soil moisture was high enough for nematodes to be out of anhydrobiosis (Figure 1 c) (Freckman et al. 1987).

Soil fauna, such as microarthropods, earthworms, nematodes, and protozoa (Edwards and Lofty 1977) have a significant role in maintaining nutrient cycles. However, broad-spectrum pesticides, such as certain nematicides, affect far more than target organisms, and may have a detrimental effect on rates of nutrient cycling. Stanton et al. (1981) found very marked decreases (> 50%) in soil microarthropod populations, and a decrease of 50% in fungal propagules in a shortgrass prairie which received dosages of a systematic nematicide. Parker et al. (1985) in a study conducted in the same area showed that chlordane has no effects on rates of decomposition or soil and litter respiration. Seastedt et al. (1988) reported that in tallgrass

prairie four years of insecticide treatment to soils failed to influence either aboveground or belowground production. They attributed this to the low amount of nitrogen in system. This is consistent with results found in this study.

It should be pointed out that some possible losses of nitrogen were not measured in this study. Immobilization by microbes during root turnover may have been important. Ammonia (NH_3) volatilization (Fisher et al. 1987) is very likely to happen in a high pH, coarse-textured soil with a low cation exchange capacity. Losses by leaching could be possible, but not very likely given the low amount of rainfall.

Whitford et al. (1981) reported that the activity of soil microarthropods in surface litter is regulated primarily by rainfall, as suggested by Noy-Meir (1974). Thus, in this study it was hypothesized that water irrigation would lead to increased microarthropod densities within the rhizosphere of Erioneuron pulchellum. However, the only significant increase of microarthropods in water amended plots occurred in April 1987 (following the November 1986 to March 1987 period when plots were not watered). Results reported here are quite different than those reported by MacKay et al. (1986), who demonstrated that the abundance of microarthopods within surface litter may be regulated more by temperature than soil moisture. In addition, MacKay et al. (1987) suggested that decomposer microflora and microfauna of the northern Chihuahuan Desert are more limited by the quantity of organic matter than by water and nitrogen. Steinberger et al. (1984) and Whitford et al. (1988a) also suggested that microarthropods may be limited by food availability rather than soil moisture. My study was

conducted within a rhizosphere system in which the amount of root biomass averaged only about 0.23 g per kg dry soil, a very low level of organic substrate for soil biota in comparison to surface litter. Thus, the lack of response to water supplementation on most sample dates may have been due to availability of food being more limiting than water. The April 1987 sample date followed winter, when soil temperature was limiting to all soil organisms, and thus following a period when organic substrate should have been accumulating. The strong response of microarthropods to water in April suggests that water was more limiting than food and/or temperature at this time.

All of the orders of microarthropods occurred at higher densities in control than water plots in June 1986. This may be related to microarthropods within control plots responding to the first large rain events of the 1986 rainy season. Microarthropods in irrigated plots likely did not respond at this time because they had already been exposed to artificial water inputs.

In this study prostigmatid mites occurred at higher densities in control than in water plots at the beginning (June and July) and end (October) of the 1986 growing season. Most of the prostigmatid mites found in this study are fungivores or onmivores. Therefore, the increase at the beginning of the growing season could be explained by an increase in fine root biomass, leading to an increase in bacteria, fungi, and nematodes as food source for microarthropods. Kamill et al. (1985) suggested that Prostigmata appear to favour somewhat poorer, less structured soils. Loots and Ryke (1967) noted an inverse relationship between the numbers of Prostigmata and quantity of

organic matter in the soil, which appears to agree with my data because organic matter in the rhizosphere of a fluff grass is very low.

In general higher densities of cryptostigmatid mites were observed after rainfall events in water plots than control plots. Most of the cryptostigmatid mites in this study belong to the species Passalozetes californicus, Passalozetes neomexicanus, Jornadia larreae, and Joshuella striata. My data show that these species had peaks in abundance during the rainy season. This is similar to data of Wallwork et al. (1986), in which the same species had peaks in abundance during the rainy season. In my study cryptostigmatid mites also had higher densities in water plots than control plots during the winter of 1987. This was likely due to the species Joshuella striata, which produces eggs in both winter and summer. These data are also similar to those of Wallwork et al. (1986), who reported higher densities of Joshuella striata in watered plots than control plots in January.

Both root biomass and cryptostigmatid mites densities had a positive response to water irrigation during the 1986 growing season. This result is in accordance with several researchers (Loots and Ryke 1967, Wood 1971, and Kamill et al. 1985) who reported cryptostigmatid mites preferring high organic soils. Luxton (1972) showed that most Cryptostigmata have rather generalized feeding habits and will consume a variety of plant material. Densities of Prostigmata were higher than densities of Cryptostigmata throughout the experiment, which is likely related to low organic matter in the rhizosphere of Erioneuron pulchellum.

The only times that mesostigmatid mites exhibited significant differences in densities were in June 1986 (control greater than water) and

April 1987 (water greater than control plots). Both times seem to be a response to water following an extended dry period. Several studies have suggested that mesostigmatid mites prey on microarthropods and nematodes (Santos et al. 1981, Whitford et al. 1981, Whitford et al. 1982, Elkins and Whitford 1982, Santos et al. 1984, Wallwork et al. 1986, Moore and Walter 1988). My study seems to support this possible predation because most peaks in abundance of mesostigmatid mites occurred simultaneously with peaks of prostigmatid mites, and nematodes.

