



Mineralization of nitrogen and carbon in adjacent crop-fallow and native range soils
by Karnes Edwin Neill

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

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Abstract:

Well water monitoring programs have detected significant levels of nitrate-nitrogen ($\text{NO}_3\text{-N}$) in groundwaters of Montana within geographical regions where crop-fallow rotation is the primary agricultural production practice. It is hypothesized that the mineralization of nitrogen (N) along with the slow but continual leaching of unused soil profile water in fallow cycles is responsible for the accumulation of $\text{NO}_3\text{-N}$ below the root zone. This study was designed to (i) determine changes in organic N and C status resulting from long-term crop-fallow management, (ii) determine differences in mineralization rates of N and C between crop-fallow and native range soils, and (iii) evaluate the potential for N mineralization to account for high $\text{NO}_3\text{-N}$ levels in groundwaters associated with long-term crop-fallow management practices.

Thirty-two soils consisting of 12 adjacent (same soil series) crop-fallow/native range pairs and eight additional soils were collected from different geographical regions in Montana. Soil characterization included pH, EC, total organic C (TOC), total Kjeldahl N (TKN), and texture. Soluble C and N characterization included dissolved organic C (DOC), anthrone reactive C (ARC), and dissolved organic N (DON) and was performed on a selected subset of 16 soils involved in an incubation study. Native range soils were observed to have significantly higher concentrations of TOC, TKN, DOC, ARC, and DON than adjacent crop-fallow soils.

Mineralization rates of N and C were measured under laboratory conditions using column reaction vessels for 14 weeks at 22.5°C . Accumulation of N and C was linear with time over the 14 week incubation. Mineralization rates of N ranged from 0.11 to 1.41 mg N kg^{-1} soil d^{-1} while mineralization rates of C ranged from 1.7 to 14.0 mg C kg^{-1} soil d^{-1} . Both N and C mineralization rates were observed to be significantly higher in native range soils than in paired crop-fallow soils.

Annual N production based on mineralization rates observed in this study suggest that production of inorganic N via mineralization may often exceed crop N uptake. This establishes conditions which may lead to leaching of $\text{NO}_3\text{-N}$ beyond the root zone.

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APPROVAL

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Karnes Edwin Neill

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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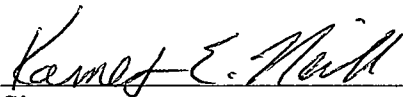
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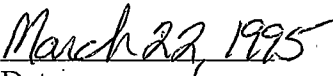
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ABSTRACT

Well water monitoring programs have detected significant levels of nitrate-nitrogen ($\text{NO}_3\text{-N}$) in groundwaters of Montana within geographical regions where crop-fallow rotation is the primary agricultural production practice. It is hypothesized that the mineralization of nitrogen (N) along with the slow but continual leaching of unused soil profile water in fallow cycles is responsible for the accumulation of $\text{NO}_3\text{-N}$ below the root zone. This study was designed to (i) determine changes in organic N and C status resulting from long-term crop-fallow management, (ii) determine differences in mineralization rates of N and C between crop-fallow and native range soils, and (iii) evaluate the potential for N mineralization to account for high $\text{NO}_3\text{-N}$ levels in groundwaters associated with long-term crop-fallow management practices.

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Annual N production based on mineralization rates observed in this study suggest that production of inorganic N via mineralization may often exceed crop N uptake. This establishes conditions which may lead to leaching of $\text{NO}_3\text{-N}$ beyond the root zone.

CHAPTER 1

LITERATURE REVIEW

Introduction

The Montana State University Extension Service conducted a Well Water Testing Program in Montana between April 1989 and November 1990. Results from this program showed that 5.8% of all wells tested had nitrate-nitrogen (NO_3^- -N) levels exceeding the EPA health standard of 10 mg L^{-1} (Bauder et al, 1991). Half of those wells exceeding the EPA health standard originated from three geographic areas encompassing seven counties. These regions are dominated by dryland agriculture and a significant correlation has been shown between the incidence of high NO_3^- -N in well water with the percent of each county in summer fallow (Bauder et al., 1993). It is hypothesized that mineralization of organic nitrogen (N), along with the continual leaching of unused soil profile water in fallow cycles, is responsible for the accumulation of NO_3^- -N below the root zone.

This study was designed to measure the mineralization of N and carbon (C) in soils from adjacent native range and crop-fallow sites under optimal conditions. Rates of mineralization were determined by a laboratory incubation under optimal temperature and moisture conditions. Functional relationships between C and N mineralization rates and soil properties were also examined.

Review of Literature

Crop-Fallow Management Problems

The practice of summer fallow is quite common in Montana and has been a major agricultural management practice for more than 60 years. Crop-fallow management practices are intended to store critical soil moisture supplies for the subsequent crop and to control weeds during the fallow season. However, many researchers have shown that crop-fallow management is not an efficient water storage practice. The average percent of water actually stored in the rooting zone during the fallow period of an alternate crop-fallow sequence throughout the Great Plains is only 16%, with a few locations storing as much as 20% (Mathews and Army, 1960; Haas and Willis, 1962; Greb et al., 1970; Tanaka, 1985). Evapotranspiration is the primary cause of water loss from dryland agricultural fields during the fallow season (Mathews and Army, 1960; Haas and Willis, 1962) with the largest increase in soil water content occurring during the winter months, after harvest, when soil surface temperatures decrease and evaporation rates are low (Greb et al., 1970; Tanaka, 1985).

Soil water stored during winter months may percolate below the rooting zone during spring thaw, eventually moving into shallow groundwater aquifers. Deep percolation of soil water and losses of NO_3^- -N under cultivated soils has been reported to occur mainly during the winter months when rates of evapotranspiration are at a minimum (Cameron and Wild, 1984; Evans et al., 1994). The percolation of unused soil

water during the fallow season provides a mechanism for transport of NO_3^- -N out of the soil profile and into groundwater (Kreitler and Jones, 1975). Levels of NO_3^- -N exceeding the EPA health standard of 10 mg L^{-1} have been observed in groundwater under many agricultural areas of the Great Plains (Bauder et al., 1991; Kreitler and Jones, 1975).

Nitrogen fertilizer is frequently cited as the probable source for high NO_3^- -N in crop-fallow soil profiles. Crop yield goals are generally fairly low (e.g. $25\text{-}35 \text{ bu acre}^{-1}$) in areas of central and eastern Montana due to a lack of available water during the growing season. Given the small amount of N required to meet these yield goals, producers rely primarily on soil-mineralized N produced during the fallow period. (Bauder et al., 1991). Consequently, over-fertilization is assumed not to be an important source of excess soil profile NO_3^- -N in crop-fallow soils. The main source of high NO_3^- -N is believed to be from accelerated mineralization of soil organic N when native soils are cultivated and remain under dryland crop-fallow farming over many years (Kreitler and Jones, 1975; Cameron and Wild, 1984; Lamb et al., 1985; Bergström, 1987; Bauder et al., 1991; Evans et al., 1994).

Soil Organic Matter Studies

It is well known that soil organic matter (SOM) decreases with time when native soils are cultivated for many years. Reported losses of total organic C and total N since the onset of cultivation have been observed to range between 16 and 58% depending on the length of time soils have been under cultivation and the quantity of crop residue

incorporated during stubble mulching (Tiessen et al., 1982; Lamb et al., 1985). The change in soil organic C and N occurs primarily in the surface horizon (Blank and Fosberg, 1989) and has been observed to decline as a function of time linearly, in a wheat-fallow farming system (Rasmussen et al., 1980; Rasmussen and Parton, 1994), as well as exponentially, under continuous cultivation (Greenland and Fore, 1964).

The loss of total C and N by continual cultivation is evidence that the C and N cycle of native systems has been disrupted. In native grasslands, the annual N requirement is met by a combination of four N supplying mechanisms (Clark, 1977). The first mechanism includes N storage in roots of grasses over the winter and the re-use of this N for new growth the following spring. The second mechanism involves the mineralization of easily decomposed organic N compounds such as above ground plant litter and various root components. A third mechanism consists of the mineralization of organic N which has been synthesized by microorganisms. Lastly, there is the slow release of available N pools from humic N comprised of polymerized N components (Clark, 1977). A fifth source of plant required N may come from fixed ammonium-N ($\text{NH}_4^+\text{-N}$) released from clay minerals as $\text{NH}_4^+\text{-N}$ concentrations in solution decrease through microbial nitrification and immobilization processes (Drury and Beauchamp, 1991). The dense root system in prairie soils enables rapid plant uptake of available inorganic N pools released from any one of the above mechanisms (DeLuca and Keeney, 1993). When native soils are cultivated, the cycle is disrupted, resulting in the rapid mineralization of organic N compounds and a subsequent reduction in plant uptake

(Cambardella and Elliot, 1992). Consequently, the net effect is an over-production of inorganic N corresponding to higher levels of inorganic N observed in cultivated soils (Broder et al., 1984; DeLuca and Keeney, 1993). Similarly, most of the C lost during long-term crop-fallow cultivation of native soils is attributed to the increased biological oxidation of C during the fallow year (Collins et al., 1992).

Long term cultivation also decreases microbial populations, and results in lower amounts of biomass C and N found in cropped soils than in native soils (Collins et al., 1992; DeLuca and Keeney, 1993a). However, as a fraction of the total microbial population, NH_4^+ -oxidizers and NO_2^- -oxidizers are more prolific in cultivated soils than in native soils (Broder et al., 1984; Follett and Schimel, 1989). As a result, immobilization and conservation of mineral N is greatly reduced by long-term tillage which is evident by the increase in inorganic N concentrations along with the decline in mineralization of organic C observed in soils after they are cultivated (Schimel et al., 1985; Follett and Schimel, 1989).

Soil Aggregation Studies

In order to understand the influence long-term tillage practices have had on the N and C status of soils, an examination of the mechanisms involved in the loss of N and C from soils is required. Recently, researchers have looked at macroaggregation properties of native and cultivated soils and have found that losses of N and C compounds associated with cultivation have been directly linked to losses of structural stability in

grassland soils (mainly in the particulate organic matter fraction). A higher proportion of total soil organic C and N is comprised of particulate organic matter-C (POM-C) and POM-N in native-sod than in bare-fallow soils. After 20 years of bare-fallow management, a loss of more than 50% of the organic C in the POM fraction has been observed (Cambardella and Elliot, 1992). The subsequent reduction in fertility by cultivation is due to a depletion of the POM fraction under cultivation along with an increase in the organo-mineral associated, less nutrient available, organic matter pool. The POM fraction is found to be aggregated by encrustation with microbial mucilage and clay to form macroaggregates (Beare et al., 1994a). These macroaggregates or water stable aggregates (WSA) comprise the majority of C and N lost during cultivation (Angers et al., 1992; Cambardella and Elliot, 1993).

Native soils tend to have more large (250- to 2000- μ m) macroaggregates than tilled soils (Cambardella and Elliot, 1992) and macroaggregates of native grassland soils have greater C and N mineralization potentials than microaggregates predominantly found in conventionally tilled soils (Beare et al., 1994b). Studies have shown that macroaggregates from grassland soils contain an enriched labile organic matter fraction (ELF) which comprise 17 to 20% of the total soil C and 9 to 25% of the total soil N (Cambardella and Elliot, 1994). This highly mineralizable ELF is thought to be physically protected from decomposition within the structure of macroaggregates (Cambardella and Elliot, 1994). Buyanovsky et al. (1994) found that 50% of the SOM was protected from microbial attack, primarily by the structural organization of particles into aggregates and by the

chemical structure of organic matter as it bonds with mineral particles. Conventional tillage causes more frequent disruption of macroaggregates, exposing more of the physically protected, but relatively labile SOM to microbial attack and mineralization (Beare et al. 1994b). Some of the most resistant N (non-hydrolyzable N) fractions and C compounds in soils become available for mineralization during long-term cultivation (Lamb et al., 1985). The pools of organic C and N associated with macroaggregates, along with undecomposed vegetative particles, have the shortest residence times in the POM fraction (1 to 2 years for large and small particles, respectively) upon cultivation (Buyanovsky et al., 1994) and rapid losses of POM when native soils are first cultivated most likely occur from the destruction of macroaggregates. As macroaggregates are reduced in size, previously unavailable (occluded) ELF is released and quickly mineralized (Beare et al., 1994a). The smaller microaggregates (<53 μm) produced have relatively low concentrations of POM and consist of highly humified C and N fractions tightly bound to soil minerals (Anderson et al., 1981; Paul, 1984; Beare et al., 1994a; 1994b). This results in longer residence times (10 years) of organic C and N pools associated with microaggregates in soils (Buyanovsky et al., 1994). Subsequently, cultivation of native soils results in rapid loss of labile, macroaggregate-protected organic C and N fractions and the proportional increase of more recalcitrant organic C and N fractions associated with microaggregates (Beare et al., 1994b).

Soluble Organic N and C Studies

Carbon and N mineralized during initial stages of POM breakdown is derived from the "active" or labile components of soil organic matter (Collins et al., 1992). Total soil organic C and N measured as TOC and TKN greatly exceed the labile pools of C and N directly available for mineralization. Therefore, many researchers have attempted to quantify the soluble, labile pools of organic C and N important in mineralization. Soluble fractions of N have been identified as amino-acid N, amino-sugar N (hydrolyzable N), and nonhydrolyzable N (Campbell et al., 1991; Németh et al., 1988). Amino-acid N and amino-sugar N are presumed to be the soluble fractions most easily mineralized in soil, especially amino-sugar N because it is found in the greatest concentrations (Németh et al., 1988). Management systems which contain fallow wheat monocultures continually deplete the amino acid- and amino sugar-N concentrations (Campbell et al., 1991). The mineralization of organic N is thought to be by the direct absorption of amino-acid substrates by microorganisms followed by the breakdown of those amino-acids by endocellular enzymes (Barak et al., 1990). The labile C fraction is thought to consist of water-soluble C (simple sugars, organic acids, proteins, and small-chained carbohydrates), microbial biomass, and microbial products that are readily metabolized during mineralization. Rapid losses of soil C after tillage come from the mineralization of soluble-C constituents found in native soils. These simple sugars and carbohydrates react with anthrone and can be quantified by spectroscopic methods (Brink et al. 1960; Sikora and McCoy, 1990; Janzen et al., 1992; DeLuca and Keeney, 1993a; 1993b; 1994).

Soluble fractions of C and N decline in a similar manner to total organic and biomass C and N under cultivation. DeLuca and Keeney (1993a, 1994) found higher soluble anthrone reactive C (ARC) and soluble amino-N concentrations (40 and 32% higher, respectively) in prairie soils of central Iowa than corresponding cultivated soils. The level of soluble or free carbohydrates and amino acids reflect a balance between degradation and assimilation of organic materials in soils, and indicate the state or condition of the N and C cycles in soils (DeLuca and Keeney, 1993a). Cultivated soils support less microbial biomass, accumulate NO_3^- -N, and generally maintain a smaller pool of soluble ARC and amino-N fractions (DeLuca and Keeney, 1993a). Because of their inferred relationship to the N cycle in soils, soluble amino-N, soluble sugars and carbohydrates (ARC), and soluble C:N ratios may be useful indices of organic matter quality when used to compare the N cycle of systems within the same soil map unit (DeLuca and Keeney, 1993a).

