

**Effects of Intensive Fertilization on the Foliar  
Nutrition and Growth of Young Lodgepole  
Pine and Spruce Forests in the Interior of  
British Columbia (E.P. 886.13)  
Establishment and Progress Report**

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2004



Ministry of Forests Forest Science Program

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R.P. Brockley and D.G. Simpson



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## PREFACE

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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. The study originated from discussions and correspondence between Rob Brockley (Research Silviculturist, MoF Research Branch) and Gordon Weetman (then Professor of Silviculture, University of British Columbia) regarding the concepts of “optimum nutrition,” and the potential to dramatically improve the productivity of boreal and sub-boreal forests by alleviating nutritional growth constraints. Research previously undertaken by Weetman in Canada, and by Carl Tamm and others in Sweden, had clearly demonstrated that sustained growth responses, and large reductions in rotation length, are achievable by repeatedly fertilizing young stands of the genera *Pinus* and *Picea*.

Extensive research has confirmed that the growth of young, managed forests in the interior of British Columbia is often significantly improved by “conventional” fertilization (i.e., a single fertilizer application) with nitrogen and other nutrients (e.g., sulphur and boron). However, a single fertilizer application typically produces only a temporary increase in tree growth. The potential productivity impacts of repeatedly fertilizing throughout the rotation have not yet been documented. To what extent can intensive fertilization potentially mitigate the mid-term timber supply shortfalls and declines in long-term harvest levels currently forecast for many forest management units in the British Columbia interior? What are the potential long-term ecological consequences of adding large quantities of nutrients to interior forests? The “maximum productivity” project was undertaken to provide forest planners and practitioners with reliable answers to these important questions.

The growth and yield objectives of the “maximum productivity” study are to compare the effects of different regimes and frequencies of repeated fertilization on the growth and development, in managed stands, of young lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and interior spruce (*Picea glauca* [Moench] Voss and *Picea engelmannii* Parry, or naturally occurring hybrids of these species) and to determine optimum fertilization regimes for maximizing stand volume production. Nine area-based field installations (six lodgepole pine and three spruce) were established on representative sites within three biogeoclimatic zones in the interior of British Columbia between 1992 and 1999. One of the pine installations was subsequently abandoned after sustaining severe mortality from small-mammal feeding injuries. In collaboration with other scientists, several companion studies were subsequently initiated at selected study sites to determine the long-term effects of large nutrient additions on above- and below-ground timber and non-timber resources.

The purpose of this report is to fully describe stand and site characteristics, experimental design, treatment regimes, plot layout, and sampling methodology for the “maximum productivity” project (E.P. 886.13), and to summarize and discuss available foliar nutrition and growth response data for each of the eight research installations within the context of previously reported “optimum nutrition” experiments.

## ABSTRACT

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The preliminary effects of different regimes and frequencies of repeated fertilization on foliar nutrition and growth of eight young lodgepole pine and interior spruce forests in north-central British Columbia are reported. At least 6 years of growth measurements have been obtained from seven of the eight “maximum productivity” installations. These results indicate that the repeated fertilization of young managed forests may be a potentially viable strategy for addressing timber supply challenges in the interior of British Columbia. Young spruce plantations are apparently particularly well suited to intensive forest management. Although four of the five lodgepole pine installations have produced significant growth gains following periodic (every 6 years) and yearly fertilization, the responses to date have been more variable and consistently smaller than those obtained at the spruce study sites. In the lodgepole pine installations, annual applications of nitrogen and other nutrients produced 6-year relative stand volume increments that ranged from 2% lower to 120% higher than control values. In contrast, 6-year stand volume increases of 213–280% were obtained from yearly fertilization at the spruce study sites. In one spruce stand, 9-year stand volume increment in the most intensively fertilized treatment was almost four times larger than in the unfertilized stand. This represented an absolute volume gain of 45 m<sup>3</sup>/ha.

Lodgepole pine growth responses appear to be inversely related to fertilization intensity. Foliar nutrient imbalances and growth disruptions have apparently been induced by large, and frequent, nitrogen additions at some lodgepole pine study sites, despite the frequent inclusion of other macro- and micronutrients in fertilizer prescriptions for repeatedly fertilized treatment plots. Conversely, the largest spruce responses have been associated with the most intensive fertilization treatments.

It is too early to project the potential impacts of intensive fertilization on harvest volume and/or rotation length of managed interior spruce and lodgepole pine forests in north-central British Columbia. However, preliminary growth responses from “maximum productivity” research installations appear to be tracking along pathways similar to the Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) “optimum nutrition” studies in Sweden. Growth projection models estimate that the rotation length of Norway spruce may be shortened by as much as 40–60 years by frequently applying balanced fertilizers. Continued monitoring of stand development in all “maximum productivity” installations is important, to see whether these early species growth trends continue, and to determine how closely growth gains from periodic fertilization (i.e., every 6 years) of spruce and pine will approximate the responses achieved by yearly nutrient additions.

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## 1 INTRODUCTION

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The timber harvesting land base (THLB) in the interior of British Columbia is shrinking, due to withdrawals for parks and the protection of non-timber forest resources. A smaller THLB, combined with age class imbalances in the timber inventory, are creating serious timber supply challenges for the forestry sector. Without strategic intervention, significant mid-term timber supply shortfalls and declines in long-term harvest levels are forecast for many interior forest management units. Increasing the productivity and accelerating the development of young, managed forests is a primary objective of several timber supply mitigation strategies being developed for interior Timber Supply Areas (TSAs) and Tree Farm Licences (TFLs) to improve the amount, and timing, of future harvests.

Fertilization is the most proven method for increasing harvest volume and accelerating the operability of established stands. As such, fertilization is widely viewed by forest planners and practitioners as a potentially valuable tool for mitigating “pinch points” in the mid-term timber supply caused by age class imbalances, and for increasing long-term harvest levels. Accelerating stand development by fertilizing may become an especially important strategy in the British Columbia interior, given the severity of the current mountain pine beetle (*Dendroctonus ponderosae* Hopk.) outbreak and its potentially large negative impact on timber supply (British Columbia Ministry of Forests 2003). However, it is important to document the potential impacts of fertilization on stand growth and development so that realistic expectations can be included in forest-level analyses and mitigation strategies.

During the past 20 years, the British Columbia Ministry of Forests has sponsored extensive research to determine the nutritional status of interior forests and to document the effectiveness of “conventional” fertilization (i.e., a single fertilizer application) on improving stand growth across a wide range of species and sites (Brockley 2001a). These studies have confirmed that nitrogen (N) deficiencies are widespread throughout the region, and that N additions often have a substantial positive effect on tree and stand growth (Weetman et al. 1988; Brockley 1991, 1992, 1995, 1996). Other nutrient deficiencies, either induced or aggravated by N fertilization, have also been implicated as factors limiting the growth response of some N-fertilized interior forests (Brockley 1991, 1995; Brockley and Sheran 1994; Swift and Brockley 1994; Kishchuk et al. 2002). Recent 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). Large-scale aerial fertilizer operations in the British Columbia interior typically use a blended N+S product (Barber 2001).

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; Weetman et al. 1995; Bergh et al. 1999a,b; Tamm et al. 1999). For example, the growth of Norway spruce in Sweden has been doubled or tripled by frequent applications of balanced fertilizers, and growth projection models estimate that rotation lengths may be shortened by up to 40–60 years (Bergh et al. 1999b). In the interior of British Columbia, produc-

tivity gains and accelerated stand development of similar magnitude would be of huge benefit in addressing timber supply challenges such as the amount, and timing, of future harvests.

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. However, increased timber production at the expense of wood value and ecosystem health is obviously not a desirable outcome. The potential detrimental impact of rapid growth on wood quality must be evaluated, as must the effects of large nutrient additions on above- and below-ground timber and non-timber resources.

Beginning in 1992, a small network of lodgepole pine and interior spruce “maximum productivity” field installations (EP 886.13) was established by the B.C. Ministry of Forests Research Branch on representative sites within three major biogeoclimatic zones in the interior of British Columbia. Nine installations (six pine and three spruce) were established in 9- to 15-year-old plantations, and in juvenile-spaced, harvest-origin stands, between 1992 and 1999. One of the naturally regenerated pine installations was subsequently abandoned following severe stem damage caused by red squirrel (*Tamiasciurus hudsonicus* Erxleben) feeding injuries. The three spruce installations were established in three different subzones of the Sub-Boreal Spruce (SBS) biogeoclimatic zone (Meidinger and Pojar 1991), representing a broad range of climatic conditions. Three of the lodgepole pine installations were also established in the SBS zone, while the other two remaining pine sites are in the Engelmann Spruce–Subalpine Fir (ESSF) and Montane Spruce (MS) biogeoclimatic zones (Meidinger and Pojar 1991).

The growth and yield objectives of the “maximum productivity” study are:

- to compare the effects of different regimes and frequencies of repeated fertilization on the growth and development of young lodgepole pine and interior spruce managed forests in the interior of British Columbia;
- to determine optimum fertilization regimes for maximum stand volume production under field conditions; and
- to identify foliar nutrient concentrations, and nutrient ratios, associated with fertilization regimes producing maximum growth.

Because the infrastructure and treatments are already in place, the “maximum productivity” installations offer efficient and cost-effective environments for conducting companion studies to determine the long-term effects of large nutrient additions on ecosystem structure, function, and processes. The statistically sound project design, and the maintenance of rigorous treatment regimes, ensures that the findings from these studies will have credible scientific foundation. In collaboration with other scientists, several studies have been completed, are under way, or are being planned at selected study sites to document the effects of large nutrient additions on above- and below-ground timber and non-timber forest resources. These include studies on:

- soil chemistry and forest floor mass
- litterfall and litter decomposition
- soil mesofauna and microbial activity
- mycorrhizae and fine root biomass
- understorey vegetation biomass and diversity
- white pine weevil activity and tree defence mechanisms
- leaf area, foliar productivity, and growth efficiency
- sapwood hydraulic properties
- wood quality and value
- nutrient leaching
- above- and below-ground biomass production, biomass allocation, and carbon sequestration

The purpose of this report is to fully describe the stand and site characteristics, experimental design, treatment regimes, plot layout, and sampling methodology for the “maximum productivity” study, and to summarize and discuss available foliar nutrition and growth response data for each of the eight research installations within the context of previously reported “optimum nutrition” experiments. The results from companion studies are being reported separately, and are not included in this report. For example, the effects of repeated fertilization on white pine weevil (*Pissodes strobi* Peck.) activity and tree defence mechanisms were recently reported by vanAkker (2002) and vanAkker et al. (2004). The effects of fertilization on lodgepole pine crown characteristics and sapwood hydraulic properties were reported by Amponsah (2003) and Amponsah et al. (2004a,b). Results from several other studies are currently being assembled for formal publication in peer-reviewed scientific journals.

## 2 METHODS

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### 2.1 Location, Site, and Stand Descriptions

The location, site, and stand characteristics of the eight “maximum productivity” field installations are described in [Table 1](#). Detailed stand and site descriptions of individual field installations are provided below.

#### 2.1.1 Lodgepole pine study sites

**Sheridan Creek** The Sheridan Creek installation is located 7.5 km east of McLeese Lake, B.C., within the Blackwater variant of the dry warm subzone of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSdw2). Soil and vegetation descriptions indicate that the site belongs to the zonal SxwFd – Pinegrass (o1) site series ([Steen and Coupé 1997](#)). It occurs on a moderately well drained, gently undulating morainal blanket. The rooting zone has a loamy texture with about 25% volume of gravel and cobbles of acidic, igneous intrusive lithology. There is a root-restricting layer at 35 cm, below which the texture is more clay-rich with more coarse fragments. The soil is classified as a Brunisolic Gray Luvisol ([Soil Classification Working Group 1998](#)). The site is occupied by a naturally regenerated lodgepole pine stand that originated from a 1978 clearcut and subsequent drag scarification. At the time of installation establishment in 1992, the 13-year-old stand had an average stand density of 20 000 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1992, the average height of the crop trees within treatment plots was 4.2 m.

**Kenneth Creek** The Kenneth Creek installation is located approximately 75 km east of Prince George, B.C., within the Willow variant of the wet cool subzone of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSwk1). Soil and vegetation descriptions indicate that the site belongs to the submesic Sxw – Huckleberry – Highbush-cranberry (o5) site series ([DeLong 2003](#)). The soil is well drained and stone-free, and is derived from thick, well-sorted glacio-fluvial 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](#)). After clearcutting and broadcast burning, the site was planted in the spring of 1983 with lodgepole pine 1+0 container stock. The plantation was chemically brushed in 1986. At the time of installation establishment in 1993, the stand was 12 years old and had an average density of approximately 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.