Whitford et al. (1988b) reported that astigmatid mites respond to water supplements with an increase in densities, and were associated with the beginning of root decomposition. However, in my research astigmatid mites occurred in very low densities and showed no significant response to water.

The microarthropod fauna of the Chihuahuan Desert is distributed among the suborders of Acarina more like the microarthropods of the Barrow tundra than temperate ecosystems (Elkins and Whitford 1982). In the tundra (Douce and Crossley 1977) and Chihuahuan Desert ecosystems (Wallwork et al. 1986) Prostigmata dominate most of the time during the year except during the rainy season where Prostigmata and Cryptostigmata densities are about the same. In temperate ecosystems Cryptostigmata, oribatei (Block 1965) dominate most of the year.

In my study Acarina were dominated by Prostigmata, followed by Cryptostigmata, Mesostigmata, and Astigmata. The majority of the prostigmatid mites reported here belonged to grazer and/or omnivore trophic groups. Cryptostigmata are primarily grazers, with some predators, while Mesostigmata are primarily predators with some omnivores.

Several researchers (Ingham et al. 1985, Ingham et al. 1986 a,b., Hunt et al. 1987) have emphasized that in microcosm experiments, nematodes are very important in nitrogen mineralization and plant growth. Hunt et al. (1987) reported that fauna are responsible for 37% of the nitrogen mineralized in a shortgrass prairie and that bacteria-feeding amoeba and nematodes together accounted for 83% of nitrogen mineralized by fauna. Ingham et al. (1985) found that fungiphagous nematodes did not cause an increase in plant growth and nitrogen uptake, because these nematodes excreted less NH_4^+-N than did bacteria-feeding nematode populations, and, because nitrogen mineralization by fungi alone was sufficient for plant growth. Ingham et al. (1986b) showed seasonal responses in trophic interactions and nitrogen mineralization-immobilization processes. In the spring, predator groups (protozoa and nematodes) increased as bacteria and fungi increased, thereby reducing microbial biomass. Reduced decomposer and increased grazer numbers led to an increase in soil inorganic nitrogen. My results do not agree with those based on microcosms. In the first year, there were no differences in nematode populations between treatments until September when nematode densities were lower in microarthropod free plots. Inorganic nitrogen was also higher in the microarthropod free plots. Bacteria tie up nitrogen in the absence of grazers (Barsdate et al. 1974, Anderson et al. 1978). Santos et al. (1981) found that bacteriophagous nematodes only enhanced decomposition if their numbers were controlled by predatory mites. There were no differences in nematode densities among the treatments in my study. Therefore, there is no evidence that microarthropods controlled nematodes. Total nematode densities from this study also agree with Freckman et al. (1987) who found

that in the Chihuahuan Desert water supplements had no significant effect on annual mean densities of total soil nematodes, fungivores, bacterivores, or omnivore predators. They also reported that bacteria-feeders and omnivore predators were the largest contributor to total soil nematode density and biomass. Furthermore nematodes were inactive (anhydrobiotic) and decoupled from decomposition processes when soil water matric potentials reached -0.4 MPa, and in my study during the growing season, soil water potential was below -0.4 MPa most of the time.

Seastedt and Crossley (1980), Santos and Whitford (1981), Whitford et al. (1983), Parker et al. (1984), Whitford et al. (1988b) and Moore and Walter (1988) suggested that fungivorous microarthropods and nematodes are important in nitrogen mineralization because they prey upon fungi, releasing nitrogen immobilized within their tissues, which then becomes available for plant growth. In my study, during the growing season of fluff grass, results were different from the above studies, with no correlation between fungivorous microarthropods and available nitrogen. Furthermore, treatments with microarthropods absent showed a small increase in available nitrogen in the soil. No changes were observed in plant root and shoot total nitrogen and growth with the presence of microarthropods. There was no correlation between nematodes and available nitrogen, or plant growth. In addition , Zak and Whitford (1988), reporting on preliminary results from a similar study being conducted in the same area, with the same plant species, showed grazing by nematodes and microarthropods to have no effect on overall fungal activity. The consequences of these interactions are no measurable effects on nutrient dynamics, and a steady rate of mineralization, unless the system is

severely stressed. Even though I have no data on bacteria, fungi, actinomycetes and protozoans, results from microarthropods and nematodes suggest that the living rhizosphere Erioneuron pulchellum, which has very low amounts of organic substrate, might not support very complex food webs.

The following can be concluded from this study:

1. Microarthropods and nematodes had a positive response to water only following extended dry periods.

2. Nematodes had a positive response to elimination of microarthropods, only during the wet winter-spring of 1986-87, when soil water potential was above -0.4 MPa most of the time.

3. Biocide treatment, used to eliminate microarthropods, led to an increase in soil inorganic nitrogen but a decrease in plant root and shoot nitrogen.

4. Neither water or microarthropods had an effect on plant shoot biomass, however, water and microarthropods overall sample dates increased plant biomass.

5. Overall sampling dates, water and microarthropods had no effect in increasing plant growth.

The results of my study failed to support the hypothesis that increasing densities of microarthropods would cause an increase in N mineralization, increasing inorganic nitrogen, and thus enhancing nitrogen availability and plant growth. Thus, microarthropods do not appear to be essential in the processes occurring within the living rhizosphere of the desert grass Erioneuron pulchellum. I suggest that the low rate of organic matter input in

the rhizosphere of fluff grass may be an important variable affecting mineralization processes.