Nitrogen Mineralization Studies

Considerable research has been performed to quantify the amount of N released from the mineralization of organic N in soils. Studies have been conducted under both field and laboratory conditions with the primary goal of identifying rates of N mineralization as a function of environmental conditions. One common approach is to conduct laboratory incubations in batch experiments, where soils are placed in reaction vessels and periodically sampled and analyzed for inorganic N. Stanford and Smith

(1972) developed a long-term laboratory incubation procedure which entailed periodic leaching of soils in incubation vessels and evaluating leachate for inorganic N concentrations. This procedure, with various modifications, has been used by many other researchers to quantify N mineralization over long-term incubations (Gavlak, 1985; Poovarodom and Tate, 1988; Richter et al., 1982; Juma et al., 1984; and many others) and has provided important kinetic information on the mineralization rates of organic N. Intact soil cores have also been used in laboratory incubation experiments to study mineralization processes of relatively undisturbed soils (Reddy, 1982). They can also be used to study transport mechanisms and crop influences on mineralization properties. Field studies of N mineralization often use a buried bag (polyethylene) approach in which soils are removed from a site, placed in polyethylene bags and buried. (Choudhury and Cornfield, 1978; Poovarodom et al., 1988). The bags are periodically sampled to estimate N accumulations under field conditions.

Kinetic models have been developed from the incubation studies to express the relationship of N mineralization as a function of time. In many studies, the accumulation of N has been observed to be linear with the square root of time (Stanford and Smith, 1972; Reddy, 1982; Poovarodom and Tate, 1988). The curvilinear relationship between N mineralized and time observed in these studies can be explained by a first-order equation (Stanford and Smith, 1972; Cassman and Munns, 1980; Talpaz et al., 1981; Richter et al., 1982; Juma et al., 1984):

$$dN_0 / dt = -k N_0 \quad (1)$$

where N_0 is potentially mineralizable N and k is the mineralization rate constant (time^{-1}).

Integration of equation (1) over time yields:

$$N = N_0 \cdot (1 - e^{(-kt)}) \quad (2)$$

where N is N mineralized in a given time interval (t). These equations have been very useful in predicting potentially mineralizable N, N_0 , for many soils and estimates of N_0 range from 20 up to over 900 mg N kg^{-1} soil (Stanford and Smith, 1972; Poovarodom and Tate, 1988). The accumulation of N in shorter studies (14 weeks) has been observed to be linear over time (Gavlak, 1985; Cabrera, 1993). The curvilinear relationship of N accumulation with time in longer experiments (30 weeks; Stanford and Smith), suggests that available N supplies are exhausted (N_0) within a given time period (somewhere between 14 and 30 weeks).

Nitrogen and C mineralization rates have been reported and vary due to incubation conditions, substrate availability, and incubation time. Rates of N mineralization from incubation experiments have been observed to fall within a range of about 0.25 to 0.7 mg N kg^{-1} soil d^{-1} (Gavlak, 1985; Barak et al., 1990). Gavlak (1985) predicted N mineralization rates to be 0.55, 0.80, 0.94, and 1.33 kg N ha^{-1} d^{-1} (0.28, 0.40, 0.47, and 0.67 mg N kg^{-1} soil d^{-1}) at 14° C for four Montana soils having 1.8, 2.4, 2.6, and 4.4% OM, respectively. Barak et al. (1990) observed an average net inorganic N mineralization of 0.6 mg N kg^{-1} soil d^{-1} over seven days. Average mineralization rates of C during the same seven day time period were observed to be 2.0 mg C kg^{-1} soil d^{-1} . The rates provide

valuable information for estimating yearly production of inorganic N in soils. Annual estimated total N mineralized has been observed to range between 38 and 53 kg N ha⁻¹ in acidic soils of New Jersey depending on organic matter content (Poovarodom et al., 1988). Gavlak (1985) estimated 39 to 84 kg N ha⁻¹ would be mineralized in a 61 day period, with approximately 20 kg N ha⁻¹ OM%⁻¹ mineralized.

The rate of N and C mineralization is highly influenced by soil temperature and moisture content. Previous studies show that temperatures between 20° and 30° C appear to be optimal for both C and N mineralization (Stanford and Smith, 1972; Choudhury and Cornfield, 1978; Cassman and Munns, 1980; Gavlak, 1985; and others). Temperature effects on N mineralization are best explained using a temperature coefficient (Q_{10}) of 2.0, which states that the rates of N mineralization change by a factor of 2 with each 10° C change in temperature (Tyler et al., 1959; Stanford et al., 1973; Westermann and Crothers, 1980; Campbell et al., 1981). Optimal moisture contents for mineralization are in the range of 0.1 to 0.3 bars (Cassman and Munns, 1980; Poovarodom and Tate, 1988).

Summary

Nitrate-N concentrations higher than the EPA health standard of 10 mg L⁻¹ have been found in groundwaters under areas dominated by crop-fallow management. The high concentrations of NO₃⁻-N observed in crop-fallow soils is believed to be from the mineralization of organic N in soil. A decline in total organic N and C levels due to

continued cultivation has been documented and the majority of the loss comes from the soluble organic N and C constituents associated with macroaggregates. Cultivation causes the destruction of macroaggregates and the subsequent release of soluble N and C fractions, which are rapidly mineralized. The net result is a loss in organic N and C and over-production of inorganic N, such as NO_3^- -N. Therefore, many years of crop-fallow management may result in the leaching of NO_3^- -N from the soil profile.

Objectives

The objectives of this study were to: (i) determine changes in soil C and N status associated with long-term crop-fallow management practices, (ii) determine changes in mineralization rates of C and N due to long-term crop-fallow management, and (iii) evaluate the potential for N mineralization to account for high NO_3^- -N levels in groundwaters associated with crop-fallow agricultural regions.

CHAPTER 2

MATERIALS AND METHODS

Soils

Thirty-two soils were collected from different geographical regions in Montana exhibiting a wide range of organic matter (OM) content. Twenty-four of the soils consisted of 12 pairs of adjacent (same soil series) crop-fallow and native-range soils. These paired crop-fallow/native range soils were collected from two dryland agriculture regions in Montana previously found to have high nitrate-nitrogen (NO_3^- -N) concentration in well water (Bauder et al, 1991). All crop-fallow sites had been under crop/fallow management for a minimum of 40 years. The paired crop-fallow/native range soils were gathered from the same soil map unit (series) and were separated by no more than 30 m (100 ft). The remaining eight soils were gathered from representative regions across the state and were not involved with the crop-fallow/native-range comparison. Six of the 24 crop-fallow/native range soil pairs exhibiting a large difference in total organic C (TOC) and total Kjeldahl N (TKN) between management practices, along with four of the eight additional soils, were included in an incubation study to determine C and N mineralization rates (Table 1). Location, land-use information and legal descriptions of the 32 soils collected for the study are contained in Appendix Table 14.

Table 1. Site locations and land-use specifications of the 16 soils used in the C and N mineralization study.

Soil Series	Land Uses	Location	MT Region	County
Farland-Cherry SiL	Crop-Fallow / Native Range	Scobey	Northeast	Daniels
Farland-Cherry SiL	Crop-Fallow / Native Range	Flaxville	Northeast	Daniels
Judith gCL	Crop-Fallow / Native Range	Stanford	Central	Judith Basin
Turner-Beaverton Complex	Crop-Fallow / Native Range	Wolf Point	Northeast	Roosevelt
Williams-Zahill L	Crop-Fallow / Native Range	Wolf Point	Northeast	Roosevelt
Williams-Zahill L	Crop-Fallow / Native Range	Flaxville	Northeast	Daniels
Beaverll	Pasture	Bozeman	Southwest	Gallatin
Creston	Crop Rotation	Creston	Northwest	Flathead
Williams L	Native Range	Miles City	East	Custer
Winifred CL	Crop-Fallow	Windham	Central	Judith Basin

Roughly 35 kg of the surface horizon (0-30 cm) was collected from each site, sealed in plastic garbage bags, then stored at field-moist condition at 4° C until further handling. All soils were sieved (< 2 mm) and mixed in their field-moist state prior to soil analysis and incubation. Field moisture content was determined by drying samples ($\approx$ 100 g) of moist soil at 105° C for 24 hours.

Chemical Analysis

Soil Characterization

Soil characterization was performed on all soils collected and included soil pH, electrical conductivity (EC), texture, total organic C (TOC), and total Kjeldahl N. Soil pH

and EC were measured by electrode on a 2:1 water : oven dry soil extract. Texture was measured by mechanical analysis (Bouyoucos method). Total OC was determined by the Walkley-Black method for measuring soil organic matter (SOM; Sims and Haby, 1971). Total OC was assumed to be half of SOM (50% C in SOM). Total N was measured as total Kjeldahl N (TKN) using an H_2SO_4 digestion (Bremner and Mulvaney, 1982).

Soluble C & N

A single 0.01M CaSO_4 soil extraction was used to determine dissolved organic C (DOC), dissolved organic N (DON), and anthrone reactive C (ARC). The extraction involved the addition of 200 mL of CaSO_4 to 100 g (oven dry basis) of field moist soil. The suspension was shaken for 2 hours, centrifuged at 10,000 rpms ($\approx 8,000 \times g$; Sorvall RC-5B Centrifuge, DuPont Instruments, Wilmington, DE) for 15 minutes, and the supernatant filtered through a 0.45 μm membrane filter. The leachate was then split into two samples and prepared for DOC, ARC, and DON analysis.

Preparation for DOC and ARC analysis included sample acidification with two drops of H_3PO_4 in approximately 15 mL of sample and sparging with pure oxygen (O_2). Dissolved OC was measured as total C (TC) on a Dohrmann DC-190 C analyzer (Rosemount Analytical, Santa Clara, CA). After DOC analysis was completed, the remaining sample was used in a colorimetric procedure described by Brink et al (1960) to measure ARC. Ten (10) mL of anthrone reagent (2.0 g anthrone in 1 L of 95% concentrated sulfuric acid- H_2SO_4) was mixed with 5 mL of sample. The sample was

shaken vigorously and analyzed on an Hitachi U-2000 Spectrophotometer (Hitachi Ltd., Tokyo, Japan) at a wavelength of 650 nm.

The second sample split from the leachate was analyzed for DON. Dissolved ON was measured as TKN of 100 mL of soil extract accounting for the NH_4^+ -N concentration of the extract.

Soils were also analyzed for resin extractable C (REC; Johns et al., 1993). A saturated paste was made of approximately 75 grams of moist soil. The paste was divided into three equal portions and placed into small plastic containers. Carbonaceous resins (de-gassed, Ambersorb 564; Supelco, Bellefonte, PA) were then placed into the saturated pastes and the containers were sealed. After 96 hours (4 days), resins were removed, washed with distilled deionized water, and sorbed C was stripped from resins with 2N NaOH. Samples were then acidified for DOC analysis (Dorhamann DC-190 C analyzer), by adding 2 mL of H_3PO_4 to 10 mL of sample. Resin extractable C (REC) was observed to be slightly higher in native range soils than in adjacent crop-fallow soils (Appendix Table 16). However, REC results are not discussed here due to elevated background levels of NaOH extractable C from resins which were not equilibrated with soil. The average REC concentration of control samples (no soil) was found to be higher than the REC concentrations observed in samples from several soils. The background C levels found on the resin capsules presumably represent traces of hydrocarbons associated with the manufacturing of the resin capsules and can be eliminated by leaching the resins with methanol prior to use.

Mineralization Studies

Incubation Chambers

Thirty-two incubation chambers were constructed with 5 cm diameter x 12.5 cm length PVC pipe and PVC end-caps (Fig. 1). To facilitate the access of extracting solutions and air to each chamber, 1/8" (NPT) plastic fittings were threaded and glued into both the top and bottom end-caps. Scotch-Brite porous pads (1/8" thick; 3M, St. Paul, MN) were placed in the end-caps to help prevent plugging of fittings with soil particulate during flushing cycles. To provide for a closed (gas tight) incubation environment, both end-caps were sealed following soil packing. The bottom end-cap was sealed with PVC cement, while the top end-cap was sealed with silicon (Dow Corning Corp., Midland, MI).

Soil Packing

Field moist soil was mixed with organic-free sand at a 60:40 sand to oven dry soil ratio. Organic material was removed from the sand by washing sand with 3 to 4% hydrogen peroxide (H_2O_2). The sixteen soil/sand mixtures were then packed into incubation chambers in duplicate (total of 32 chambers). Calculated bulk densities (based on an estimated chamber volume of 265 cm³) for the 32 chambers ranged from 1.3 to 1.7 g cm⁻³ for fine textured and sandy soils, respectively. The chambers were packed using a combination of manual tapping and vibration with a hand held vibrator.



Figure 1. Incubation chambers with CO₂-trap system attached. Air passes through the chamber and is directed to 25 mL test-tubes containing 20 mL of 0.5M NaOH where CO₂ is stripped from the air.

Incubation

All incubation chambers were placed on a holding rack (Fig. 2) and incubated for 14 weeks at room temperature. The rack consisted of a 120 cm x 60 cm plywood base with 5 cm diameter holes (32 total) and was elevated 45 cm for access to chamber bottoms. Styro-foam (2" thick) was glued to the plywood for chamber support.



Figure 2. The thirty-two incubation chambers were placed on an incubation stand. Air manifold in background distributed compressed air to each chamber during incubation.

Temperature was recorded three times per day using a mercury thermometer attached to the stand. Over the course of the incubation study the temperature fluctuated between 27° C and 17° C with an average of $22.5^{\circ} \pm 0.5^{\circ}$ C. The temperature dropped below 20° C (optimal minimum temperature) for several days during weeks 8 and 9. However, the cooling trend observed during weeks 8 and 9 did not have any observable influence on N accumulation. A small, but insignificant, decrease in C accumulation was observed during the short cooling trend.

Immediately prior to incubation (time = 0), chambers were flushed with 100 mL ($\approx$ 1 pore volume) of 0.01M CaCl_2 followed by 120 mL ($\approx$ 1.2 pore volumes) of a non-N nutrient solution to remove initial NO_3^- and NH_4^+ -N. The nutrient solution consisted of 2.0 mM $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, 1.0 mM MgSO_4 , 0.5 mM K_2SO_4 , and 0.05 mM KH_2PO_4 . Following the initial flushing cycle, the incubation chambers were flushed weekly for 10 weeks, then biweekly until the end of the incubation (14 weeks) with 100 mL of 0.01M CaCl_2 (leachate 1) followed by 120 mL of the non-N nutrient solution (leachate 2). The extracting solutions were pumped through the chambers with an IsmaTec MV-Pumpsystem (Cole-Parmer Instrument Company, Chicago, IL) at an average rate of 3 mL min^{-1} . Ester-grade Nalgene 280 (1/8" I.D.) tubing was used for delivering the extracting solutions to each chamber, and Tygon R-6360 (3/32" I.D.) tubing was used on the exit ports to deliver leachate into 250 mL polypropylene collection flasks (Fig. 3). Leachates were frozen until analyzed for NO_3^- and NH_4^+ -N. Six to eight hours were required to complete each flushing cycle.