**McKendrick Pass** The McKendrick Pass installation is located approximately 23 km north of Smithers, B.C., within the moist cold subzone of the Engelmann Spruce–Subalpine Fir Biogeoclimatic Zone (ESSFmc). Soil and vegetation descriptions indicate that mid- and lower slope positions belong to the zonal Bl – Huckleberry – Leafy liverwort (o1) site series ([Banner et al. 1993](#)). The soils at these slope positions are derived from morainal material and are relatively stone-free at the surface with 30–40% gravels and cobbles

TABLE 1 Site and stand descriptions of the eight "maximum productivity" installations

Inst. no.*	Location	Forest District	Latitude	Longitude	Mapsheet	Opening	Species	Stand origin†	Year estab.	Age @ estab.	BEC subzone/variant	Site series	SI <sub>50</sub> (m)‡	Initial height (m)
1	Sheridan Creek	Central Cariboo	52° 25'	122° 11'	93B.050	19, 40	Pl	N	1992	13	SBSdw2	01	21.0	4.2
2	Kenneth Creek	Prince George	53° 49'	121° 47'	93H.082	9	Pl	P	1993	12	SBSwk1	05	21.0	5.6
3	Crow Creek	Nadina	54° 20'	126° 17'	93L.039	506	Sx	P	1994	10	SBSmc2	01	18.7	2.4
4	McKendrick Pass	Skeena Stikine	54° 49'	126° 48'	93L.087	118	Pl	P	1995	9	ESSFmc	01,04	16.2	2.5
5	Lodi Lake	Prince George	53° 22'	122° 06'	93G.040	36	Sx	P	1995	11	SBSwk1	01	21.3	2.3
6	Tutu Creek	Mackenzie	55° 27'	123° 12'	93O.045	1	Pl	P	1995	10	SBSmk2	04	18.0	3.7
7	Crater Lake	Quesnel	52° 50'	123° 44'	93B.082	32	Pl	N	1996	15	MSxv	01,04	18.0	4.0
9	Hand Lake	Prince George	54° 24'	122° 53'	93J.036	1	Sx	P	1999	14	SBSmk1	01	21.1	3.3

† P = Planted, N = Natural

‡ Site index estimates by Site Series (SIBEC) – second approximation ([www.for.gov.bc.ca/hre/sibec](http://www.for.gov.bc.ca/hre/sibec))

\* Installation #8 at Coyote Creek (Rocky Mountain Forest District) was abandoned in 2003

at depths greater than 15 cm. The upper portions of the site are slightly drier and likely belong to the submesic Bl – Huckleberry – Heron’s-bill (04) site series. Soils at upper slope positions are partially derived from colluvial material and have a higher percentage of coarse fragments. Soils at all slope positions are morphologically consistent with Orthic Humo-Ferric Podzols (Soil Classification Working Group 1998). The site was clearcut harvested in 1987 and subsequently broadcast burned. In June 1988, the site was planted with lodgepole pine 1+0 container stock. At the time of installation establishment in 1995, the stand was 9 years old and had an average density of approximately 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 1995, the average height of the crop trees within treatment plots was 2.5 m.

**Tutu Creek** The Tutu Creek installation is located approximately 15 km north of Mackenzie, B.C., within the Williston variant of the moist cool subzone of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSmk2). Soil and vegetation descriptions indicate that the site belongs to the submesic Sb – Huckleberry – Spirea (04) site series (DeLong 2000). Derived from well-sorted glaciofluvial outwash parent material, the soil is well drained with a medium sandy loam texture and approximately 60% coarse fragments consisting mainly of gravels. 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 tentatively classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998). The previous stand was clearcut harvested in 1985 and broadcast burned in 1986. The site was planted in the spring of 1987 with lodgepole pine 1+0 container stock. The plantation was mechanically brushed in 1992. At the time of installation establishment in 1995, the stand was 10 years old and had an average density of approximately 1230 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1995, the average height of the crop trees within treatment plots was 3.7 m.

**Crater Lake** The Crater Lake installation is located approximately 85 km west of Quesnel, B.C., within the very dry very cold subzone of the Montane Spruce Biogeoclimatic Zone (MSxv). Depending on slope position, soil and vegetation descriptions indicate that the site belongs to two site series—the submesic Pl – Grouseberry – Kinnikinnick (04) site series and the zonal Pl – Grouseberry – Feathermoss (01) site series (Steen and Coupé 1997). The soil is derived from morainal parent material and is well drained with a sandy loam texture and 60% coarse fragments (mainly gravel and cobbles). The soil is classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998). The previous stand was clearcut harvested in 1978 and chain dragged in the fall of 1979. Landings were burned in the fall of 1980, and escapes from these fires lightly burned portions of the surrounding cutblock. The naturally regenerated lodgepole pine stand was juvenile spaced in 1995. At the time of installation establishment in 1996, the stand was approximately 15 years old and had an average density of approximately 2000 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1996, the average height of the crop trees within treatment plots was 4.0 m.

### 2.1.2 Spruce study sites

**Crow Creek** The Crow Creek installation is located approximately 60 km southeast of Houston, B.C., within the Babine variant of the moist cold subzone of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSmc2). Soil and vegetation descriptions indicate that the site belongs to the zonal Sxw – Huckleberry (o1) site series (Banner et al. 1993). The well-drained soil is derived from a thick morainal blanket and is silty loam in texture with about 25% 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). After clearcutting and broadcast burning in 1985, the site was planted in the spring of 1986 with spruce 1+0 container stock. At the time of installation establishment in 1994, the stand was 10 years old and had an average density of approximately 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.

**Lodi Lake** The Lodi Lake installation is located approximately 40 km southeast of Hixon, B.C., on Tree Farm Licence 53 (Dunkley Lumber Ltd.), within the Willow wet cool variant of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSwk1). Based on slope position, soil characteristics, and dominant shrub and herb species, the site most clearly matches the zonal (o1) site series for this variant (DeLong 2003). The soil is derived from morainal parent material and is well to moderately well drained. The soil is classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998), and is relatively stone-free with a sandy loam texture. The previous mature forest was clearcut harvested in 1985 and subsequently broadcast burned. The site was planted with 2+1 bareroot interior spruce seedlings in 1987. At the time of installation establishment in 1995, the stand was 11 years old, and crop trees averaged 2.3 m in height.

**Hand Lake** The Hand Lake installation is located approximately 88 km northwest of Prince George, B.C., within the Mossvale variant of the moist cool subzone of the Sub-Boreal Spruce Biogeoclimatic Zone (SBSmk1). Soil and vegetation descriptions indicate that the site belongs primarily to the zonal Sxw – Huckleberry – Highbush-cranberry (o1) site series (DeLong et al. 1993). Derived from morainal parent material, the soil has a fine loamy texture. Soils have few coarse fragments near the surface, with up to 25% coarse fragments at depth consisting of gravels and cobbles. Soils are classified mostly as Orthic Dystric Brunisols, with some Gleyed Dystric Brunisols where there is evidence of mottling at depth (Soil Classification Working Group 1998). The previous mature forest was clearcut harvested in 1985 and the cutblock was broadcast burned in 1986. The site was planted with spruce 2+0 container stock in August 1987. The plantation was chemically brushed in 1989. At the time of installation establishment in 1999, the stand was 14 years old and had an average density of approximately 1350 stems per hectare. All treatment plots were thinned to a uniform density of 1100 stems per hectare during plot establishment. In the fall of 1999, the average height of the crop trees within treatment plots was 3.3 m.

## 2.2 Treatment Description

Within each of the eight installations, six treatments are replicated three times for a total of 18, 0.164-ha treatment plots. The six treatments are:

1. Control (i.e., not fertilized)
2. NB – fertilize every 6 years with (kg/ha): 200N, 1.5B
3. NSB – fertilize every 6 years with (kg/ha): 200N, 50S, 1.5B
4. Complete – fertilize every 6 years with (kg/ha): 200N, 100P, 100K, 50S, 25Mg, 1.5B
5. ON<sub>1</sub> – yearly fertilization to maintain foliar N concentration at 1.3% and other nutrients in balance with foliar N
6. ON<sub>2</sub> – yearly fertilization to maintain foliar N concentration at 1.6% and other nutrients in balance with foliar N

Boron (B) is added to treatments 2, 3, and 4 to safeguard against the possibility of B deficiencies induced by repeated N additions. Treatments 3 and 4 are included to test for incremental growth responses attributable to S and other added nutrients. Previous studies have clearly documented B and S deficiencies in interior forests (Brockley 1990, 2000, 2003, 2004; Brockley and Sheran 1994; Swift and Brockley 1994).

The ON<sub>1</sub> and ON<sub>2</sub> treatments are patterned after Scots pine and Norway spruce “optimum nutrition” experiments in Sweden (Tamm et al. 1999) and Canada (Weetman et al. 1995; Kishchuk et al. 2002), in which N is added frequently in order to maintain elevated foliar N levels. The ON<sub>1</sub> and ON<sub>2</sub> treatment plots typically receive 50–100 kg N/ha and 100–200 kg N/ha, respectively, each spring. Other nutrients (P, K, Mg, S, B, Cu, Fe) are added periodically to provide an appropriate nutrient balance and to minimize growth limitations caused by secondary deficiencies (see Ingestad 1979 and Linder 1995). Yearly fertilizer prescriptions for ON<sub>1</sub> and ON<sub>2</sub> treatments are developed following foliar sampling and nutrient analysis each fall.

## 2.3 Plot Establishment

Each “maximum productivity” field installation consists of 18 rectangular, 0.164-ha treatment plots. Each treatment plot consists of an inner, square 0.058-ha “assessment” plot surrounded by a treated buffer. The assessment plot is offset at one end of the treatment plot to reserve an enlarged buffer area for future destructive sampling. Three sides of the assessment plot are surrounded by a 6.04-m buffer; the buffer on the fourth side is 15.1 m wide. Treatment plot and assessment plot dimensions are shown in Table 2.

TABLE 2 *Treatment plot specifications*

Portion of plot	Plot dimensions (m)	Plot size (ha)	No. of trees	Approximate inter-tree spacing (m)
Treatment	36.24 / 45.30	0.164	180	3.0
Assessment	24.16 / 24.16	0.058	64	3.0

Each treatment plot contains approximately 180 crop trees, equivalent to a stand density of 1100 stems per hectare at 3-m square spacing. Growth analyses for each plot are based on periodic measurement of 64 permanently tagged trees within the inner assessment plot. Surplus trees within the assessment plot and buffer were selected and removed at the time of plot establishment. Conifer and broadleaf ingress is periodically removed from treatment plots.

At each study site, treatment plots were systematically located so that within- and between-plot conditions (e.g., stand density, tree height, tree dbh, soil characteristics, and minor vegetation) were as uniform as possible. The outer boundaries of adjacent treatment plots are separated by a minimum distance of 5 m. A minimum distance of 20 m separates the outer treatment plot boundaries from major disturbances (e.g., roads or large stand openings).

At four study sites (Kenneth, Crow Creek, Tutu Creek, and Hand Lake), treatments were randomly assigned to each of the plots such that each treatment was applied to three plots (i.e., completely randomized experimental design). At the four other sites (Sheridan Creek, McKendrick Pass, Lodi Lake, and Crater Lake), geographic separation of plots or possible site differences (e.g., slope position) dictated a randomized complete block experimental design. In these cases, treatment plots were grouped into three blocks (e.g., six plots per block) such that site and stand conditions were as uniform as possible within each block (e.g., upper, middle, lower slope position). Each of the six treatments was randomly assigned to one plot within each block.

## 2.4 Pruning

At Sheridan Creek and Kenneth Creek, all lodgepole pine crop trees within each of the 18 treatment plots were pruned 7 years after plot establishment (1999 and 2000, respectively). All trees taller than 6 m were pruned to a height of 3 m. All trees shorter than 6 m were pruned so that the remaining live crown was approximately, but not less than, 50% of total tree height. All branches longer than 3 cm were removed from the boles of crop trees to the proper lift height.

## 2.5 Foliar Sampling and Analysis

Replicated samples of the current year's foliage are collected from the control, ON<sub>1</sub>, and ON<sub>2</sub> treatment plots each fall (late September to late October). For all other treatments (NB, NSB, and Complete), foliage is collected in the fall prior to each fertilizer application and after the first, third, and sixth growing seasons following fertilization.

Foliage is collected from 10 representative healthy dominant or codominant trees evenly distributed within each assessment plot. Samples are collected from the lower portion of the top third of the live crown, consistent with standardized foliar sampling guidelines (Brockley 2001b). Whenever possible, the same trees are sampled each year. Individual foliage samples are frozen following field collection, and then dried in a forced-air oven at 70 °C for 20 hours before analysis. One composite sample, consisting of equal amounts of foliage from each of the 10 trees per treatment plot, is prepared for chemical analysis. Dried composite samples are ground in an electric coffee grinder and sent to the laboratory for chemical analysis.

Prior to 2000, foliar nutrients were analyzed by a commercial analytical laboratory. Sub-samples of foliage were digested using a variation of the sulphuric acid–hydrogen peroxide procedure described by Parkinson and Allen

(1975). The digests were analyzed colorimetrically for N on a Technicon Autoanalyzer using the Bertholot (phenol-hypochlorite) reaction (Weatherburn 1967). A spectrophotometer measured P, using a procedure based on the reduction of the ammonium molybdiphosphate complex by ascorbic acid (Watanabe and Olson 1965). Total K, Ca, Mg, Mn, and Al were determined by atomic absorption spectrophotometry. Separate sub-samples were dry-ashed, and Cu, Zn, and Fe concentrations were determined by atomic absorption spectrophotometry. After dry-ashing, B was determined colorimetrically using the azomethine-H method described by Gaines and Mitchell (1979). Total S was determined by combustion using a LECO sulphur analyzer. Inorganic sulphate S was extracted with boiling 0.01 N hydrochloric acid (HCl) and determined colorimetrically on an HI-Bismuth reducible distillate (Johnson and Nishita 1952).

Beginning in 2000, foliar nutrients have been analyzed by the B.C. Ministry of Forests analytical laboratory. Analysis of total N and total S is by combustion, using a Fisons NA-1500 elemental analyzer, followed by determination by an inductively coupled plasma (ICP) optical emission spectrometer. All other macro- and micronutrients are wet-ashed with concentrated HNO<sub>3</sub>-HCl acid (vanadium added as internal standard) and hydrogen peroxide, using a closed-vessel microwave digestion system (Kalra and Maynard 1991). The digest solutions are diluted with HCl, and individual nutrients are determined by using ICP, as above. Sulphate-S is extracted with dilute HCl and determined by ion chromatography (Waters IC system).

Foliar analysis results can be affected by inter-laboratory differences in analytical methodology used for the extraction and determination of foliar nutrients. Extensive inter-laboratory comparisons between the commercial laboratory and the Ministry of Forests analytical laboratory were undertaken in 2000 and 2001 in order to evaluate the consequences of switching analytical laboratories. For most nutrients, inter-laboratory differences were small. However, N levels were consistently higher in foliage submitted to the Ministry of Forests laboratory than in foliage analyzed by the commercial laboratory. Conversely, foliar S levels were consistently lower in foliage analyzed by the Ministry of Forests laboratory than in foliage submitted to the commercial laboratory. Inter-laboratory foliar N and S relationships were examined using regression analysis. Regression models that explained 95% and 88% of the inter-laboratory variation in foliar N and S, respectively, were used to “normalize” foliar N and S values obtained from the Ministry of Forests laboratory (post-1999 analysis). These adjustments facilitated the assessment of within-treatment changes in foliar N and S over time, irrespective of laboratory differences.