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APPENDIX A

Analysis of Variance

Table A1. Split plot through time AOV table of 1986-87 log-transformed total microarthropod densities with chlordane and water as main factors.

Total Microarthropod Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	472.437	1406.06	<0.0001
WATER	1	3.287	9.78	0.0065
CHLORDANE*WATER	1	2.468	7.34	0.0155
ERROR (a)	16	0.336		
DATE	13	2.840	11.71	<0.0001
DATE*CHLORDANE	13	3.448	14.40	<0.0001
DATE*WATER	13	0.485	2.02	0.0203
DATE*CHLORDANE*WATER	13	0.953	3.98	<0.0001
ERROR (b)	208	0.239		

Table A2. Split plot through time AOV table of 1986-87 log-transformed Order Astigmata (Acari) densities with chlordane and water as main factors.

Order Astigmata Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.205	1.297	0.2715
WATER	1	0.195	1.234	0.2830
CHLORDANE*WATER	1	0.135	0.854	0.3789
ERROR (a)	16	0.158		
DATE	13	0.083	0.97	0.4773
DATE*CHLORDANE	13	0.080	0.94	0.5151
DATE*WATER	13	0.080	0.94	0.5151
DATE*CHLORDANE*WATER	13	0.080	0.94	0.5151
ERROR(b)	208	0.085		

Table A3. Split plot through time AOV table of 1986-87 log-transformed Order Cryptostigmata (Acari) densities with chlordane and water as main factors.

Order Cryptostigmata Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	5563.029	497.36	<0.0001
WATER	1	31.694	2.83	0.1119
CHLORDANE*WATER	1	15.822	1.41	0.2524
ERROR (a)	16	11.185		
DATE	13	186.325	17.78	<0.0001
DATE*CHLORDANE	13	149.665	14.28	<0.0001
DATE*WATER	13	61.508	5.87	<0.0001
DATE*CHLORDANE*WATER	13	59.866	5.71	<0.0001
ERROR (b)	208	10.482		

Table A4. Split plot through time AOV table of 1986-87 log-transformed Order Mesostigmata (Acari) densities with chlordane and water as main factors.

Order Mesostigmata Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	274.570	102.49	<0.0001
WATER	1	0.389	0.14	0.5378
CHLORDANE*WATER	1	0.298	0.11	0.7479
ERROR (a)	16	2.679		
DATE	13	18.999	6.22	<0.0001
DATE*CHLORDANE	13	19.439	6.36	<0.0001
DATE*WATER	13	7.322	2.40	<0.0001
DATE*CHLORDANE*WATER	13	7.262	2.38	<0.0001
ERROR	208	3.056		

Table A5. Split plot through time AOV table of 1986-87 log-transformed Order Prostigmata (Acari) densities with chlordane and water as main factors.

Order Prostigmata Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	84760.655	714.18	<0.0001
WATER	1	662.620	5.58	0.0312
CHLORDANE*WATER	1	14.902	0.12	0.7372
ERROR (a)	16	118.681		
DATE	13	3498.368	22.28	<0.0001
DATE*CHLORDANE	13	3974.319	25.31	<0.0001
DATE*WATER	13	1988.397	12.66	<0.0001
DATE*CHLORDANE*WATER	13	2122.291	13.52	<0.0001
ERROR (b)	208	157.012		

Table A6. Split plot through time AOV table of 1986-87 log-transformed Collembola (Insecta) densities with chlordane and water as main factors.

Order Collembola Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	126.000	60.00	<0.0001
WATER	1	0.127	0.06	0.8122
CHLORDANE*WATER	1	0.063	0.03	0.8665
ERROR (a)	16	2.100		
DATE	13	38.711	21.55	<0.0001
DATE*CHLORDANE	13	39.232	21.84	<0.0001
DATE*WATER	13	6.497	3.62	<0.0001
DATE*CHLORDANE*WATER	13	6.299	3.51	<0.0001
ERROR (b)	208	1.796		

Table A7. Split plot through time AOV table of 1986-87 log-transformed Order Diplura (Insecta) densities with chlordane and water as main factors.

Order Diplura Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	12.386	179.50	<0.0001
WATER	1	0.588	8.52	0.0100
CHLORDANE*WATER	1	0.491	7.11	0.0169
ERROR (a)	16	0.069		
DATE	13	2.945	30.74	<0.0001
DATE*CHLORDANE	13	2.748	28.68	<0.0001
DATE*WATER	13	0.311	3.25	0.0002
DATE*CHLORDANE*WATER	13	0.203	2.12	0.0144
ERROR (b)	208	0.095		

Table A8. Split plot through time AOV table of 1986-87 log-transformed microarthropod grazer trophic group densities with chlordane and water as main factors.

Microarthropod Grazer Trophic Group Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	334.761	1902.05	<0.0001
WATER	1	2.230	12.67	0.0026
CHLORDANE*WATER	1	1.294	7.35	0.0154
ERROR (a)	16	0.176		
DATE	13	3.187	18.60	<0.0001
DATE*CHLORDANE	13	2.199	12.83	<0.0001
DATE*WATER	13	0.531	3.10	0.0003
DATE*CHLORDANE*WATER	13	1.063	6.21	<0.0001
ERROR (b)	208	0.171		

Table A9 . Split plot through time AOV table of 1986-87 log-transformed microarthropod omnivore trophic group densities with chlordane and water as main factors.