The two leachates from each chamber were combined and analyzed for NO_3^- -N and NH_4^+ -N. Preliminary studies indicated that the two flushing cycles effectively removed all NO_3^- and NH_4^+ -N from the soil columns. Analysis of NO_3^- -N and NH_4^+ -N was performed colorimetrically (automated cadmium-reduction method and automated phenate method, respectively; Clesceri et al., 1989) on an AlpKem colorimetric auto-analyzer (Wilsonville, OR). The sum of NO_3^- -N and NH_4^+ -N was assumed to represent the amount of N mineralized during each week.



Figure 3. Polypropylene bottles (250 mL) were placed next to chambers to collect leachate during flushing cycles. Leaching solutions were pumped up through the chambers and collected in the bottles .

Following each flushing cycle, chambers were placed under vacuum (≈ 0.2 bars) for 20 - 25 minutes to remove excess solution and maintain constant matric potential at near field-capacity moisture content. A vacuum manifold equipped with pressure gauge was used to simultaneously apply vacuum to eight incubation chambers (Fig. 4). Preliminary studies showed that the vacuum leachate contained insignificant concentrations of NO_3^- -N and NH_4^+ -N. Consequently, this solution was not included with leachates for NO_3^- -N and NH_4^+ -N analysis.

During incubation, CO_2 -free, compressed-air (Midwest Distribution, Inc., Bozeman, MT) was supplied to the bottom of each chamber at a rate of 0.6 ± 0.2 mL

min^{-1} to ensure proper aeration. The compressed-air was stripped of CO_2 and was humidified by sparging through a 1.0M NaOH solution followed by deionized-distilled water prior to entering each incubation chamber.

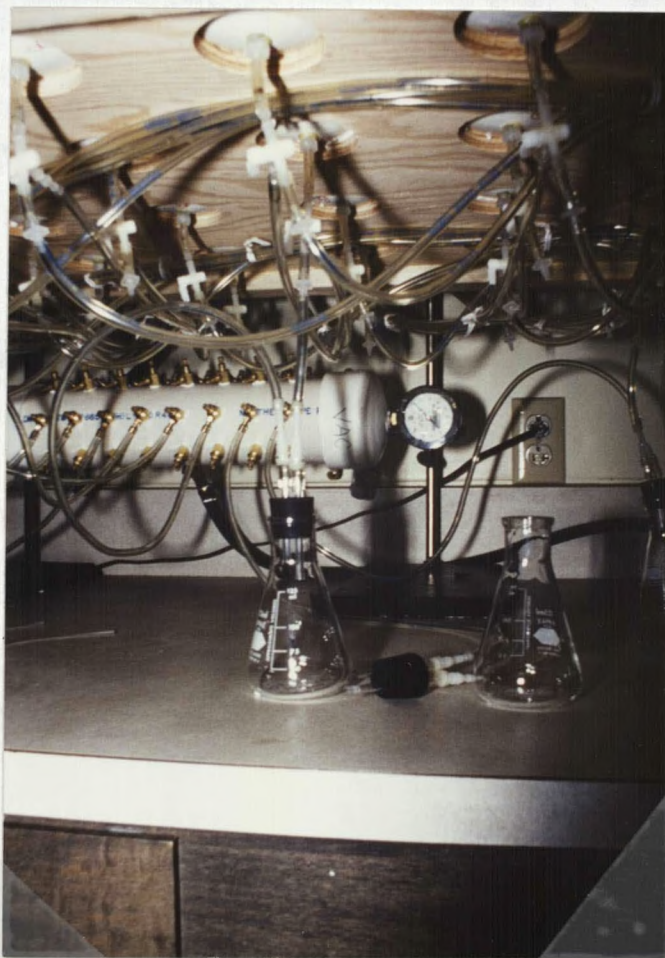


Figure 4. View under the incubation rack. Vacuum manifold in the background allows for eight chambers to be placed under vacuum at one time. Erlenmeyer flasks (125 mL) with two-holed rubber stoppers were used to collect vacuum leachate. Air and extracting solutions are supplied to the bottoms of each chamber.

Air was delivered to the incubation chambers by a specially designed air manifold constructed from 7.5 cm diameter x 40 cm length PVC pipe (Fig. 2). The manifold contained 33 brass needle-valves (32 chambers + 1 control). Air pressure in the manifold was monitored by a pressure gauge inserted into one end of the manifold and was maintained at 0.069 MPa (0.69 bars). Ether-grade Nalgene 280 (1/8" I.D.) tubing was used to deliver air to each chamber. Air exiting the top of each incubation chamber was bubbled (Tygon R-6360 3/32" I.D. tubing) through 20 mL of 0.5M NaOH to trap CO₂ produced by C mineralization. Twenty-five mL test tubes with entry and exiting ports were used as CO₂ traps (Fig. 1). Carbon dioxide produced via C mineralization was quantified using acid-base titration to pH 8.2 (phenolphthalein) and pH 4.6 (mixed, methyl red and bromocresol green) endpoints.

Statistical Analysis

Rates of N and C mineralization were determined through linear regression analysis of the amount of cumulative N or C produced as a function of time. Regression analysis and paired sample mean t-tests were conducted using statistical functions found in the Quattro Pro 5.0 for Windows (Borland International, Inc., Scotts Valley, CA) spreadsheet program. MSUSTAT (Lund, 1994) was used for correlation and multiple regression analysis.

CHAPTER 3

RESULTS AND DISCUSSION

Soil Characterization

Soil characterization of all 32 soils included examination of total organic C, total N, pH, EC, and texture (Appendix Table 15). Substrate pools potentially available for microbial degradation were characterized for only the 16 soils involved in the incubation study (Table 2). Soluble organic fractions were measured as dissolved organic C (DOC), dissolved organic N (DON), and anthrone reactive C (ARC) fractions. These fractions are more readily available for microbial decomposition and may be better indices of potentially mineralizable N and C than TOC and TKN. Anthrone reactive C (ARC) is a measure of simple sugars and small chained carbohydrates (Brink et al, 1960). The fraction of soluble C existing as ARC is assumed to be quite labile relative to microbial mineralization and may be a good indicator of potentially mineralizable C in soils.

Total OC and TKN were characterized for all 32 soils collected. In the 24 crop-fallow/native range pairs, native range soils were observed to have significantly (0.05 level) higher concentrations of TOC and TKN compared to the paired crop-fallow soils (Table 3). Similarly, in the 16 soils included in the incubation study, native range soils

Table 2. Total organic C (TOC), total Kjeldahl N (TKN), soluble fractions of C and N, initial NO_3^- -N, and initial C:N ratios of the 16 soils used in the incubation study.

Soil Series (Location)	Land Use*	TOC — % —	TKN — —	DOC — —	ARC — $\mu\text{g mL}^{-1}$ —	DON — —	NO_3^- -N [†] — mg kg^{-1} soil —	C:N
Farland-Cherry (Scobey)	C-F	0.97	0.11	8.7	1.9	0.6	16.0	9.2
	N-R	1.76	0.18	22.6	5.2	1.7	91.9	9.7
Farland-Cherry (Flaxville)	C-F	1.53	0.16	5.8	0.1	0.5	17.7	9.3
	N-R	2.68	0.29	29.9	2.8	3.3	10.2	9.1
Judith (Stanford)	C-F	1.45	0.17	5.1	1.2	0.5	8.9	8.6
	N-R	1.99	0.22	12.3	1.8	1.4	8.3	8.9
Turner-Beaverton (W. Point)	C-F	0.26	0.04	3.2	0.7	0.5	4.6	6.5
	N-R	0.38	0.05	4.6	1.2	0.5	7.5	7.1
Williams-Zahill (Wolf Point)	C-F	0.64	0.09	5.6	1.6	0.3	16.9	7.4
	N-R	1.17	0.13	9.8	1.8	0.9	10.8	9.0
Williams-Zahill (Flaxville)	C-F	1.21	0.15	6.3	0.7	0.9	13.2	7.9
	N-R	1.79	0.18	17.9	3.6	1.8	2.5	9.7
Beaverell (Bozeman)	P	2.49	0.28	16.5	3.6	0.9	78.9	8.8
Creston (Creston)	C-R	1.68	0.15	5.7	1.6	0.5	44.1	11.2
Williams (Miles City)	N-R	3.72	0.35	3.4	3.9	0.9	7.6	10.6
Winifred (Windham)	C-F	2.21	0.23	13.0	1.5	0.7	41.1	9.6

* C-F, N-R, C-R, and P represent crop-fallow, native range, crop rotation, and pasture land uses, respectively.

[†] Initial NO_3^- -N from t = 0 flushing cycle.

were observed to have significantly (0.05 level) higher concentrations of DOC, DON, ARC, and initial C:N ratios than paired crop-fallow soils.

Table 3. Paired two sample means t-test results of total organic C (TOC), total Kjeldahl N (TKN), pH, electrical conductivity (EC), dissolved organic C (DOC), anthrone reactive C (ARC), dissolved organic N (DON), and initial C:N ratio for crop-fallow and native range sites.

Soil Attribute	Means		Paired T-Test
	Crop-Fallow	Native Range	P-Value
TOC* (%C)	1.13	1.49	0.003
TKN* (%N)	0.13	0.16	0.007
pH*	6.7	6.8	0.219
EC* (mmhos cm ⁻¹)	0.19	0.25	0.065
DOC (µg C mL ⁻¹)	5.8	16.2	0.013
ARC (µg C mL ⁻¹)	1.0	2.7	0.016
DON (µg N mL ⁻¹)	0.6	1.6	0.021
C:N	8.2	8.9	0.033

* Means were computed on 24 crop-fallow/native range soils collected for the study.

Total OC and TKN concentrations are expected to be higher in native, undisturbed soils than in soils under continual cultivation for more than 40 years. It is well documented that tillage results in loss of organic C over time due to increased mineralization of C. The higher concentrations of soluble pools of N and C observed in native soils of this study differ from findings observed by DeLuca and Keeney (1994). They observed higher concentrations of DOC and ARC in cultivated soils compared to paired prairie soils in central Iowa. Annual cropping systems in central Iowa involve yearly incorporation of crop residues and high N inputs which result in the rapid conversion of crop residues into soluble C and N constituents. The intensity of annual cropping prevents the complete mineralization of the soluble C and N pools. By

comparison, crop-fallow systems involve the incorporation of crop residue in alternate years and low N inputs. Complete mineralization of crop residue during the fallow cycle explains the lower soluble C and N fractions observed in crop-fallow soils in this study.

The higher concentrations of soluble C and N fractions observed in native soils are protected within macroaggregates and are not readily available for microbial degradation. Constituents of soluble C and N have been shown to act as cementing agents which stabilize macroaggregates in prairie soils (Cambardella and Elliot, 1994). Handling of the soils collected for this study could be construed as simulating cultivation. The disruption of the samples during moist sieving (2 mm) destroyed macroaggregation, resulting in the release of soluble C and N fractions (i.e. DOC, ARC, and DON fractions).

A t-test for paired two-sample means was applied to initial NO_3^- -N concentrations on the six paired crop-fallow/native range soils. Native range soils appeared to have higher concentrations of NO_3^- -N than paired crop-fallow soils with averages of 21.9 and 12.9 for native range and crop-fallow soils, respectively (Table 4). However, this difference was not statistically significant (p -value = 0.268). This is due to the unexpectedly high initial NO_3^- -N concentration observed in the Farland-Cherry native range soil collected near Scobey, Montana (Table 2). If the Scobey Farland-Cherry crop-fallow/native range pair is removed from the t-test analysis, initial NO_3^- -N concentrations become generally higher (but not quite significantly higher; p -value = 0.075) in crop-fallow soils than native range soils (Table 4). The unexpectedly high inorganic N

concentration observed in the Scobey Farland-Cherry native range soil is unclear, but may be linked to grazing management practices at the site.

Table 4. Average initial NO_3^- -N concentrations for all six paired crop-fallow and native range soils in the incubation study and with the Farland-Cherry (Scobey) crop-fallow/native range pair removed from analysis.

	Average Initial NO_3^- -N*	
	6 Crop-Fallow/Native Range Pairs	Farland-Cherry (Scobey) CF/NR Pair Removed
	mg kg^{-1} soil	
Crop-Fallow	12.9	12.3
Native Range	21.9	7.9
T-Test P-Value	0.268	0.075

* Initial NO_3^- -N concentrations from initial ($t = 0$) flushing cycle.

The general trend of higher initial NO_3^- -N concentrations in crop-fallow soils compared to native range soils observed in this study compares favorably with other researchers (Cambardella and Elliot, 1992; DeLuca and Keeney, 1993). DeLuca and Keeney (1993a; 1994) observed higher concentrations of NO_3^- -N in cultivated soils versus uncultivated prairie soils in central Iowa. They attributed the higher NO_3^- -N concentration in cultivated soils to the disruption of the N cycle, which in native soils is highly conservative of inorganic N. When native soils are cultivated macroaggregates are disrupted and soluble pools of organic N and C are released to the soil solution. Inorganic N concentrations increase due to an increase in microbial populations of ammonifiers and nitrifiers (Broder et al., 1984).

Mineralization Study

Mineralization Rates

The majority of inorganic N measured on weekly intervals was in the form of NO_3^- -N (Table 5) which is consistent with other studies (Cassman and Munn, 1980; Choudhury and Cornfield, 1978; Ellert and Bettany, 1992; Lamb et al., 1985). It is assumed that the abundance of NO_3^- -N concentrations is a reflection of rapid nitrification of NH_4^+ -N produced during the mineralization of organic N under optimal temperature, moisture and proper aeration. However, NH_4^+ -fixation by illitic clay minerals may influence NH_4^+ -N effluent concentrations.

Cumulative release of total inorganic N and $\text{CO}_2(\text{g})$ over the course of the 14 week incubation period was best described using a linear relationship for all soils studied which is consistent with previous studies using Montana soils (Gavlak, 1985). An example of the linear accumulation of both N and C (as CO_2 evolution) with time is shown in Figure 5. Appendix Figures 6-15 contain a complete set of plots for the accumulation of N and C of the 16 soils involved in the incubation.

Rates of N and C mineralization over the 14 wk incubation were computed from linear regression analyses performed on N and C accumulation as a function of time (Table 6). N mineralization rate (R_N) ranged from 0.11 to 1.41 mg N kg^{-1} soil d^{-1} while C mineralization rate (R_C) ranged from 1.7 to 14.0 mg C kg^{-1} soil d^{-1} , for all soils studied. Based on paired two sample means t-test results, rates of both N and C mineralization

were found to be higher in native range soils than in paired crop-fallow soils (Table 7). This is consistent with soil attributes showing that native range soils had higher TOC, TKN, DOC, ARC, and DON than crop-fallow soils. A summary of total N mineralized over the course of the 14 week incubation for each soil can be found in Appendix Table 17.

Table 5. Cumulative total inorganic N ($\text{NO}_3^- + \text{NH}_4^+$ -N), NO_3^- -N, and NH_4^+ -N mineralized and the percent of total N mineralized measured as NO_3^- -N after 14 weeks of incubation.