## 2.6 Fertilization

At each study site, all NB, NSB, and Complete treatment plots were fertilized in the spring following installation establishment and are scheduled for re-fertilization 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 ON<sub>1</sub> and ON<sub>2</sub> 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 ON<sub>1</sub> and ON<sub>2</sub> treatment plots each spring, soon after snowmelt. Urea is the primary N source for ON<sub>1</sub> and ON<sub>2</sub> fertilization at all study sites. 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) is used to supply additional K, S, and Mg, respectively. Boron is supplied as granular borate.

Complete fertilization histories for each of the nine “maximum productivity” installations from the time of installation establishment through spring 2003 are shown in [Appendices 1–8](#).

Each treatment plot is divided into 16 equal-sized sectors prior to fertilizer application. Aluminum “line” stakes are permanently positioned around the outer perimeter of each treatment plot at intervals corresponding to sector boundaries. String is stretched between the corresponding aluminum line stakes on opposite sides of the treatment plot. To facilitate this process, 1-m lengths of PVC pipe are permanently positioned at all grid intersections within each treatment plot. Pre-measured amounts of the specified fertilizer blend are uniformly broadcast-applied by hand to each of the 16 sectors.

## 2.7 Measurement

At each installation, the diameter at breast height (dbh), total height, and height to live crown of all 64 tagged trees within each measurement plot were measured at the time of establishment and every 3 years thereafter. Standard codes are used to describe the condition and form of each tagged tree at each remeasurement. Beginning in 2003, the crown width (the vertically projected maximum horizontal distance between opposite crown margins) of each tagged tree was also measured and recorded.

Diameters are measured with a steel diameter tape at a permanently marked point approximately 1.30 m above ground level. Heights are measured with a telescoping height pole or with an electronic measuring device (e.g., a Forestor Vertex<sup>®</sup> hypsometer). Height to live crown is measured with a telescoping height pole, and crown width is measured in two directions (at right angles) with a steel measuring tape.

## 2.8 Leaf Area Index

The development of apparent stand leaf area index (LAI) is being monitored at each “maximum productivity” installation, with all measurements timed to coincide with 3-year growth measurements. Field measurements are conducted in late spring immediately prior to bud flush following the previous

fall's growth measurement. The measurement of LAI following foliage abscission in the fall and before bud flush in the spring ensures a relatively stable environment that will facilitate year-to-year comparison of LAI development in "maximum productivity" installations.

Leaf area was measured following the ninth growing season after installation establishment at Sheridan Creek, Kenneth Creek, and Crow Creek. At four sites (McKendrick Pass, Lodi Lake, Tutu Creek, and Crater Lake), LAI measurements coincided with sixth-year remeasurement. At Hand Lake, LAI was measured 3 years after installation establishment.

Leaf area index was measured with a Li-Cor LAI-2000 plant canopy analyzer (Li-Cor 1991). Within each treatment plot, measurements were obtained at a height of 80–100 cm above the ground at the nine permanently marked points used to facilitate fertilizer application. Two readings were obtained at each point, one facing northwest and the other facing northeast, before and after solar noon, respectively. Sensors were equipped with a 180-degree view cap. Simultaneously, above-canopy light measurements were collected in an open area adjacent to the study site where the light sensor had an unobstructed view of the sky.

## 2.9 Data Analysis

For each installation, the effects of fertilization on individual-tree basal area (BA) and height increments were subjected to analysis of variance (ANOVA) using the general linear model procedure (SAS Institute Inc. 1989). Basal area and height increments were calculated for all trees alive at the most recent measurement (i.e., 6 or 9 years), and were adjusted by covariance analysis, using initial BA and height, respectively, as the covariates. The 1- to 3-, 4- to 6-, and 7- to 9-year (where available) analyses were based on a completely randomized design for four sites (2, 3, 6, 9), and on a randomized complete block design for the other four sites (1, 4, 5, 7). The Bonferroni correction was used to adjust the p-values of least-square means for multiple comparisons. A level of significance of  $\alpha=0.05$  is used throughout the text for inferring statistical significance.

For each installation, stand total volume was estimated at the time of establishment and at 3-year intervals for the 6- or 9-year period following fertilization. Total bole volume (inside bark) was estimated for each tree per plot using volume equations developed for previous lodgepole pine and spruce fertilization studies (R. Brockley, unpublished data). Each equation was based on sectional measurements of 36 trees selected to cover the size range of trees at the study site. Sectional measurements were conducted according to the methodology outlined by Kovats (1977). The inside bark section volumes were calculated using Smalian's formula (Chapman and Meyer 1949). Least-square estimates of the coefficients  $a_1$  and  $a_2$  were determined by regressing measured volume per tree ( $\text{cm}^3$ ) against the combined variable of dbh (cm) squared times total height (m). The general form of each equation was  $V = a_1 + a_2 D^2 H$ . Calculated stem volumes do not account for possible treatment-related changes in tree taper and form. For each measurement interval, stand volume per hectare was determined by summing individual tree volumes in each plot and converting plot area to a per-hectare basis. Treatment means were obtained by averaging the three replicate plot means per treatment. Area-based volume estimates are net values (i.e., they exclude mortality), because only those trees alive at the latest measurement were used for volume calculations.

Linear regression was used to quantify the relationship between productivity and leaf area index. The base relationship was in the form of a simple model:

$$BA = \beta_0 + (\beta_1LAI) \quad (1)$$

where the dependent variable was stand BA (m<sup>2</sup>/ha) at 3, 6, or 9 years, and LAI was the corresponding leaf area index (m<sup>2</sup>/m<sup>2</sup>). The BA and LAI treatment means for each installation were used in the analyses.

### 3 RESULTS

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#### 3.1 Foliar Nitrogen

**3.1.1 Yearly fertilization (ON<sub>1</sub> and ON<sub>2</sub>)** Pre-treatment foliar N levels in control, ON<sub>1</sub>, and ON<sub>2</sub> treatments, and patterns of changes over time, are illustrated in [Figures 1 and 2](#), for lodgepole pine and spruce installations, respectively.

For lodgepole pine, pre-fertilization foliar N concentration was between 1.1 and 1.2% at all study sites ([Figure 1](#)). In no case were between-treatment differences in pre-treatment foliar N statistically significant. Foliar N levels in control plots at the pine sites have fluctuated in the years since trial establishment, but have generally remained below 1.2%. In contrast, foliar N concentrations in ON<sub>1</sub> and ON<sub>2</sub> treatment plots responded positively following the initial fertilizer application, and have remained higher than control N levels since that time. Year-to-year fluctuations have been largely synchronized between control, ON<sub>1</sub>, and ON<sub>2</sub> treatments, and the different rates of yearly fertilization have created distinct separation between the foliar N levels at most sites. In most lodgepole pine installations, foliar N concentrations in ON<sub>1</sub> and ON<sub>2</sub> treatments have more-or-less stabilized after several years of annual fertilization. However, the target value of 1.6% for the ON<sub>2</sub> treatment has not yet been achieved at any of the lodgepole pine study sites. Foliar N in ON<sub>1</sub> treatments remains below target (1.3%) in three of the five installations.

Pre-fertilization foliar N levels were between 0.9 and 1.1% at the three spruce study sites ([Figure 2](#)). Foliar N concentrations in control plots have remained relatively stable over time. Foliar N concentration in ON<sub>1</sub> and ON<sub>2</sub> treatments increased sharply immediately following the initial fertilization at all three spruce sites. However, levels have subsequently declined, and N concentrations in ON<sub>2</sub> treatments remain below target (1.6%) at all three sites. Year-to-year fluctuations in foliar N concentration have been highly synchronized, and the different rates of yearly N additions have created a distinct separation between ON<sub>1</sub> and ON<sub>2</sub> treatments at both Crow Creek and Lodi Lake. However, 4 years of N additions have yet not achieved distinct separation between control and repeatedly fertilized foliar N levels at Hand Lake.

**3.1.2 Periodic fertilization (NB, NSB, Complete)** As illustrated in [Figures 3 and 4](#), foliar N levels in lodgepole pine and spruce responded positively, and almost equally, immediately following initial application of NB, NSB, and Complete fertilizers. Foliar levels peaked in year 1 and dropped sharply in years 3 and 6. Foliar N levels in all treatments were generally at, or below, control levels after 3 years. Foliar N response in the year following re-fertilization in NB, NSB, and Complete treatments (year 7) was often less than that obtained after the initial fertilization in year 1 ([Figure 3b,c,d](#) and [Figure 4b](#)).

#### 3.2 Foliar Nutrient Balance

**3.2.1 Yearly fertilization (ON<sub>1</sub> and ON<sub>2</sub>)** Periodic inclusion of P, K, S, and B in ON<sub>1</sub> and ON<sub>2</sub> fertilizer regimes has generally maintained foliar concentrations of these nutrients at, or above, pre-treatment levels (data not shown). Consequently, favourable balances between N and these added macro- and micronutrients have been maintained at most lodgepole pine and spruce study sites ([Figures 5–12](#)). However, foliar N/P, N/K, and N/S ratios in ON<sub>2</sub> treatments have sometimes risen above target thresholds at Kenneth Creek ([Figures 5b, 7b, and 9b](#)). Foliar N/K and N/S thresholds have,

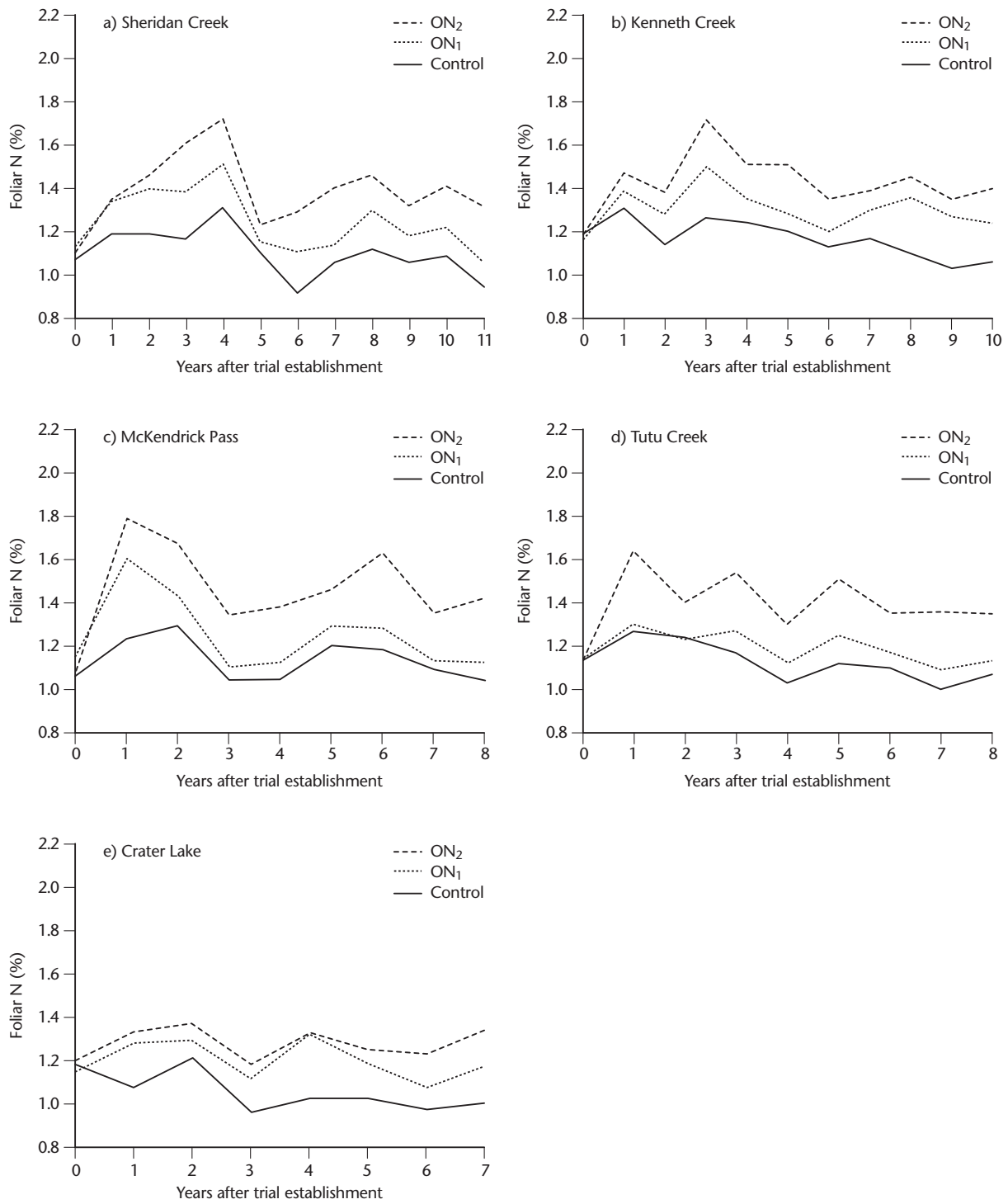


FIGURE 1 Foliar nitrogen concentration by treatment and year in lodgepole pine "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