Microarthropod Omnivore Trophic Group Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	291.688	1027.07	<0.0001
WATER	1	0.077	0.273	0.4145
CHLORDANE*WATER	1	0.809	2.848	0.1109
ERROR (a)	16	0.284		
DATE	13	3.291	18.61	<0.0001
DATE*CHLORDANE	13	3.009	17.02	<0.0001
DATE*WATER	13	0.450	2.55	0.0028
DATE*CHLORDANE*WATER	13	0.954	5.40	<0.0001
ERROR (b)	208	0.176		

Table A10. Split plot through time AOV table of 1986-87 log-transformed microarthropod predator trophic group densities with chlordane and water as main factors.

Microarthropod Predator Trophic Group Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	151.753	925.32	<0.0001
WATER	1	1.294	7.89	0.0126
CHLORDANE*WATER	1	0.747	4.55	0.0488
ERROR (a)	16	0.164		
DATE	13	1.616	9.80	<0.0001
DATE*CHLORDANE	13	1.732	10.50	<0.0001
DATE*WATER	13	0.642	3.89	<0.0001
DATE*CHLORDANE*WATER	13	0.918	5.57	<0.0001
ERROR (b)	208	0.165		

Table A11. Split plot through time AOV table of 1986-87 log-transformed microarthropod unknown trophic group densities with chlordane and water as main factors.

Microarthropod Unknown Trophic Group Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	204.512	560.30	<0.0001
WATER	1	4.629	12.66	0.0026
CHLORDANE*WATER	1	0.126	0.34	0.5741
ERROR (a)	16	0.365		
DATE	13	4.873	17.54	<0.0001
DATE*CHLORDANE	13	2.591	9.33	<0.0001
DATE*WATER	13	0.890	3.20	0.0002
DATE*CHLORDANE*WATER	13	0.613	2.21	<0.0104
ERROR (b)	208	0.277		

Table A12. Split plot through time AOV table of 1986-87 log-transformed plant shoot total nitrogen with chlordane and water as main factors.

	Plant Shoot total nitrogen mg g^{-1} dry wt.			
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0111	9.97	0.0018
WATER	1	0.0899	8.07	0.0049
CHLORDANE*WATER	1	0.1903	17.03	<0.001
ERROR (a)	16	0.0143		
DATE	13	0.2849	25.58	0.0052
DATE*CHLORDANE	13	0.0747	6.71	0.0151
DATE*WATER	13	0.0384	3.45	0.0451
DATE*CHLORDANE*WATER	13	0.0065	0.59	>0.1000
ERROR (b)	208	0.0111		

Table A13. Split plot through time AOV table of 1986-87 log-transformed plant root total nitrogen with chlordane and water as main factors.

Plant Root total nitrogen mg g^{-1} dry wt.				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.1297	5.81	0.0283
WATER	1	0.1497	6.71	0.0197
CHLORDANE*WATER	1	0.0033	0.14	0.7171
ERROR (a)	16	0.0223		
DATE	13	0.0830	11.77	<0.0001
DATE*CHLORDANE	13	0.0182	2.58	0.0025
DATE*WATER	13	0.0107	1.52	0.1122
DATE*CHLORDANE*WATER	13	0.0060	0.86	0.5992
ERROR (b)	208	0.0070		

Table A14. Split plot through time AOV table of 1986-87 log-transformed soil total nitrogen with chlordane and water as main factors.

Soil total nitrogen mg kg^{-1} dry wt.				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0048	0.48	0.5056
WATER	1	0.0129	1.32	0.2675
CHLORDANE*WATER	1	0.0018	0.18	0.6815
ERROR (a)	16	0.0098		
DATE	3	1.1045	208.13	<0.0001
DATE*CHLORDANE	3	0.0235	4.44	0.0079
DATE*WATER	3	0.0030	0.57	0.6342
DATE*CHLORDANE*WATER	3	0.0235	4.44	0.0079
ERROR (b)	48	0.0053		

Table A15. Split plot through time AOV table of 1986-87 log-transformed total nematode (Nematoda) densities with chlordane and water as main factors.

Total Nematode Densities kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	6.7208	28.61	<0.0001
WATER	1	0.1393	0.59	0.4617
CHLORDANE*WATER	1	0.0003	0.00	1.0000
ERROR (a)	16	0.2349		
DATE	11	13.9026	85.22	<0.0001
DATE*CHLORDANE	11	0.4117	2.52	0.0056
DATE*WATER	11	0.5556	3.41	0.0003
DATE*CHLORDANE*WATER	11	0.2826	1.73	0.0696
ERROR (b)	176	0.1631		

Table A16. Split plot through time AOV table of 1986-87 log-transformed root biomass with chlordane and water as main factors.

Root Biomass g kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0001	0.006	0.9400
WATER	1	0.2628	16.122	0.0010
CHLORDANE*WATER	1	0.0001	0.006	0.9400
ERROR (a)	16	0.0163		
DATE	13	0.0496	18.14	<0.0001
DATE*CHLORDANE	13	0.0066	2.41	0.0048
DATE*WATER	13	0.0093	3.41	<0.0001
DATE*CHLORDANE*WATER	13	0.0024	0.90	0.5495
ERROR (b)	208	0.0027		

Table A17. Split plot through time AOV table of 1986-87 log-transformed soil NH_4^+-N with chlordane and water as main factors.

