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Effects of Repeated Fertilization on Forest Floor and Mineral Soil Properties in Young Lodgepole Pine and Spruce Forests in Central British Columbia

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Ministry of Forests and Range
Forest Science Program

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Rob Brockley and Paul Sanborn

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PREFACE

Experimental Project (EP) 886.13 *Maximizing the Productivity of Lodgepole Pine and Spruce in the Interior of British Columbia* was implemented by the B.C. Ministry of Forests Research Branch in 1992 to examine the potential to dramatically improve the productivity of interior forests by permanently alleviating nutritional growth constraints. Research previously undertaken in Swedish boreal forests had clearly demonstrated that sustained growth responses and large reductions in rotation length are achievable by repeatedly fertilizing young conifer stands. Similar productivity gains in young lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and interior spruce (*Picea glauca* [Moench] Voss, *Picea engelmannii* Parry, and their naturally occurring hybrids) sub-boreal forests would be of great benefit in addressing future timber supply challenges in the British Columbia Interior. Nine area-based field installations (six pine and three spruce) were established on representative sites within three biogeoclimatic zones between 1992 and 1999.

The growth and yield objectives of the "maximum productivity" study are to compare the effects of different regimes and frequencies of repeated fertilization on forest growth and development and to determine optimum fertilization regimes for maximizing stand volume production. In addition, several companion studies have been undertaken at selected sites to determine the long-term effects of large nutrient additions on above- and below-ground timber and non-timber forest resources.

The purpose of this report is to examine the 12-year effects of repeated fertilization on forest floor and mineral soil properties at two study sites (one pine and one spruce) in central British Columbia.

ABSTRACT

The 12-year effects of different regimes and frequencies of repeated fertilization (applied periodically and yearly) on forest floor and mineral soil properties were evaluated at two study sites in central British Columbia. When applied at 6-year intervals to 10- to 12-year-old lodgepole pine and spruce plantations, two applications of urea (totalling 400 kg N/ha), with and without other added nutrients, had few measurable effects on forest floor or mineral soil properties 12 years after initial fertilization. Conversely, 12 years of annual nutrient additions (775–1600 kg N/ha in total) had significant effects on several forest floor and mineral soil properties, but the effects were different at the two study sites. At Crow Creek, yearly fertilization of spruce resulted in larger forest floor mass, lower carbon/nitrogen ratio, lower pH, higher mineralizable nitrogen (N), and larger pools of total N, carbon (C), and sulphur (S) in the forest floor and mineral soil. Pools of forest floor total phosphorus (P) and potassium (K) were larger in annually fertilized plots than in control plots after 12 years. Extractable P, N, and S, and exchangeable K and magnesium (Mg) levels were also higher in intensively fertilized forest floors and mineral soils at Crow Creek. These results indicate that large and frequent nutrient additions may increase the rate of N cycling and site

quality and may also promote above- and below-ground C sequestration. The low levels of soil NO_3–N at Crow Creek indicate minimal nitrification and/or rapid N uptake or immobilization of added N in vegetation and soils. Also, the continuous input of organic C from above- and below-ground sources may increase the immobilization capacity in these repeatedly fertilized soils. The apparent high retention capacity of the added N at Crow Creek and low levels of NO_3–N indicates that this system is not N saturated. In contrast, yearly fertilization of lodgepole pine at Kenneth Creek had no measurable effects on forest floor mass, C/N ratio, mineralizable N, and total N, C, and S. Relatively high forest floor and mineral soil NO_3–N levels in heavily fertilized treatment plots may indicate N saturation and high NO_3^- leaching potential. The coarse-textured soils, relatively high precipitation, and poor tree growth may have contributed to high leaching losses in repeatedly fertilized treatments at Kenneth Creek.

Results indicate that large, and frequent, nutrient additions may be an effective way to build up soil organic matter reserves and sequester atmospheric C on sites where increased tree growth stimulates litter production, root growth, and understorey development. Intensive fertilization may, therefore, be a biologically viable management option for rehabilitating forested sites that have been degraded from poor management practices such as severe broadcast burning or scarification and for reducing the contribution of greenhouse gas emissions to climate change. However, our results indicate that not all forested sites offer equal opportunities in this regard. Also, the amount of greenhouse gas emissions through all stages of forest fertilization must be considered when evaluating the net effect of intensive fertilization on C sequestration.

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1 INTRODUCTION

Nitrogen (N) deficiencies are widespread in forests throughout the British Columbia Interior, and a single N fertilization often has a substantial positive effect on tree and stand growth (Weetman et al. 1988; Brockley 1991, 1992, 1996, 2006). Other nutrient deficiencies, either induced or aggravated by N fertilization, have been implicated as factors limiting the growth response of some N-fertilized interior forests. Several studies have confirmed that growth responses may be enhanced if sulphur (S) and/or boron (B) is combined with N in fertilizer prescriptions (Brockley 2000, 2001a, 2003, 2004).

Because it is a proven method for accelerating the operability of established stands, fertilization is widely viewed by interior forest planners and practitioners as a potentially valuable tool for mitigating the effects of catastrophic mortality losses from the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) on the amount and timing of future timber supplies (B.C. Ministry of Forests and Range 2005). Large-scale aerial fertilizer operations are currently being undertaken in several interior forest management units.

A single fertilizer application typically produces only a temporary increase in tree and stand growth (usually 6–9 years). However, fertilization research with *Pinus* and *Picea* species in boreal forest regions has indicated that sustained growth responses, and large reductions in rotation length, are achievable by repeatedly fertilizing young stands (Tamm 1985, 1991; Malkonen and Kukkola 1991; Bergh et al. 1999; Tamm et al. 1999). Based on the results from long-term fertilization experiments, Bergh et al. (2005) estimated that the growth of Norway spruce (*Picea abies* L.) in northern Sweden could potentially be tripled by frequent applications of balanced fertilizers. The increased productivity would shorten rotation lengths by as much as 40–60 years (Bergh et al. 2005). Large productivity gains in young lodgepole pine and interior spruce[1] sub-boreal forests would be of great benefit in addressing future timber supply challenges in the British Columbia Interior. However, long-term growth response data from area-based field experiments are needed to document the potential impacts of "high input" silviculture on the growth and development of interior managed forests so that appropriate stand management treatments and realistic expectations can be included in forest-level analyses and timber supply mitigation strategies. The effects of large nutrient additions on other forest resources, and the potential impacts on ecosystem function and sustainability, must also be documented.

Beginning in 1992, the B.C. Ministry of Forests established a small network of lodgepole pine and interior spruce long-term "maximum productivity" research installations (EP 886.13) to document the effects of different regimes and frequencies of repeated fertilization on above- and below-ground timber and non-timber forest resources. Nine installations (six pine and three spruce) were established in 9- to 15-year-old plantations and juvenile-spaced, harvest-origin stands between 1992 and 1999. A complete project description is provided by Brockley and Simpson (2004).

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[1] In this report, references to "pine" and "spruce" indicate these two species.

Fertilization effects on tree and stand development (Brockley and Simpson 2004; Brockley 2007a), forest health (vanAkker et al. 2004, 2005), soil biota (Berch et al. 2006; Berch and Brockley 2008), and understorey vegetation (Brockley 2007b) have been previously reported. This report examines the 12-year effects of different regimes and frequencies of nutrient additions on forest floor mass, soil acidity, nutrient availability, and nutrient pools at two "maximum productivity" study sites (one pine and one spruce) in central British Columbia.

2 METHODS

2.1 Location, Site, and Stand Descriptions

2.1.1 Kenneth Creek The Kenneth Creek study site is located approximately 75 km east of Prince George, B.C. (53°49'N, 121°47'W) within the Willow variant of the Wet Cool subzone of the Sub-Boreal Spruce biogeoclimatic zone (SBSwk1), immediately adjacent to one of the westernmost outliers of the Slim variant of the the Very Wet Cool subzone of the Interior Cedar–Hemlock zone (ICHvk2) (DeLong 2003). Soil and vegetation description indicates that the site belongs to the submesic Sxw–Huckleberry–Highbush-Cranberry (05) site series (DeLong 2003). The site is on a level to slightly undulating sandy glaciofluvial terrace north of the Bowron River at approximately 810 m elevation. The well-drained and stone-free soil is derived from thick, well-sorted glaciofluvial outwash parent material with a fine to medium loamy sand texture. Although distinct Ae and Bf horizons are evident, the latter horizon is too thin to meet the requirements of the Podzolic order. The soil is classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998).

The site was logged in 1980, broadcast burned in 1982, and planted to lodgepole pine in 1983. Estimated lodgepole pine site index (SI_{50} – height at breast height age 50) according to site units of the biogeoclimatic ecosystem classification system of British Columbia is 21 m (B.C. Ministry of Forests and Range 2008). At the time of installation establishment in the fall of 1993, the stand was 12 years old and had an average density of about 1360 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1993, the average height of the crop trees within treatment plots was 5.6 m.

This plantation also includes another research trial examining the fate and transformations of fertilizer S using stable isotope tracer methods (EP 886.15). Additional details of soil characteristics are given by Arocena and Sanborn (1999) and Sanborn et al. (2005).

2.1.2 Crow Creek The Crow Creek study site is located approximately 60 km southeast of Houston, B.C. (54°20'N, 126°17'W) within the Babine variant of the Moist Cold subzone of the Sub-Boreal Spruce biogeoclimatic zone (SBSmc2) at an elevation of 1000 m. Soil and vegetation description indicates that the site belongs to the zonal Sxw–Huckleberry (01) site series (Banner et al. 1993). The well-drained soil is derived from a thick morainal blanket and is silt loam in texture with about 30% coarse fragments (predominantly gravels) in the upper mineral soil. Depending on the thickness of the Bf horizon, the soil classification is either an Eluviated Dystric Brunisol or an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998).

The site was logged and broadcast burned in 1985 and planted to spruce in 1986. Estimated spruce SI_{50} according to site units of the biogeoclimatic ecosystem classification system of British Columbia is 18.7 m (B.C. Ministry of Forests and Range 2008). At the time of installation establishment in the fall of 1994, the stand was 10 years old and had an average density of about 1200 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1994, the average height of the crop trees within treatment plots was 2.4 m.

2.2 Experimental Design and Treatment Description

At each study site, six treatments are replicated three times in a completely randomized design for a total of eighteen 0.164-ha treatment plots. Each treatment plot consists of an inner, 0.058-ha assessment area surrounded by a treated buffer. Treatment plots are systematically located so that within- and between-plot conditions (e.g., stand density, tree size, soil characteristics, and minor vegetation) are as uniform as possible. A minimum distance of 5 m separates the outer boundaries of adjacent treatment plots. A minimum distance of 20 m separates the outer treatment plot boundaries from major disturbances (e.g., roads or large stand openings).

The six treatments are described in Table 1. All of the fertilized treatments include B to safeguard against the possibility of B deficiencies induced by repeated N additions. The NSB and Complete treatments are included to test for incremental growth responses attributable to S and other added nutrients. Previous studies have indicated the presence of B and S deficiencies in interior forests (Brockley 2000, 2003, 2004). The ON1 and ON2 treatments are patterned after "optimum nutrition" fertilization experiments in Sweden (Tamm 1991; Tamm et al. 1999) and Canada (Weetman et al. 1995; Kishchuk et al. 2002), in which N is added frequently to maintain elevated foliar N levels. The ON1 and ON2 treatment plots typically receive 50–100 kg N/ha and 100–200 kg N/ha, respectively, each spring. Other nutrients (e.g., S, B, phosphorus [P], potassium [K], magnesium [Mg], copper [Cu], and iron [Fe]) are added periodically to provide an appropriate nutrient balance and to minimize growth limitations caused by secondary deficiencies.

TABLE 1 *Description of fertilizer treatments*

Treatment code	Treatment
Control	Not fertilized
NB	Fertilize every 6 years with 200N, 1.5B
NSB	Fertilize every 6 years with 200N, 50S, 1.5B
Complete	Fertilize every 6 years with 200N, 100P, 100K, 50S, 25Mg, 1.5B
ON1	Fertilize yearly to maintain foliar N concentration at 1.3% and other nutrients in balance with foliar N
ON2	Fertilize yearly to maintain foliar N concentration at 1.6% and other nutrients in balance with foliar N

Note: For each treatment, numbers preceding each nutrient symbol represent nutrient application rate (kg/ha). B, boron; K, potassium; Mg, magnesium; N, nitrogen; P, phosphorus; S, sulphur.

2.3 Fertilization

At each study site, all NB, NSB, and Complete treatment plots were fertilized in the spring following installation establishment and are refertilized every 6 years.

The NB treatment is a customized combination of urea (46–0–0; N–P–K) and granular borate (15% B) blended to deliver 200 kg N/ha (200N) and 1.5 kg B/ha (1.5B). Urea, ammonium sulphate (21–0–0–24; N–P–K–S), and granular borate are combined to deliver 200N, 50S, and 1.5B in the NSB treatment.

In the Complete treatment, urea is the major source of N. A small amount of N (24% of the total) is added as monoammonium phosphate (11–52–0; N-P–K), which also serves as the P source. Potassium is delivered as potassium chloride (0–0–60; N–P–K) and sulphate potash magnesia (0–0–22–22–11; N–P–K–S–Mg). The latter fertilizer is also the source of S and Mg. As in the NB and NSB treatments, B is added as granular borate. The individual sources are combined to deliver 200N, 100P, 100K, 50S, 25Mg, and 1.5B.

Yearly fertilizer prescriptions for ON1 and ON2 treatments are developed following foliar sampling and nutrient analysis each fall. Individual nutrients are included in customized blends in amounts and frequencies that are required to maintain individual foliar nutrient levels, and nutrient ratios (e.g., N/P, N/K, N/S, N/Mg) within suitable ranges as indicated in published forest nutrition literature (Ingestad 1979; Linder 1995; Brockley 2001b). Specifically, the upper threshold targets for foliar nutrient ratios are as follows: N/P – 10, N/K – 3, N/S – 14.5, N/Mg – 20, N/Ca – 20; N/B – 1000; N/Fe – 500; N/Cu – 5000.

Customized fertilizer blends are applied to the ON1 and ON2 treatment plots each spring, soon after snowmelt (ON1 and ON2 treatment plots at Kenneth Creek were not fertilized in 1997). Urea is the primary N source for the ON1 and ON2 treatments. Additional sources of N are monoammonium phosphate and ammonium nitrate (34–0–0; N–P–K). Phosphorus is always added as monoammonium phosphate. Sulphate potash magnesia is used extensively as a source of K, S, and Mg. Potassium chloride, ammonium sulphate, and ProMag 36 (36% Mg) are used to supply additional K, S, and Mg, respectively. Boron is supplied as granular borate.

Complete fertilization histories at Kenneth Creek and Crow Creek from the time of installation establishment until the completion of 12th-season soil sampling are shown in Tables 2 and 3, respectively. At Kenneth Creek, yearly N additions to ON1 and ON2 treatments totalled 775 and 1350 kg/ha, respectively, over 11 years (soil sampling was completed in May 2005, immediately before 12th-season fertilization of ON1 and ON2 treatment plots). For ON1, the total amounts of other added nutrients were (kg/ha): 400P, 400K, 284S, 257Mg, 6B, 8Cu, 20Fe, and 6Zn. For ON2, the total amounts of other added nutrients were (kg/ha): 400P, 400K, 293S, 307Mg, 6B, 8Cu, 20Fe, and 6Zn. At Crow Creek, ON1 and ON2 plots received 925 and 1600 kg N/ha, respectively, over 12 years (soil sampling was completed in September 2006, four months after 12th-season fertilization of ON1 and ON2 treatment plots). Additions of other nutrients to ON1 and ON2 plots totalled (kg/ha): 400P, 450K, 419S, 257Mg, 7.5B, 13Cu, 30Fe, and 9Zn.

TABLE 2 *Fertilization regimes by treatment and year at Kenneth Creek (EP 886.13 Installation #2)*

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1994	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1995				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
1996				100N, 100Mg, 17S	200N, 100Mg, 17S
1997				None	None
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 50P, 50K, 63S, 32Mg	150N, 50P, 50K, 63S, 32Mg
2001				100N, 2.5S, 3Cu, 10Fe, 2.5Zn	100N, 50Mg, 11S, 3Cu, 10Fe, 2.5Zn
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn

N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

TABLE 3 *Fertilization regimes by treatment and year at Crow Creek (EP 886.13 Installation #3)*

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1995	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1996				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
1997				50N, 50P, 50K, 100Mg, 50S, 1.5B	100N, 50P, 50K, 100Mg, 50S, 1.5B
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63S, 32Mg	150N, 50K, 63S, 32Mg
2001	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 2S, 3Cu, 10Fe	150N, 10Fe, 3Cu, 2.4S
2002				50N, 1.5B	100N, 1.5B
2003				100N, 50S	150N, 50S
2004				100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	150N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
2005				75N, 50S	100N, 50S
2006				50N, 50P, 50K, 52S, 25Mg, 5Cu, 10Fe, 3Zn	100N, 50P, 50K, 52S, 25Mg, 5Cu, 10Fe, 3Zn

N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

2.4 Soil Sampling

At both study sites, forest floor and mineral soils samples were collected throughout each 0.164-ha treatment plot using a stratified random approach, with eight random sampling points located in each of four 0.014-ha (11.33 × 36.24 m) subplots. Within each subplot, sampling points were located by generating a list of random co-ordinates (with embedded constraints to ensure that all sampling points were located a minimum of 1 m from plot boundaries). Sampling points that landed on a stump, solid log, or any other spot that was physically impossible to sample were discarded and a new set of random co-ordinates was used to locate a suitable sampling point.