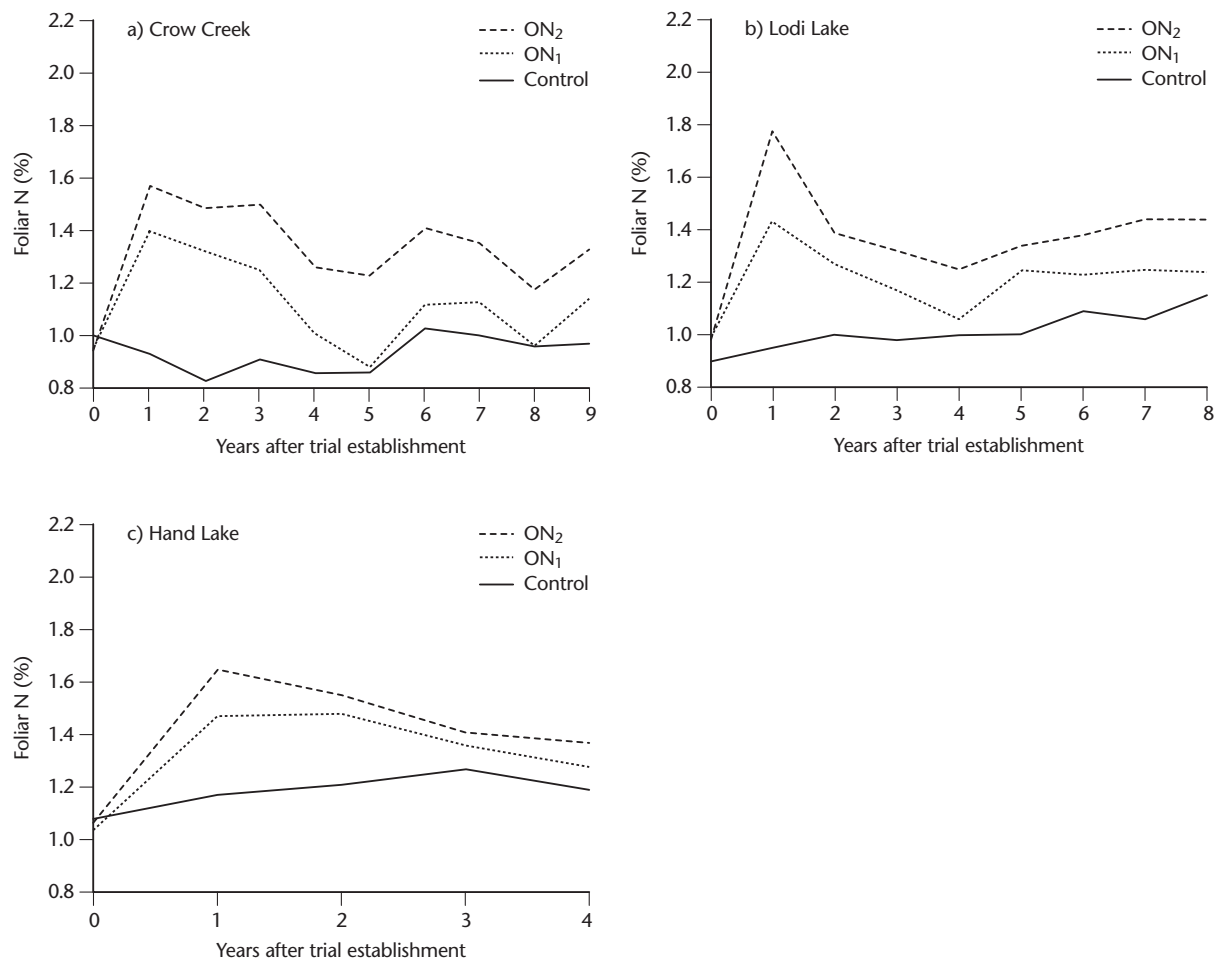


FIGURE 2 Foliar nitrogen concentration by treatment and year in spruce “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

at times, also been slightly exceeded at Sheridan Creek and McKendrick Pass, respectively (Figures 7a and 9c). Foliar N/B levels were slightly below threshold values at the time of establishment at most pine and spruce study sites (Figures 11 and 12). The N/B levels in control treatments have generally remained near, or have exceeded, the threshold in subsequent years. Boron additions have generally improved foliar N/B balance in both species.

Despite the inclusion of small amounts of Mg in fertilizer prescriptions, foliar N/Mg ratios in ON<sub>1</sub> and ON<sub>2</sub> treatments at several lodgepole pine and spruce study sites increased sharply shortly after trial establishment (Figures 13 and 14). Relatively large quantities of Mg-containing fertilizers were subsequently added to all “maximum productivity” installations (Appendices 1–8). These Mg additions have generally succeeded in increasing foliar Mg and restoring favourable foliar N/Mg balance.

Supplementary Ca has not been included in ON<sub>1</sub> and ON<sub>2</sub> fertilizer regimes to date. Consequently, foliar N/Ca ratios increased following fertilization, and a distinct separation between levels in control, ON<sub>1</sub>, and ON<sub>2</sub>

treatments is apparent at most study sites (Figures 15 and 16). However, except for the ON<sub>2</sub> treatment at McKendrick Pass, N/Ca ratios remain well below the upper threshold value of 20 in all installations.

Except for B, micronutrients have not been routinely included in ON<sub>1</sub> and ON<sub>2</sub> fertilizer prescriptions. As illustrated in Figures 17 and 18, foliar N/Cu ratios in ON<sub>1</sub> and/or ON<sub>2</sub> treatments currently exceed threshold values at several of the lodgepole pine and spruce study sites. At Kenneth Creek, the inclusion of 3 kg Cu/ha in the fertilizer prescription in year 8 was apparently effective, at least temporarily, at lowering the N/Cu ratio in the ON<sub>2</sub> treatment (Figure 17b). However, supplementary Cu added in year 7 was apparently less effective at lowering N/Cu ratios at Crow Creek (Figure 18a). Copper supplements have not yet been included in fertilizer regimes at other study sites. Foliar N/Fe ratios in control, ON<sub>1</sub>, and ON<sub>2</sub> treatments have approached, or exceeded, threshold values at several lodgepole pine and spruce study sites (Figures 19 and 20). At Crow Creek and Kenneth Creek, 10 kg/ha of supplemental Fe in years 7 and 8, respectively, has had little apparent impact on foliar N/Fe balance (Figures 19b and 20a).

**3.2.2 Periodic fertilization (NB, NSB, Complete)** Foliar B levels in all lodgepole pine and spruce installations increased immediately following initial application of NB, NSB, and Complete fertilizers (Figures 21 and 22). In most cases, B levels remained higher than control values after 6 years. Foliar B response was also positive in the year following a second fertilizer application (year 7).

Foliar N/S ratios in NB treatments slightly exceeded threshold values following initial fertilization at several of the lodgepole pine and spruce “maximum productivity” sites (Figures 23 and 24). Added S was generally effective in maintaining favourable foliar N/S balance in NSB and Complete treatments. Interestingly, foliar N/S levels in the year following the second fertilization (year 7) were almost always higher than those obtained after the initial fertilization (year 1). For NB treatments, the elevated foliar N/S ratios following the second fertilization far exceeded the threshold value at several pine and spruce study sites.

Foliar N/Mg ratios were temporarily increased following fertilization with NB, NSB, and Complete fertilizers and, in several cases, approached or exceeded N/Mg threshold values in year 1 (Figures 25 and 26). In all cases, foliar N/Mg ratios remained below threshold values after re-fertilization in year 7.

### 3.3 Individual-tree Growth

#### 3.3.1 Basal area

**Lodgepole pine** Basal area (BA) increments for lodgepole pine “maximum productivity” installations are shown in Figure 27. Except for Kenneth Creek (Figure 27b), all lodgepole pine sites have responded positively to fertilization. For responsive pine stands, BA responses to yearly nutrient additions (ON<sub>1</sub> and ON<sub>2</sub>) were no different than responses to single applications of NB, NSB, or Complete fertilizer during the 1- to 3-year response period. However, growth responses to the ON<sub>1</sub> and ON<sub>2</sub> treatments were always significantly larger than in other treatments during the 4- to 6-year response period.

In the four responsive installations, BA increments to single applications of NB, NSB, and Complete fertilizer averaged 21%, 24%, and 25% higher, respectively, than growth of unfertilized trees over 6 years. Six-year BA

responses in ON<sub>1</sub> and ON<sub>2</sub> treatments averaged 42% (range 34–51%) and 51% (range 40–67%), respectively. At Sheridan Creek, the ON<sub>1</sub> and ON<sub>2</sub> treatments produced BA gains of about 50% above control growth over 9 years (Figure 27a). These gains were only slightly higher than those recorded following two applications of Complete fertilizer.

At Sheridan Creek, the relative effectiveness of the NB, NSB, and Complete treatments apparently varied between the first fertilization (year 1) and the second fertilization (year 7). These nutrient regimes produced 6-year BA responses in the order of: Complete >NSB>NB (Figure 27a). However, the relative responses were modest (17–30%), and were not significantly different from each other. The order of response remained the same in the 3-year period following re-fertilization (7- to 9-year), but differences among the three treatments were much larger—relative growth gains in the NSB and Complete treatments (49% and 64%, respectively) were at least twice as large as those achieved with NB application (25%) (Figure 27a).

One lodgepole pine installation (Kenneth Creek) has not responded significantly to single or repeated fertilizer applications (Figure 27b). In fact, the most intensive fertilizer treatment (ON<sub>2</sub>) apparently resulted in a slightly negative response (relative to control) during the 7- to 9-year response period.

**Spruce** Fertilization has produced large, and statistically significant, growth gains at all of the three spruce “maximum productivity” study sites (Figure 28). Over 3 years, the largest relative BA gains were achieved at Crow Creek, with increases ranging from 80 to 98% above growth measured in control treatments. The least responsive stand was Hand Lake, where BA responses (relative to control) ranged from 27 to 42%.

Basal area responses in the NB, NSB, and Complete treatments were very similar during the 1- to 3- and 4- to 6-year response periods at spruce sites (Figure 28). Although differences were not statistically significant, growth responses following re-fertilization (i.e., 7- to 9-year) at Crow Creek were slightly smaller in the NB treatment than in NSB or Complete treatments (Figure 28a).

At all three spruce sites, single applications of NB, NSB, and Complete fertilizers were generally equally as effective as yearly ON<sub>1</sub> and ON<sub>2</sub> nutrient additions during the 1- to 3-year response period. However, at both spruce sites with at least 6 years of growth data, BA responses in the ON<sub>1</sub> and ON<sub>2</sub> treatments were much larger than those in the NB, NSB, and Complete treatments during the 4- to 6- and 7- to 9-year response periods (Figure 28a,b). After 6 years, BA gains (relative to control) in ON<sub>1</sub> and ON<sub>2</sub> treatments at Crow Creek were 141% and 153%, respectively. The corresponding relative responses over 9 years were 137% and 174%. At Lodi Lake, 6-year responses were 72% and 116% greater in ON<sub>1</sub> and ON<sub>2</sub> treatments, respectively, than in the control.

### 3.3.2 Height

**Lodgepole pine** Height increments for lodgepole pine “maximum productivity” installations are shown in Figure 29. Four of five lodgepole pine sites showed virtually no height response, or negative height response, to fertilization. Height increments within these installations were apparently inversely related to fertilization intensity, with the smallest increments being observed at the highest fertilization intensity ( $ON_2$ ). This effect was most pronounced at Kenneth Creek, where 9-year height increment was 22% less in the  $ON_2$  treatment than in the control treatment (Figure 29b). The negative impact of large nutrient additions on tree height was clearly evident after 3 years at this site, and has become more pronounced at each subsequent remeasurement. In absolute terms, the reductions in height growth at Kenneth Creek totalled 1.2 m over 9 years. Conversely, modest but statistically significant positive height responses were measured in the  $ON_1$  and  $ON_2$  treatments at Crater Lake (Figure 29e).

**Spruce** Fertilization has produced large, and statistically significant, height responses at two of the three spruce sites (Figure 30). The largest height gains, both in absolute and relative terms, have been achieved at Crow Creek. Six-year height responses ranged from 40 to 65% greater than control increments at this site.

Height responses at Crow Creek and Lodi Lake are positively related to fertilization intensity, with the largest gains measured in the  $ON_2$  treatments. Spruce trees in the  $ON_2$  treatment at Crow Creek achieved 1.5 m more height increment than unfertilized trees over 9 years, representing a relative increase of 54%. At Lodi Lake, fertilization clearly increased the incidence and severity of leader damage from the white pine terminal weevil (data not shown). Despite these injuries, height increments were 38% higher in  $ON_2$  treatments than in control treatments over 6 years. In absolute terms, height increment gains totalled 77 cm more than for unfertilized trees at Lodi Lake.

**3.3.3 Stem taper** The effects of fertilization on mean stem taper in lodgepole pine and spruce “maximum productivity” installations are illustrated in Figures 31 and 32, respectively. In no case were between-treatment differences in initial taper statistically significant. At two of the lodgepole pine sites (McKendrick Pass and Crater Lake) and at all three spruce sites, the taper of unfertilized trees increased over time. At three pine sites, the taper of unfertilized trees remained constant, or decreased slightly, over time.

In seven of the eight “maximum productivity” installations, the effects of fertilization on taper were highly significant. After 3, 6, or 9 years, fertilized trees at these sites had significantly higher taper than unfertilized trees. The taper in NB, NSB, and Complete treatments was approximately equal, with taper increases relative to control ranging from 3 to 11% in lodgepole pine installations and from 11 to 18% in spruce installations. In all cases, the largest taper was measured in  $ON_2$  treatments, with relative increases ranging from 16 to 23% and from 32 to 33% in pine and spruce installations, respectively. The relative and absolute taper difference between control and  $ON_2$  treatments is apparently increasing over time.

### 3.4 Area-based Growth

**3.4.1 Lodgepole pine** Stand volume development ( $\text{m}^3/\text{ha}$ ) in lodgepole pine “maximum productivity” installations is shown in [Figure 33](#). In four of the five stands, fertilized treatments produced between 5 and 13  $\text{m}^3/\text{ha}$  more volume than control treatments over 6 years, with the largest stand-level responses in  $\text{ON}_1$  and  $\text{ON}_2$  treatment plots. Relative 6-year increases over control growth ranged from 39–76% in  $\text{ON}_1$  treatments to 28–120% in  $\text{ON}_2$  treatments. Over 9 years, 40% and 51% more volume was produced in  $\text{ON}_1$  and  $\text{ON}_2$  treatments, respectively, than in the control treatment at Sheridan Creek. At Kenneth Creek, stand volume gains following fertilization were small. After 9 years of annual fertilizer additions, the stand volume in the  $\text{ON}_2$  treatment was no different than in the control treatment ([Figure 33b](#)).