NH_4^+-N $mgkg^{-1}$ dry soil in the Rhizosphere

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	1.2554	9.58	0.0070
WATER	1	0.3444	2.63	0.1244
CHLORDANE*WATER	1	0.2708	2.06	0.1705
ERROR (a)	16	0.1310		
DATE	12	0.9442	17.24	<0.0001
DATE*CHLORDANE	12	0.3270	5.97	<0.0001
DATE*WATER	12	0.1671	3.04	0.0006
DATE*CHLORDANE*WATER	12	0.0797	1.46	0.1438
ERROR (b)	192	0.0547		

Table A18. Split plot through time AOV table of 1986-87 log-transformed soil NO_3^--N with chlordane and water as main factors.

NO_3^--N mg kg^{-1} dry soil in the Rhizosphere				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0698	1.77	0.2020
WATER	1	0.0389	0.98	0.3474
CHLORDANE*WATER	1	0.0416	1.05	0.3208
ERROR (a)	16	0.0394		
DATE	12	0.5522	25.06	<0.0001
DATE*CHLORDANE	12	0.1234	5.60	<0.0001
DATE*WATER	12	0.0435	1.97	0.0284
DATE*CHLORDANE*WATER	12	0.0153	0.69	0.7559
ERROR (b)	192	0.0220		

Table A19. Split plot through time AOV table of 1986-87 log-transformed total inorganic nitrogen with chlordane and water as main factors.

Total Inorganic Nitrogen mg kg^{-1} dry soil in the Rhizosphere				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	1.2695	9.66	0.0068
WATER	1	0.2539	1.93	0.1838
CHLORDANE*WATER	1	0.0848	0.64	0.4438
ERROR (a)	16	0.1314		
DATE	12	0.4494	8.37	<0.0001
DATE*CHLORDANE	12	0.2788	5.20	<0.0001
DATE*WATER	12	0.1230	2.29	0.0095
DATE*CHLORDANE*WATER	12	0.0619	1.15	0.3187
ERROR (b)	192	0.0536		

Table A20. Split plot through time AOV table of 1986-87 log-transformed gravimetric soil moisture content with chlordane and water as main factors.

Gravimetric Soil Moisture Content (%)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.6648	5.02	<0.0001
WATER	1	1.5935	123.52	<0.0001
CHLORDANE*WATER	1	0.0895	6.94	0.0180
ERROR (a)	16	0.0129		
DATE	12	3.4692	498.01	<0.0001
DATE*CHLORDANE	12	0.0257	3.70	<0.0001
DATE*WATER	12	0.1329	19.09	<0.0001
DATE*CHLORDANE*WATER	12	0.0125	1.80	0.0499
ERROR (b)	192	0.0069		

Table A21. Split plot through time AOV table of 1986-87 log-transformed soil NH_4^+-N (captured using buried cation exchange resin bags) with chlordane and water as main factors.

NH_4^+-N ($\mu g\ bag^{-1}$)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0280	0.79	0.3966
WATER	1	0.0024	0.07	0.7975
CHLORDANE*WATER	1	0.0124	0.35	0.5686
ERROR (a)	16	0.0355		
DATE	2	1.1946	31.32	<0.0001
DATE*CHLORDANE	2	0.0028	0.08	0.9278
DATE*WATER	2	0.0026	0.07	0.9338
DATE*CHLORDANE*WATER	2	0.0124	0.33	0.7241
ERROR (b)	32	0.0381		

Table A22. Split plot through time AOV table of 1986-87 log-transformed soil NO_3^--N (captured using buried anion exchange resin bags) with chlordane and water as main factors.

NO_3^--N ($\mu g\ bag^{-1}$)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.1066	2.49	0.1341
WATER	1	0.0759	1.78	0.2008
CHLORDANE*WATER	1	0.0282	0.66	0.4370
ERROR (a)	16	0.0427		
DATE	2	3.8468	151.70	<0.0001
DATE*CHLORDANE	2	0.0646	2.55	0.0940
DATE*WATER	2	0.0110	0.43	0.6513
DATE*CHLORDANE*WATER	2	0.0075	0.30	0.7454
ERROR (b)	32	0.0253		

Table A23. Split plot through time AOV table of 1986-87 log transformed nitrogen mineralization potential with chlordane and water as main factors.

Nitrogen mineralization Potential (mg N kg^{-1} dry soil)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0325	1.49	0.2399
WATER	1	0.0864	3.98	0.0634
CHLORDANE*WATER	1	0.0014	0.06	0.8122
ERROR (a)	16	0.0217		
DATE	1	0.2329	8.20	0.0113
DATE*CHLORDANE	1	0.1420	5.00	0.0400
DATE*WATER	1	0.1173	4.13	0.0591
DATE*CHLORDANE*WATER	1	0.0073	0.26	0.0617
ERROR (b)	16	0.0284		

Table A24. Split plot through time AOV table of July log-transformed plant growth with chlordane and water as main factors.

Plant Growth - July -(volume cm^3)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.463	5.74	0.0435
WATER	1	0.004	0.047	0.8355
CHLORDANE*WATER	1	0.062	0.767	0.4158
ERROR	16	0.081		

Table A25. Split plot through time AOV table of September log-transformed plant growth with chlordane and water as main factors.