Series (Location)	Land Use*	Inorganic N Mineralized			% N Mineralized as NO_3^- -N [#]
		NO_3^- -N	NH_4^+ -N	Total N	
		mg N kg soil ⁻¹			
Farland-Cherry (Scobey)	C-F	37.47	0.43	37.90	98.85
	N-R	103.75	0.88	104.63	99.16
Farland-Cherry (Flaxville)	C-F	22.43	0.90	23.33	96.14
	N-R	61.40	0.45	61.85	99.27
Judith (Stanford)	C-F	64.16	0.67	64.83	98.97
	N-R	78.48	0.47	78.95	99.40
Turner-Beaverton (W. Point)	C-F	11.19	0.36	11.55	96.88
	N-R	21.25	0.51	21.76	97.66
Williams-Zahill (Wolf Point)	C-F	26.31	0.55	26.86	97.95
	N-R	35.12	0.61	35.73	98.29
Williams-Zahill (Flaxville)	C-F	26.80	0.42	27.22	98.46
	N-R	35.06	0.49	35.55	98.62
Beaverell (Bozeman)	P	106.06	0.93	106.99	99.13
Creston (Creston)	C-R	43.64	0.46	44.10	98.96
Williams (Miles City)	N-R	81.76	0.82	82.58	99.01
Winifred (Windham)	C-F	66.80	0.37	67.17	99.44
Averages:		51.35	0.59	51.94	98.51

* C-F, N-R, C-R, and P represent crop-fallow, native range, crop rotation and pasture land uses, respectively.

[#] Computed as NO_3^- -N mineralized divided by Total N mineralized.

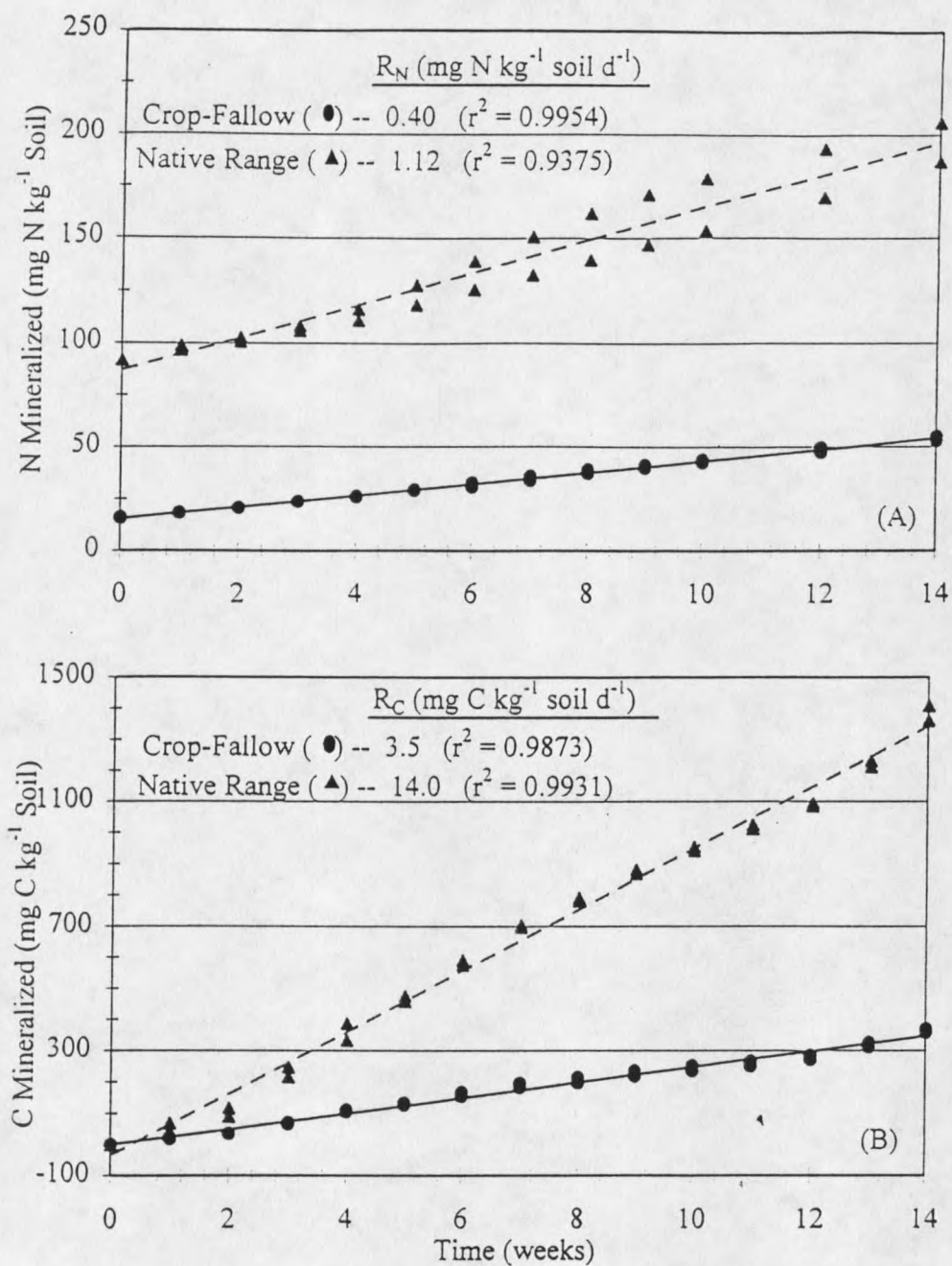


Figure 5. Plots of cumulative N (A) and C (B) over 14 weeks of incubation for adjacent native range (triangle) and crop-fallow (circle) Farland-Cherry soils collected near Scobey, MT.

Table 6. Mineralization rates of N (R_N) and C (R_C) obtained from cumulative N and C released over 14 weeks of incubation at 22.5° C.

Series (Location)	Land Use*	Mineralization Rates		Mineralization Rate C:N Ratio
		R_N	R_C	
		mg kg ⁻¹ soil d ⁻¹		
Farland-Cherry (Scobey)	C-F	0.40 ± 0.01	3.5 ± 0.2	9.0
	N-R	1.12 ± 0.13	14.0 ± 0.5	12.6
Farland-Cherry (Flaxville)	C-F	0.23 ± 0.00	2.5 ± 0.1	10.8
	N-R	0.58 ± 0.05	8.1 ± 0.5	13.9
Judith (Stanford)	C-F	0.67 ± 0.02	6.4 ± 0.3	9.6
	N-R	0.83 ± 0.03	10.5 ± 0.4	12.6
Turner-Beaverton (W. Point)	C-F	0.11 ± 0.01	1.7 ± 0.1	15.4
	N-R	0.21 ± 0.01	2.8 ± 0.1	12.9
Williams-Zahill (Wolf Point)	C-F	0.27 ± 0.01	3.5 ± 0.2	13.1
	N-R	0.35 ± 0.02	5.2 ± 0.2	14.8
Williams-Zahill (Flaxville)	C-F	0.28 ± 0.01	2.1 ± 0.1	7.5
	N-R	0.35 ± 0.03	5.7 ± 0.4	16.6
Beaverell (Bozeman)	P	1.41 ± 0.15	14.0 ± 0.6	10.0
Creston (Creston)	C-R	0.52 ± 0.05	4.6 ± 0.1	8.9
Williams (Miles City)	N-R	0.81 ± 0.04	10.8 ± 0.4	13.3
Winifred (Windham)	C-F	0.71 ± 0.03	6.9 ± 0.3	9.8

* C-F, N-R, C-R, and P represent crop-fallow, native range, crop rotation, and pasture land uses, respectively.

Table 7. Paired two sample means t-test results for N and C mineralization rates and the C:N mineralization rate ratio (MRR).

	Crop-Fallow	Native Range	p-value	Pearson Correlation	df	t
N-Min. Rate (mg N kg ⁻¹ soil d ⁻¹)	0.33	0.57	0.031	0.6888	5	2.39
C-Min. Rate (mg C kg ⁻¹ soil d ⁻¹)	3.29	7.72	0.012	0.5969	5	3.18
MRR	10.88	13.91	0.052	-0.3336	5	1.99

Nitrogen mineralization rates observed in this study are comparable to those observed by Gavlak (1985) and Barak et al. (1990). Barak et al. (1990) observed an

average N mineralization rate of $0.6 \text{ mg N kg}^{-1} \text{ soil d}^{-1}$ for a Hubbard loamy sand in Minnesota. over a 7 day incubation at 20° C . Gavlak predicted cumulative net N mineralization rates to be between 0.5 and $1.3 \text{ kg N ha}^{-1} \text{ d}^{-1}$ (0.28 and $0.67 \text{ mg N kg}^{-1} \text{ soil d}^{-1}$, respectively) at 14° C for a 12 week incubation experiment. To properly compare the mineralization rates observed in this study at 22.5° C to mineralization rates predicted at 14° C by Gavlak, a temperature coefficient (Q_{10}) was employed. A Q_{10} of 2.0 (2 fold increase in rate for a 10° C increase in temperature) has been observed to adequately describe the temperature effect on N mineralization (Tyler et al., 1959; Stanford et al., 1973; Westermann and Crothers, 1980; Campbell et al., 1981). Mineralization rates (Table 6) adjusted to 14° C ranged from 0.1 to $0.8 \text{ mg N kg}^{-1} \text{ soil d}^{-1}$, which encompasses the range observed by Gavlak.

Predicting N and C Mineralization Rates

Correlation analyses (Table 8) showed that N mineralization rates (R_N), were significantly (0.01 level) correlated with TOC, TKN, ARC, initial $\text{NO}_3\text{-N}$, and C mineralization rates. Similarly, C mineralization rates (R_C) were significantly (0.01 level) correlated with TOC, TKN, ARC, and N mineralization rates. Anthrone reactive C (ARC) was found to be a good predictor of N and C mineralization rates. Dissolved OC, DON, and initial C:N ratios were not good predictors of N or C mineralization rates.

Table 8. Correlation matrix (Pearson coefficients) of the linear relationships between N and C mineralization rates (R_N & R_C , respectively), TOC, TKN, DOC, ARC, DON, initial C:N ratios, and initial NO_3^- -N concentrations.

	R_N	R_C	TOC	TKN	DOC	ARC	DON	C:N	NO_3^- -N
R_N	1								
R_C	0.952**	1							
TOC	0.660**	0.709**	1						
TKN	0.697**	0.733**	0.986**	1					
DOC	0.468	0.569*	0.411	0.464	1				
ARC	0.699**	0.823**	0.574*	0.553*	0.612*	1			
DON	0.256	0.424	0.471	0.508*	0.891**	0.505*	1		
C:N	0.418	0.431	0.700**	0.612*	0.253	0.451	0.228	1	
NO_3^- -N	0.698**	0.648**	0.193	0.192	0.427	0.605*	-0.092	0.297	1

** Significant at the 99% level ($p_{|r|} < 0.01$).

* Significant at the 95% level ($p_{|r|} < 0.05$).

Multiple regression analyses were conducted for N and C mineralization rates with selected soil attributes exhibiting significant linear relationships. In examining those attributes having a significant linear relationship with N mineralization rates, ARC, initial NO_3^- -N, and TKN appeared to be the best predictors of N mineralization rates. Through a step-wise reversible multiple regression analysis, initial NO_3^- -N and TKN combined to account for 82% of the variability ($r^2 = 0.819$) in N mineralization rates (R_N):

$$R_N = -0.223 + 0.0421(\text{NO}_3^- \text{-N}) + 17.19(\text{TKN}) \quad (3)$$

In equation (3), initial NO_3^- -N and TKN have the same significance for predicting N mineralization rate ($T = 4.87$; $p = 0.000$). Due to the variability of initial NO_3^- -N concentrations, initial NO_3^- -N was removed from the multiple regression analysis. If one assumes that initial NO_3^- -N is a result of mineralization of organic N in the field prior to

sampling and any mineralization occurring during cold storage, then soils with higher initial NO_3^- -N values would be expected to have higher N mineralization rates. The uncertainty of fertilizer N contributions to initial NO_3^- -N levels in crop-fallow soils complicates the relationship between initial NO_3^- -N and N mineralization rate. Consequently, initial NO_3^- -N concentrations are either a direct result of mineralization or residual fertilizer additions (crop-fallow soils) and it is difficult to invoke a causal relationship between NO_3^- -N and N mineralization rate in all soils.

Of the other chemical attributes measured for these soils, ARC and TKN were the most important (Table 8). When combined in multiple regression analyses, ARC and TKN accounted for 63% ($r^2 = 0.63$) of the variation in the rate of N mineralization (R_N):

$$R_N = -0.131 + 0.820(\text{ARC}) + 13.15(\text{TKN}) \quad (4)$$

Equation (4) indicates that of the chemical attributes measured which may influence the rate N mineralization, ARC and TKN are the most important. Within the equation ARC and TKN are equally significant in predicting N mineralization rate ($p = 0.044$ & 0.045 , respectively).

ARC, DOC, and TOC were evaluated in a step-wise, reversible multiple regression analysis for predicting C mineralization rates. ARC and TOC combined were found to be more important in predicting C mineralization rates than ARC, TOC, and DOC in any

other combination and accounted for 76% of the variation ($r^2 = 0.761$) in C mineralization rate (R_C):

$$R_C = -0.0156 + 12.84(\text{ARC}) + 11.14(\text{TOC}) \quad (5)$$

ARC had higher significance than TOC for predicting C mineralization rate ($p = 0.002$ & 0.054 , respectively).

The correlation of N and C mineralization rates with ARC indicates that ARC may be useful for describing labile pools of both C and N in soils. Anthrone reactive C was a better indicator of mineralization rates than DOC or DON, indicating that simple sugars and small chain carbohydrates are more available for degradation than the larger more complex C and N constituents included in DOC and DON fractions.

Normalized Rates

Mineralization rates of N were normalized to TKN and mineralization rates of C were normalized to TOC (Table 9). This normalization process was designed to determine how mineralization rates of the crop-fallow/native range soils compared when based on the total substrate available in each soil. If all C measured as TOC and all N measured as TKN were equally available for mineralization, then normalized mineralization rates would be identical for all soils. Average normalized mineralization rates of C were generally higher (Table 10) in native range soils indicating that per unit mass of organic C, native range soils contained more labile C susceptible to mineralization

than crop-fallow soils. This is consistent with other studies showing that disruption of macroaggregation releases pools of labile C (Cambardella and Elliot, 1992; 1993; 1994; DeLuca and Keeney, 1993a). Average normalized mineralization rates of N were also higher (Table 10) in native range soils compared to crop-fallow soils, although not to the same level of statistical significance as C mineralization rates.

Table 9. N and C mineralization rates normalized to total Kjeldahl N (TKN) and total C (TOC), respectively.