**3.4.2 Spruce** Stand-level volume development ( $\text{m}^3/\text{ha}$ ) for two of the three spruce “maximum productivity” installations is shown in [Figure 34](#). Because only 3 years of response data are available, area-based responses for Hand Lake are not presented. Large stand volume gains following fertilization have been achieved at both Crow Creek and Lodi Lake. Growth responses to yearly nutrient additions ( $\text{ON}_1$  and  $\text{ON}_2$ ) have been especially large. Over 6 years, the  $\text{ON}_1$  treatments produced 16  $\text{m}^3/\text{ha}$  more stand volume than control treatments at both sites, representing relative increases of more than 200%. In  $\text{ON}_2$  treatments, 6-year volume gains totalled 19 and 22  $\text{m}^3/\text{ha}$  at Crow Creek and Lodi Lake, respectively. In relative terms, the corresponding increases were 254% and 280%. Crow Creek is the only spruce “maximum productivity” installation to have received annual additions of fertilizer over a 9-year period. In  $\text{ON}_1$  treatments, yearly additions of fertilizer have produced 32  $\text{m}^3/\text{ha}$  more wood than control treatments (a 209% increase) over this period. Stand volume increment in the  $\text{ON}_2$  treatment was 45  $\text{m}^3/\text{ha}$  higher than in the control treatment over 9 years, representing a relative increase of 290% ([Figure 34a](#)).

### 3.5 Leaf Area Index

Leaf area index in lodgepole pine and spruce installations is illustrated in [Figures 35](#) and [36](#), respectively. Leaf area has responded positively to fertilization at all lodgepole pine sites. Differences in LAI between the NB, NSB, and Complete treatments are generally small, with larger LAIs measured in the  $\text{ON}_1$  and  $\text{ON}_2$  treatment plots. Except for Kenneth Creek, the largest LAI was always obtained in the  $\text{ON}_2$  treatment ([Figure 35](#)). Similar patterns are evident at two of the three spruce sites (Crow Creek and Lodi Lake), although the absolute and relative LAI gains are considerably higher than those at the lodgepole pine sites ([Figure 36](#)). At Hand Lake, the positive effects of fertilization on LAI after 3 years are relatively small, with the smallest gains achieved in the  $\text{ON}_1$  and  $\text{ON}_2$  treatments.

As illustrated in [Figure 37](#), there was a significant, positive linear relationship between stand BA and LAI. Eighty-eight percent of the variation in stand BA was accounted for by differences in LAI.

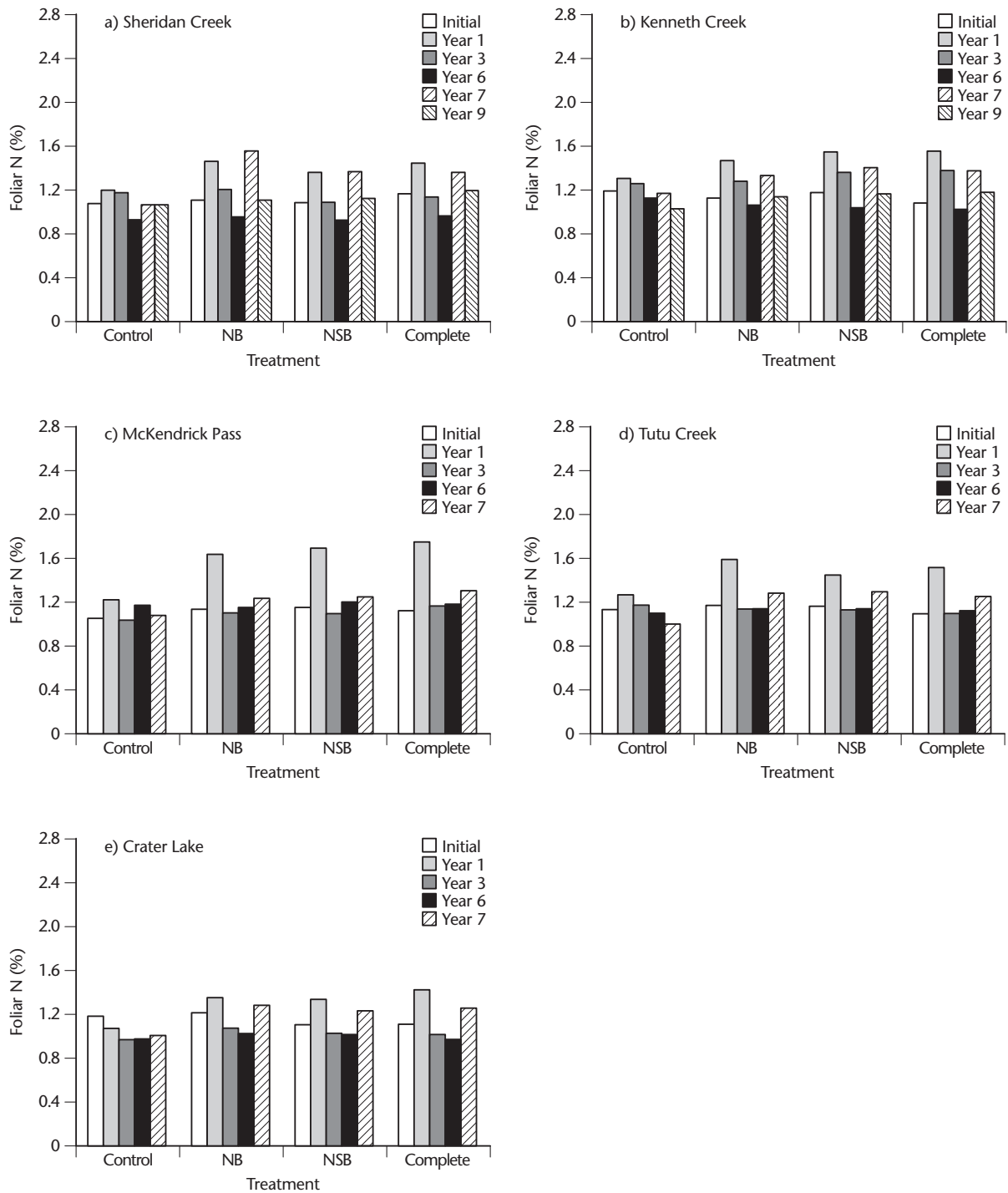


FIGURE 3 Foliar nitrogen concentration by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite).

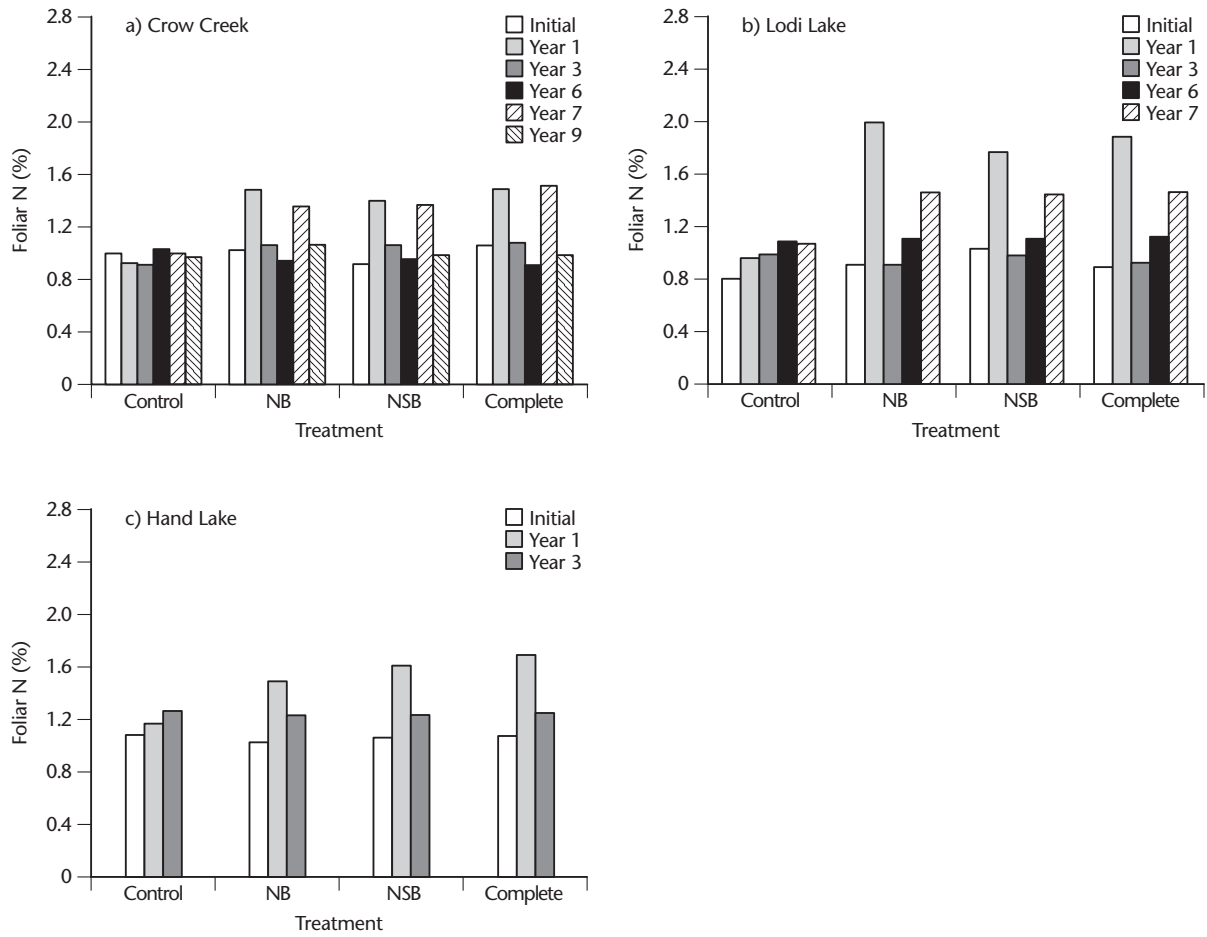


FIGURE 4 Foliar nitrogen concentration by treatment and year in spruce “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite).

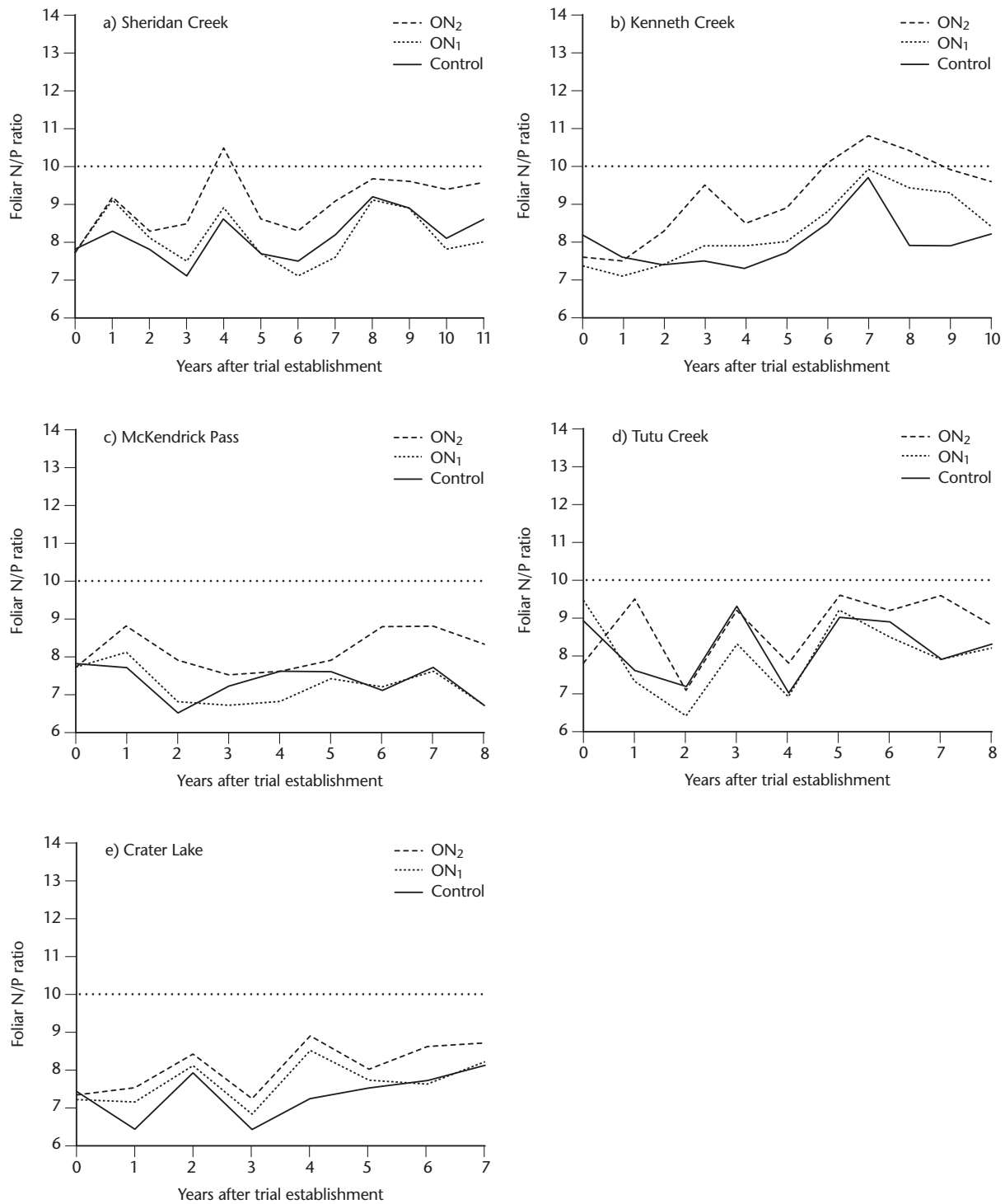


FIGURE 5 Foliar nitrogen:phosphorus (N/P) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