Plant Growth -September-(volume cm^3)				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.3329	1.549	0.2485
WATER	1	0.1806	0.849	0.3934
CHLORDANE*WATER	1	0.4478	0.210	0.6635
ERROR	11	0.2129		

Table A 26. Split plot through time AOV table of 1986 log-transformed relative plant shoot growth with chlordane and water as main factors.

RELATIVE PLANT SHOOT GROWTH

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.1393	0.54	0.4910
WATER	1	0.0052	0.02	0.8941
CHLORDANE*WATER	1	0.0165	0.06	0.8079
ERROR (a)	8	0.2566		
DATE	1	1.6892	20.25	0.0020
DATE*CHLORDANE	1	0.1485	1.78	0.2188
DATE*WATER	1	0.0013	0.02	0.9008
DATE*CHLORDANE*WATER	1	0.0996	1.19	0.3062
ERROR (b)	8	0.0834		

Table A27. Split plot through time AOV table of 1986 log-transformed relative plant root growth with chlordane and water as main factors.

RELATIVE PLANT ROOT GROWTH

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0022	0.38	0.5590
WATER	1	0.0033	0.57	0.4788
CHLORDANE*WATER	1	0.0231	3.91	0.0832
ERROR (a)	8	0.0059		
DATE	1	0.0486	136.79	<0.0001
DATE*CHLORDANE	1	0.0000	0.24	0.6373
DATE*WATER	1	0.0014	4.20	0.0745
DATE*CHLORDANE*WATER	1	0.0006	1.74	0.2232
ERROR (b)	8	0.0003		

Table A28. Split plot through time AOV table of 1986 log-transformed plant root total nitrogen with chlordane and water as main factors.

Plant Root total nitrogen (mg N/rhizosphere)

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.2398	85.30	<0.0001
WATER	1	0.0432	15.38	0.0012
CHLORDANE*WATER	1	0.0197	7.03	0.0174
ERROR (a)	16	0.0028		
DATE	2	0.0400	165.97	<0.0001
DATE*CHLORDANE	2	0.0002	1.11	0.3463
DATE*WATER	2	0.0007	2.86	0.0772
DATE*CHLORDANE*WATER	2	0.0004	1.79	0.1889
ERROR (b)	24	0.0002		

Table A29. Split plot through time AOV table of 1986 log-transformed plant shoot total nitrogen with chlordane and water as main factors.

Plant Shoot total nitrogen (mg N/aboveground plant)

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.1333	0.25	0.6296
WATER	1	0.0965	0.18	0.6819
CHLORDANE*WATER	1	0.8576	1.59	0.2244
ERROR (a)	16	0.5367		
DATE	2	12.4350	528.55	<0.0001
DATE*CHLORDANE	2	0.0304	1.29	0.2926
DATE*WATER	2	0.0326	1.39	0.2689
DATE*CHLORDANE*WATER	2	0.0500	2.13	0.1411
ERROR (b)	24	0.0235		

Table A30. Split plot through time AOV table of 1986 log-transformed soil inorganic nitrogen with chlordane and water as main factors.

Soil Inorganic nitrogen (mg N/rhizosphere)

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	2.6161	23.12	<0.0001
WATER	1	0.0512	0.45	0.5116
CHLORDANE*WATER	1	0.0405	0.35	0.5657
ERROR (a)	16	0.1128		
DATE	2	0.1996	2.14	0.1347
DATE*CHLORDANE	2	0.3712	3.97	0.0288
DATE*WATER	2	0.1485	1.59	0.2199
DATE*CHLORDANE*WATER	2	0.0075	0.08	0.9229
ERROR (b)	32	8.9595		

Table A31. Split plot through time AOV table of 1986 log-transformed of rhizosphere total nitrogen with chlordane and water as main factors.

Rhizosphere total nitrogen (mg N/volume)

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.7606	8.22	0.0111
WATER	1	0.0835	0.90	0.3666
CHLORDANE*WATER	1	0.0247	0.269	0.6165
ERROR (a)	16	0.0923		
DATE	2	0.1000	1.76	0.1927
DATE*CHLORDANE	2	0.1851	3.26	0.0557
DATE*WATER	2	0.0754	1.33	0.2830
DATE*CHLORDANE*WATER	2	0.0323	0.57	0.5727
ERROR (b)	24	0.0567		

Table A32. Split plot through time AOV table of 1986 log-transformed of whole system total nitrogen with chlordane and water as main factors.

Whole System total nitrogen (mg N/whole plant)

Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.0038	0.01	0.9177
WATER	1	0.1936	0.57	0.4662
CHLORDANE*WATER	1	0.3830	1.14	0.3008
ERROR (a)	16	0.3349		
DATE	2	6.6359	210.11	<0.0001
DATE*CHLORDANE	2	0.0368	1.17	0.3285
DATE*WATER	2	0.0774	2.45	0.1074
DATE*CHLORDANE*WATER	2	0.1139	3.61	0.0427
ERROR (b)	24	0.0315		