2.4.1 Forest floor sampling At each sampling point, a square metal sampling frame and knife were used to carefully remove all forest floor materials down to the mineral soil boundary. At Kenneth Creek, a 20 × 20 cm forest floor sample was removed at each sampling location. Individual forest floor samples were air-dried and weighed, and then composited by subplot (eight samples per subplot). Following repeated sample splitting, a representative 500-g subsample was selected from each composite and ground in a hammermill before shipping to the Ministry of Forests and Range analytical laboratory. All composite subsamples were oven-dried at the laboratory, and the moisture correction value for each subsample was applied to all eight air-dry forest floor values from each subplot. At Crow Creek, a 15 × 15 cm forest floor sample was removed at each sampling location. The eight samples per subplot were combined into one composite sample in the field and shipped to the analytical laboratory where each of the 72 composite samples was air-dried and weighed. Representative subsamples were then milled and oven-dried. The moisture correction value for each subsample was applied to the air-dry composite forest floor value from each subplot.

At both sites, all woody debris situated on the forest floor surface and not completely covered by needle litter was excluded from the sample. Terrestrial lichens, green upper portions of mosses, green stems and leaves of living herbaceous plants, and living roots > 5 mm in diameter were also removed from each sample.

2.4.2 Mineral soil sampling Following forest floor removal, an Eijelkamp "stony soil auger" was used to collect mineral soil from the 0–20 cm depth at each of the eight sampling points within each subplot. The eight individual mineral soil samples per subplot were combined into one composite sample (four composite samples per treatment plot). The 72 composite samples from Kenneth Creek were air-dried and sieved to remove coarse fragments and roots (> 2 mm), and a sample splitter was used to select a representative subsample from the fine fraction for shipment to the laboratory. The composite mineral soil samples from Crow Creek (with large coarse fragments removed) were shipped immediately to the laboratory where air-drying, sieving, sample splitting, and oven-drying were completed.

2.4.3 Mineral soil bulk density At Crow Creek, soil bulk density sampling was undertaken at two randomly located sampling points within each subplot (i.e., eight sampling points per treatment plot). After removing the forest floor down to mineral soil, a 20 cm deep hole (~ 1.2 L volume) was carefully excavated and all excavated material was individually bagged. A plastic bag was inserted into the excavated hole and filled with glass beads to estimate the volume of the excavation. The procedure was repeated three times at each sampling location, or until three volume estimates agreed within 5%. Bulk density was measured at Kenneth Creek in 1999 during an earlier study, using cylindrical cores (5 cm diameter × 4 cm length) collected at 10- to 14-cm depth at two randomly located sampling points within each subplot.

For estimating total nutrient pools on an area basis (g/m^2), the bulk density was calculated as the mass of the fine fraction (< 2 mm) divided by the excavation or core volume, as applicable.

2.5 Soil Analysis

The following chemical analyses were completed by the Ministry of Forests and Range analytical laboratory:

1. forest floor and mineral soils:
   - total C and N (LECO CHN-600 Elemental Analyzer),
   - total S (LECO SC-132 S Analyzer),
   - mineralizable N (anaerobic incubation; Powers 1980),
   - extractable P (Bray P1 method; Kalra and Maynard 1991),
   - extractable inorganic sulphate-S (SO_4–S) (forest floors extracted with 0.01 M NH_4Cl; mineral soils with 500 Mg/L P as $Ca(H_4PO_4)2 \bullet H_2O$; SO_4^{2-}; determined by ion chromatography),
   - extractable ammonium-N (NH_4–N) and nitrate-N (NO_3–N) (extracted with 2M KCl; colorimetric determination by auto analyzer),
   - pH (H_2O, 0.01 M $CaCl_2$; Kalra and Maynard 1991),
   - cation exchange capacity (CEC) ($BaCl_2$ method; Hendershot and Duquette 1986), with exchangeable cations (Ca, Mg, K, Na, Fe, Al, Mn) determined by inductively coupled argon plasma–atomic emission spectroscopy (ICAP).

2. forest floor samples:
   - total elemental concentrations (Al, B, Ca, Cu, Fe, K, Mn, Mg, P, Zn) determined with microwave digestion in HNO_3–H_2O_2–HCl (Kalra and Maynard 1991) and ICAP.

The acid digestion–ICAP method may not completely solubilize nutrients, especially those that are associated with mineral material that may be part of the forest floor sample. All data were reported on an oven-dry basis.

2.6 Data Analysis

Analysis of variance using the GLM procedure in SAS (SAS Institute Inc. 2004) was used to test the following hypothesis with respect to the various soil parameters:

H_0: There were no differences among the six treatments.
Pre-planned single degree of freedom unadjusted linear contrasts were performed using the GLM procedure in SAS to test the following hypotheses regarding differences among the fertilizer treatments:
H_0a: There was no difference between the control treatment and the treatments fertilized every 6 years (NB, NSB, Complete).
H_0b: There was no difference between the control treatment and the treatments fertilized every year (ON1, ON2).
H_0c: There was no difference between annual fertilization frequency (ON1, ON2) and 6-year fertilization frequency (NB, NSB, Complete).
H_0d: There was no difference between different rates of annual fertilization (ON1 vs. ON2).

A level of significance of 0.05 is used throughout this technical report for inferring statistical significance. Within each ANOVA, the combined type I error probability with the four pre-planned contrasts may exceed 0.05. To compensate for this possibility, the reader may wish to apply a more stringent level of significance when interpreting the contrasts.

3 RESULTS

3.1 Forest Floor

3.1.1 Forest floor mass Forest floor mass was unaffected by fertilization at Kenneth Creek after 12 years (Figure 1a; Table 4). At Crow Creek, differences in forest floor mass between the control and periodic or annual fertilizer treatments were not statistically significant (Figure 1b; Table 4). However, fertilization with NB and NSB apparently had a slightly negative effect on forest floor mass, whereas the effects of the Complete fertilizer were positive (Figure 1b). Annual fertilization (ON1 and ON2) resulted in significantly larger forest floor mass, than periodic application of NB, NSB, and Complete fertilizers (Figure 1b; Table 4) at Crow Creek. Mean forest floor mass in ON1 plots was 53% greater than in the control plots over 12 years.

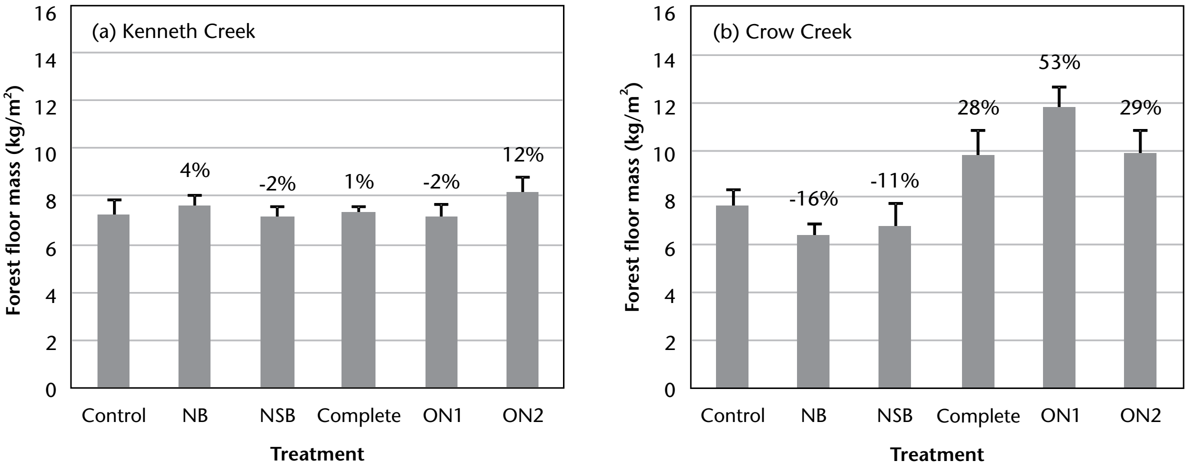

FIGURE 1 *Mean forest floor mass by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Values above bars indicate change relative to the control treatment. Error bars represent standard error of the mean.*

TABLE 4 *ANOVA summary table for forest floor mass (kg/m^2) showing observed F statistics, probability (p) values, and error mean squares*

Source of variation	df	*F*	*p>F*
Kenneth Creek			
Treatment	5	0.23	0.940
Control vs. periodic	1	0.01	0.922
Control vs. annual	1	0.16	0.698
Periodic vs. annual	1	0.17	0.692
ON1 vs. ON2	1	0.80	0.388
Error mean square	12	7.220	
Crow Creek			
Treatment	5	2.17	0.125
Control vs. periodic	1	0.00	0.994
Control vs. annual	1	3.30	0.094
Periodic vs. annual	1	5.89	0.032
ON1 vs. ON2	1	0.88	0.366
Error mean square	12	23.943	

3.1.2 Soil pH Forest floor pH was relatively unaffected by either periodic or annual fertilization at Kenneth Creek (Figure 2a, c; Table 5). At Crow Creek, differences in soil pH between the control and periodic fertilizer treatments were not statistically different (Figure 2b, d; Table 5). However, annual fertilization (especially ON1) lowered forest floor pH, and pH differences between periodic and annual fertilizer treatments were also statistically significant (Figure 2b, d; Table 5).

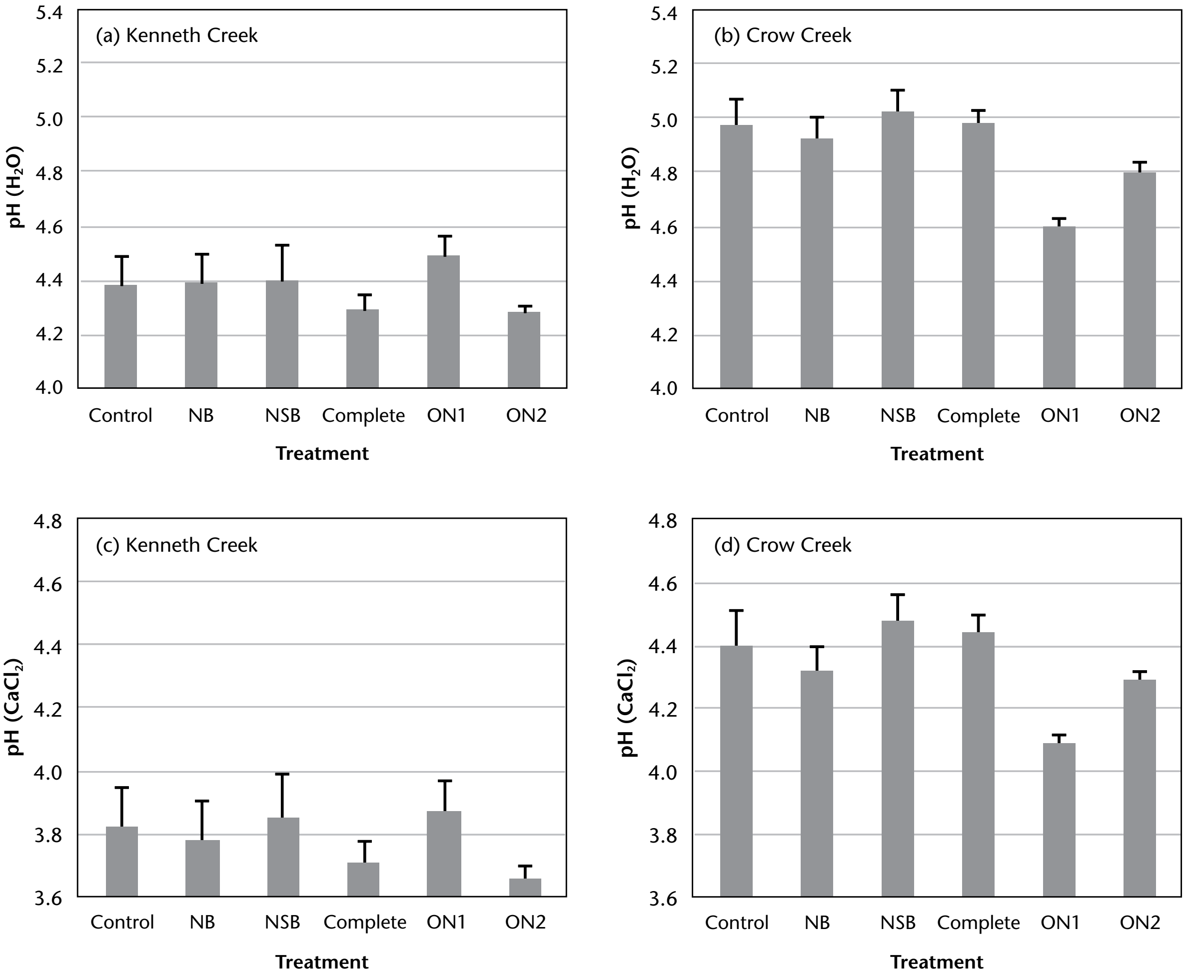

FIGURE 2 *Mean forest floor pH by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 5 *ANOVA summary table for forest floor pH showing observed F statistics, probability (p) values, and error mean squares*

		pH (H_2O)		pH ($CaCl_2$)	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***
Kenneth Creek					
Treatment	5	0.17	0.970	0.12	0.985
Control vs. periodic	1	0.01	0.914	0.02	0.879
Control vs. annual	1	0.00	0.994	0.04	0.840
Periodic vs. annual	1	0.02	0.884	0.01	0.937
ON1 vs. ON2	1	0.60	0.453	0.40	0.540
Error mean square	12	0.439		0.643	
Crow Creek					
Treatment	5	7.90	<0.001	1.66	0.219
Control vs. periodic	1	0.00	0.985	0.02	0.904
Control vs. annual	1	4.98	0.045	2.43	0.145
Periodic vs. annual	1	9.11	0.011	5.04	0.044
ON1 vs. ON2	1	1.96	0.186	1.63	0.225
Error mean square	12	0.122		0.140	

3.1.3 Total carbon, nitrogen, and sulphur Forest floor total C concentrations at Kenneth Creek and Crow Creek were relatively unaffected by either periodic or annual fertilization (Figure 3a, b; Table 6).

Total N and S levels were unaffected by periodic fertilization at Kenneth Creek and at Crow Creek (Figure 3c–f; Table 6). However, N and S levels were significantly higher in annual fertilizer treatments than in the control or periodic treatments at both study sites. Mean forest floor N was apparently slightly higher in ON2 treatments than in ON1 treatments after 12 years, although differences were not statistically significant (Figure 3c, d; Table 6).

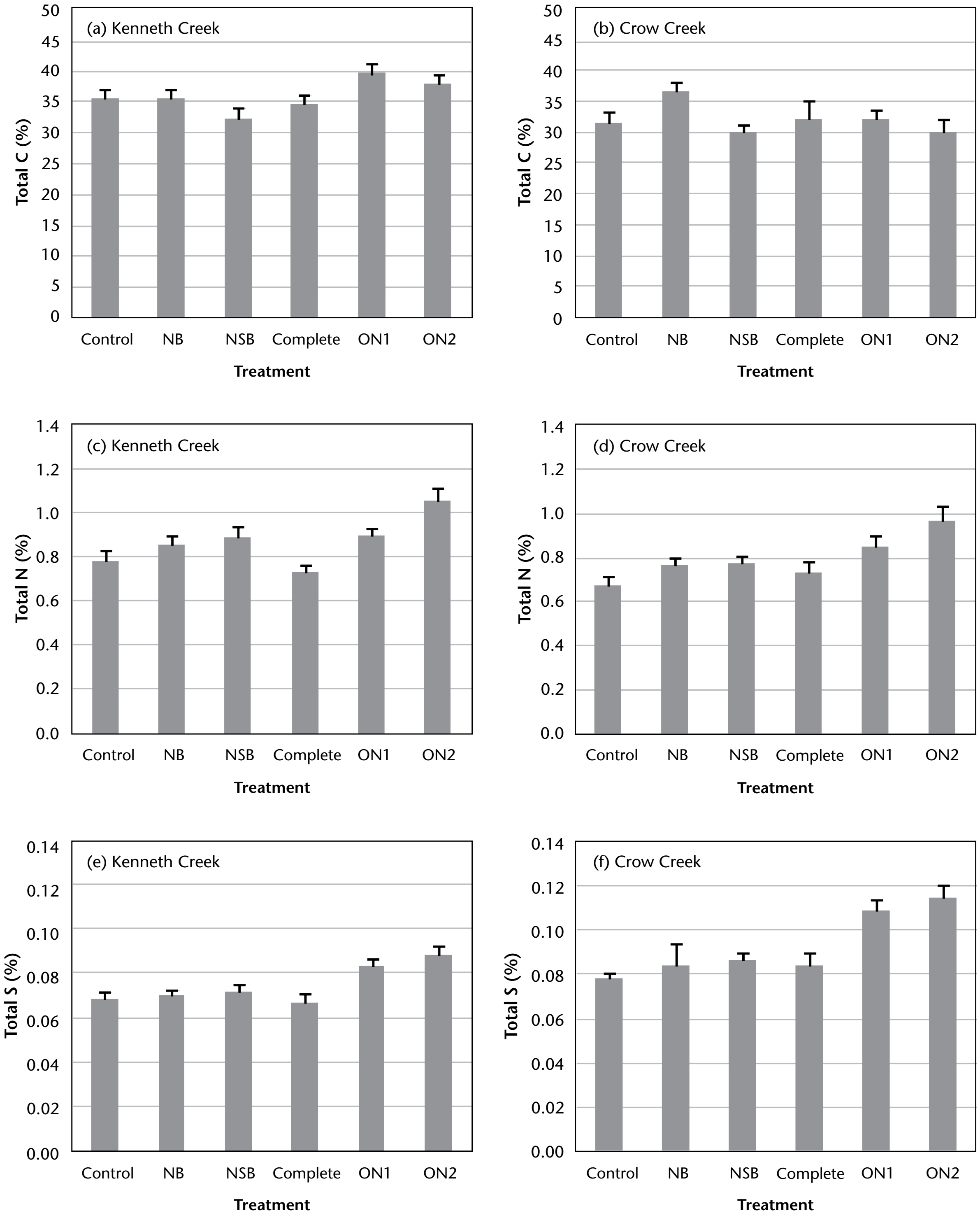

FIGURE 3 *Mean forest floor total percent carbon (C), nitrogen (N), and sulphur (S) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 6 *ANOVA summary table for forest floor total percent carbon (C), nitrogen (N), and sulphur (S), and C/N ratio showing observed* F *statistics, probability* (p) *values, and error mean squares*

		Total							
		C		N		S		C/N ratio	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek									
Treatment	5	1.03	0.444	2.25	0.116	4.45	0.016	0.61	0.697
Control vs. periodic	1	0.24	0.630	0.22	0.651	0.01	0.923	0.32	0.580
Control vs. annual	1	1.05	0.326	4.34	0.059	11.01	0.006	0.67	0.427
Periodic vs. annual	1	4.00	0.069	4.87	0.047	18.73	0.001	0.15	0.709
ON1 vs. ON2	1	0.26	0.621	2.34	0.152	0.56	0.469	0.80	0.388
Error mean square	12	73.17		0.068		0.00023		496.72	
Crow Creek									
Treatment	5	0.62	0.690	7.51	<0.001	3.28	0.043	2.41	0.098
Control vs. periodic	1	0.19	0.670	1.12	0.310	1.14	0.306	0.71	0.416
Control vs. annual	1	0.00	0.959	8.14	0.014	11.85	0.005	6.48	0.026
Periodic vs. annual	1	0.39	0.545	6.19	0.029	10.67	0.007	5.52	0.037
ON1 vs. ON2	1	0.22	0.647	1.49	0.246	0.28	0.609	1.12	0.311
Error mean square	12	117.66		0.056		0.00078		240.65	

3.1.4 Carbon/nitrogen ratio Forest floor C/N ratio was unaffected by either periodic or annual fertilization at Kenneth Creek (Figure 4a; Table 6). At Crow Creek, differences in C/N between the control and periodic fertilizer treatments were also statistically insignificant (Figure 4b; Table 6). However, annual fertilization (especially ON2) at Crow Creek resulted in significantly lower C/N ratios than the control and periodic applications of NB, NSB, and Complete fertilizers after 12 years.