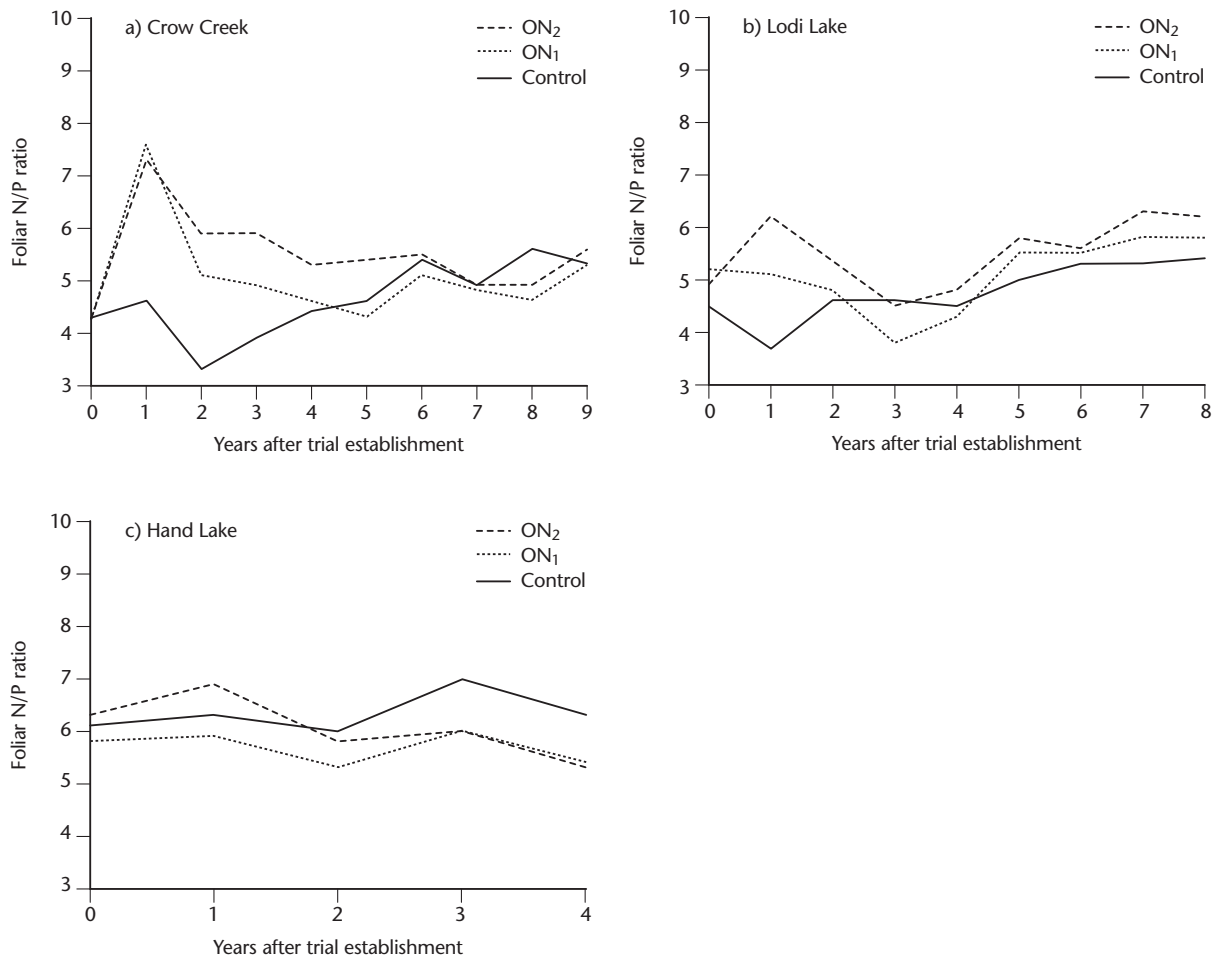


FIGURE 6 Foliar nitrogen:phosphorus (N/P) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

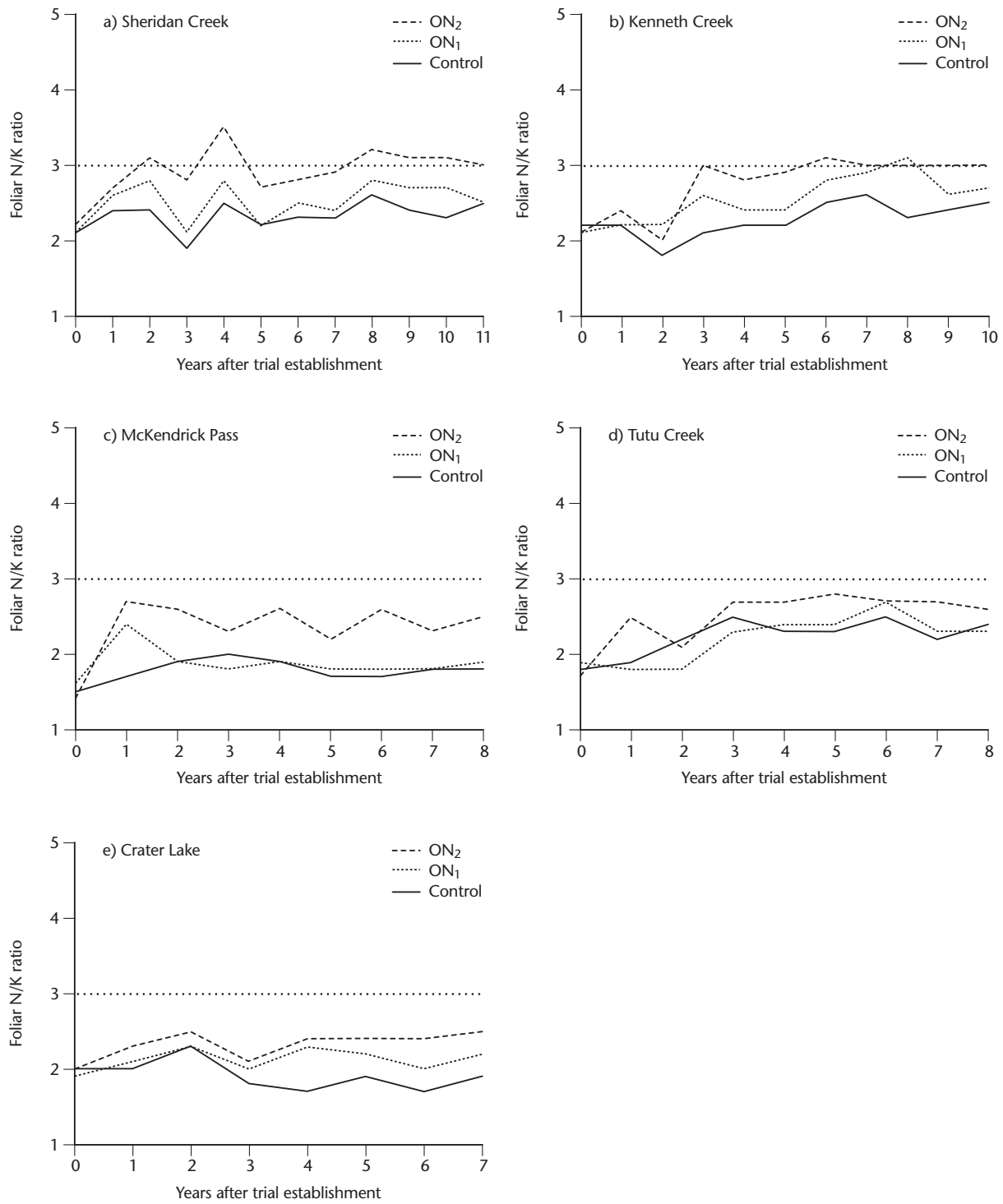


FIGURE 7 Foliar nitrogen:potassium (N/K) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

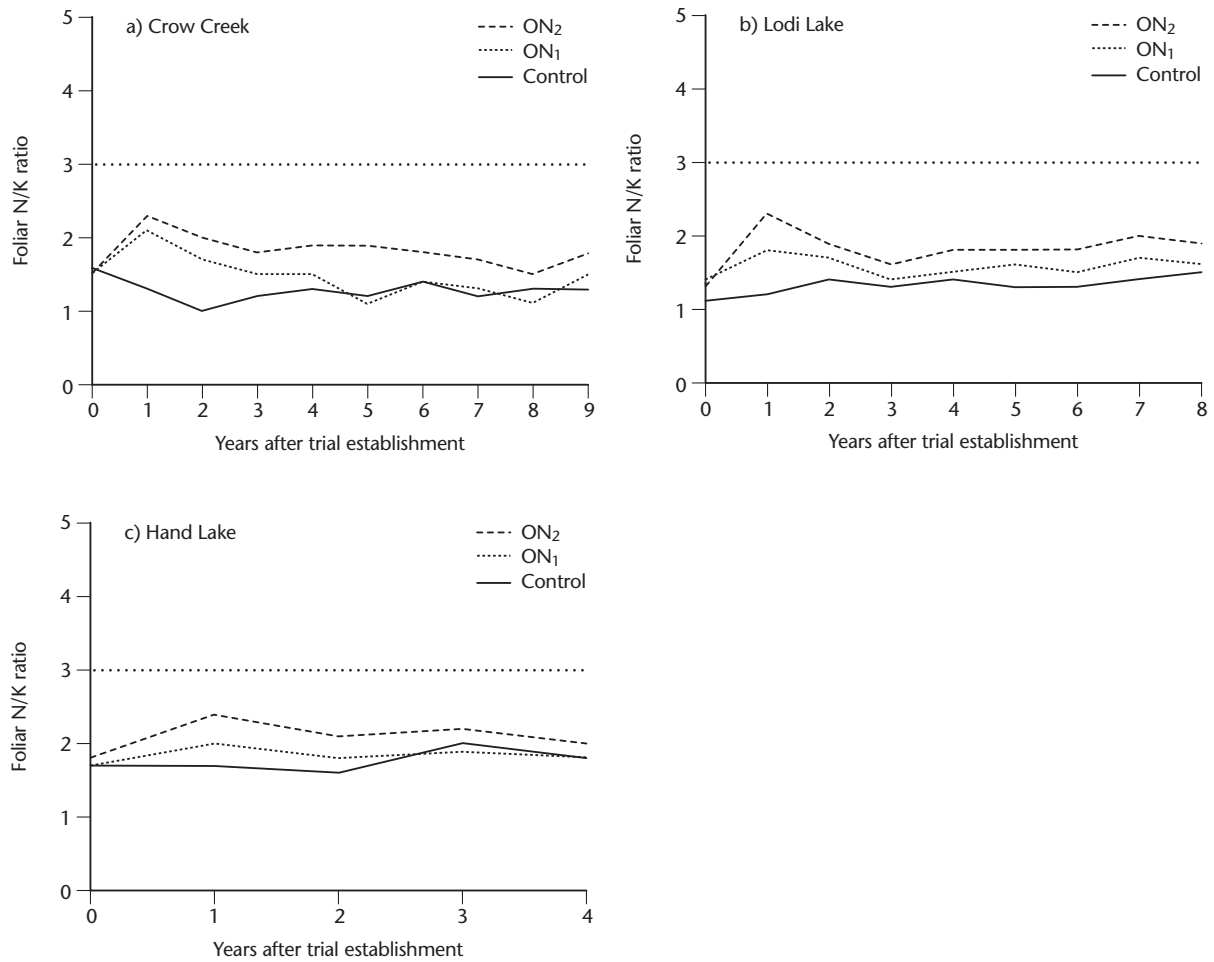


FIGURE 8 Foliar nitrogen:potassium (N/K) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

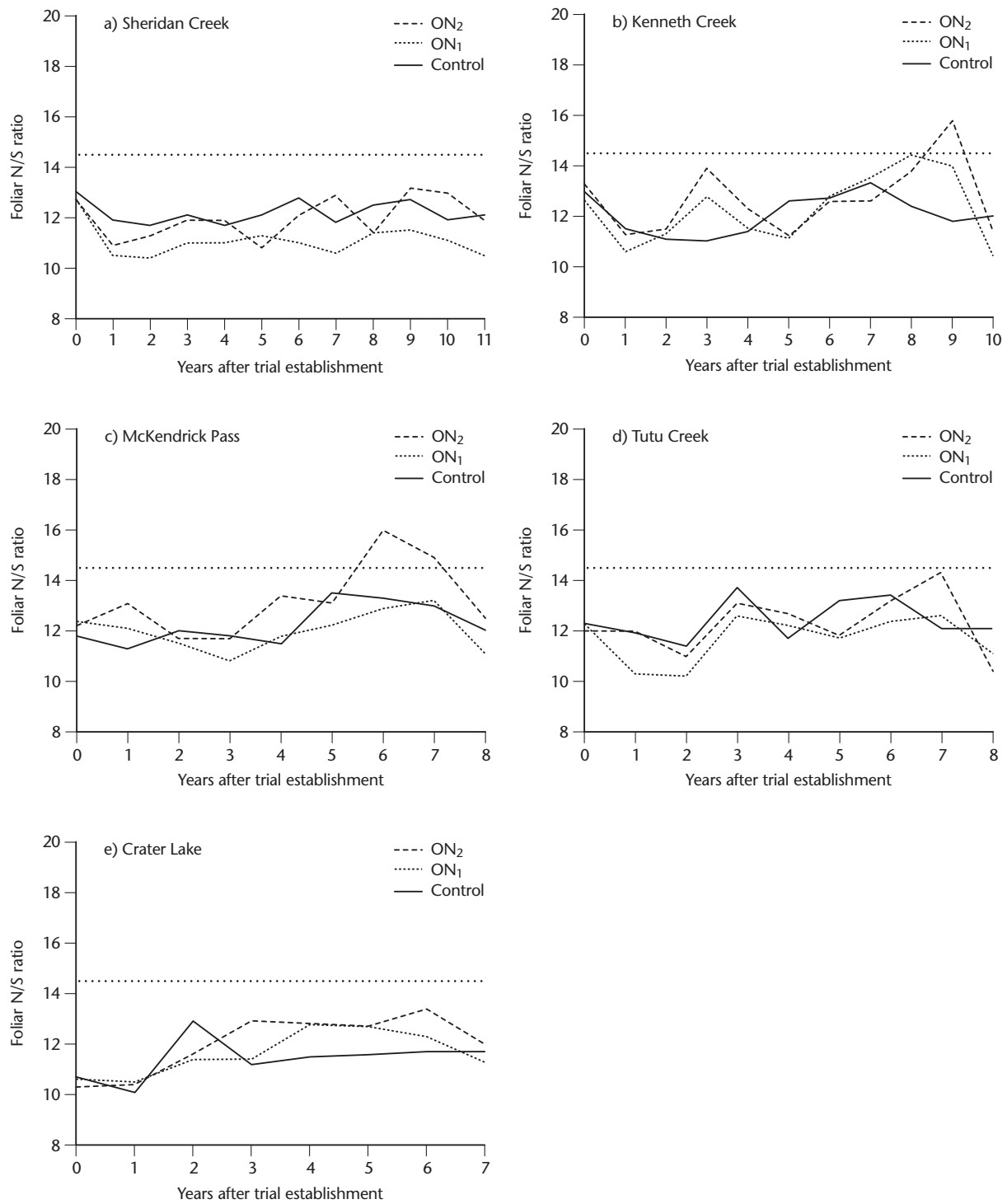


FIGURE 9 Foliar nitrogen:sulphur (N/S) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