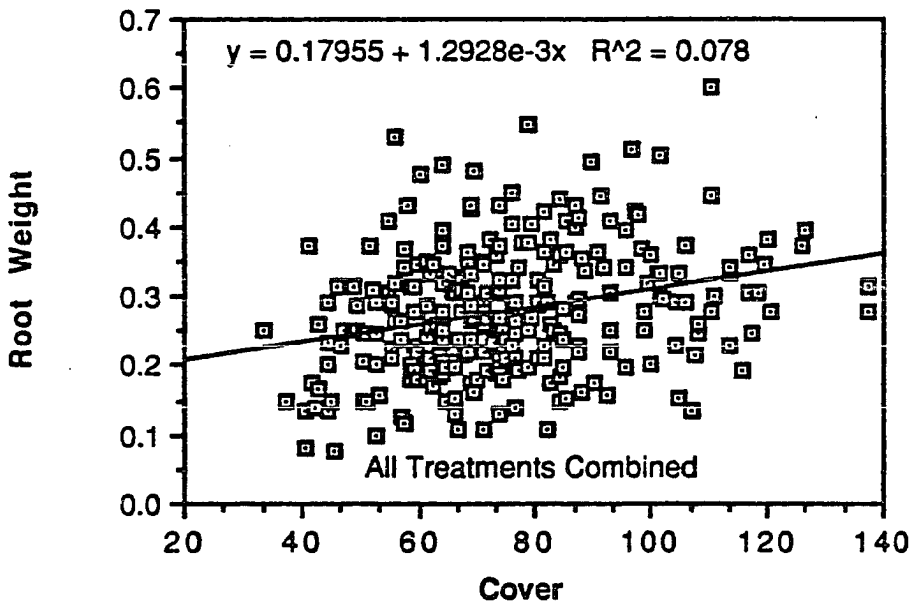
Table A33. Split plot through time AOV table of 1986-87 log-transformed shoot biomass with chlordane and water as main factors.

Shoot Biomass g kg^{-1} dry soil				
Source of Variation	df	Mean Square	F Ratio	Significance
CHLORDANE	1	0.1110	7.7286	0.0126
WATER	1	0.0899	6.2558	0.0180
CHLORDANE*WATER	1	0.1903	13.2480	0.0026
ERROR (a)	16	0.0145		
DATE	13	0.2849	25.58	<0.0001
DATE*CHLORDANE	13	0.0746	6.71	<0.0001
DATE*WATER	13	0.0384	3.45	<0.0001
DATE*CHLORDANE*WATER	13	0.0065	0.59	0.8624
ERROR (b)	208	0.0111		

APPENDIX B

Regression Figures

Figure B1. Linear regressions of A) root and B) shoot biomass (g dry wt per plant sample) versus shoot cover [X- projected aerial cover (cm^2)]. All dates and treatments combined.