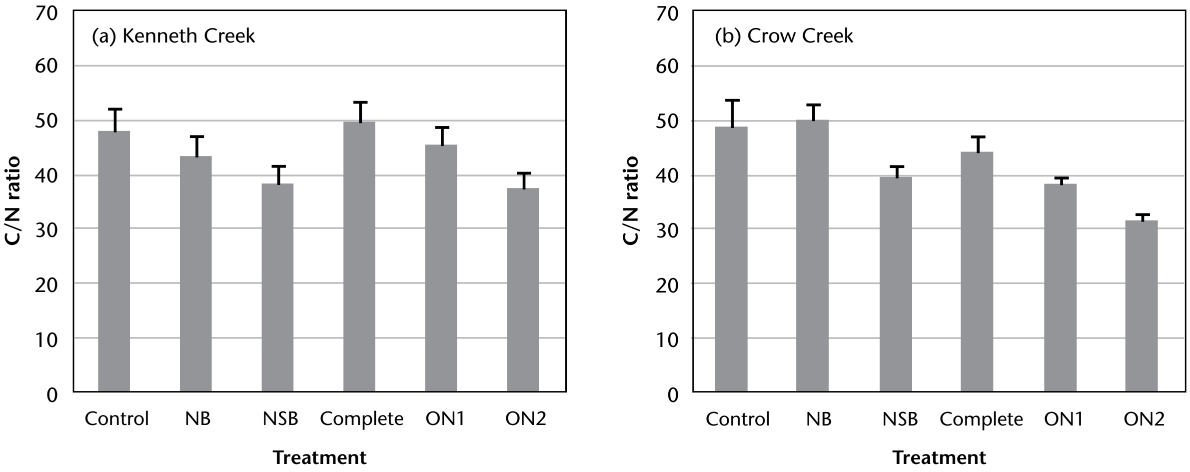

FIGURE 4 *Mean forest floor carbon/nitrogen (C/N) ratio by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

3.1.5 Total acid digestible nutrients The concentrations of several forest floor macronutrients (P, K, Ca, Mg) were relatively unaffected by either periodic or annual fertilization at Kenneth Creek (Figure 5; Table 7). At Crow Creek, differences in acid digestible macronutrient concentrations between the control and periodic fertilizer treatments were not statistically different (Figure 5; Table 7). Among periodic treatments, mean P, K, and Mg levels were lowest in NB plots and highest in Complete plots (where periodic nutrient additions included P, K, and Mg) (Figure 5). At Crow Creek, total P, K, and Mg levels were significantly higher in annual fertilizer treatments (ON1 and ON2) than in the control and periodic treatments (Figure 5; Table 7). Conversely, Ca levels were significantly lower in annual treatments compared to periodic treatments and the control after 12 years (Figure 5f; Table 7). Levels of several forest floor micronutrients were higher in fertilized treatments at both Kenneth Creek and Crow Creek after 12 years (Figure 6). Differences in B levels between the control and periodic treatments were statistically significant at Crow Creek (Table 8). Differences in the total levels of other micronutrients between the control and periodic fertilizer treat-

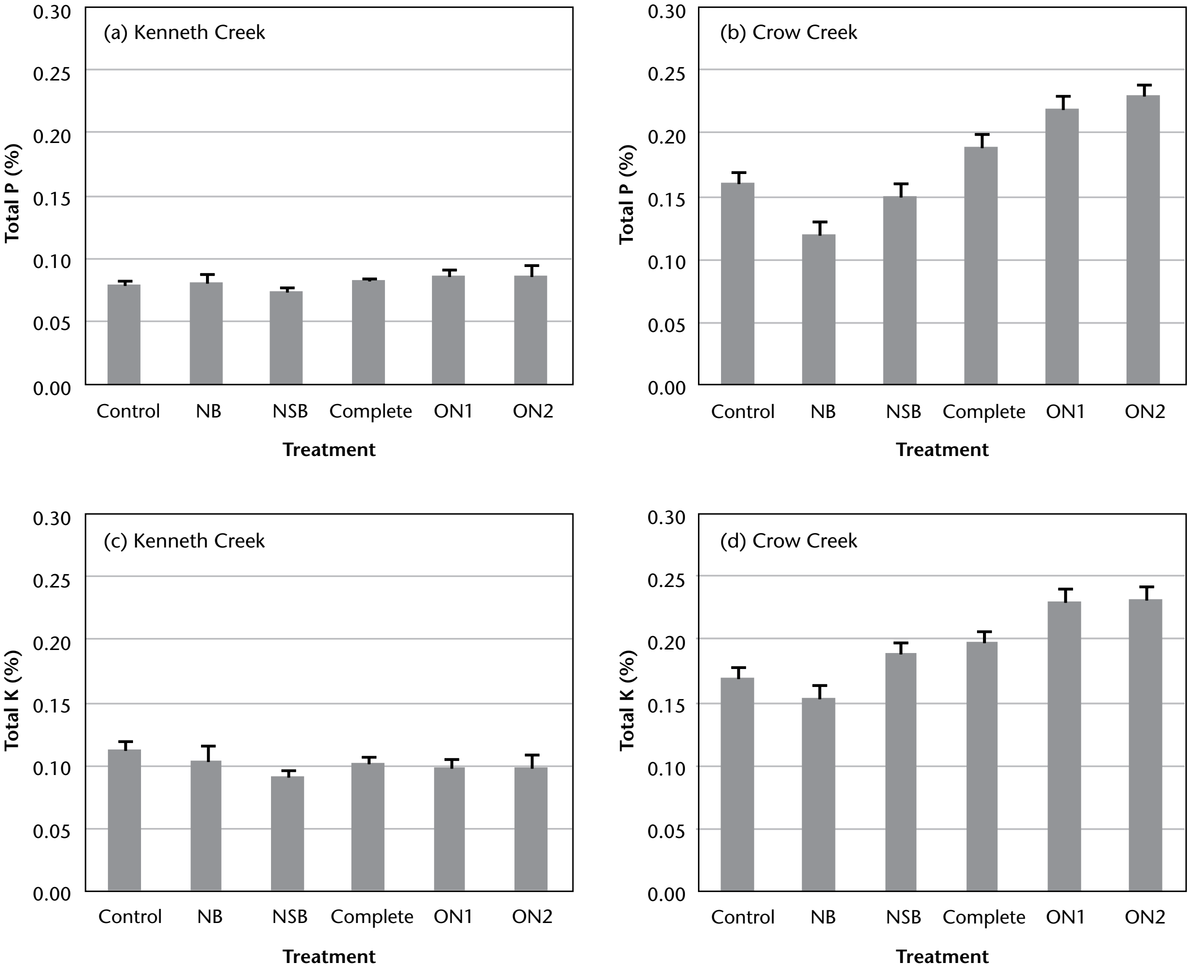

FIGURE 5 *Mean forest floor acid digestible total macronutrients by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

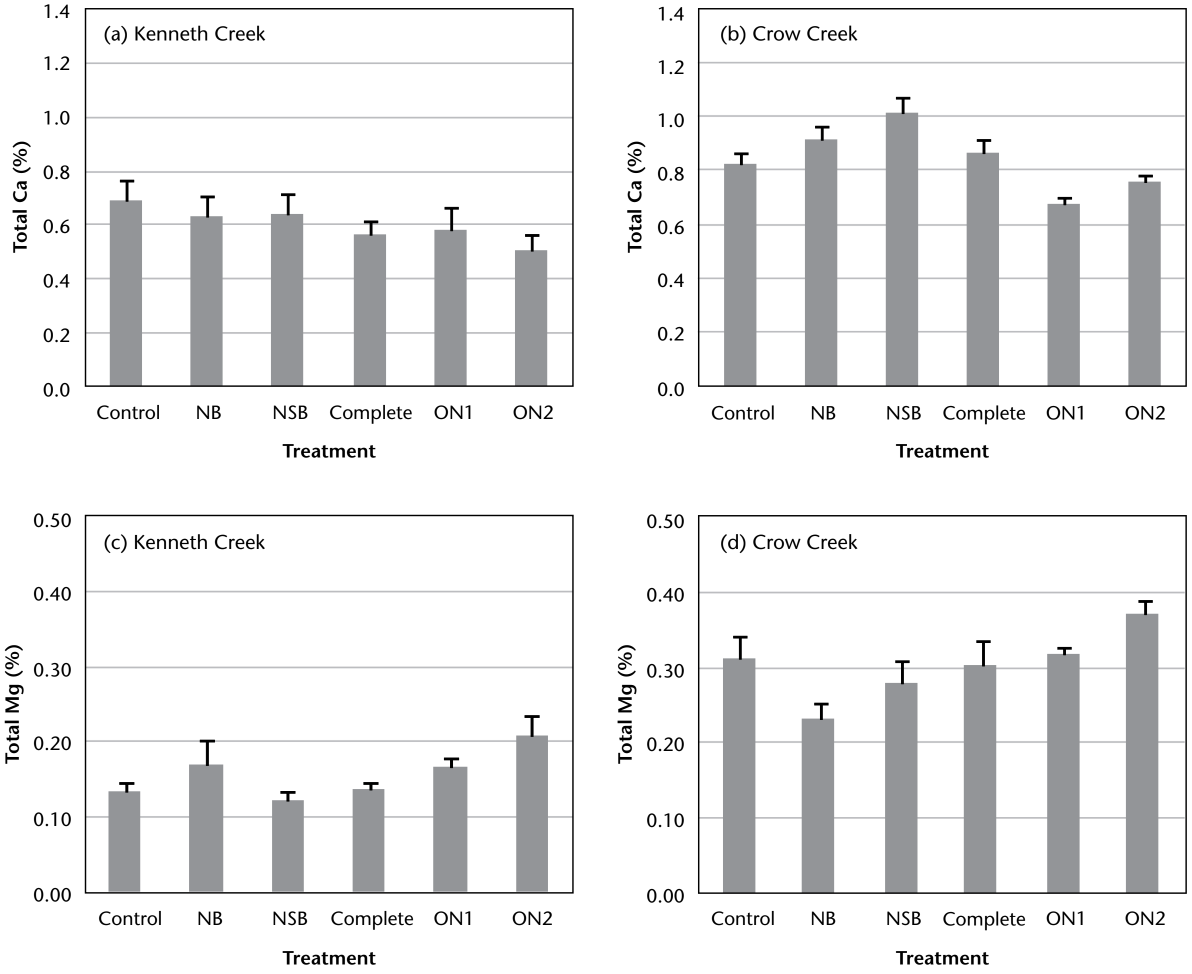

FIGURE 5 *Continued.*

ments were not statistically different at either site. Levels of B, Cu, and Zn were higher in annual fertilizer treatments compared to the control and periodic treatments at both study sites (Figure 6a–f; Table 8). All three of these micronutrients were periodically included in ON1 and ON2 fertilizer prescriptions. Conversely, Fe (which was also added) levels were unaffected by annual fertilization at both sites (Figure 6g, h; Table 8).

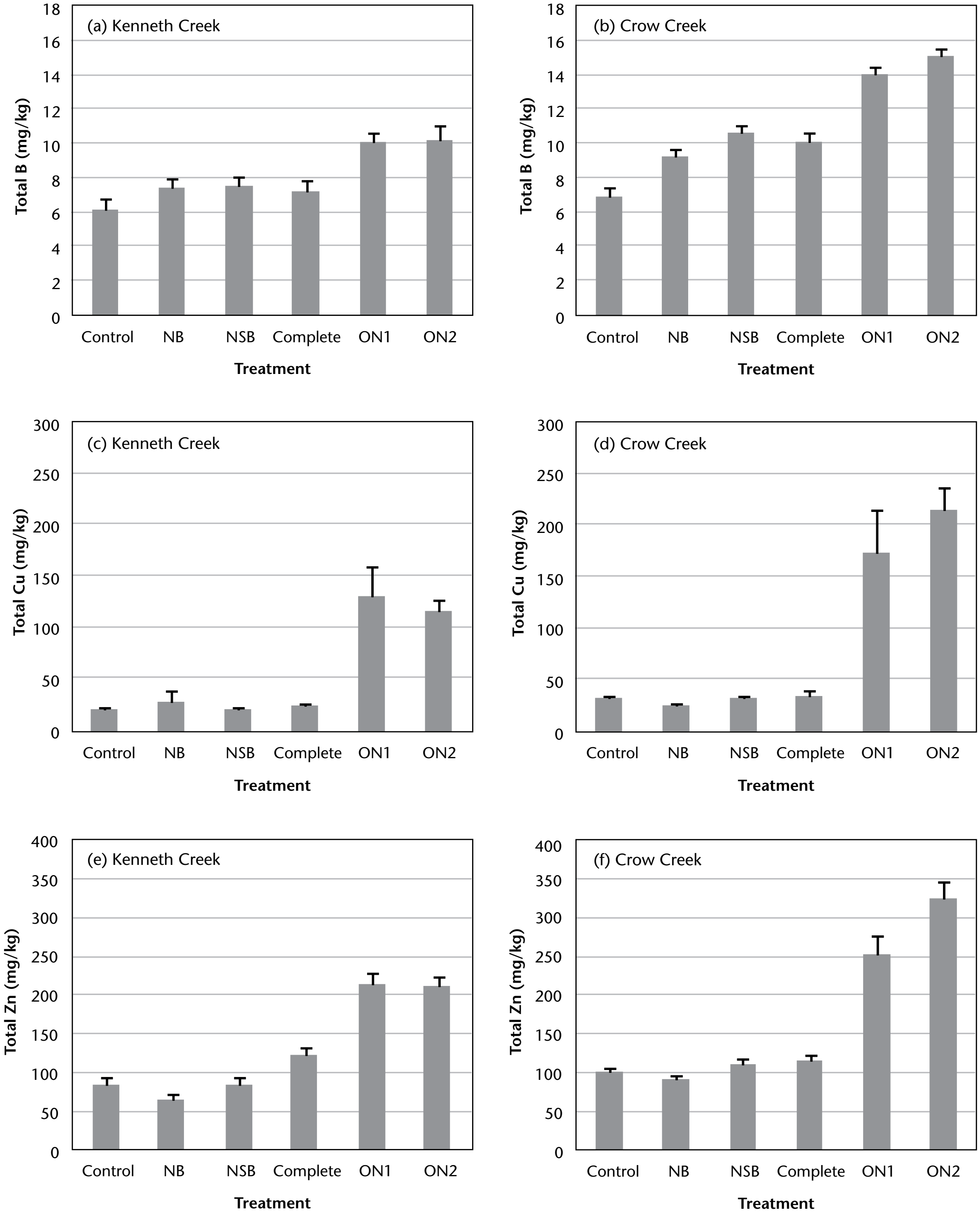

FIGURE 6 *Mean forest floor acid digestible total micronutrients by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

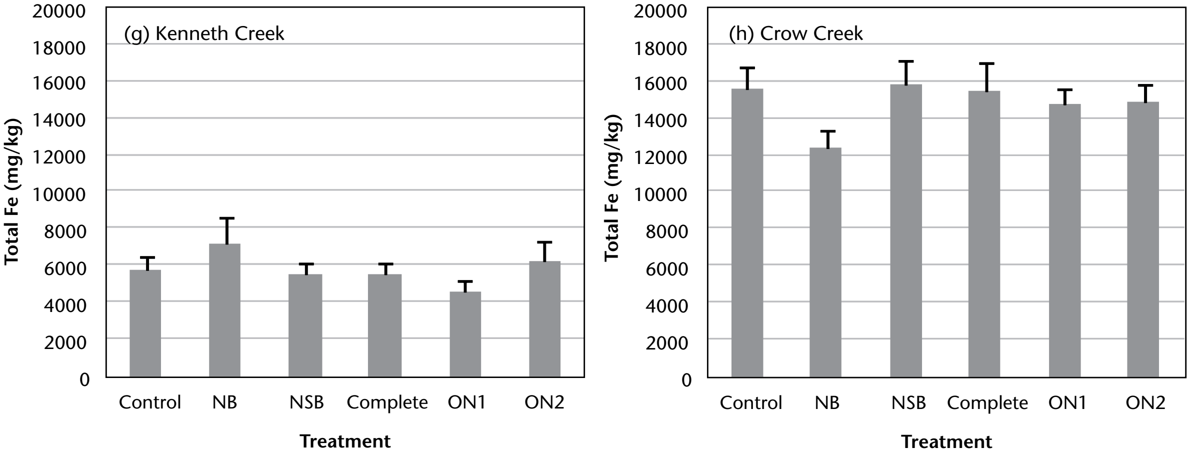

FIGURE 6 *Continued.*

TABLE 7 *ANOVA summary table for forest floor total acid digestible macronutrients (%) showing observed* F *statistics, probability (*p*) values, and error mean squares*