Series (Location)	Land Use*	TKN Normalized	TOC Normalized
		N-Mineralization Rate — g N kg ⁻¹ TKN d ⁻¹ —	C-Mineralization Rate — g C kg ⁻¹ TOC d ⁻¹ —
Farland-Cherry (Scobey)	C-F	0.37 ± 0.01	0.37 ± 0.01
	N R	0.62 ± 0.07	0.80 ± 0.03
Farland-Cherry (Flaxville)	C-F	0.14 ± 0.00	0.16 ± 0.05
	N R	0.20 ± 0.02	0.30 ± 0.02
Judith (Stanford)	C-F	0.40 ± 0.01	0.44 ± 0.02
	N R	0.37 ± 0.01	0.53 ± 0.02
Turner-Beaverton (W. Point)	C-F	0.28 ± 0.02	0.66 ± 0.04
	N R	0.40 ± 0.02	0.73 ± 0.25
Williams-Zahill (Wolf Point)	C-F	0.31 ± 0.01	0.56 ± 0.03
	N R	0.27 ± 0.01	0.44 ± 0.01
Williams-Zahill (Flaxville)	C-F	0.19 ± 0.01	0.17 ± 0.02
	N R	0.19 ± 0.02	0.32 ± 0.02
Beaverell (Bozeman)	P	0.50 ± 0.05	0.56 ± 0.02
Creston (Creston)	R-C	0.35 ± 0.03	0.28 ± 0.01
Williams (Miles City)	N R	0.22 ± 0.01	0.29 ± 0.01
Winifred (Windham)	C-F	0.31 ± 0.01	0.31 ± 0.02

* C-F, N-R, C-R, and P represent crop-fallow, native range crop rotation and pastures land uses, respectively.

Table 10. Paired two sample means t-test results for TKN and TOC normalized N and C mineralization rates, respectively.

	TKN Normalized N Mineralization Rate	TOC Normalized C Mineralization Rate
	Mean	Mean
	— mg N kg ⁻¹ TKN d ⁻¹ —	— mg C kg ⁻¹ TOC d ⁻¹ —
Crop-Fallow	0.28	0.39
Native Range	0.34	0.52
p - Value	0.121	0.071

Nitrogen Production Estimates

The N mineralization rates observed in this study can be used to estimate the amount of inorganic N on a yearly basis. The optimal moisture and temperature conditions of the laboratory study will not be maintained for 12 months under field conditions. The months of June, July, August and September are generally the warmest months and are assumed to represent months of maximum potential mineralization of organic N and C. Historic mean monthly temperatures of the five regions representing sample locations of soils used in this study were averaged for June-September (Table 11).

Mineralization rates observed during the laboratory incubation (22.5° C) were adjusted to average temperatures during the growing season using a Q_{10} of 2.0 (Table 12). Adjusted N mineralization rates ranged from 0.08 to 0.96 mg N kg⁻¹ soil d⁻¹ and yielded between 40 and 466 kg N ha⁻¹ produced during a four month period in a 30 cm depth (36 and 416 lbs N acre-ft⁻¹).

Table 11. Mean temperatures for 4 months of the growing season of regions representing soils used in the current study.*

Series (Location)	Region in Montana	Mean Temperature over 4 Months ° C
Farland-Cherry (Scobey)	Northeast	18.5
Farland-Cherry (Flaxville)	Northeast	18.5
Judith (Stanford)	Central	16.5
Turner-Beaverton (Wolf Point)	Northeast	18.5
Williams-Zahill (Wolf Point)	Northeast	18.5
Williams-Zahill (Flaxville)	Northeast	18.5
Beaverll.(Bozeman)	Southwest	17.0 ⁺
Creston (Creston)	Northwest	15.5
Williams (Miles City)	Southeast	19.0
Winifred (Windham)	Central	16.5

* Compiled by the Montana Agricultural Statistics Service.

⁺ Mean Temperature for Bozeman (Montana State University) only.

These estimates might be representative of the amount of potentially mineralizable N in crop-fallow management or following cultivation of native range soils. In order to estimate the N requirements for two crops most commonly grown in the counties where soils were collected, average winter wheat and barley yields over the last 10 years were obtained from annual county average yields (Montana Agricultural Statistics Service, Helena, MT, 1995; Table 10). Winter wheat and barley yields averaged 1.48 to 2.15 Mg ha⁻¹ (22 to 32 bu acre⁻¹) and 1.24 to 1.77 Mg ha⁻¹ (23 to 33 bu acre⁻¹), respectively. These average yields correspond to N requirements of 52 to 78 lbs acre⁻¹ for winter wheat and 31 to 46 lbs acre⁻¹ for barley (Lichthardt and Jacobsen, 1992).

Table 12. Nitrogen mineralization rates adjusted for temperature and estimates of the mass of N mineralized over a 4 month period.

Series (Location)	Land Use*	N Mineralization Rate ^s	Mass of N Mineralized in 4 Months [#]	
		— mg kg ⁻¹ soil d ⁻¹ —	— kg ha ⁻¹ —	— lbs acre ⁻¹ —
Farland-Cherry (Scobey)	C-F	0.30	147	131
	N-R	0.85	411	367
Farland-Cherry (Flaxville)	C-F	0.17	84	75
	N-R	0.44	213	190
Judith (Stanford)	C-F	0.44	214	191
	N-R	0.55	265	237
Turner-Beaverton (W. Point)	C-F	0.08	40	36
	N-R	0.16	77	69
Williams-Zahill (Wolf Point)	C-F	0.20	99	88
	N-R	0.27	128	115
Williams-Zahill (Flaxville)	C-F	0.21	102	91
	N-R	0.27	128	115
Beaverell (Bozeman)	P	0.96	466	416
Creston (Creston)	C-R	0.32	155	138
Williams (Miles City)	N-R	0.64	307	275
Winifred (Windham)	C-F	0.47	227	202

* C-F, N-R, C-R, and P represent crop-fallow, native range, crop rotation, and pasture land uses, respectively.

^s Nitrogen mineralization rates adjusted for regional temperatures based on a Q₁₀ of 2.0.

[#] Mass of N mineralized in 1 foot of soil.

It is apparent from estimates of potentially mineralizable N (Table 12) and average N requirements (Table 13), that production of inorganic N via mineralization may often exceed crop N uptake. Also, our results suggest that the majority of NH₄⁺-N produced from mineralization is rapidly nitrified to NO₃⁻-N (Table 5). This establishes conditions which may lead to leaching of NO₃⁻-N beyond the root zone. Mineralized N produced during fallow years would be especially susceptible to movement out of the root zone

given the absence of crop H_2O and N uptake. The potential for significant amounts of NO_3^- -N to move out of the root zone is by continued crop-fallow cycles over many years (> 40 yr. in some regions).

Table 13. County averages of winter wheat and barley yields for sites with crop-fallow/native range pairs.

Series (Location)	County	Average Yields*		N Requirement ⁺	
		W. Wheat	Barley	W. Wheat	Barley
		Mg ha ⁻¹		kg ha ⁻¹	
		(bu acre ⁻¹)		(lbs acre ⁻¹)	
Farland-Cherry (Scobey)	Daniels	1.5 (22)	1.2 (23)	52 (46)	31 (28)
Farland-Cherry (Falxville)	Daniels	1.5 (22)	1.2 (23)	52 (46)	31 (28)
Judith (Stanford)	Judith Basin	2.2 (32)	1.8 (33)	78 (70)	46 (41)
Turner-Beaverton (W. Point)	Roosevelt	1.7 (25)	1.3 (25)	59 (53)	35 (31)
Williams-Zahill (Wolf Point)	Roosevelt	1.7 (25)	1.3 (25)	59 (53)	35 (31)
Williams-Zahill (Flaxville)	Daniels	1.5 (22)	1.2 (23)	52 (46)	31 (28)

* Ten year (1984 to 1993) county average yields obtained from the Montana Agricultural Statistics Service (1995).

⁺ Nitrogen requirements for potential crop yields to a 60 cm depth (Lichthardt and Jacobsen, 1992).

Conclusions

Mineralization rates of N and C were faster in soils collected from native range sites than in adjacent soils from crop-fallow sites. A larger pool of available organic N and C was observed in native range soils than in crop-fallow soils (i.e. DOC, ARC, TKN, and DON). It is thought that soluble pools of N and C are bound in macroaggregates in native soils and are not readily available. However, upon disturbance (i.e. cultivation), these soluble organic fractions are released and quickly mineralized (Cambardella and Elliot, 1994; DeLuca and Keeney, 1993a). The manner in which the soils were handled during

collection and prior to incubation simulated cultivation, resulting in the release of soluble pools of N and C from macroaggregates, and the subsequent higher mineralization rates in native soils than in crop-fallow soils.

It is hypothesized that rates of C and N mineralization observed in native soils following the disturbance of collection and sieving represent rates which may have occurred following sod-busting and cultivation of native soils. Over the 40+ years of continual crop-fallow cycles, mineralization rates have decreased as substrate supplies decrease. The slower rates observed in the crop-fallow soils are a result of this steady decline in available substrate.

Soil attributes which can be used as indices of soluble pools of N and C in soils are very useful for predicting N and C mineralization in soils. Anthrone reactive C (ARC) was found to be a good predictor of both N and C mineralization rates in the soils used in this study.

Due to inefficient N cycling in crop-fallow management, NO_3^- -N released from N mineralization may be transported beyond the root zone and eventually migrate to groundwater. Further work needs to be done to determine the relationship between N mineralization and levels of NO_3^- -N found in groundwaters of regions under crop-fallow management for greater than 40 years.

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APPENDIX
RAW DATA

Appendix Table 14. Site location, land-use specifications, and legal descriptions of all 32 soils collected for the study.

Soil Series	Land Uses ⁺	Location	Region in		Legal Description			
			Montana	County	Twp.	Rng.	Sec.	1/4
Danvers CL	C-F/N-R	Denton	Central	Fergus	19N	14E	24	NE
Fairfield-Danvers CL	C-F/N-R	Denton	Central	Fergus	18N	15E	30	SE
Farland-Cherry SiL	C-F/N-R	Scobey	Northeast	Daniels	36N	48E	31	SE
Farland-Cherry	C-F/N-R	Flaxville	Northeast	Daniels	35N	50E	5	NE
Farnuf L	C-F/N-R	Denton	Central	Fergus	19N	14E	33	NW
Farnuf L	C-F/N-R	Wolf Point	Northeast	Roosevelt	31N	47E	4	SW
Judith gCL	C-F/N-R	Stanford	Central	Jud. Basin	19N	14E	33	NW
Tally SL	C-F/N-R	Wolf Point	Northeast	Roosevelt	31N	46E	35	NE
Turner SL	C-F/N-R	Madoc	Northeast	Daniels	35N	49E	4	SE
Turner-Beaverton Complex	C-F/N-R	Wolf Point	Northeast	Roosevelt	30N	46E	2	SE
Williams-Zahill L	C-F/N-R	Wolf Point	Northeast	Roosevelt	32N	47E	19	SE
Williams-Zahill L	C-F/N-R	Flaxville	Northeast	Daniels	35N	50E	13	SW
Beaverell	P	Bozeman	Southwest	Gallatin	01S	04E	34	SW
Burnt Fork SL	C-R	Corvallis	West	Ravalli	07N	20W	27	SW
Creston	C-R	Creston	Northwest	Flathead	28N	20W	15	SW
Eapa L	N-R	Miles City	East	Custer	*	*	*	*
Lonna SiCL	N-R	Miles City	East	Custer	*	*	*	*
Sonnet SiCL	N-R	Miles City	East	Custer	*	*	*	*
Williams L	N-R	Miles City	East	Custer	*	*	*	*
Winifred CL	C-F	Windham	Central	Jud. Basin	16N	13E	31	SW

⁺ C-F, N-R, C-R, and P represent crop-fallow, native range, crop rotation and pasture land-uses, respectively.

* Legal descriptions are unknown. These soils were collected by SCS personnel from the Miles City field office.

Appendix Table 15. Total organic C (TOC), total Kjeldahl N (TKN), texture, pH, and electrical conductivity (EC) measured on all 32 soils.

Series	Site Location	Land Use	TOC	TKN	Texture			2:1	
					Clay %	Sand	Class*	pH	EC —mmhos cm ⁻¹ —
Danvers	Denton	Crop-Fallow	1.78	0.18	34	30	CL	5.4	0.25
Danvers	Denton	Native Range	1.83	0.18	29	39	CL/L	5.3	0.19
Fairfield-Danvers	Denton	Crop-Fallow	1.34	0.16	36	34	CL	7.3	0.22
Fairfield-Danvers	Denton	Native Range	1.23	0.14	34	34	CL	7.2	0.28
Farland-Cherry	Scobey	Crop-Fallow	0.97	0.11	22	46	L	7.8	0.24
Farland-Cherry	Scobey	Native Range	1.76	0.18	21	45	L	7.5	0.66
Farland-Cherry	Flaxville	Crop-Fallow	1.53	0.16	25	43	L	7.4	0.21
Farland-Cherry	Flaxville	Native Range	2.68	0.29	18	48	L	7.7	0.33
Farnuf	Coffee Creek	Crop-Fallow	2.27	0.24	28	28	CL/L	7.1	0.38
Farnuf	Coffee Creek	Native Range	2.53	0.24	28	26	CL/L	7.5	0.53
Farnuf	Wolf Point	Crop-Fallow	0.68	0.08	14	69	SL	5.5	0.14
Farnuf	Wolf Point	Native Range	0.90	0.11	16	67	SL/SCL	6.1	0.12
Judith	Stanford	Crop-Fallow	1.45	0.17	39	29	CL/C	7.2	0.16
Judith	Stanford	Native Range	1.99	0.22	38	33	CL	7.2	0.21
Tally	Wolf Point	Crop-Fallow	0.61	0.08	15	70	SL	7.0	0.10
Tally	Wolf Point	Native Range	0.74	0.10	14	70	SL	6.4	0.14

* C, L, S, and Si represent Clay, Loam, Sand, and Silt, respectively.

Appendix Table 15.—Continued

Series	Site	Land Use	TOC	TKN	Texture			2:1	
	Location				Clay	Sand	Class*	pH	EC
Turner	Madoc	Crop-Fallow	0.83	0.09	19	62	SL/SCL	6.0	0.15
Turner	Madoc	Native Range	0.93	0.11	15	65	SL	6.4	0.12
Turner-Beaverton	Wolf Point	Crop-Fallow	0.26	0.04	11	81	LS/SL	6.4	0.07
Turner-Beaverton	Wolf Point	Native Range	0.38	0.05	11	81	LS/SL	6.4	0.09
Williams-Zahill	Wolf Point	Crop-Fallow	0.64	0.09	18	65	SL	5.8	0.15
Williams-Zahill	Wolf Point	Native Range	1.17	0.13	17	63	SL	6.3	0.12
Williams-Zahill	Flaxville	Crop-Fallow	1.21	0.15	42	25	C	8.0	0.24
Williams-Zahill	Flaxville	Native Range	1.79	0.18	34	30	CL	7.9	0.25
Beaverell	Bozeman	Pasture	2.49	0.28	27	37	L	7.3	0.58
Burnt Fork	Corvallis	Crop Rotation	1.21	0.13	15	54	SL/L	7.4	0.33
Creston	Creston	Crop Rotation	1.68	0.15	10	66	SL	6.9	0.28
Eapa	Miles City	Native Range	0.96	0.11	28	31	CL/L	6.7	0.20
Lonna	Miles City	Native Range	1.63	0.19	30	16	SiCL/SiL	8.0	0.28
Sonnet	Miles City	Native Range	2.11	0.2	37	6	SiCL	7.6	0.18
Williams	Miles City	Native Range	3.72	0.35	30	20	CL/SiCL	5.6	0.33
Winifred	Windham	Crop-Fallow	2.21	0.23	38	30	CL	7.1	0.47

* C, L, S, and Si represent Clay, Loam, Sand, and Silt, respectively.