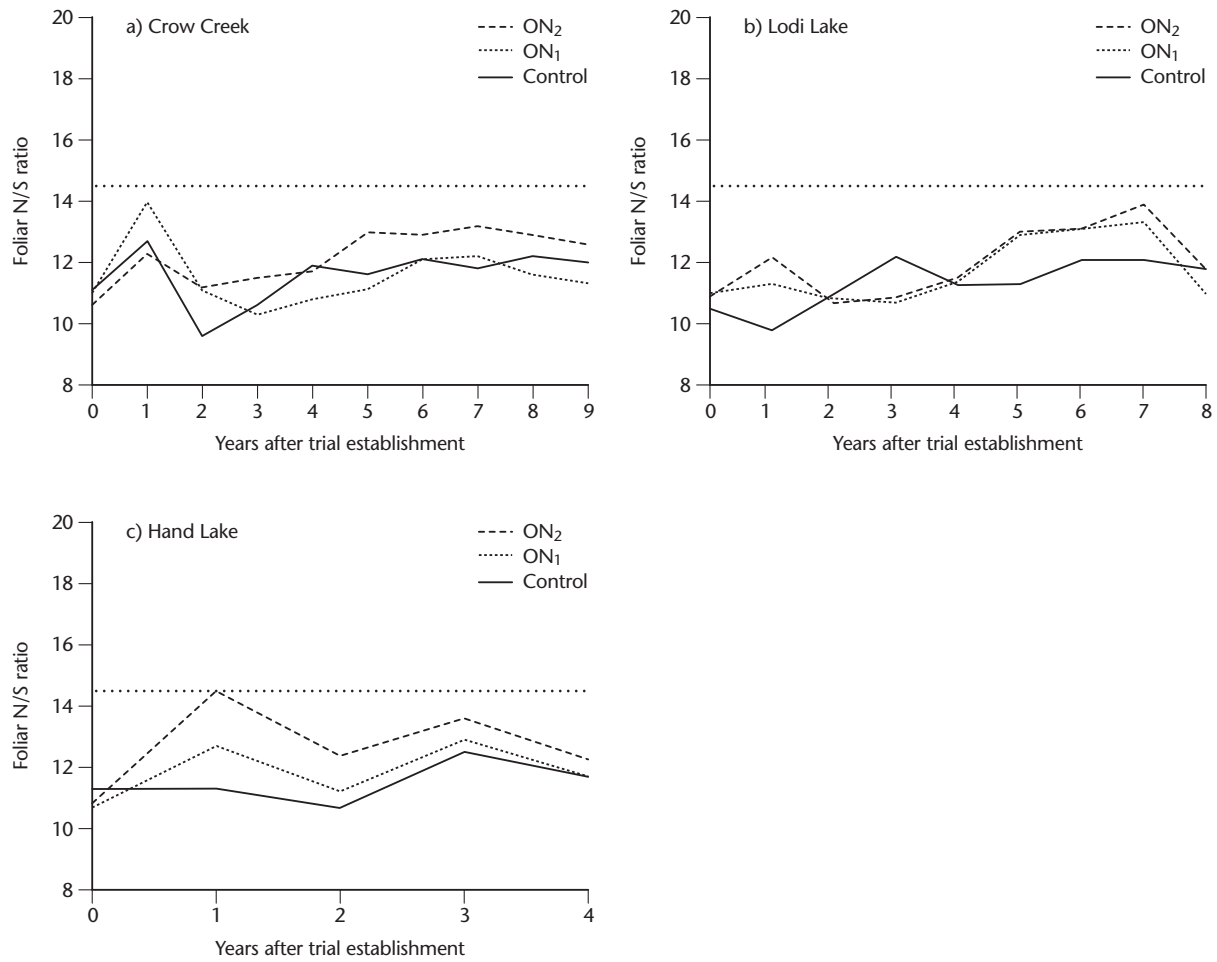


FIGURE 10 Foliar nitrogen:sulphur (N/S) ratio by treatment and year in spruce "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

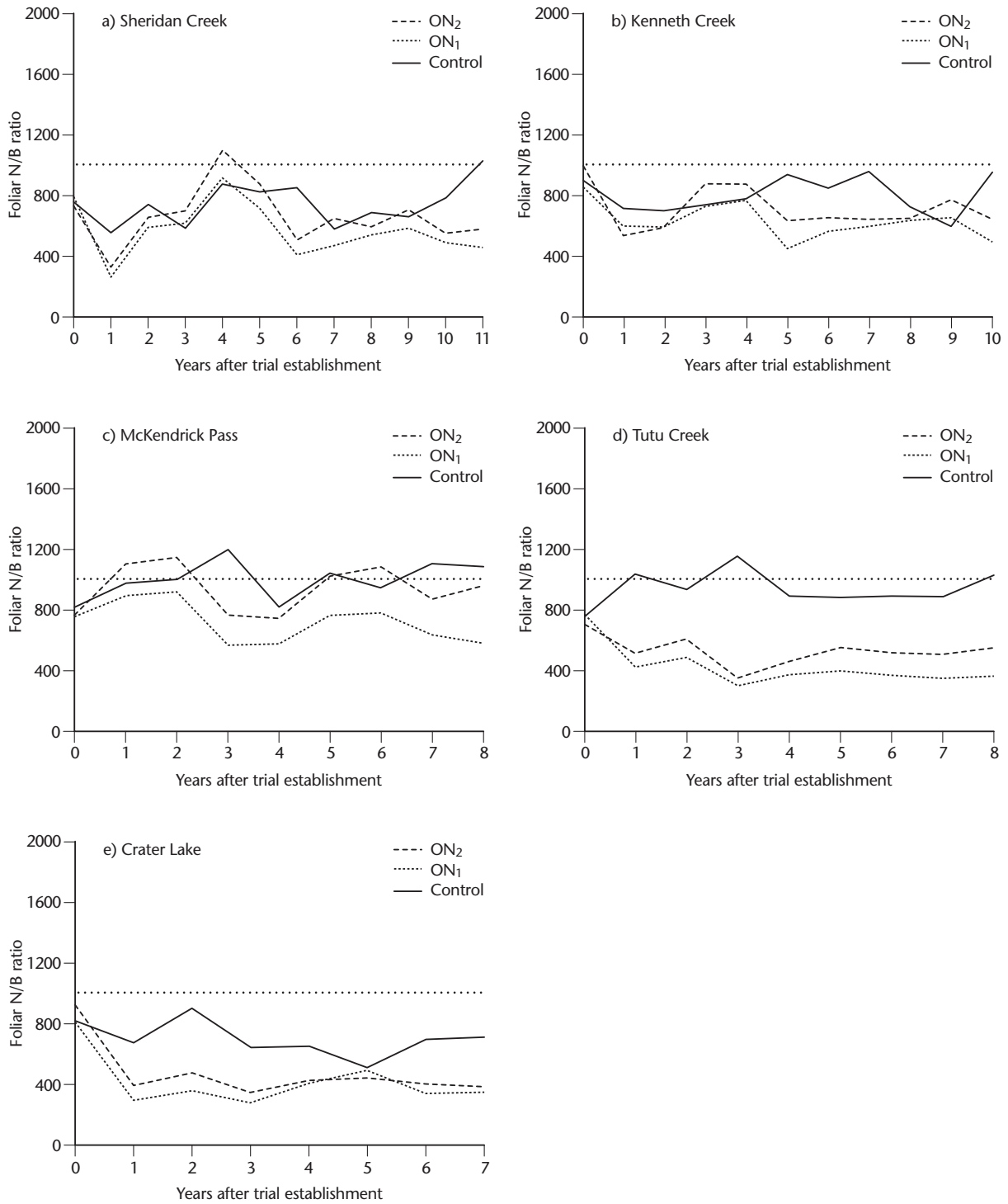


FIGURE 11 Foliar nitrogen:boron (N/B) ratio by treatment and year in lodgepole pine "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

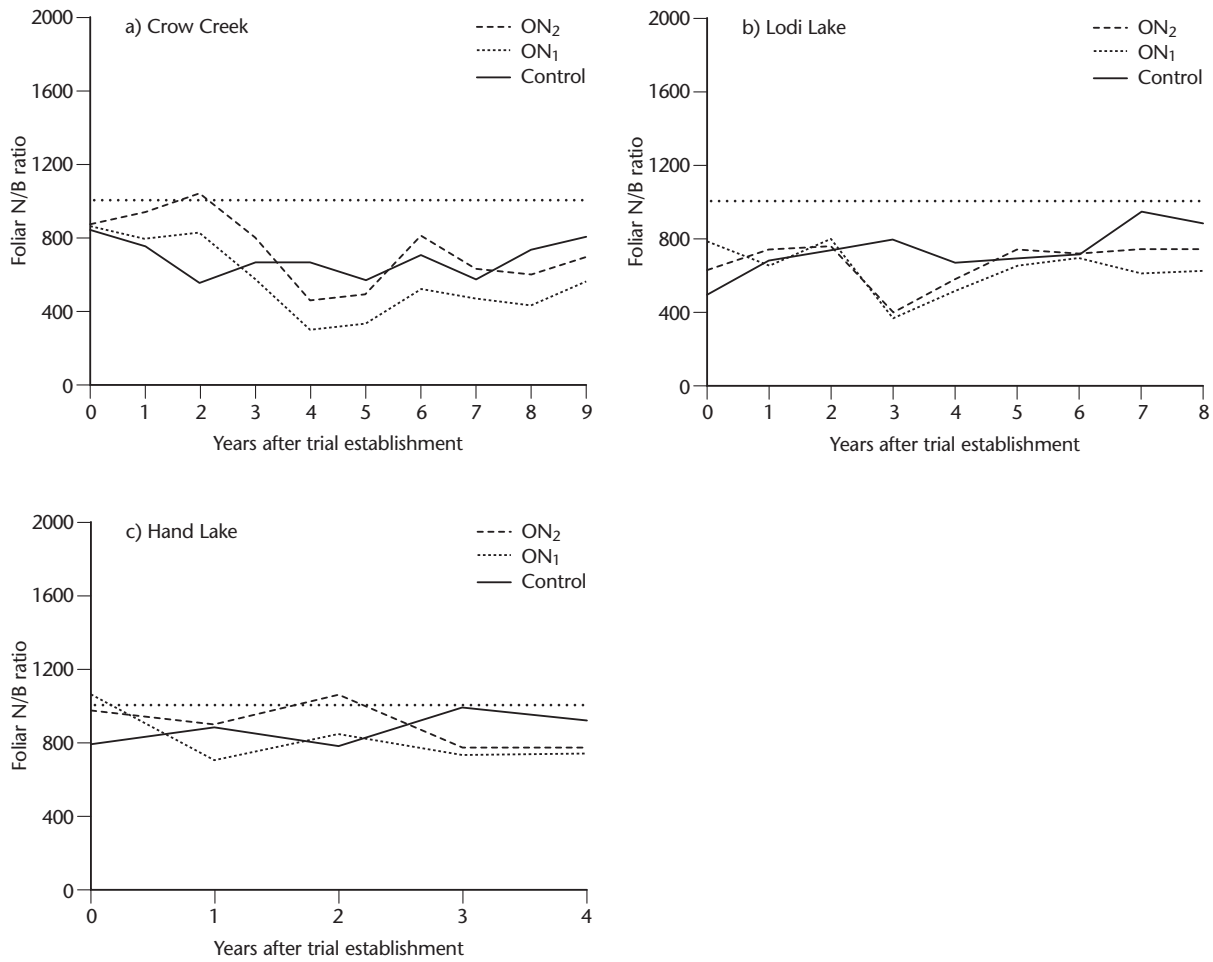


FIGURE 12 Foliar nitrogen:boron (N/B) ratio by treatment and year in spruce "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