		Total acid digestible							
		P		**K**		**Ca**		**Mg**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek									
Treatment	5	0.25	0.933	0.21	0.953	0.19	0.960	0.68	0.650
Control vs. periodic	1	0.00	0.996	0.53	0.481	0.20	0.661	0.05	0.824
Control vs. annual	1	0.41	0.534	0.53	0.481	0.66	0.433	1.31	0.275
Periodic vs. annual	1	0.75	0.404	0.00	0.956	0.27	0.613	1.55	0.237
ON1 vs. ON2	1	0.00	0.991	0.00	0.950	0.12	0.739	0.55	0.471
Error mean square	12	0.0012		0.0029		0.2593		0.0185	
Crow Creek									
Treatment	5	14.97	<0.001	5.77	0.006	3.56	0.033	1.96	0.158
Control vs. periodic	1	0.22	0.650	0.47	0.504	2.18	0.166	1.09	0.318
Control vs. annual	1	23.52	<0.001	14.59	0.002	1.94	0.189	0.63	0.443
Periodic vs. annual	1	50.34	<0.001	18.09	0.001	13.94	0.003	5.68	0.034
ON1 vs. ON2	1	0.53	0.482	0.00	0.965	0.92	0.356	1.35	0.268
Error mean square	12	0.0016		0.0021		0.0470		0.0131	

TABLE 8 *ANOVA summary table for forest floor total acid digestible micronutrients (mg/kg) showing observed* F *statistics, probability* (p) *values, and error mean squares*

		Total acid digestible							
		Cu		**Zn**		**Fe**		**B**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek									
Treatment	5	13.84	<0.001	14.71	<0.001	0.28	0.916	2.28	0.112
Control vs. periodic	1	0.07	0.793	0.13	0.722	0.03	0.869	0.96	0.347
Control vs. annual	1	36.48	<0.001	36.80	<0.001	0.03	0.862	8.84	0.012
Periodic vs. annual	1	60.29	<0.001	58.96	<0.001	0.20	0.659	7.57	0.018
ON1 vs. ON2	1	0.55	0.472	0.01	0.918	0.49	0.499	0.01	0.908
Error mean square	12	2342.1		3584.5		32321096		14.28	
Crow Creek									
Treatment	5	14.59	<0.001	29.96	<0.001	0.59	0.711	21.10	<0.001
Control vs. periodic	1	0.00	0.976	0.04	0.839	0.33	0.576	16.88	0.001
Control vs. annual	1	35.25	<0.001	72.68	<0.001	0.14	0.712	89.00	<0.001
Periodic vs. annual	1	64.09	<0.001	124.89	<0.001	0.05	0.830	55.66	<0.001
ON1 vs. ON2	1	1.84	0.200	8.21	0.014	0.00	0.962	1.26	0.284
Error mean square	12	5995.4		3779.1		32515298		5.35	

3.1.6 Extractable nutrients Periodic fertilization had only small, statistically insignificant effects on the concentrations of extractable P, NH_4–N, NO_3–N, and SO_4–S in forest floors at both Kenneth Creek and Crow Creek (Figure 7; Table 9). Except for SO_4–S at Kenneth Creek, the levels of these extractable ions were higher in ON1 and ON2 treatment plots than in the control and periodic treatments at both study sites. Mean forest floor extractable NO_3–N was significantly higher in ON2 than in ON1 treatment plots at both Kenneth Creek and Crow Creek (Figure 7e, f; Table 9). At Crow Creek, levels of extractable NH_4–N were also significantly higher in ON2 than in ON1 treatment plots (Figure 7d; Table 9). Conversely, SO_4–S was significantly lower in ON2 than in ON1 treatment plots at Crow Creek after 12 years (Figure 7h; Table 9).

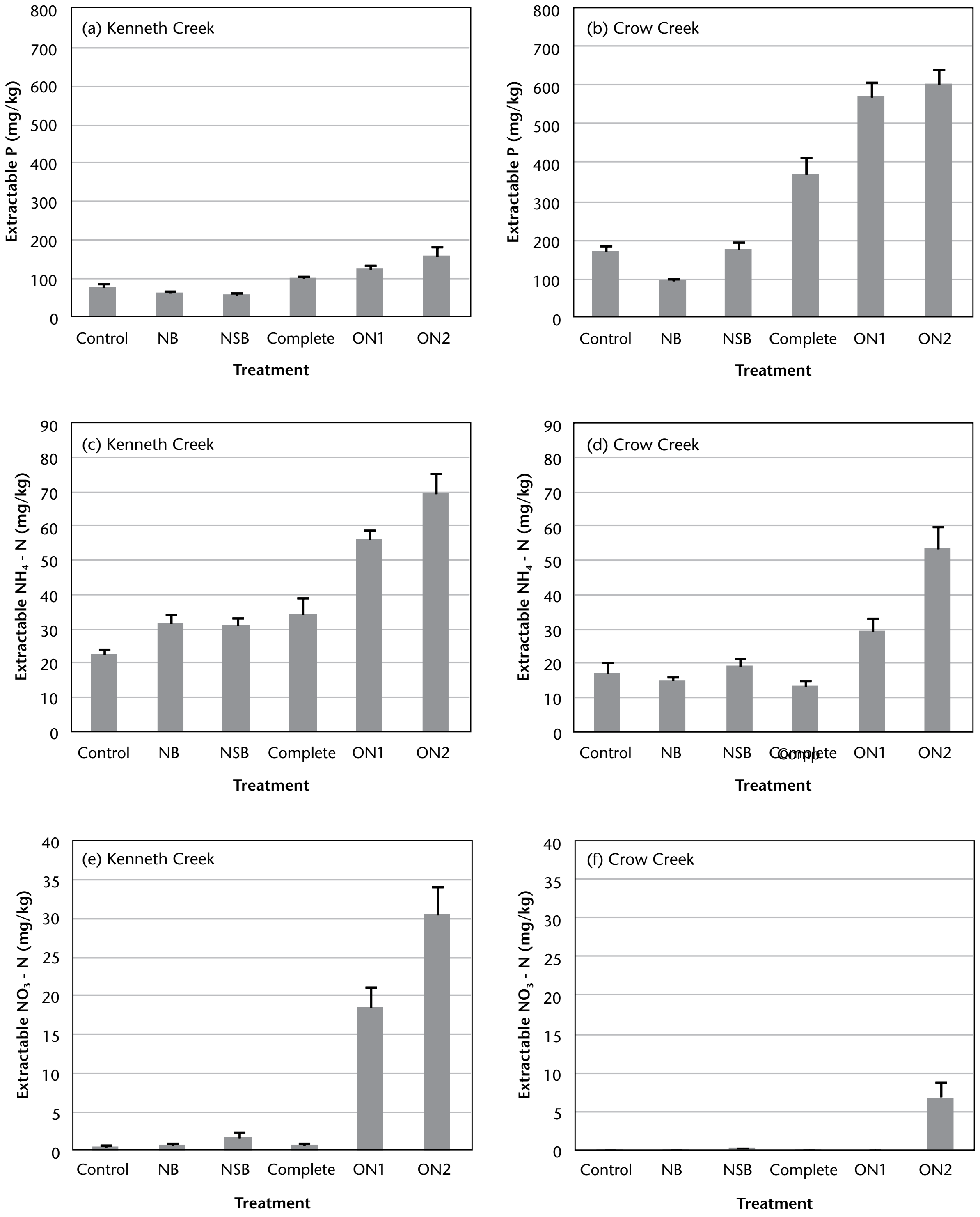

FIGURE 7 *Mean forest floor extractable phosphorus (K), ammonium* (NH_4)*–N, nitrate* (NO_3)*–N, and sulphate* (SO_4)*–S by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

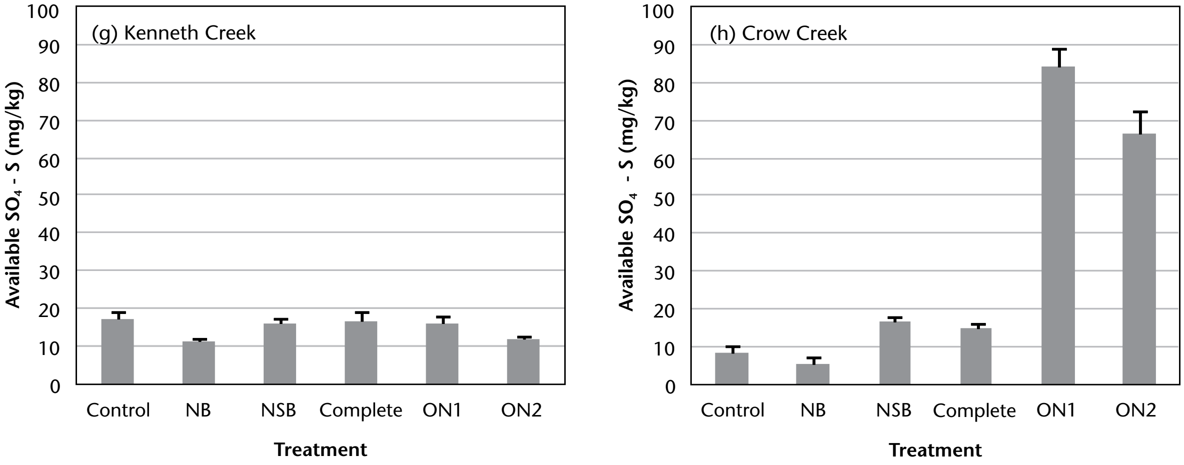

FIGURE 7 *Continued.*

3.1.7 Mineralizable nitrogen At Kenneth Creek, mineralizable N was significantly higher in periodically fertilized treatments (especially NB and NSB) than in the control treatment (Figure 8a; Table 9). Levels declined in annual fertilization treatments (especially ON2) and differences in mineralizable N between annual and control treatments were not statistically significant. Conversely, mineralizable N was unaffected by periodic fertilization at Crow Creek, but was significantly higher in annual fertilization treatments (especially ON2) than in the control after 12 years (Figure 8b; Table 9).

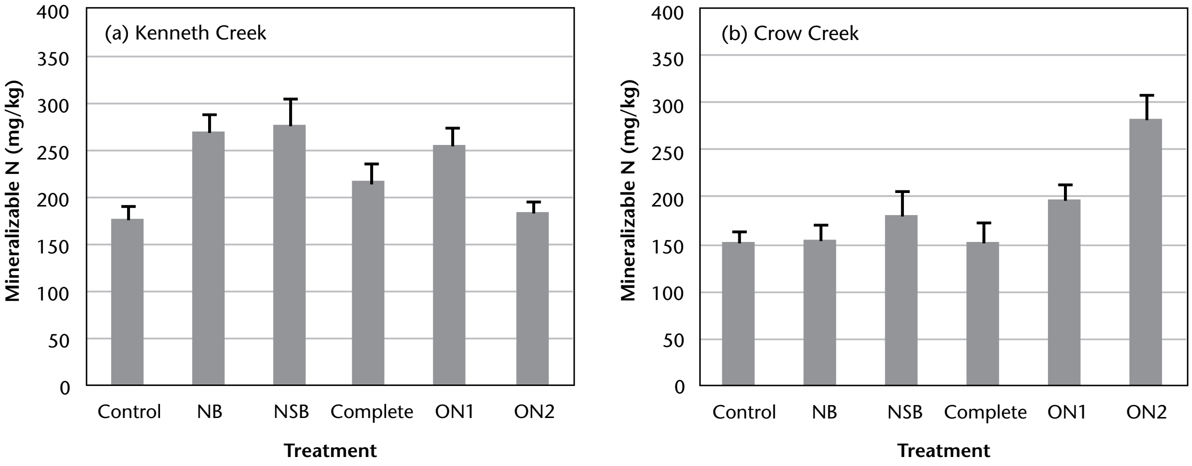

FIGURE 8 *Mean forest floor mineralizable nitrogen (N) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 9 *ANOVA summary table for forest floor extractable nutrients and mineralizable nitrogen (N) (mg/kg) showing observed* F *statistics, probability* (p) *values, and error mean squares*

		Extractable									
		P		**NH_4-N**		**NO_3-N**		**SO_4-S**		**Mineralizable N**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek											
Treatment	5	3.37	0.039	9.06	<0.001	13.30	<0.001	2.25	0.116	2.23	0.119
Control vs. periodic	1	0.05	0.835	2.19	0.164	0.01	0.917	1.75	0.210	5.33	0.039
Control vs. annual	1	5.88	0.032	30.84	<0.001	31.13	<0.001	2.63	0.131	1.47	0.249
Periodic vs. annual	1	12.40	0.004	31.10	<0.001	54.03	<0.001	0.25	0.624	1.67	0.220
ON1 vs. ON2	1	1.27	0.282	2.35	0.151	5.81	0.033	2.46	0.143	2.87	0.116
Error mean square	12	5525.6		427.3		146.1		37.76		10287	
Crow Creek											
Treatment	5	34.64	<0.001	6.50	0.004	6.58	0.004	47.57	<0.001	2.69	0.075
Control vs. periodic	1	1.09	0.317	0.04	0.853	0.00	0.977	0.41	0.532	0.10	0.760
Control vs. annual	1	84.05	<0.001	11.06	0.006	6.52	0.025	123.87	<0.001	5.52	0.037
Periodic vs. annual	1	120.55	<0.001	22.11	<0.001	11.49	0.005	199.35	<0.001	7.60	0.017
ON1 vs. ON2	1	0.42	0.531	7.99	0.015	20.05	<0.001	6.49	0.026	3.75	0.077
Error mean square	12	16544.5		431.2		13.77		288.47		11399	

3.1.8 Exchangeable cations The concentrations of exchangeable cations in forest floors were relatively unaffected by periodic fertilization at either Kenneth Creek or Crow Creek (Figure 9; Table 10). However, exchangeable Mg was significantly higher in ON1 and ON2 treatments than in periodic or control treatments at both study sites (Figure 9a, b; Table 10). The same was true for exchangeable K at Crow Creek (Figure 9d; Table 10). Both of these nutrients were frequently added to ON1 and ON2 fertilizer prescriptions. Conversely, Ca (not included in added fertilizer) was significantly lower in the ON1 and ON2 treatments than in the periodic treatments (NB, NSB, Complete) at Crow Creek (Figure 9f; Table 9). Cation exchange capacity (CEC) was unaffected by either periodic or annual fertilization at Kenneth Creek or at Crow Creek after 12 years (Figure 10; Table 10).

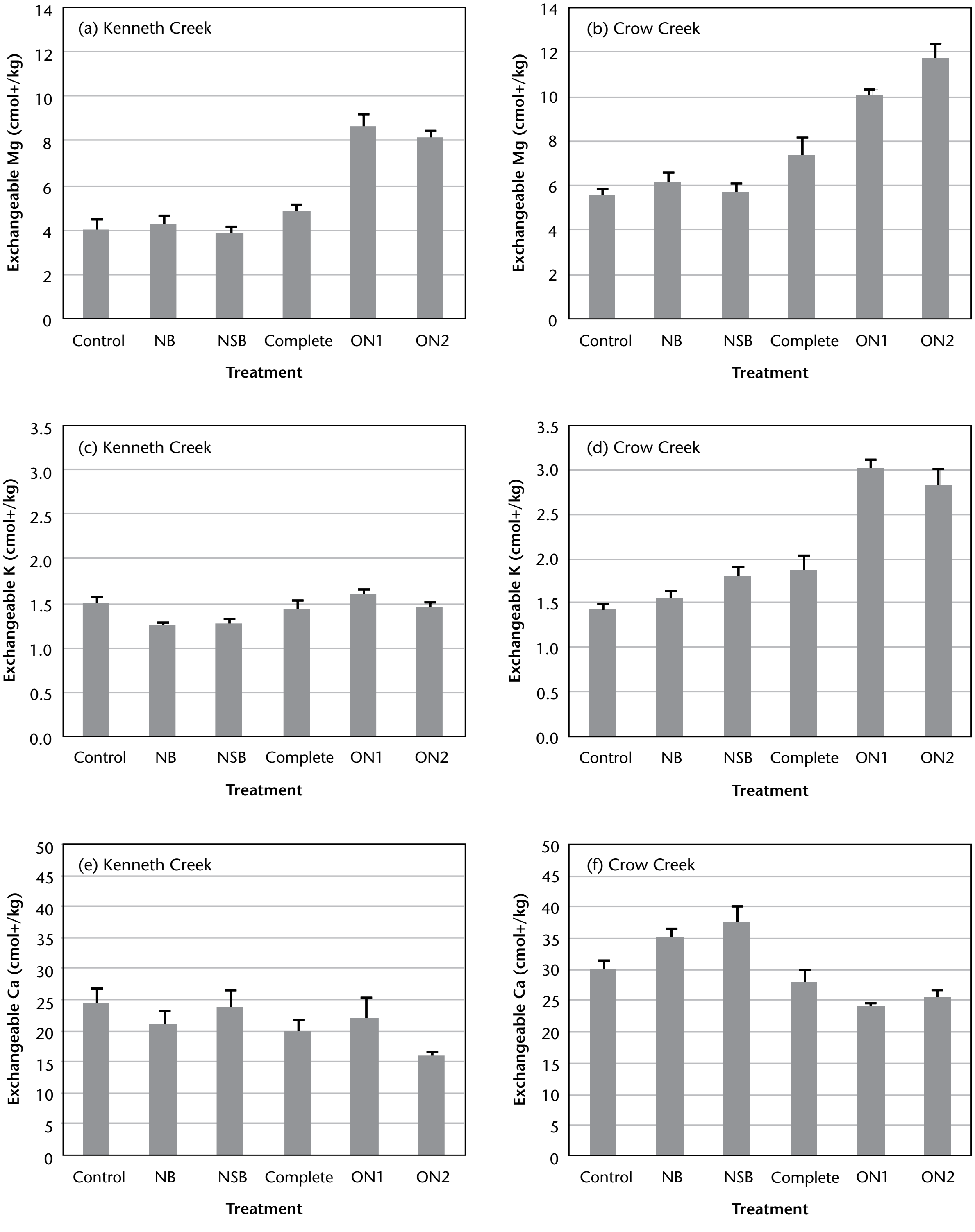

FIGURE 9 *Mean forest floor exchangeable cations by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 10 *ANOVA summary table for forest floor soil exchangeable nutrients and cation exchange capacity (CEC) (cmol [+]/kg) showing observed* F *statistics, probability* (p) *values, and error mean squares*