Appendix Table 16. Dissolved organic C (DOC), anthrone reactive C (ARC), dissolved organic N (DON), initial NO_3^- -N, resin extractable C (REC), and initial and mineralization rate (MRR) C:N ratios measured for the 16 soils included in the incubation study.

Series (Location)	Land Use ⁺	DOC	ARC	DON	NO_3^- -N*	REC [†]	C:N Ratios	
							Initial	MRR
		$\mu\text{g mL}^{-1}$			$\text{mg kg}^{-1} \text{ soil}$	$\mu\text{g capsule}^{-1}$		
Farland-Cherry (Scobey)	C-F	8.7	1.9	0.6	16.04	143.58	9.2	9.1
	N-R	22.6	5.2	1.7	91.87	257.85	9.7	12.8
Farland-Cherry (Flaxville)	C-F	5.8	0.1	0.5	17.27	134.31	9.3	10.9
	N-R	29.9	2.8	3.3	10.16	346.22	9.1	14.2
Judith (Stanford)	C-F	5.1	1.2	0.5	8.85	181.24	8.6	9.8
	N-R	12.3	1.8	1.4	8.34	193.52	8.9	12.9
Turner-Beaverton (W. Point)	C-F	3.2	0.7	0.5	4.59	130.14	6.5	15.6
	N-R	4.6	1.2	0.5	7.54	272.38	7.1	13.1
Williams-Zahill (Wolf Point)	C-F	5.6	1.6	0.3	16.86	174.48	7.4	13.2
	N-R	9.8	1.8	0.9	10.77	176.20	9.0	15.1
Williams-Zahill (Flaxville)	C-F	6.3	0.7	0.9	13.23	163.73	7.9	7.6
	N-R	17.9	3.6	1.8	2.53	239.49	9.7	16.9
Beaverell (Bozeman)	P	16.5	3.6	0.9	78.90	201.78	8.8	10.0
Creston (Creston)	C-R	5.7	1.6	0.5	44.05	190.26	11.2	9.0
Williams (Miles City)	N-R	3.4	3.9	0.9	7.55	162.59	10.6	13.5
Winifred (Windham)	C-F	13.0	1.5	0.7	41.07	151.55	9.6	9.9

⁺ C-F, N-R, C-R, P represent crop-fallow, native range, crop rotation, and pasture land uses, respectively.

* Initial NO_3^- -N concentration obtained from initial ($t = 0$) chamber flushing.

[†] Values for REC do not account for levels C observed in the control ($166.10 \mu\text{g C capsule}^{-1}$)

Appendix Table 17. Summarized initial total inorganic N ($\text{NO}_3^- + \text{NH}_4^+ \text{-N}$) and mineralized N ($\text{NO}_3^- + \text{NH}_4^+ \text{-N}$) for all 16 soils over 14 weeks of incubation at 22.5° C.

Series (Location)	Land Use ⁺	Initial*	Weeks					
			1	2	3	4	5	6
			mg kg ⁻¹ soil					
Farland-Cherry (Scobey)	C-F	16.04	2.14	2.51	2.92	2.41	3.18	2.55
	N-R	91.87 [#]	6.15	3.80	5.85	6.17	9.46	9.35
Farland-Cherry (Flaxville)	C-F	17.27	2.37	1.43	1.60	1.45	1.84	1.34
	N-R	10.16	6.46	2.39	2.62	2.14	3.26	2.77
Judith (Stanford)	C-F	8.85	5.29	4.96	4.58	4.64	6.56	3.80
	N-R	8.43	5.72	5.62	3.76	5.24	7.91	6.80
Turner-Beaverton (W. Point)	C-F	4.59	1.88	0.95	1.08	0.72	0.79	0.69
	N-R	7.54	2.39	1.35	1.43	1.40	1.57	1.23
Williams-Zahill (Wolf Point)	C-F	16.86	2.58	1.99	2.51	1.95	2.30	1.88
	N-R	10.77	3.50	3.25	2.47	2.42	2.41	1.85
Williams-Zahill (Flaxville)	C-F	13.23	2.09	1.95	2.30	1.68	2.06	1.99
	N-R	2.53	3.42	2.32	1.63	1.23	1.78	1.96
Beaverell (Bozeman)	P	78.90	5.84	10.06	8.26	11.66	16.73	13.09
Creston (Creston)	C-R	44.05	3.51	2.45	4.67	4.01	4.78	3.17
Williams (Miles City)	N-R	7.55	6.81	6.69	5.95	5.24	5.75	5.36
Winifred (Windham)	C-F	41.07	2.62	3.23	3.90	3.43	5.45	4.35

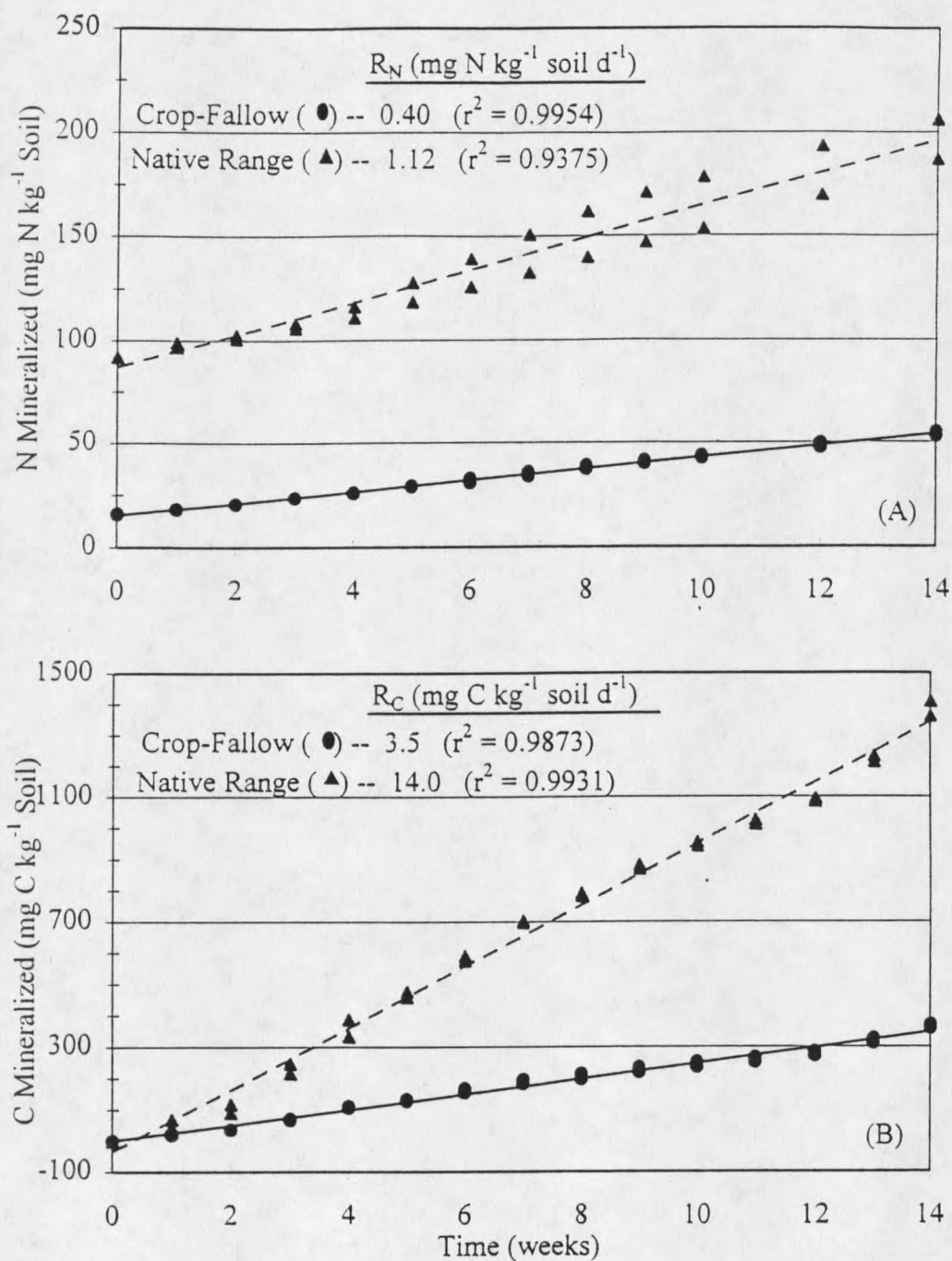
⁺ C-F, N-R, C-R, and P represent crop-fallow, native range, crop-rotation, and pasture land uses, respectively.

* Values of total N mineralized are averages of replicate chambers.

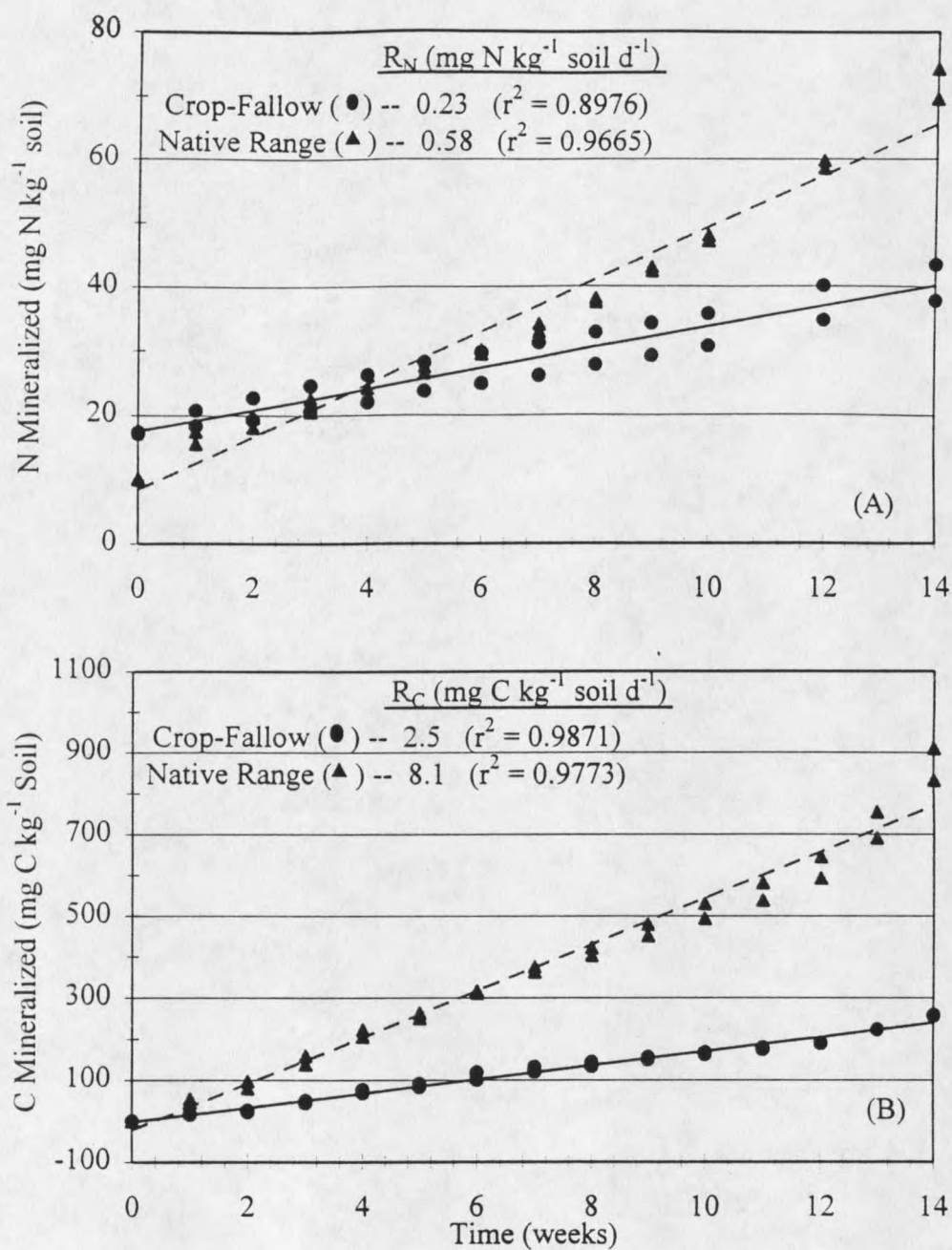
[#] Initial value of total N for this soil is for one replicate.

Appendix Table-17. Continued

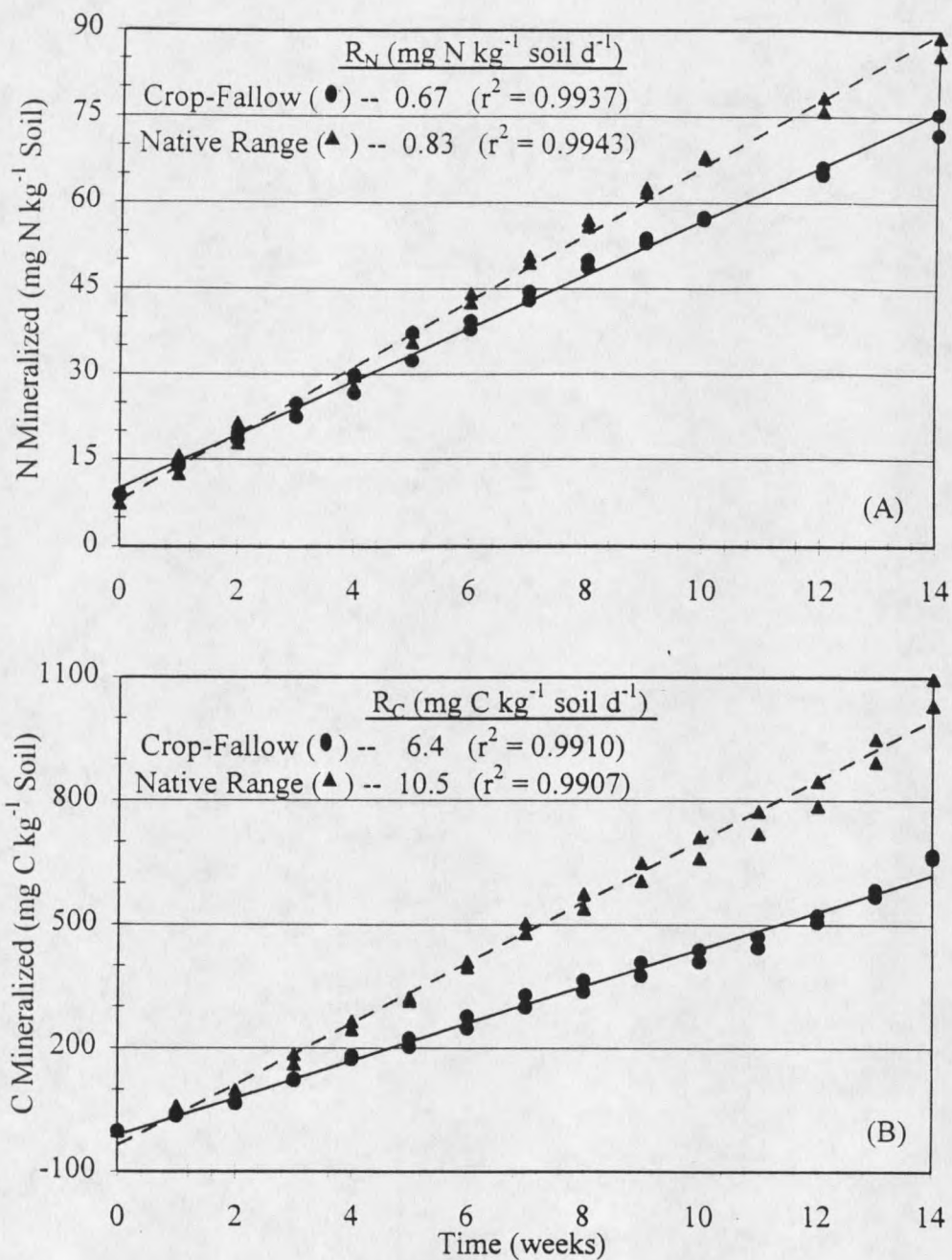
Series (Location)	Land Use [†]	Weeks						Total N Mineralized
		7	8	9	10	12	14	
		mg kg ⁻¹ soil						
Farland-Cherry (Scobey)	C-F	3.05	3.42	2.44	2.57	5.38	5.32	53.93
	N-R	9.13	9.29	8.06	7.10	15.56	14.71	196.50
Farland-Cherry (Flaxville)	C-F	1.36	1.57	1.48	1.48	4.18	3.22	40.59
	N-R	3.70	4.33	4.89	4.81	11.66	12.81	72.00
Judith (Stanford)	C-F	5.13	5.60	3.98	3.91	8.09	8.29	73.68
	N-R	6.69	6.42	5.77	5.58	9.26	10.19	87.39
Turner-Beaverton (W. Point)	C-F	0.62	0.67	0.59	0.59	1.57	1.40	16.14
	N-R	1.30	1.50	1.44	1.31	3.84	3.00	29.30
Williams-Zahill (Wolf Point)	C-F	1.65	1.83	1.72	1.57	3.20	3.68	43.72
	N-R	2.16	2.48	2.14	2.29	5.47	5.28	46.49
Williams-Zahill (Flaxville)	C-F	1.80	2.08	1.80	1.69	3.62	4.16	40.45
	N-R	2.21	2.79	1.83	2.18	4.51	3.89	32.38
Beaverll (Bozeman)	P	8.04	6.63	3.90	5.23	7.47	10.08	185.89
Creston (Creston)	C-R	3.28	3.62	2.96	2.93	4.47	4.25	88.15
Williams (Miles City)	N-R	5.16	6.12	3.82	5.10	12.53	14.05	90.13
Winifred (Windham)	C-F	5.32	6.27	5.31	5.21	12.36	9.72	108.24