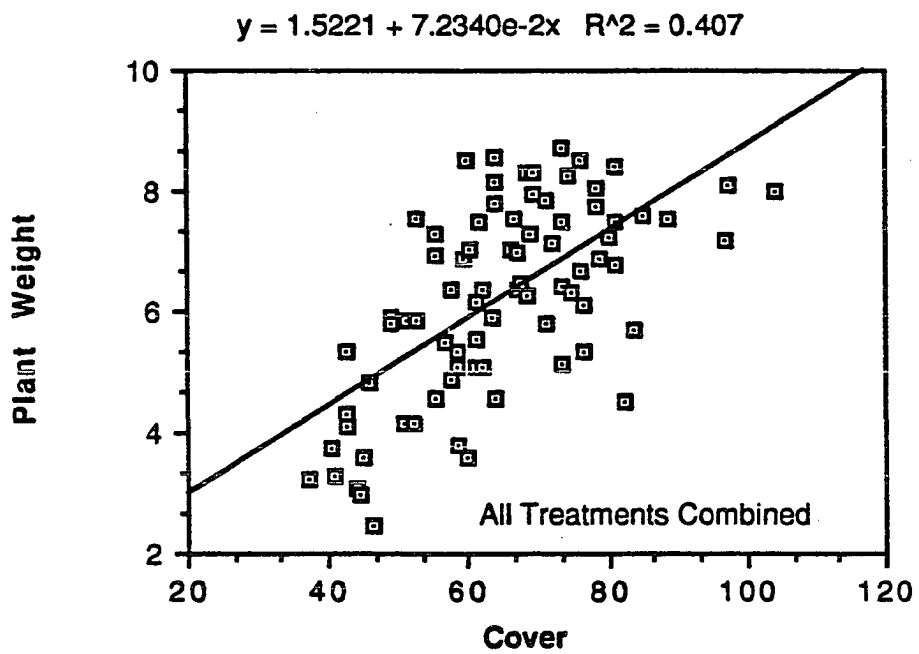
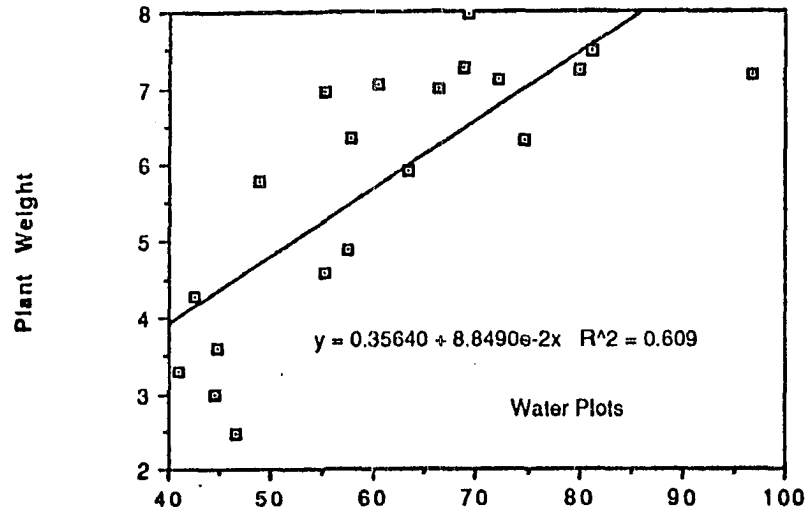
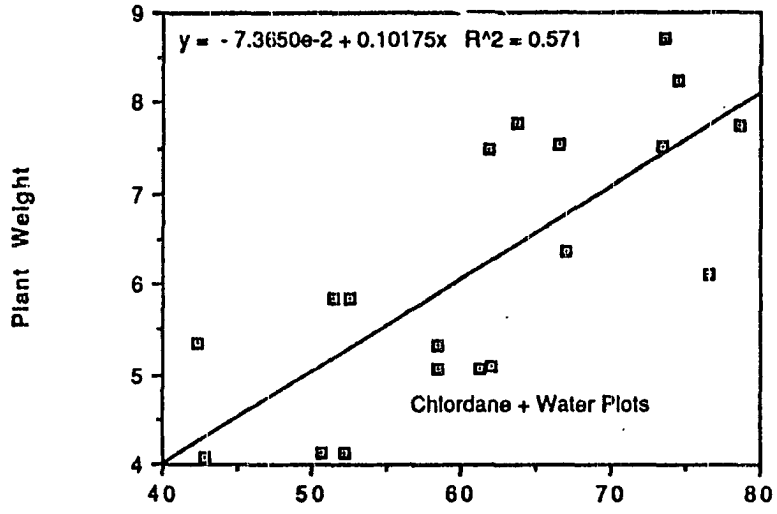
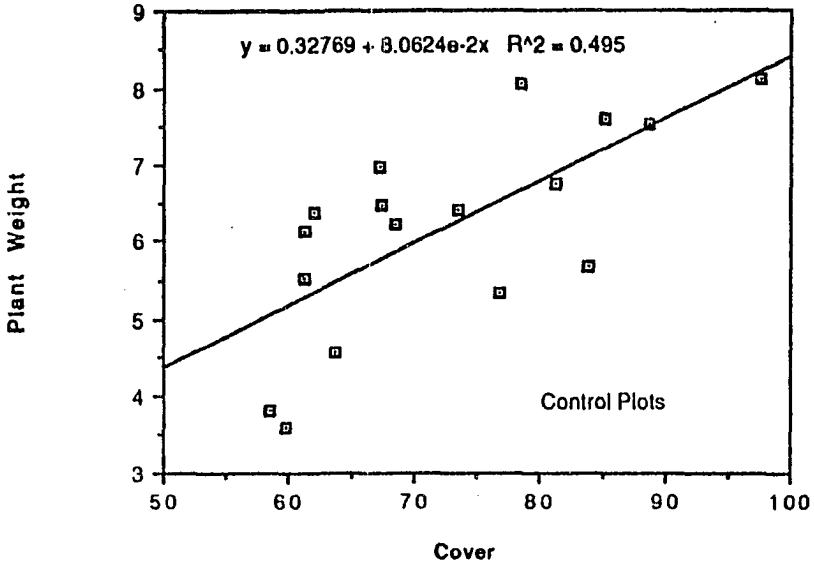


Figure B2. Linear regressions of shoot biomass (g dry wt per plant) versus shoot cover [X- projected aerial cover (cm^2)]for each treatment. All dates combined.







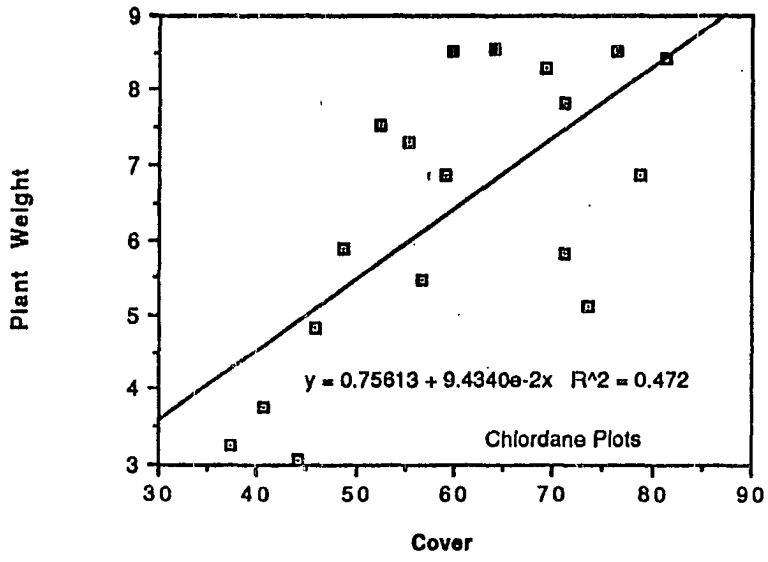


Figure B3. Linear regressions of root biomass (g dry wt per plant) versus shoot cover [X- projected aerial cover (cm^2)]for each treatment. All dates combined.