		Exchangeable cations							
		K		**Ca**		**Mg**		**CEC**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek									
Treatment	5	1.77	0.194	0.34	0.877	6.97	0.003	0.19	0.960
Control vs. periodic	1	2.14	0.169	0.21	0.654	0.06	0.806	0.17	0.685
Control vs. annual	1	0.07	0.800	0.72	0.414	18.41	0.001	0.02	0.880
Periodic vs. annual	1	4.84	0.048	0.31	0.590	29.57	<0.001	0.10	0.756
ON1 vs. ON2	1	1.13	0.308	0.67	0.427	0.20	0.662	0.61	0.450
Error mean square	12	0.130		341.29		8.346		392.91	
Crow Creek									
Treatment	5	21.94	<0.001	3.77	0.028	10.67	<0.001	1.06	0.431
Control vs. periodic	1	3.97	0.070	1.19	0.297	0.86	0.373	1.42	0.256
Control vs. annual	1	73.23	<0.001	2.47	0.142	30.70	<0.001	0.30	0.592
Periodic vs. annual	1	80.32	<0.001	12.16	0.004	39.24	<0.001	0.59	0.456
ON1 vs. ON2	1	0.92	0.356	0.20	0.660	2.25	0.160	0.30	0.592
Error mean square	12	0.247		91.32		7.332		122.13	

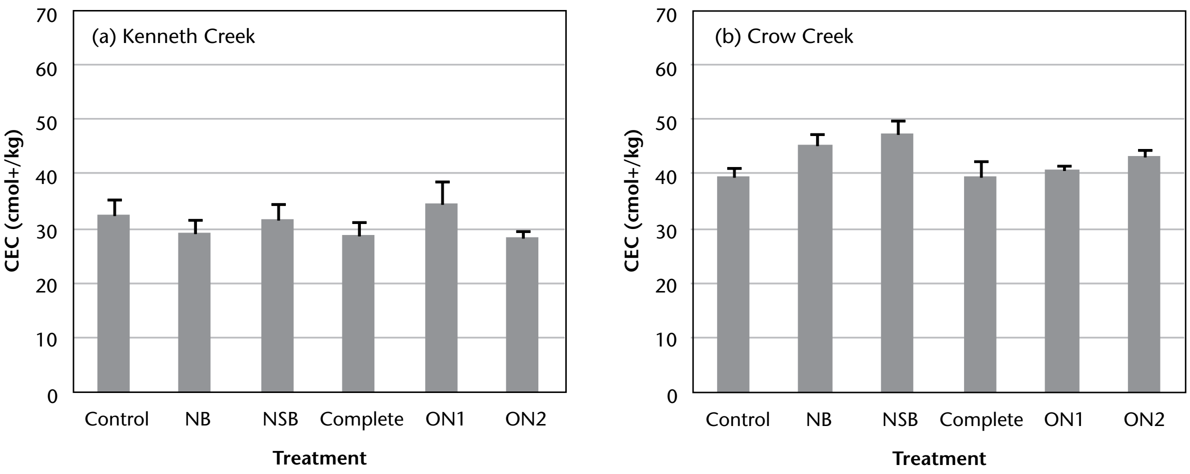

FIGURE 10 *Mean forest floor cation exchange capacity (CEC) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

3.1.9 Carbon and macronutrient pools Neither periodic nor annual fertilization had significant effects on total forest floor C and macronutrient pools at Kenneth Creek after 12 years (Figure 11; Table 11). Overall, C and macronutrient pools at Crow Creek were not significantly affected by periodic fertilization (Table 11). However, these effects apparently varied differentially among periodic treatments, and nutrient pools were either unaffected or depleted by NB and NSB fertilization and increased by Complete fertilization in comparison to the control treatment (Figure 11). At Crow Creek, amounts of most nutrients (except Ca) were higher in annual fertilizer treatments than in the control and periodic treatments after 12 years (Figure 11; Table 11).

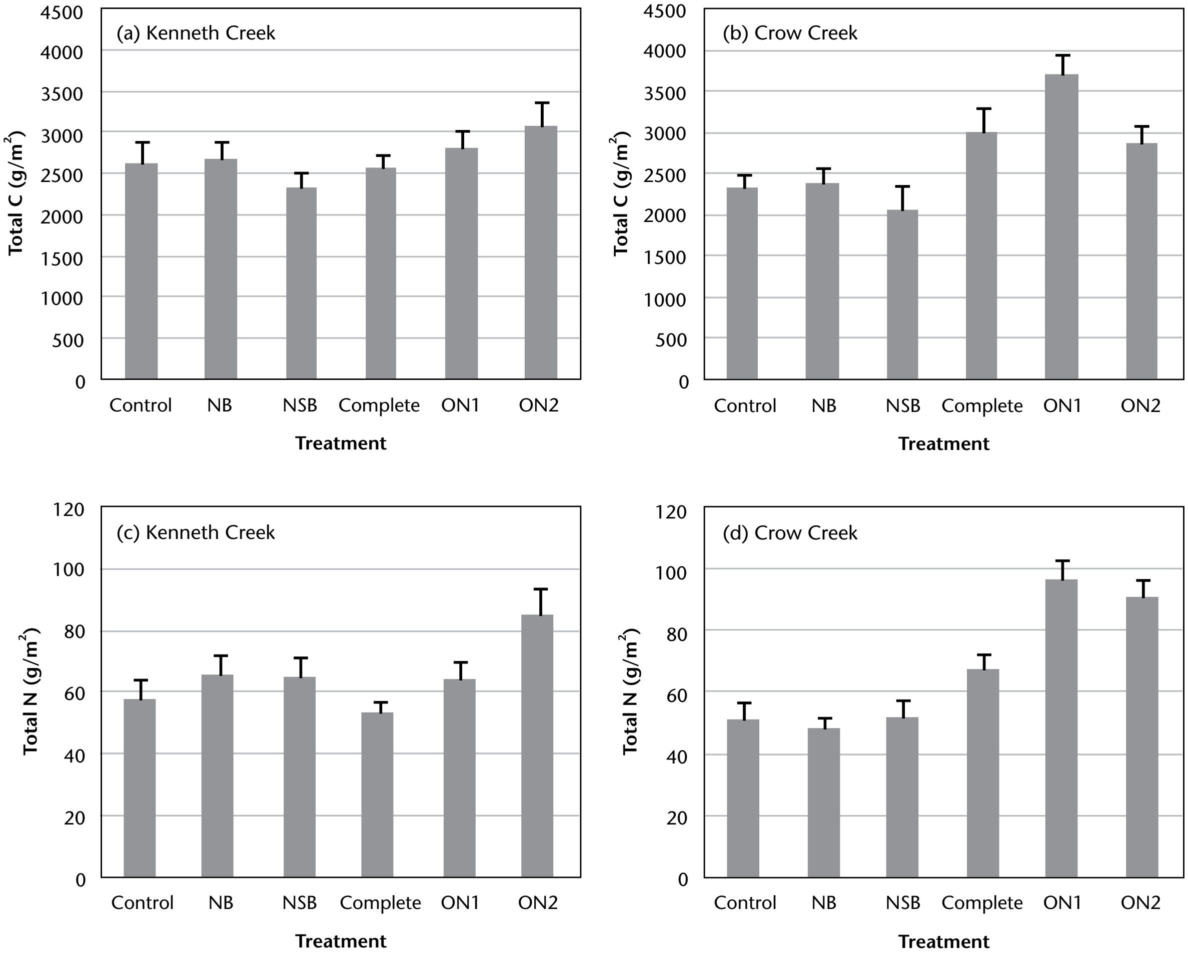

FIGURE 11 *Mean forest floor carbon (C) and macronutrient pool estimates by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

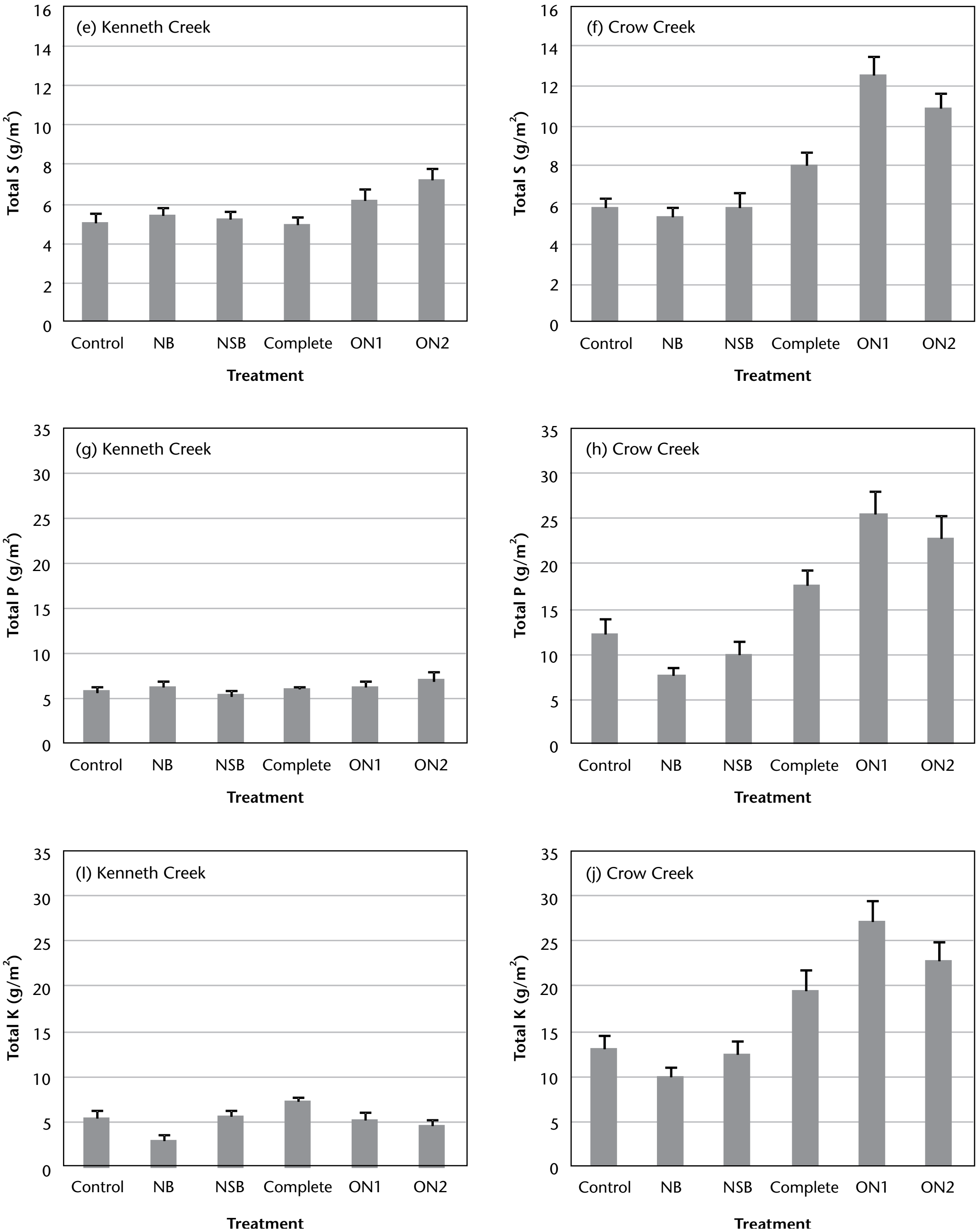

FIGURE 11 *Continued.*

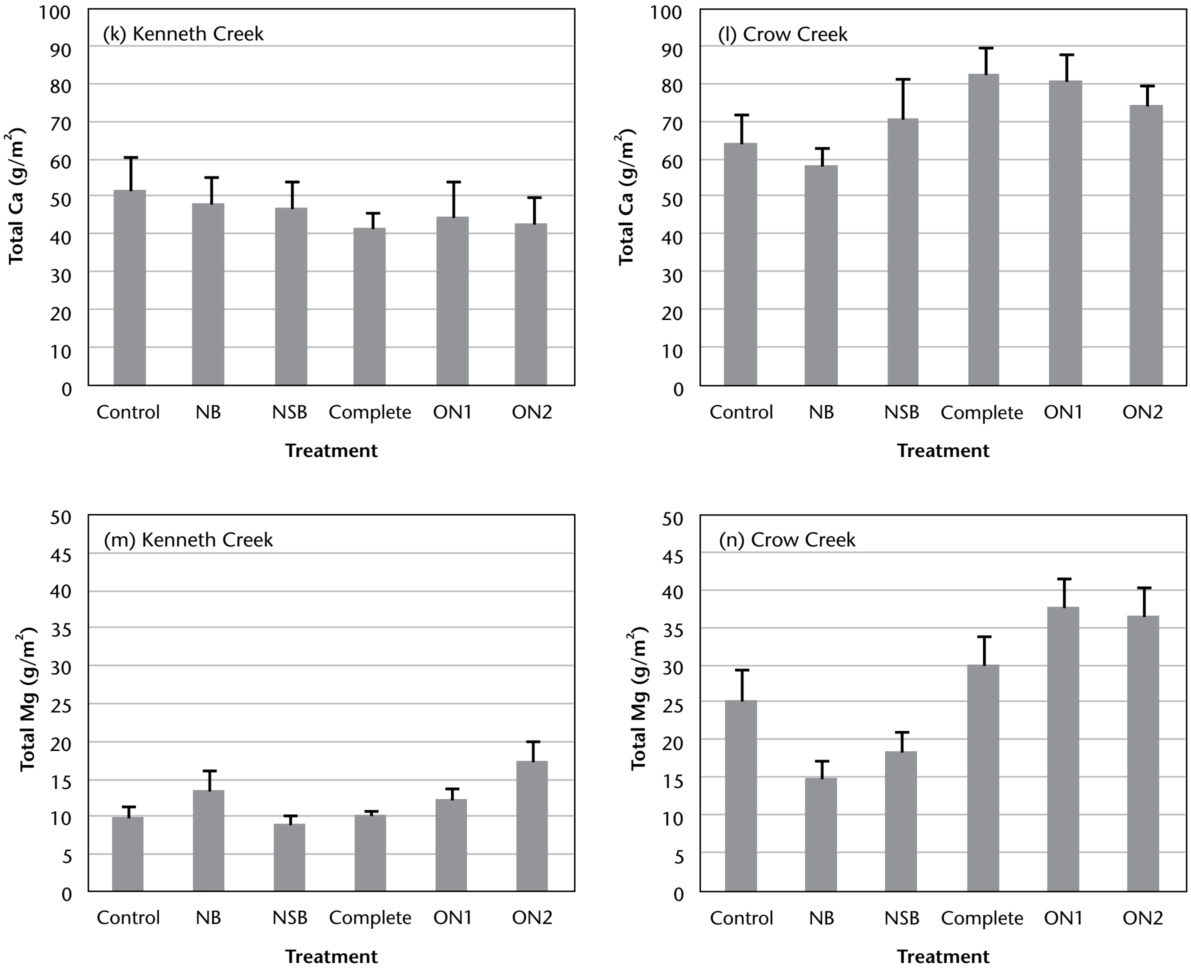

FIGURE 11 *Continued.*

3.2 Mineral Soil

3.2.1 Soil pH Mineral soil pH was not significantly affected by either periodic or annual fertilization at Kenneth Creek. However, the lowest mean pH (H_2O) was apparently associated with the largest nutrient additions (ON2) (Figure 12a, c; Table 12). At Crow Creek, differences in mineral soil pH between the control and periodic fertilizer treatments were not statistically different (Figure 12b, d; Table 12). However, soil pH was distinctly lower in annual treatments (ON1 and ON2), and differences in pH (H_2O) between the control and either periodic or annual treatments were statistically significant (Figure 12b, d; Table 12).