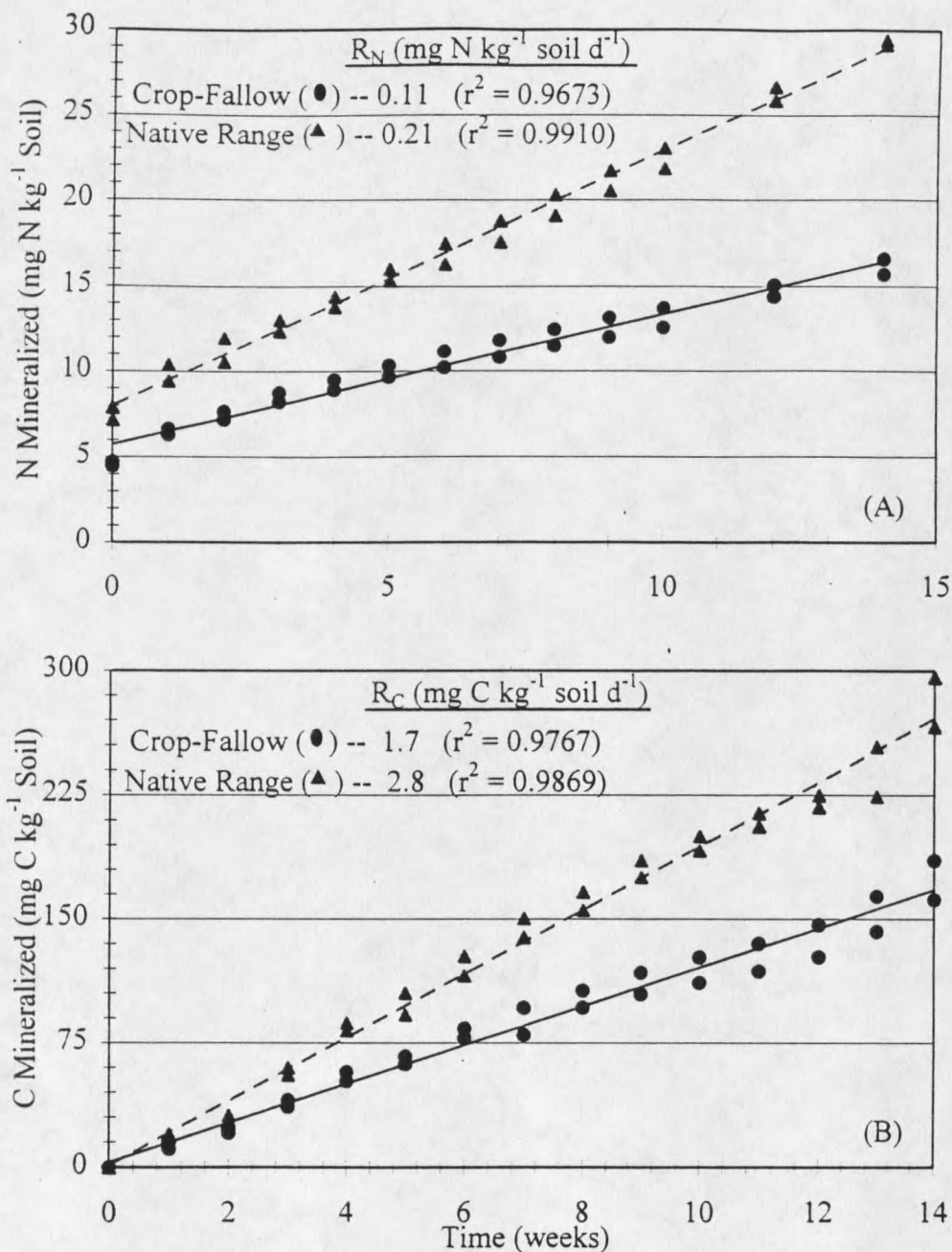
Appendix Figure 6. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Farland-Cherry crop-fallow/native range pair collected near Scobey, Montana.



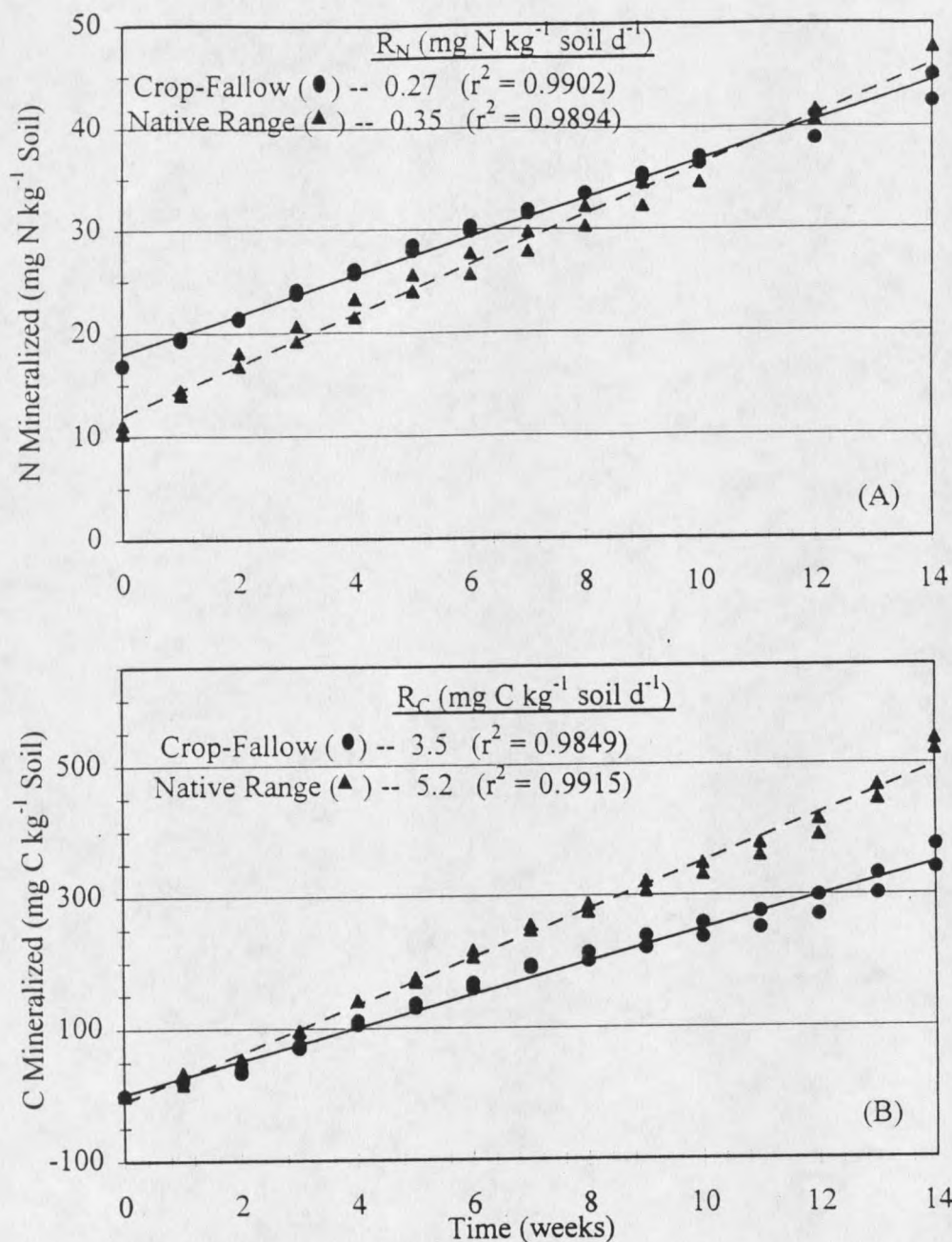
Appendix Figure 7. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Farland-Cherry crop-fallow/native range pair collected near Flaxville, Montana.



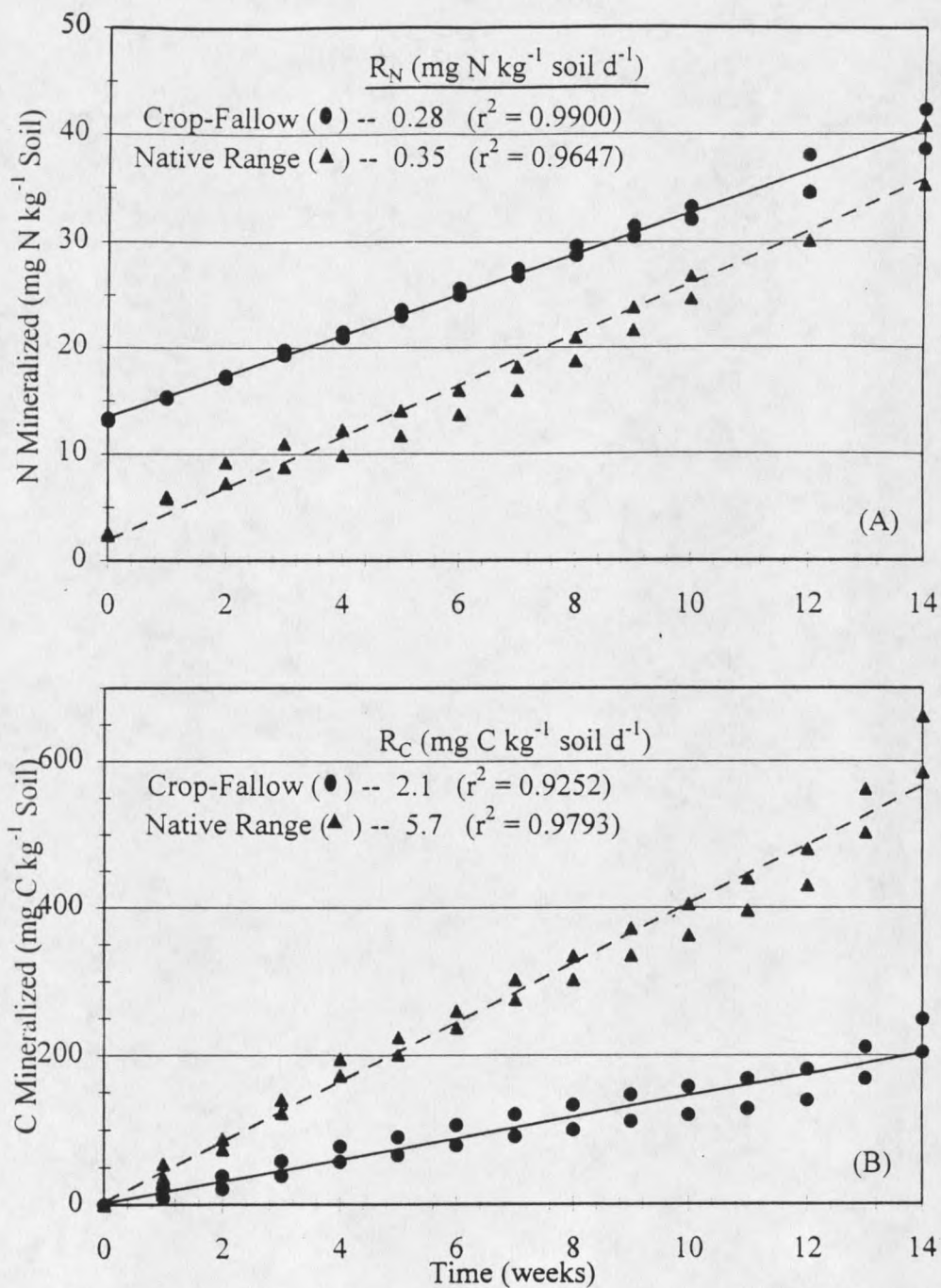
Appendix Figure 8. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Judith crop-fallow/native range pair collected near Stanford, Montana.