TABLE 11 *ANOVA summary table for forest floor total carbon (C) and macronutrient pools (g/m^2) showing observed* F *statistics, probability* (p) *values, and error mean squares*

		C		**N**		**S**		**P**		**K**		**Ca**		**Mg**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek															
Treatment	5	1.32	0.321	0.87	0.528	0.99	0.465	0.18	0.965	3.59	0.032	0.06	0.997	0.53	0.748
Control vs. periodic	1	0.16	0.699	0.08	0.781	0.02	0.900	0.01	0.937	0.02	0.877	0.12	0.735	0.04	0.854
Control vs. annual	1	1.43	0.255	1.44	0.254	2.31	0.154	0.31	0.589	0.38	0.547	0.19	0.674	0.89	0.363
Periodic vs. annual	1	4.43	0.057	1.56	0.236	3.52	0.085	0.41	0.532	0.40	0.539	0.02	0.891	1.06	0.323
ON1 vs. ON2	1	0.74	0.407	1.63	0.226	0.72	0.412	0.16	0.696	0.26	0.621	0.01	0.940	0.72	0.41
Error mean square	12	564254		1644.0		8.970		21.761		6.889		2996.2		212.44	
Crow Creek															
Treatment	5	3.93	0.024	8.61	0.001	11.02	<0.001	5.00	0.010	4.06	0.022	0.44	0.812	2.36	0.104
Control vs. periodic	1	0.20	0.664	0.28	0.604	0.28	0.607	0.02	0.901	0.05	0.820	0.15	0.706	0.32	0.580
Control vs. annual	1	6.82	0.023	22.65	<0.001	28.13	<0.001	9.07	0.011	8.41	0.013	0.58	0.463	2.59	0.13
Periodic vs. annual	1	8.64	0.012	32.61	<0.001	41.57	<0.001	17.65	0.001	12.94	0.004	0.28	0.606	8.28	0.014
ON1 vs. ON2	1	3.82	0.074	0.31	0.587	1.68	0.220	0.37	0.556	0.86	0.372	0.11	0.748	0.02	0.887
Error mean square	12	1069696		636.1		9.768		125.95		133.93		2356.4		437.28	

TABLE 12 *ANOVA summary table for mineral soil pH showing observed* F *statistics, probability* (p) *values, and error mean squares*

		pH (H_2O)		pH ($CaCl_2$)	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***
Kenneth Creek					
Treatment	5	0.53	0.746	0.28	0.914
Control vs. periodic	1	0.88	0.367	1.00	0.338
Control vs. annual	1	1.73	0.213	0.50	0.492
Periodic vs. annual	1	0.33	0.575	0.10	0.760
ON1 vs. ON2	1	0.71	0.416	0.14	0.714
Error mean square	12	0.2233		0.2443	
Crow Creek					
Treatment	5	2.65	0.078	1.07	0.422
Control vs. periodic	1	0.58	0.460	0.93	0.355
Control vs. annual	1	9.25	0.010	4.54	0.054
Periodic vs. annual	1	9.71	0.009	2.70	0.126
ON1 vs. ON2	1	0.07	0.800	0.01	0.919
Error mean square	12	0.0851		0.0555	

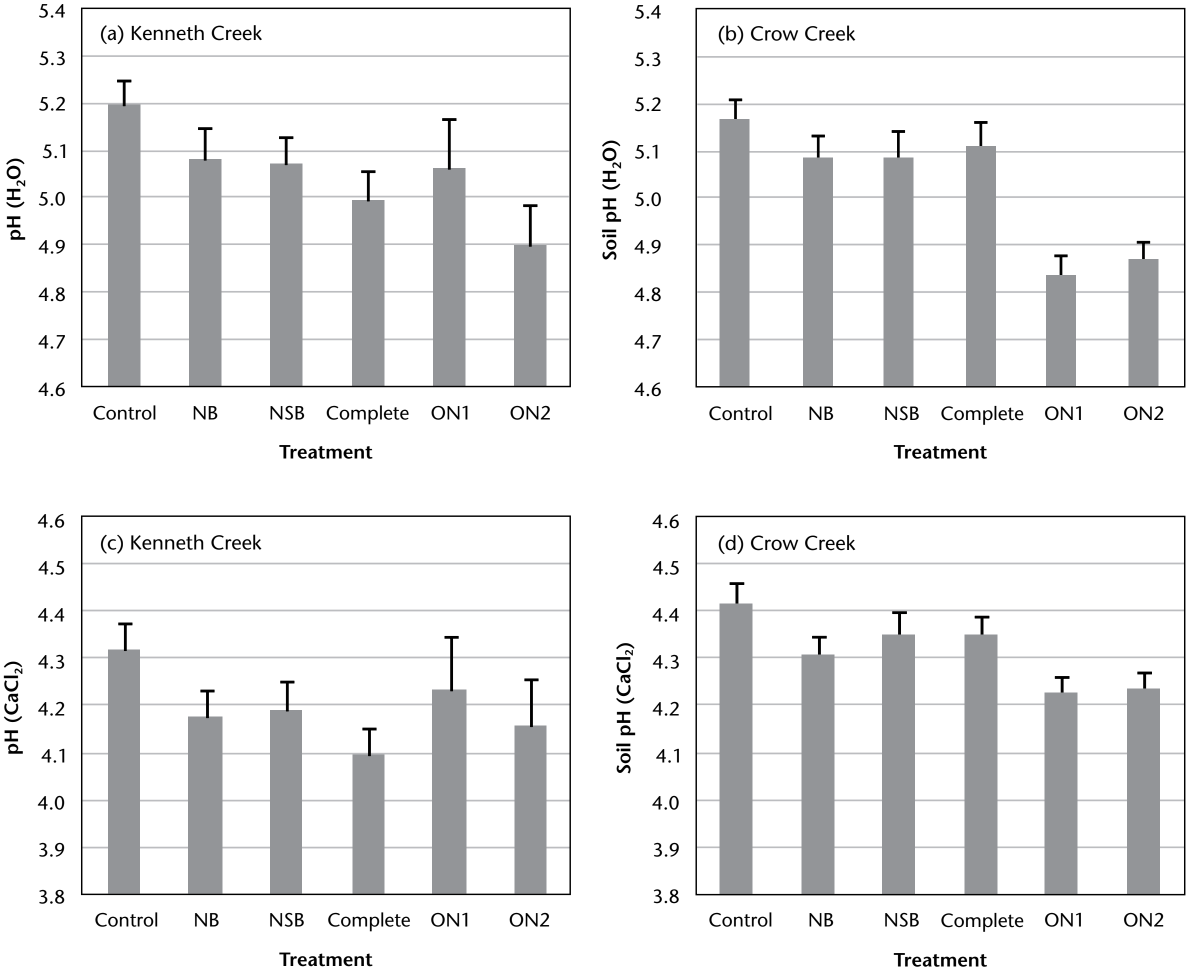

FIGURE 12 *Mean mineral soil pH by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

3.2.2 Total carbon, nitrogen, and sulphur Total C concentration in mineral soil was unaffected by treatment at both Kenneth Creek and at Crow Creek (Figure 13a, b; Table 13).

Total N and S levels were unaffected by periodic fertilization at both study sites (Figure 13c–f; Table 13). However, mineral soil S levels in control and annual fertilization treatments were significantly different at Crow Creek, with the highest levels being measured in the ON1 and ON2 treatments (Figure 13f; Table 13). Also, total N and S levels were significantly higher in annual treatments than in periodic treatments at Crow Creek after 12 years (Figure 13d, f; Table 13).

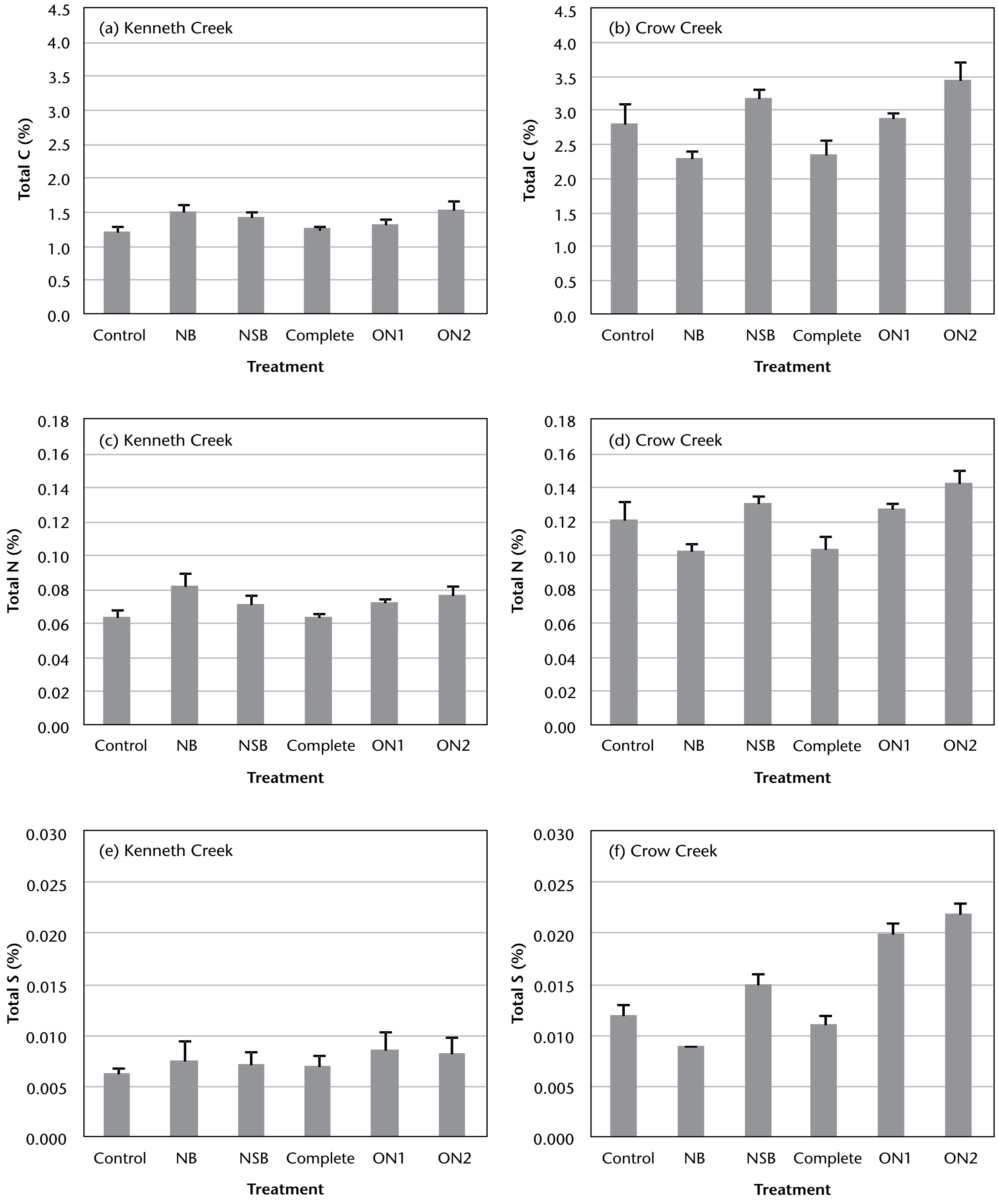

FIGURE 13 *Mean mineral soil total carbon (C), nitrogen (N), and sulphur (S) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 13 *ANOVA summary table for mineral soil total percent carbon (C), nitrogen (N), and sulphur (S), showing observed* F *statistics, probability (*p*) values, and error mean squares*

		Total (%)					
		C		N		S	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek							
Treatment	5	0.49	0.777	0.52	0.754	1.54	0.251
Control vs. periodic	1	0.70	0.418	0.48	0.500	1.43	0.256
Control vs. annual	1	0.93	0.355	0.70	0.419	6.59	0.025
Periodic vs. annual	1	0.05	0.821	0.06	0.813	3.74	0.077
ON1 vs. ON2	1	0.59	0.456	0.10	0.760	0.03	0.871
Error mean square	12	0.4288		0.0011		0.0000055	
Crow Creek							
Treatment	5	2.34	0.106	3.04	0.053	15.72	<0.001
Control vs. periodic	1	0.33	0.578	0.69	0.421	0.00	0.957
Control vs. annual	1	1.04	0.327	1.63	0.226	34.75	<0.001
Periodic vs. annual	1	4.39	0.058	7.65	0.017	61.46	<0.001
ON1 vs. ON2	1	1.84	0.200	1.45	0.251	1.57	0.234
Error mean square	12	1.0505		0.0009		0.0000208	

3.2.3 Extractable nutrients Periodic fertilization had variable, and statistically insignificant, effects on the concentrations of extractable P, NH_4–N, NO_3–N, and SO4–S in mineral soils at both Kenneth Creek and Crow Creek (Figure 14; Table 14).

Differences in extractable P levels between the control and annual treatments were statistically significant at Kenneth Creek, with higher levels occurring in ON1 and ON2 treatment plots (Figure 14a; Table 14). At Kenneth Creek, extractable P levels were also significantly higher in annual fertilizer treatments than in periodic treatments (Figure 14a; Table 14). At Crow Creek, differences in extractable P levels between the control and either periodic or annual fertilizer treatments were not statistically significant after 12 years (Figure 14b; Table 14).

At Kenneth Creek, the effects of periodic and annual fertilization on extractable NH_4–N were variable and statistically insignificant (Figure 14c; Table 14). High NH_4–N levels were measured in ON2 treatment plots at Crow Creek and differences between periodic and annual treatments and between ON1 and ON2 treatments were statistically significant after 12 years (Figure 14d; Table 14).

Differences in extractable NO_3–N levels between the annual treatments and the control and periodic treatments were statistically significant at Kenneth Creek, with the highest levels associated with yearly nutrient additions (especially ON2) (Figure 14e; Table 14). Conversely, neither periodic nor annual fertilization had any measurable effect on mineral soil NO_3–N at Crow Creek (Figure 14f; Table 14).

At Kenneth Creek, levels of mineral soil SO4–S were apparently slightly higher in annual treatments (ON1 and ON2) than in the control or periodic treatments, but these differences were not statistically significant ($p = 0.087$) (Figure 14g; Table 14). Yearly fertilization increased extractable SO4–S at

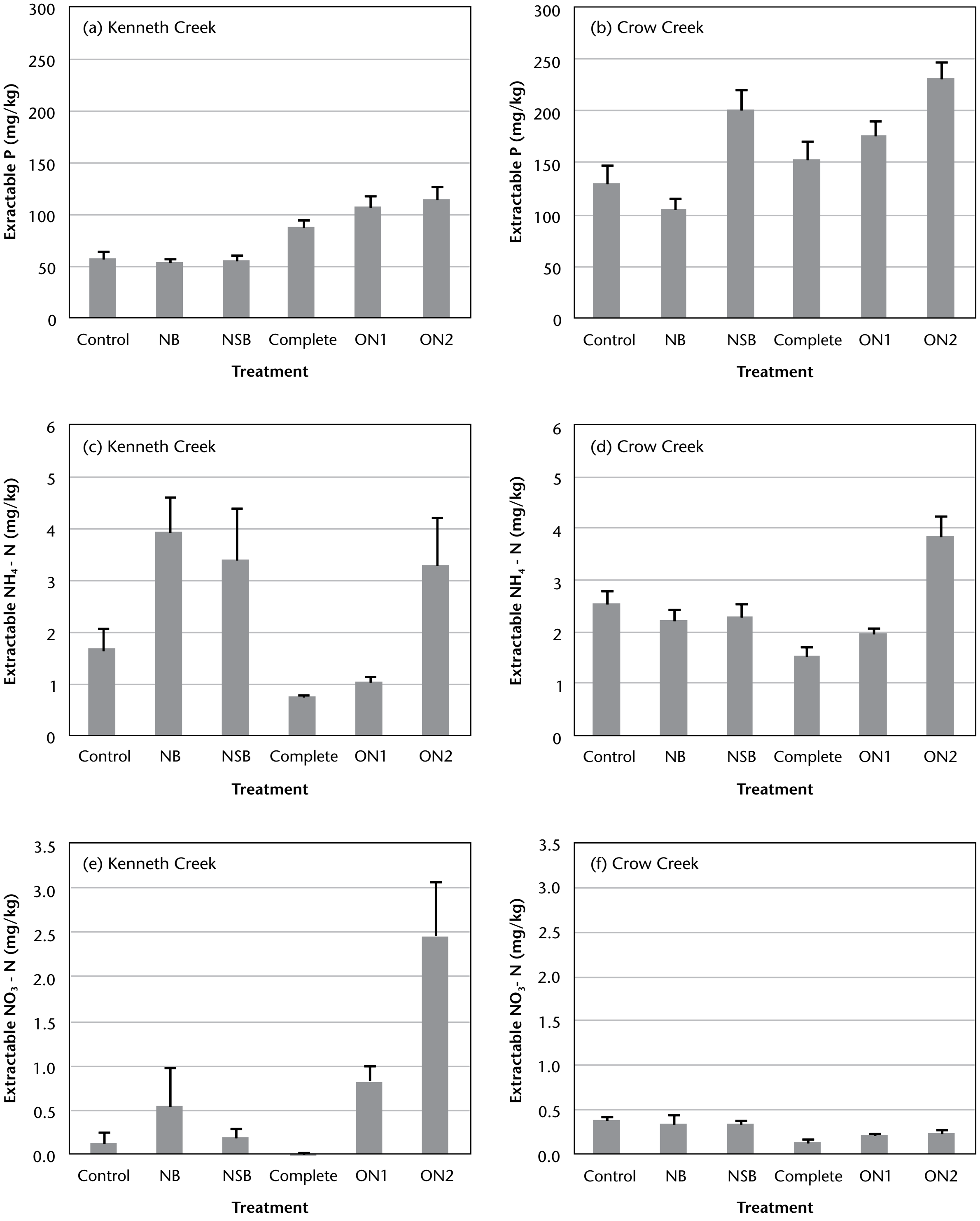

FIGURE 14 *Mean mineral soil extractable phosphorus (P), ammonium (NH_4)–N, nitrate (NO_3)–N, and sulphate (SO_4)–S by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

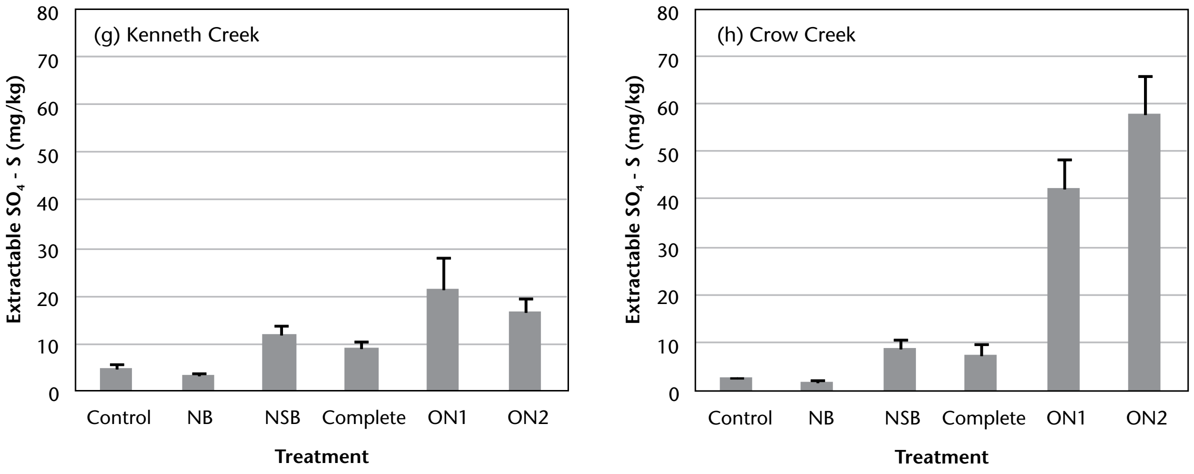

FIGURE 14 *Continued.*

TABLE 14 *ANOVA summary table for mineral soil extractable nutrients and mineralizable nitrogen (N) (mg/kg) showing observed* F *statistics, probability (*p*) values, and error mean squares*

		Extractable									
		P		**NH_4-N**		**NO_3-N**		**SO_4-S**		**Mineralizable N**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek											
Treatment	5	3.54	0.034	1.03	0.443	2.90	0.061	1.22	0.357	0.15	0.975
Control vs. periodic	1	0.27	0.610	0.45	0.516	0.03	0.856	0.24	0.630	0.00	0.993
Control vs. annual	1	9.09	0.011	0.09	0.768	5.26	0.041	3.46	0.087	0.01	0.916
Periodic vs. annual	1	11.45	0.005	0.19	0.667	8.08	0.015	3.47	0.087	0.02	0.880
ON1 vs. ON2	1	0.11	0.743	1.41	0.257	4.59	0.053	0.30	0.593	0.18	0.678
Error mean square	12	2614.3		21.451		3.510		454.28		257.23	
Crow Creek											
Treatment	5	2.16	0.128	5.58	0.007	1.17	0.379	19.94	<0.001	3.73	0.029
Control vs. periodic	1	0.39	0.546	1.93	0.190	0.99	0.340	0.34	0.572	3.25	0.096
Control vs. annual	1	3.58	0.083	0.82	0.383	1.90	0.193	52.85	<0.001	0.00	0.956
Periodic vs. annual	1	3.07	0.105	8.84	0.012	0.35	0.564	81.33	<0.001	5.56	0.036
ON1 vs. ON2	1	1.56	0.236	15.83	0.002	0.05	0.830	4.27	0.061	10.71	0.007
Error mean square	12	12084.9		1.315		0.0999		348.20		44.56	

Crow Creek and differences in SO4–S levels between the annual and periodic or control treatments were statistically significant after 12 years (Figure 14h; Table 14).