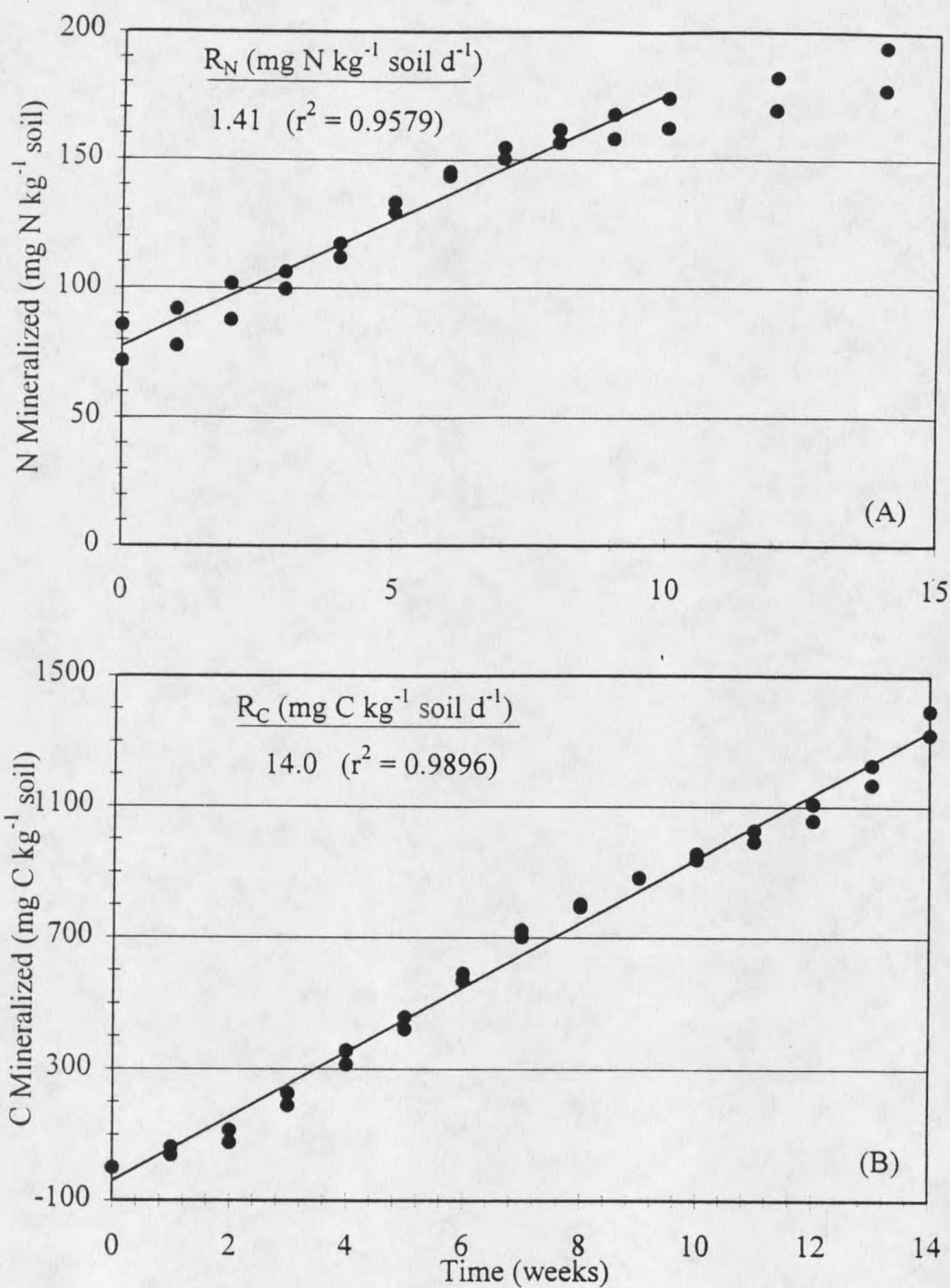
Appendix Figure 9. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Turner-Beaverton crop-fallow/native range pair collected near Wolf Point, Montana.



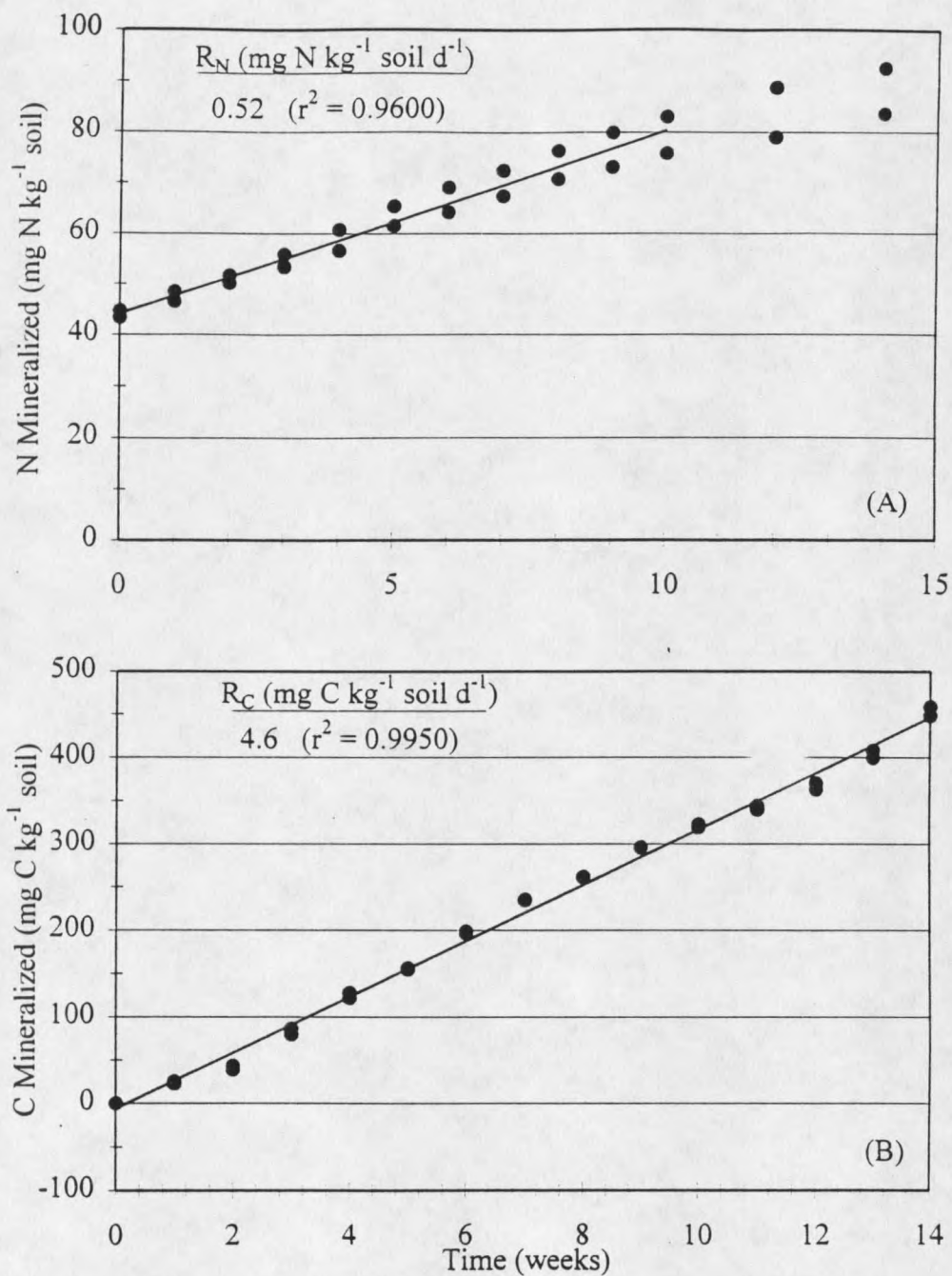
Appendix Figure 10. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Williams-Zahill crop-fallow/native range pair collected near Wolf Point, Montana.



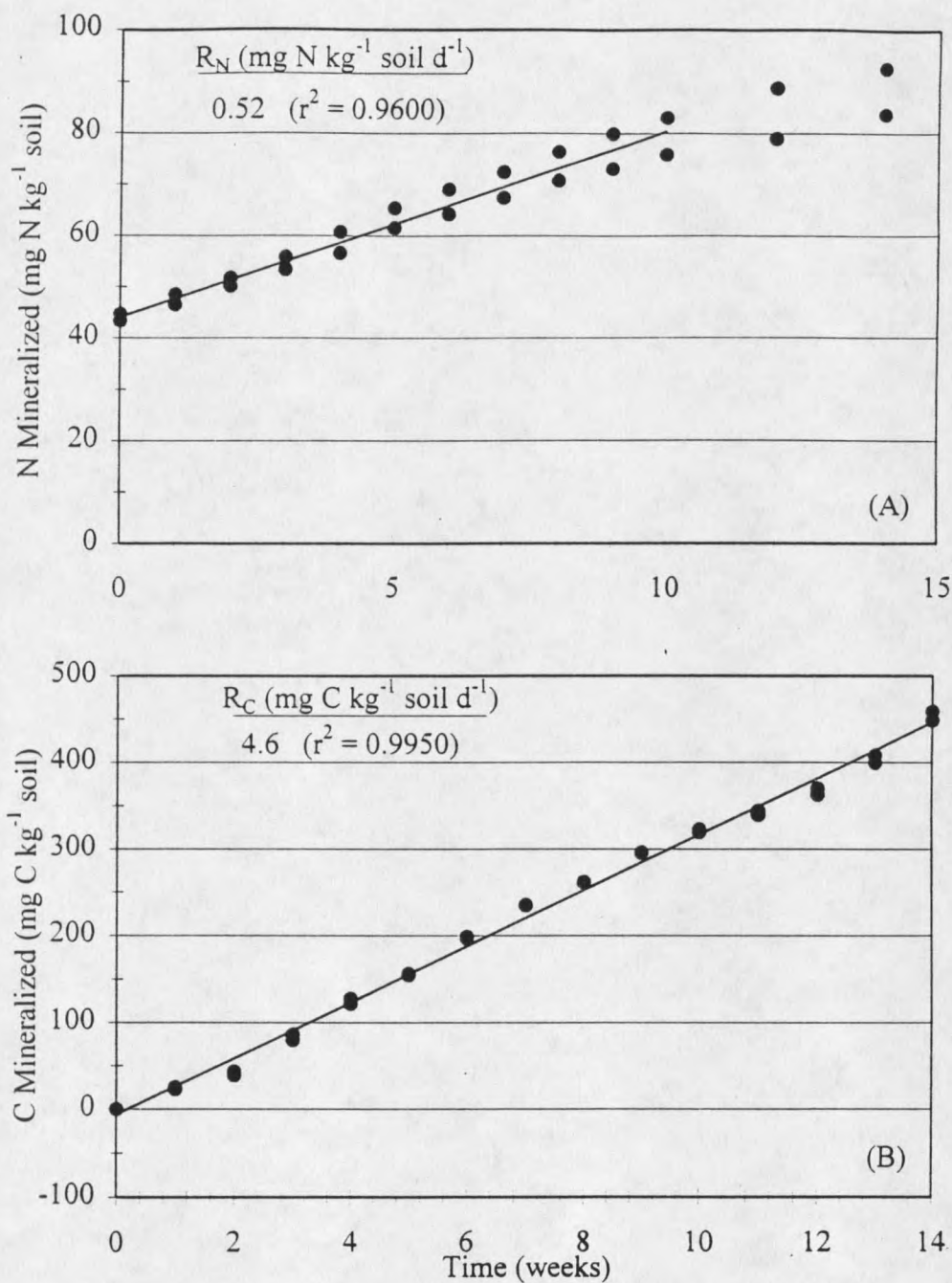
Appendix Figure 11. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Williams-Zahill crop-fallow/native range pair collected near Flaxville, Montana.



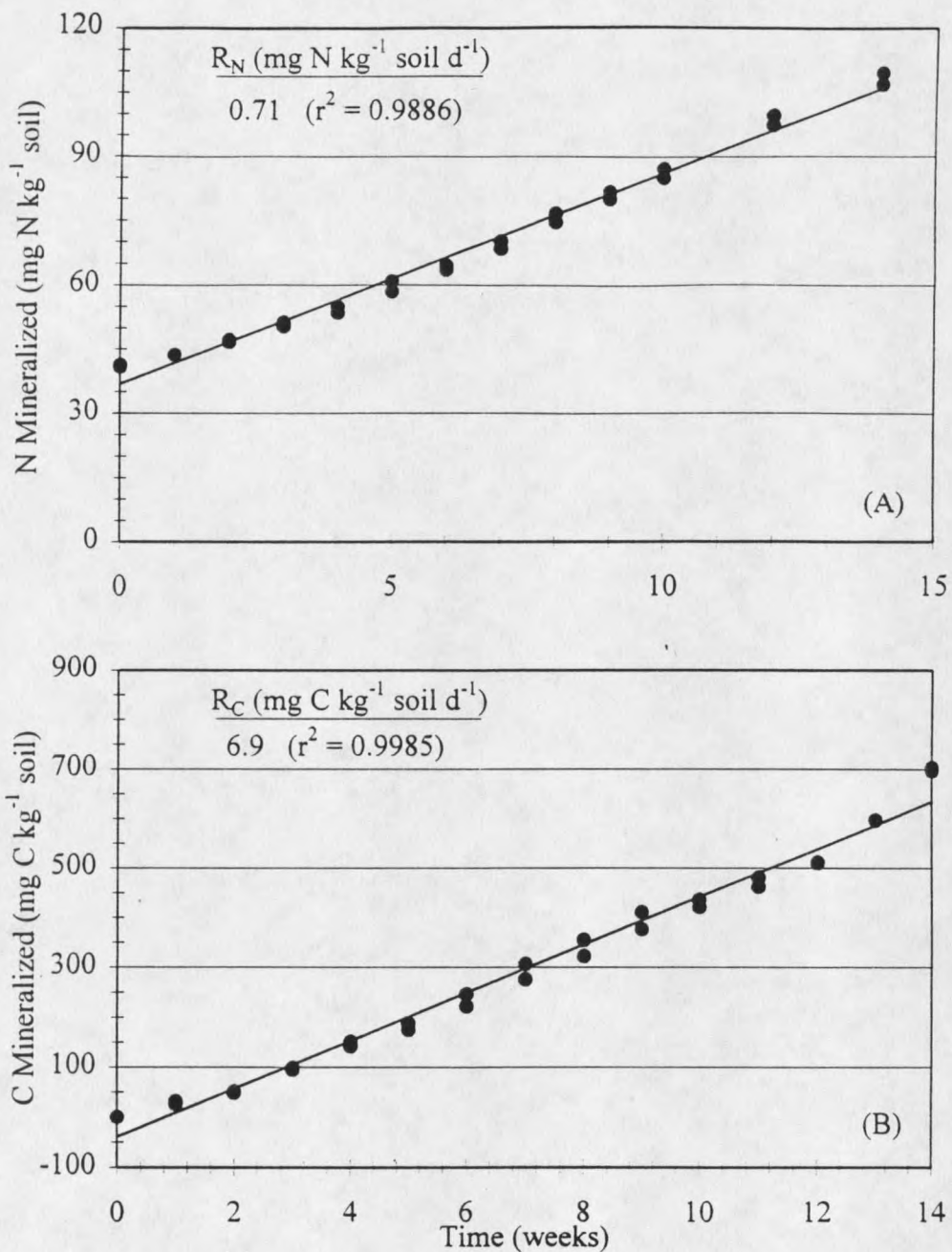
Appendix Figure 12. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Beaverell pasture soil collected near Bozeman, Montana.



Appendix Figure 13. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Creston crop rotation soil collected at the Northwestern Agricultural Research Center, Creston, Montana.



Appendix Figure 14. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Williams native range soil collected near Miles City, Montana.



Appendix Figure 15. Nitrogen (A) and C (B) accumulation over 14 weeks of incubation for the Winifred crop-fallow soil collected near Windham, Montana.

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