3.2.4 Mineralizable nitrogen Mineral soil mineralizable N was unaffected by either periodic or annual fertilization at Kenneth Creek (Figure 15a; Table 14). At Crow Creek, mineralizable N was slightly lower in periodic treatments than in the control, although differences were not statistically significant (Figure 15b; Table 14). Conversely, mineralizable N was sharply higher in ON2 treatment plots, and differences between periodic and annual treatments were statistically significant (Figure 15b; Table 14). Mineralizable N levels were significantly higher in ON2 than in ON1 treatments at Crow Creek after 12 years (Table 14).

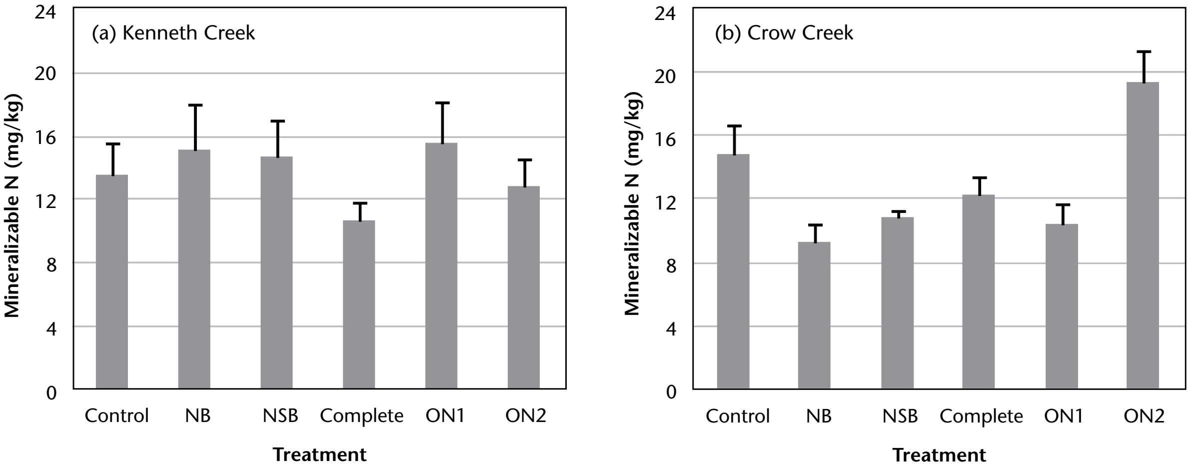

FIGURE 15 *Mean mineral soil mineralizable nitrogen (N) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

3.2.5 Exchangeable cations The mineral soil levels of most exchangeable cations were relatively unaffected by either periodic or annual fertilization at Kenneth Creek and at Crow Creek (Figure 16; Table 15). However, exchangeable K levels were significantly higher in annual fertilizer treatments than in periodic treatments or the control at both study sites (Figure 16a, b; Table 15). Differences in exchangeable Mg levels between periodic and annual treatments were marginally significant at Kenneth Creek ($p = 0.051$) (Figure 16e; Table 15).

Cation exchange capacity was relatively unaffected by either periodic or annual fertilization at Kenneth Creek or at Crow Creek after 12 years (Figure 17; Table 15). However, differences in CEC between periodic and annual fertilization were marginally significant ($p = 0.050$) at Crow Creek (Table 15).

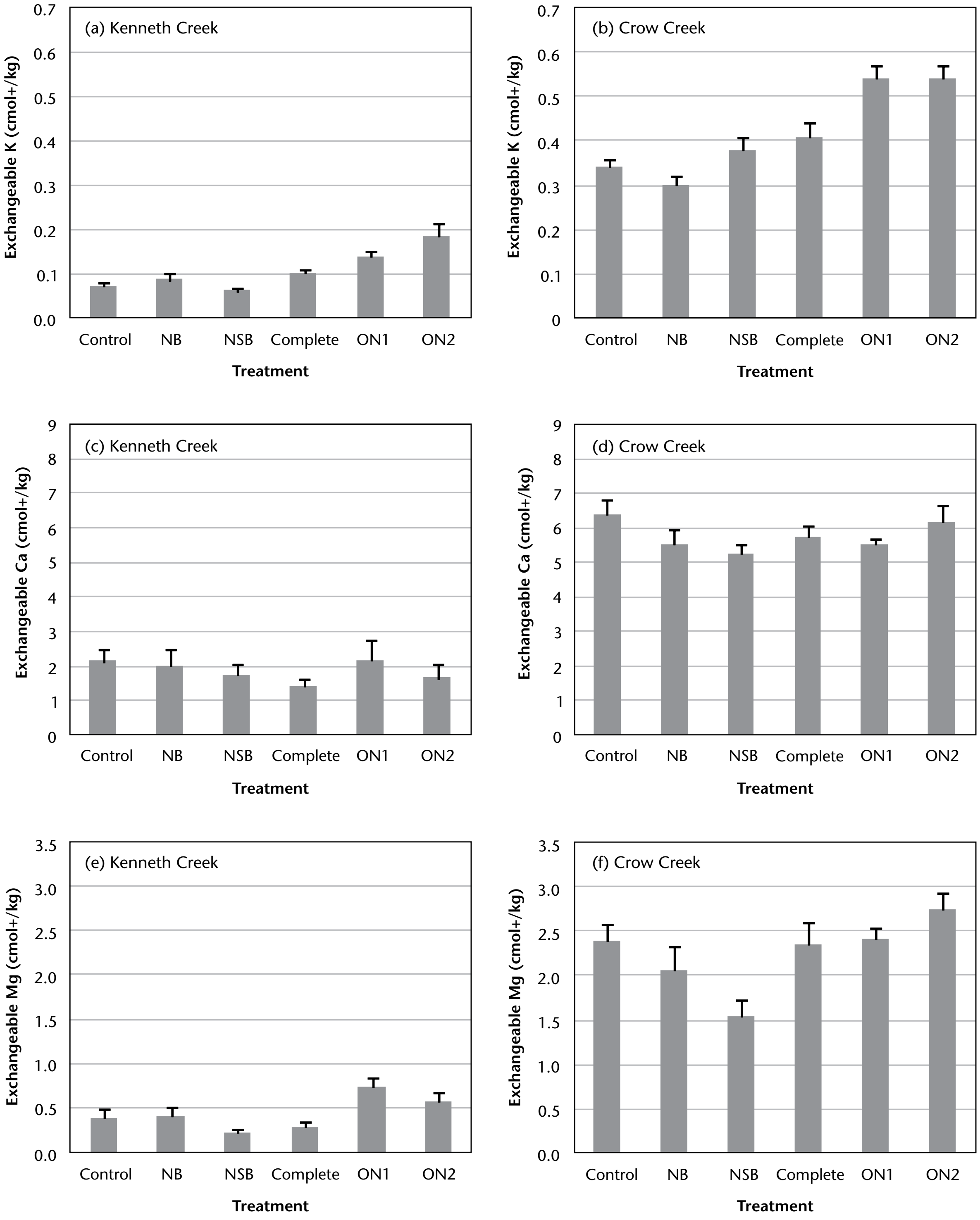

FIGURE 16 *Mean mineral soil exchangeable cations by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 15 *ANOVA summary table for mineral soil exchangeable nutrients and cation exchange capacity (CEC) (cmol [+]/kg) showing observed* F *statistics, probability (*p*) values, and error mean squares*

		Exchangeable cations							
		K		**Ca**		**Mg**		**CEC**	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek									
Treatment	5	2.50	0.090	0.11	0.987	1.10	0.410	0.20	0.955
Control vs. periodic	1	0.12	0.739	0.18	0.677	0.14	0.712	0.01	0.925
Control vs. annual	1	6.28	0.028	0.02	0.893	1.62	0.227	0.25	0.626
Periodic vs. annual	1	8.49	0.013	0.12	0.734	4.69	0.051	0.62	0.448
ON1 vs. ON2	1	1.73	0.213	0.09	0.775	0.17	0.685	0.00	0.995
Error mean square	12	0.0113		8.964		0.4060		8.342	
Crow Creek									
Treatment	5	4.96	0.011	0.68	0.644	1.28	0.334	1.25	0.347
Control vs. periodic	1	0.14	0.713	2.05	0.177	0.98	0.342	1.27	0.281
Control vs. annual	1	12.63	0.004	0.65	0.435	0.15	0.706	0.31	0.587
Periodic vs. annual	1	18.42	0.001	0.53	0.479	3.13	0.102	4.73	0.050
ON1 vs. ON2	1	0.00	0.990	0.83	0.379	0.42	0.529	0.78	0.395
Error mean square	12	0.0240		3.272		1.5758		8.838	

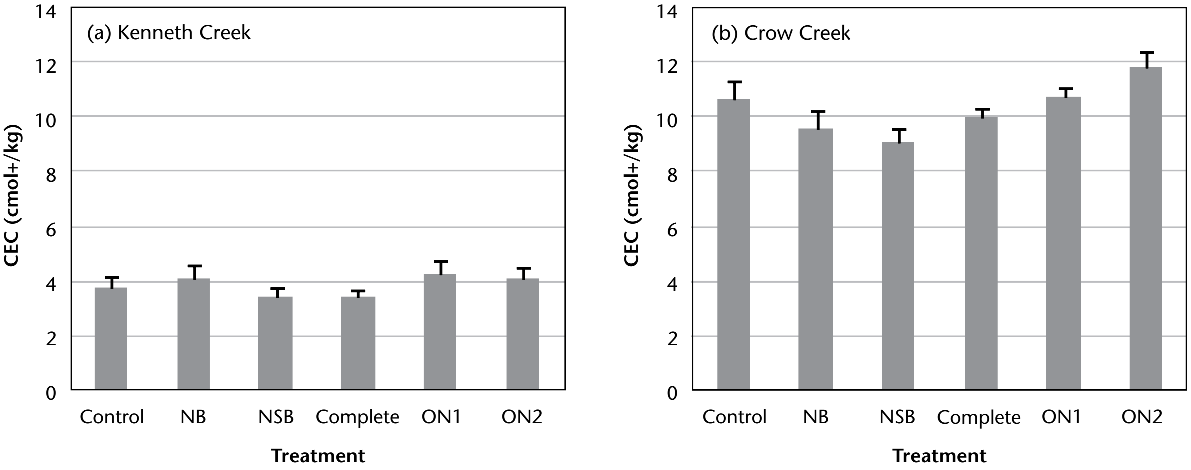

FIGURE 17 *Mean mineral soil cation exchange capacity (CEC) by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

3.2.6 Carbon, nitrogen, and sulphur pools Neither periodic nor annual fertilization had significant effects on total amounts of C, N, and S in mineral soils at Kenneth Creek after 12 years (Figure 18; Table 16). At Crow Creek, nutrient pools were not significantly affected by periodic fertilization. However, total S levels were significantly higher in annual fertilizer treatments than in periodic treatments or the control at Crow Creek (Figure 18f; Table 16). Although not statistically significant, levels of C and N were also slightly higher in annual treatments (especially ON2) compared to the control and periodic treatments at Crow Creek (Figure 16b, d).

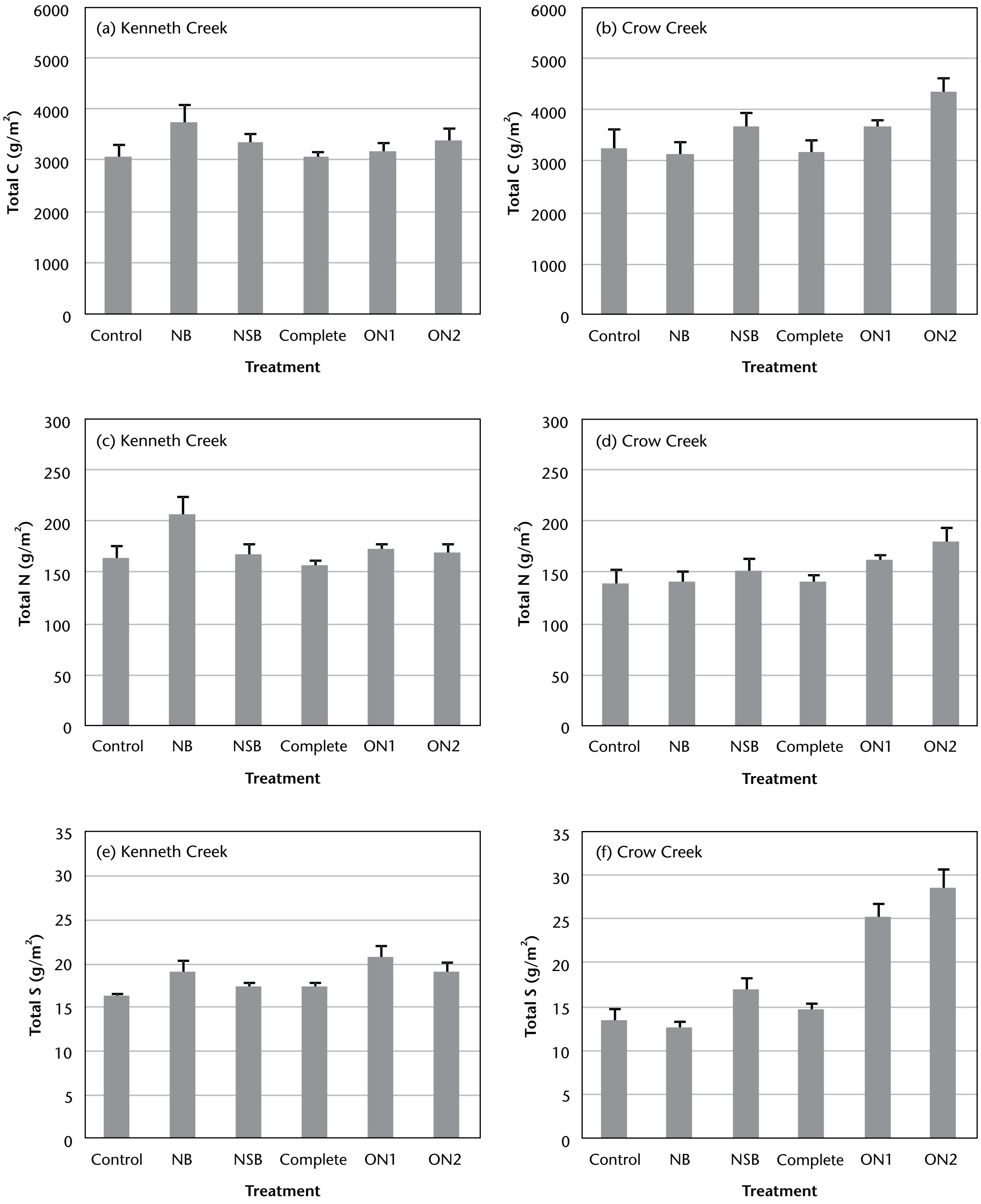

FIGURE 18 *Mean mineral soil carbon (C), nitrogen (N), and sulphur (S) pool estimates by treatment. Each bar represents the mean of three treatment plots (four composite samples/plot). Error bars represent standard error of the mean.*

TABLE 16 *ANOVA summary table for mineral soil total carbon (C), nitrogen (N), and sulphur (S) pools (g/m^2) showing observed* F *statistics, probability* (p) *values, and error mean squares*

		Total (%)					
		C		N		S	
Source of variation	**df**	***F***	***p>F***	***F***	***p>F***	***F***	***p>F***
Kenneth Creek							
Treatment	5	0.43	0.820	0.67	0.651	0.79	0.576
Control vs. periodic	1	0.47	0.507	0.26	0.618	0.62	0.447
Control vs. annual	1	0.18	0.678	0.06	0.804	2.68	0.128
Periodic vs. annual	1	0.09	0.774	0.09	0.765	1.44	0.253
ON1 vs. ON2	1	0.16	0.698	0.01	0.910	0.37	0.553
Error mean square	12	1947276		5248		40.12	
Crow Creek							
Treatment	5	1.29	0.332	1.03	0.441	11.33	<0.001
Control vs. periodic	1	0.02	0.896	0.05	0.820	0.32	0.580
Control vs. annual	1	2.28	0.157	2.56	0.136	30.66	<0.001
Periodic vs. annual	1	3.46	0.088	3.43	0.089	45.01	<0.001
ON1 vs. ON2	1	1.34	0.269	0.70	0.420	1.26	0.284
Error mean square	12	1981508		3156		47.47	

4 DISCUSSION

Soil sampling was not undertaken at the time of trial establishment at either study site. Therefore, although the selected treatment plot locations were as homogeneous as possible, the natural within- and between-plot variation in soil properties may confound reliable interpretation of 12-year treatment effects. Also, soil sampling at Kenneth Creek was completed before the annual spring fertilization of ON1 and ON2 treatment plots, whereas soils at Crow Creek were collected 4 months after yearly fertilization. Differences in the timing of soil sampling relative to annual fertilizer application may partially explain the apparent larger effects of annual nutrient additions on several soil properties at Crow Creek than at Kenneth Creek. Nevertheless, general conclusions regarding the effects of periodic and repeated fertilization on soil properties appear to be justified.

4.1 Periodic Fertilization

When applied at 6-year intervals, two applications of urea (400 kg N/ha in total), with and without other added nutrients (S, P, K, Mg), had few measurable effects on forest floor or mineral soil properties 12 years after initial fertilization at either study site. The only exceptions were increased forest floor mineralizable N at Kenneth Creek and increased forest floor total B levels at Crow Creek. These results are generally consistent with several other forest fertilization studies, where only small and temporal changes to soil properties were reported following single-shot or periodic nutrient additions (Nohrstedt 1990, 2001; Jacobson and Nohrstedt 1993). In studies where fertilizer was added at intervals of 4–7 years, pH changes in the forest floor and mineral soil were minor or absent a few years after the last urea application (Nohrstedt et al. 2000). Only in rare cases has low-intensity fertilization resulted in long-term increases in net N mineralization rates (Binkley and Reid 1985; Strader and Binkley 1989). The apparent increase in N availability following periodic fertilization at Kenneth Creek may have been caused by either increased N mineralization or decreased immobilization. The effectiveness of small B additions on increasing soil B levels is consistent with previously reported prolonged positive effects of B fertilization on foliar B levels in lodgepole pine foliage (Brockley 2003; Brockley and Simpson 2004).

4.2 Yearly Fertilization

The apparent increase in forest floor mass in annually fertilized treatment plots (especially ON1) at Crow Creek is consistent with several other studies that have reported an accumulation of surface organic matter following repeated forest fertilization (Nohrstedt 1990; Malkonen and Kukkola 1991; Neilsen and Lynch 1998). Accumulations are generally explained by a combination of increased litterfall (Miller et al. 1996; Vestgarden et al. 2004) and decreased decomposition of litter and humus (Berg and Matzner 1997). Repression of lignin-degrading fungi and formation of structurally more complex, and hence recalcitrant, compounds are possible mechanisms by which N additions suppress lignin degradation during the latter stages of decomposition (Fog 1988). However, whereas slower litter decomposition has been well documented following repeated fertilization of Scots pine (*Pinus sylvestris* L.), Berg (2000) concluded that N fertilization does not change the substrate quality of Norway spruce litter and thus does not cause any extra buildup of humus. At Crow Creek, therefore, the accumulation of forest floor mass in ON1 and ON2 treatment plots can most likely be explained by higher spruce litter inputs from rapidly growing fertilized trees and by three- to four-fold increases in understorey biomass (Brockley and Simpson 2004; Brockley 2007b). In contrast, forest floor mass was unaffected by yearly fertilization of lodgepole pine at Kenneth Creek. This result differs from the reported accumulation of forest floor material in repeatedly fertilized Scots pine stands (Berg 2000). Whereas large and rapid increases in litterfall rates were reported for intensively fertilized Scots pine (Tamm et al. 1999), mean litterfall amounts (1995–1999) did not differ significantly among the control and annually fertilized treatments at Kenneth Creek.[2] Ågren and Knecht (2001) reported higher production of litter by Scots pine than by lodgepole pine. Small increases in litterfall, combined with poor tree growth and only modest increases in leaf area index (Brockley and Simpson 2004), likely contributed to the statistically insignificant increase in forest floor mass in ON1 and ON2 treatment plots at Kenneth Creek.

Numerous studies have documented decreases in mineral soil pH following long-term yearly fertilization, with the greatest declines associated with high N application rates (Nilsson et al. 1988; Tamm and Popovic 1995; Fox 2004). For example, mineral soil pH (H_2O) decreased by as much as 1.2 units at the highest N application rate (1800 kg N/ha in total) after 17 years of annual fertilization with urea (Tamm and Popovic 1995). The reduction in soil pH also increased with depth, from 0.3 units in the 0–5 cm layer to 1.2 units in the 10–20 cm layer (Tamm and Popovic 1995). In contrast, forest floor pH increased with increasing N application rate (Tamm et al. 1999). By compari-

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[2] P.T. Sanborn and R.P. Brockley. 2006. Litterfall in a lodgepole pine fertilization experiment, Sub-Boreal Spruce zone, central interior British Columbia. Unpubl. report.

son, the effects of repeated nutrient additions (1350–1600 kg N/ha in total) on mineral soil pH (H_2O) were relatively small at Kenneth Creek and Crow Creek, with declines of only 0.2–0.3 units at soil depths of 0–20 cm. The forest floor pH was either not affected, or slightly lower, in the ON1 and ON2 treatments at both study sites.

Increased nitrification is usually the main cause for lower mineral soil pH in repeatedly fertilized forest soils. Nitrification of the ammonium (NH_4^+) produced during urea hydrolysis produces H^+ ions, which increases soil acidity (Killham 1990). The release of H^+ by tree roots following increased NH_4^+ uptake, leaching of base cations (and replacement with H^+ and Al^{+3}), and increased cation exchange between NH_4^+ and exchangeable H^+ and Al^{+3} in solution may also contribute to increased soil acidity following repeated fertilization (Havlin et al. 1999). Although net nitrification in unfertilized acid forest soils is usually negligible, nitrification may increase significantly following repeated N fertilization (Vitousek et al. 1982; Aarnio and Martikainen 1992; McNulty and Aber 1993; Smolander et al. 1995; Fox 2004). High NO_3–N N levels in forest soils are often a symptom of N saturation (Aber et al. 1998). The high forest floor and mineral soil NO_3–N levels in the ON1 and ON2 treatments at Kenneth Creek are consistent with these earlier studies. It can be assumed that most of the NO_3–N at Kenneth Creek was the product of nitrification, since virtually all of the added fertilizer N was in the form of urea or NH_4–N. Conversely, the low levels of NO_3–N at Crow Creek indicate minimal nitrification and/or rapid immobilization, uptake, or leaching of the produced NO_3–. The relatively high levels of forest floor and mineral soil NH_4–N in the ON2 treatment at Crow Creek indicate that nitrification may have been inhibited, possibly due to insufficient soil moisture or low soil pH. Also, the continuous input of organic C in above- and below-ground litter may have increased the immobilization capacity in the fertilized soils (Nilsson et al. 1988).

Higher mineralizable N and lower C/N ratio of the forest floor in the ON2 treatment at Crow Creek suggests that annual fertilization may improve long-term N availability and potentially improve soil quality. These results are consistent with other studies that have reported long-term increases in N mineralization following repeated applications of small amounts of N fertilizer (McNulty and Aber 1993; Aarnio and Martikainen 1994; Fox 2004). By applying frequent doses of N that are large relative to total N capital, the capacity of the soil to immobilize the added N may be overcome, thereby increasing N availability and site quality (Miller 1988). Conversely, forest floor mineralizable N at Kenneth Creek apparently increased following low rates of periodic or annual fertilization but was lower in the heavily fertilized ON2 treatment. These results are consistent with several other studies that have reported decreased N mineralization following frequent additions of large doses of fertilizer N (Söderström et al. 1983; McNulty and Aber 1993; Fox 2004). Several studies have reported declines in soil microbial activity and biomass after high rates of N fertilization (Söderström et al. 1983; Arnebrant et al. 1996; Berch et al. 2006). Decreased microbial activity may be partially attributable to high salt concentrations in the soil solution (Martikainen 1985; Aarnio and Martikainen 1994). Myrold (1987) demonstrated that the anaerobic incubation method used in studies of N availability in forest soils measures N released primarily from dead aerobic micro-organisms killed by the anaerobic conditions. Therefore, the lower mineralizable N in the ON2 treatment at Kenneth Creek may be closely linked to the reported declines in soil microbial activity in heavily fertilized forest soils. Other factors such as repression of lignin-degrading enzymes and changes to the chemical bond structure of organic matter may also reduce N mineralization in N-rich regimes (Berg and Matzner 1997).

The larger amount of soil N in the forest floor and upper mineral soil (0–20 cm) in ON1 and ON2 treatment plots relative to control plots at Crow Creek was equivalent to about 73% and 51%, respectively, of the total amount of fertilizer N added during the experimental period. This is higher than the mean percent soil N recoveries (~ 40%) reported from a wide variety of repeatedly fertilized forests (Johnson 1992; Homann et al. 2001). However, given that soil was not sampled at the beginning of the study, not all of the differences between control and fertilized plots can necessarily be attributed to the effects of fertilization. Conversely, the corresponding increases in soil N measured at Kenneth Creek were only 19% and 24% of the total amounts applied over 12 years. Similarly, the recovery of added S was apparently also much higher at Crow Creek than at Kenneth Creek. At Crow Creek, 44–48% of the total amount of added S was recovered in the forest floor and upper mineral soil, whereas only 17–19% of the added S was accounted for in soils at Kenneth Creek after 12 years. Given the poor stand growth response at Kenneth Creek (Brockley and Simpson 2004), the amount of added N and S incorporated into above-ground tree biomass is likely small relative to Crow Creek (where growth response was large). The sandy soils (with low cation exchange capacity) at Kenneth Creek, combined with a ready supply of accompanying cations and anions from applied multi-nutrient fertilizers and smaller buildup of forest floor, likely contributed to larger leaching losses of N (as NH_4–N and NO_3–N) and S (as SO_4–S) at Kenneth Creek than at Crow Creek. The ON1 and ON2 treatments at Kenneth Creek thus may represent N-saturated ecosystems, in the sense that N availability exceeds the utilization capacity of vegetation and micro-organisms (Aber et al. 1989). Large leaching losses of NO_3–N and accompanying base cations in N-saturated soils have been implicated as a cause of forest decline in Europe (Van Dijk and Roelofs 1988; Huttl 1990). Nutrient uptake from a rapidly growing forest combined with increased immobilization capacity caused by large inputs of organic carbon from litterfall and fine root decay can prevent large leaching losses even at high nutrient inputs (Nilsson et al. 1988). These conditions, combined with finer-textured soils (and higher cation exchange capacity), likely helped to increase N and S retention at Crow Creek.

Lower C/N ratios, higher N mineralization, and larger nutrient pools and forest floor mass in ON1 and ON2 treatments at Crow Creek were associated with very large positive effects on tree growth and neutral or positive effects on spruce fine root length and vigour, mycorrhizal colonization, and soil mesofauna (Brockley and Simpson 2004; Berch and Brockley 2008). In contrast, higher soil NO_3^- levels and no measurable changes to C/N ratio, N mineralization, and soil nutrient pools after 12 years of annual fertilization at Kenneth Creek were associated with minimal (or negative) effects on the growth of lodgepole pine (Brockley and Simpson 2004). Tree growth, fine root biomass and vigour, ectomycorrhizal colonization, and components of the mesofauna and microbial communities were negatively affected in ON2-fertilized treatment plots at another lodgepole pine "maximum productivity" trial in central British Columbia (Berch et al. 2006). Leaching of nitrates and cations and foliar nutrient imbalance have been linked to reduced growth and acute mortality following repeated N additions to Scots pine in Sweden (Tamm et al. 1999; Högberg et al. 2006) and to red pine (*Pinus resinosa* Ait.) in the northeastern United States (Bauer et al. 2004; Magill et al. 2004). Results from Crow Creek strongly support published evidence that repeated fertilization increases C sequestration in forest soils (Nohrstedt et al. 1989; Johnson 1992; Magill and Aber 1998; Hyvönen et al. 2008). At Crow Creek, the amount of C in forest floor and mineral soil (0–20 cm) was 32% and 29% higher in ON1 and ON2 treatment plots, respectively, than in control plots after 12 years of annual fertilization. The increased soil C storage amounted to approximately 17.9 and 16.3 tonnes of C/ha in the ON1 and ON2 treatments, respectively, over 12 years. The cumulative additions of 925 kg N/ha over 12 years resulted in an "N-use efficiency" of about 19.1 kg of soil C sequestered per kilogram of added N in ON1 treatment plots at Crow Creek. The corresponding N-use efficiency in the ON2 treatment was 10.2. By comparison, Hyvönen et al. (2008) reported average N-use efficiencies of 13 for studies of repeatedly fertilized Norway spruce in northern Europe. Yearly fertilization was much less effective at promoting soil C storage at Kenneth Creek. At Kenneth Creek, the amounts of soil C in forest floor and mineral soil (0–20 cm) were only 5% and 14% higher in ON1 and ON2 treatment plots, respectively, than in control plots after 12 years of annual nutrient additions. The corresponding absolute increases in soil C sequestration were 2.8 and 7.7 tonnes of C/ha. This amounted to N-use efficiencies of only 3.6 and 5.7 kg C sequestered per kilogram of added N for ON1 and ON2 treatments, respectively. Interestingly, Hyvönen et al. (2008) also reported much smaller amounts of soil C sequestration and N-use efficiency in repeatedly fertilized Scots pine than in Norway spruce.

5 SUMMARY AND MANAGEMENT IMPLICATIONS

When applied at 6-year intervals to 10- to 12-year-old lodgepole pine and spruce plantations, two applications of urea (totalling 400 kg N/ha), with and without other added nutrients, had few measurable effects on forest floor or mineral soil properties 12 years after initial fertilization. These results are generally consistent with reported effects of single-shot or periodic fertilization on soil properties in other studies. Typical large-scale aerial forest fertilization operations in British Columbia do not exceed the amounts and frequency of nutrient additions used in the periodic treatments in this study (200 kg N/ha applied a 6-year intervals). Therefore, current operational fertilization practices can likely continue without undue concern about possible negative impacts on soil properties. On the other hand, results indicate that periodic fertilization is unlikely to have significant positive effects on soil nutrient availability, total nutrient capital, C sequestration, or organic matter reserves.

Twelve years of annual nutrient additions had significant effects on several forest floor and mineral soil properties, but the effects were different at the two study sites. At Crow Creek, yearly fertilization of spruce apparently resulted in larger forest floor mass, lower C/N ratio, lower pH, higher mineralizable N, and larger pools of total N, C, and S in the forest floor and mineral soil. Pools of forest floor total P and K were larger in ON1 and ON2 plots than in control plots after 12 years. Extractable P, N, and S, and exchangeable K and Mg levels were also higher in intensively fertilized forest floors and mineral soils at Crow Creek. These results indicate that large and frequent nutrient additions may permanently increase the rate of N cycling and site quality and may also promote above- and below-ground C sequestration. The low levels of soil NO_3– at Crow Creek indicate minimal nitrification and/or rapid N uptake or immobilization of added N in vegetation and soils. Also, the continuous input of organic C from above- and below-ground sources may increase the immobilization capacity in these repeatedly fertilized soils. The apparent high retention capacity of the added N at Crow Creek and low levels of NO_3–N indicate that this system is not N saturated. In contrast, yearly fertilization of lodgepole pine at Kenneth Creek had no measurable effects on forest floor mass, C/N ratio, mineralizable N, and total N, C, and S. Relatively high forest floor and mineral soil NO_3– levels in ON2 treatment plots may indicate N saturation and high NO_3– leaching potential. The coarse-textured soils, relatively high precipitation, and poor tree growth may have contributed to high leaching losses in repeatedly fertilized treatments at Kenneth Creek.

It is not possible to ascribe the different responses of forest floor mass and soil chemistry to annual fertilization at the Kenneth Creek and Crow Creek study sites to a specific cause, nor is it possible to state with certainty that the previously reported differences in tree growth responses, fine roots, and soil biota at pine and spruce "maximum productivity" sites are directly linked to the changes in soil properties. However, the reported large differences in growth and N nutrition between lodgepole pine and interior spruce across soil disturbance treatments at two SBS sites in central British Columbia indicate that these two species may respond differently to site manipulation (Kranabetter et al. 2006). Examination of soil properties at other pine and spruce "maximum productivity" study sites is needed to further understand the relationship between tree species and/or site and above- and below-ground changes following repeated fertilization, and the functional relevance of these effects.

Intensive fertilization would unlikely be economically viable if undertaken solely to increase wood fibre production. However, the high costs associated with frequent nutrient additions may be more practicable if the benefits of growth gains are combined with the potential benefits of soil rehabilitation and increased above- and below-ground C sequestration. Results from this study indicate that repeated fertilization may be an effective way to build up soil organic matter reserves and sequester atmospheric C on sites where increased tree growth stimulates litter production, root growth, and understorey development. Intensive fertilization may, therefore, be a biologically viable management option for rehabilitating forested sites that have been degraded from poor management practices such as severe broadcast burning or scarification and for reducing the contribution of greenhouse gas emissions to climate change. However, our results indicate that not all forested sites offer equal opportunities in this regard. Also, the amount of greenhouse gas emissions through all stages of forest fertilization (i.e., fertilizer manufacture, transportation, aerial application, and release of greenhouse gasses after application) must be considered when evaluating the net effect of intensive fertilization on C sequestration.

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