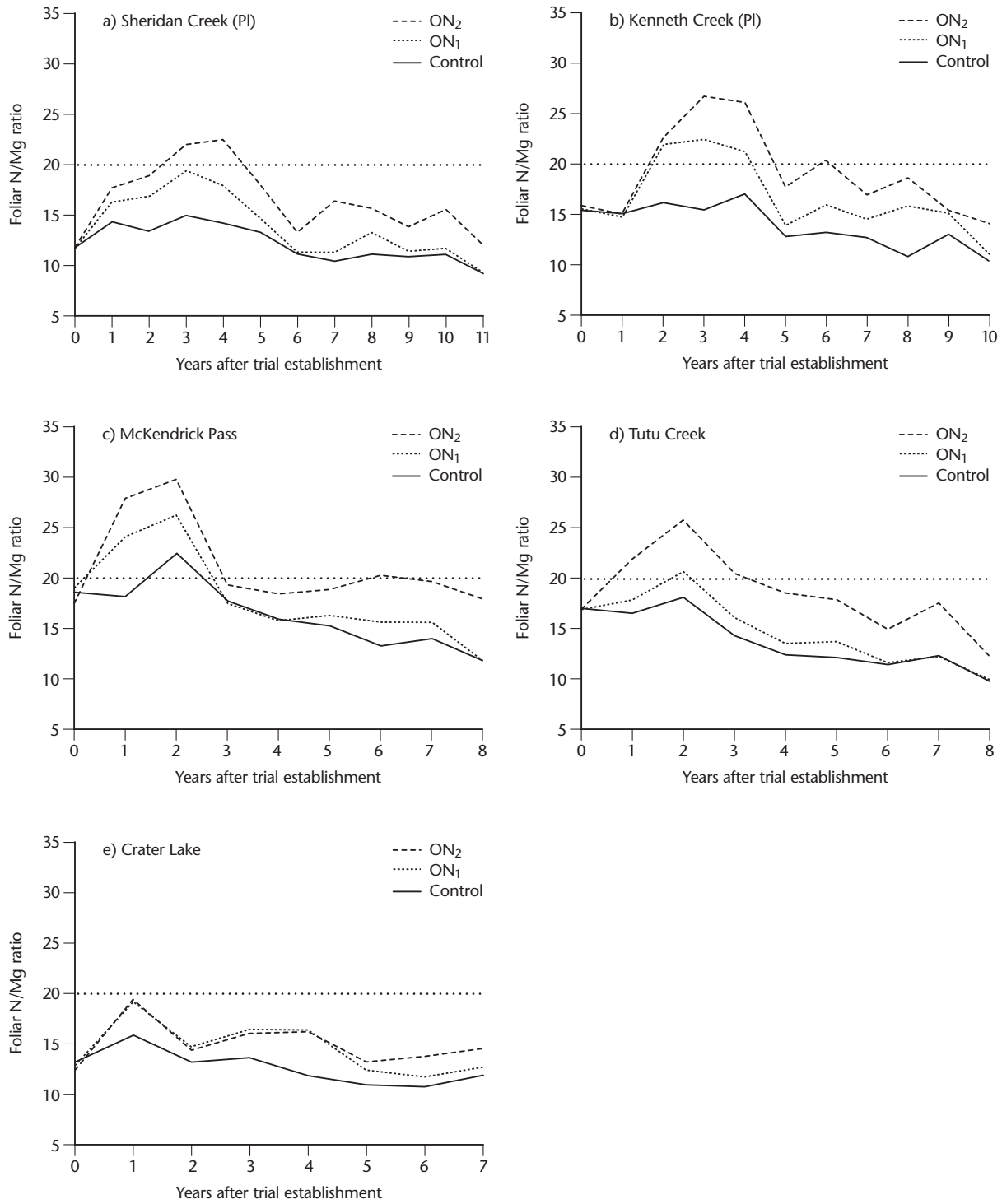


FIGURE 13 Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

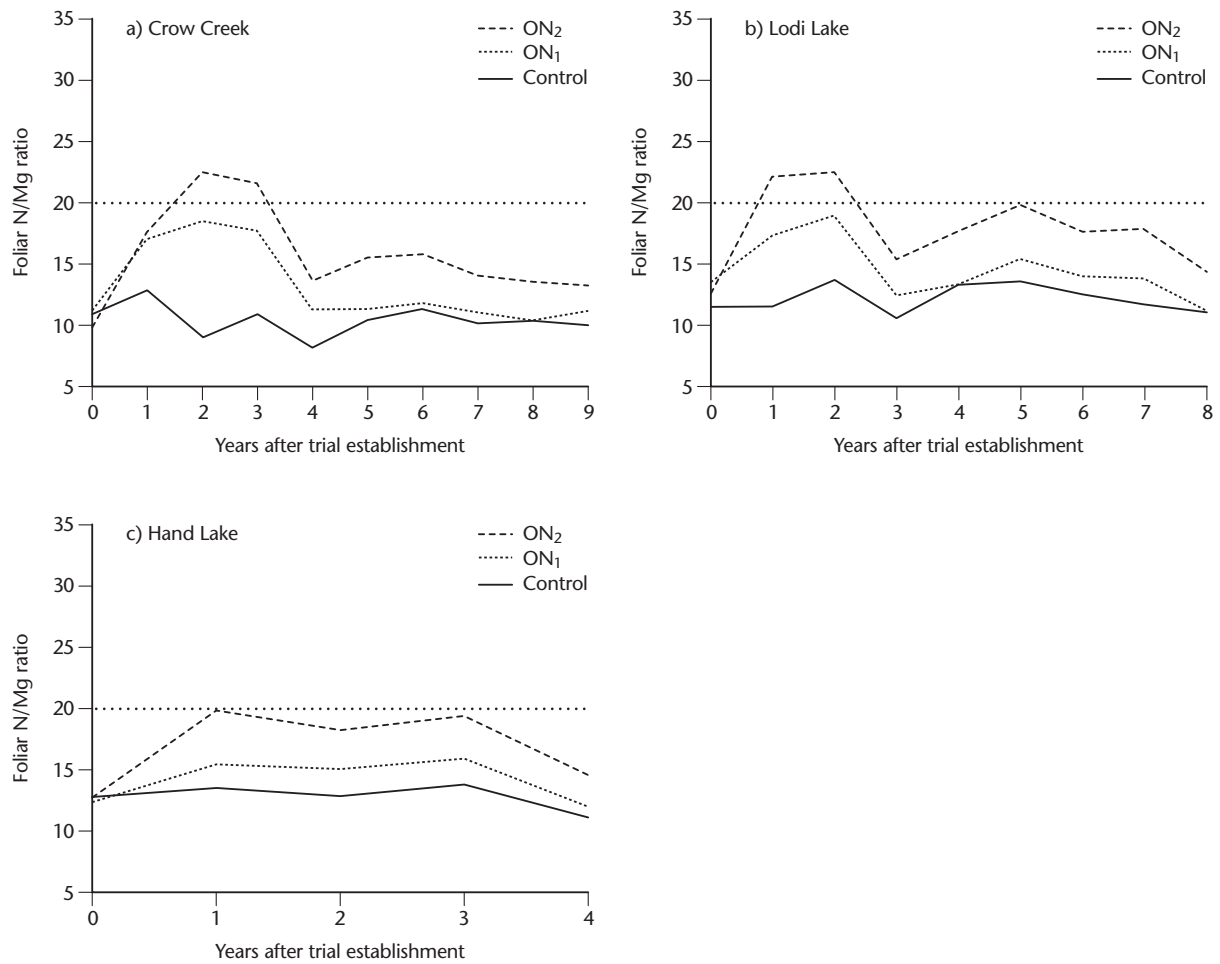


FIGURE 14 Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

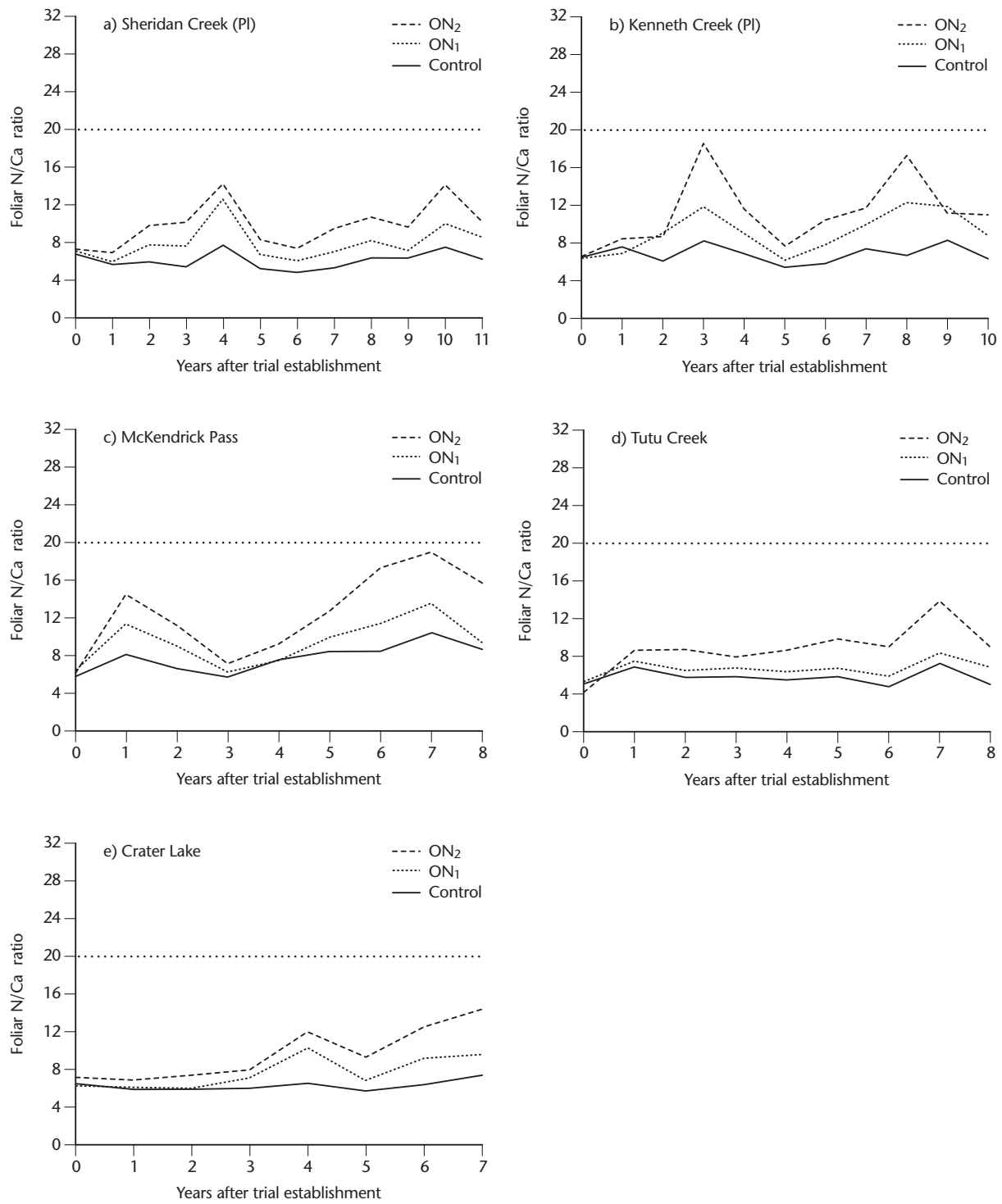


FIGURE 15 Foliar nitrogen:calcium (N/Ca) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

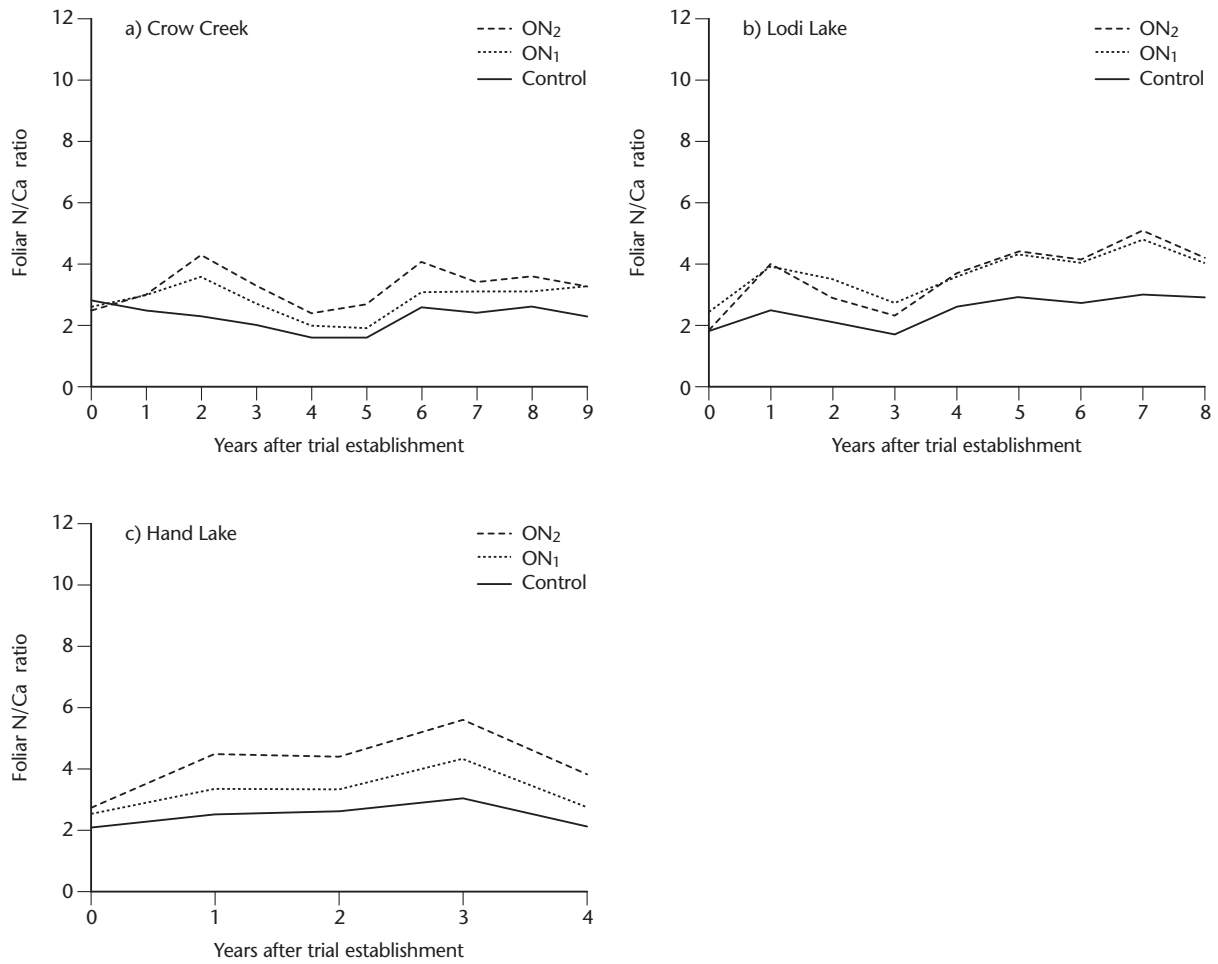


FIGURE 16 Foliar nitrogen:calcium (N/Ca) ratio by treatment and year in spruce "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite).

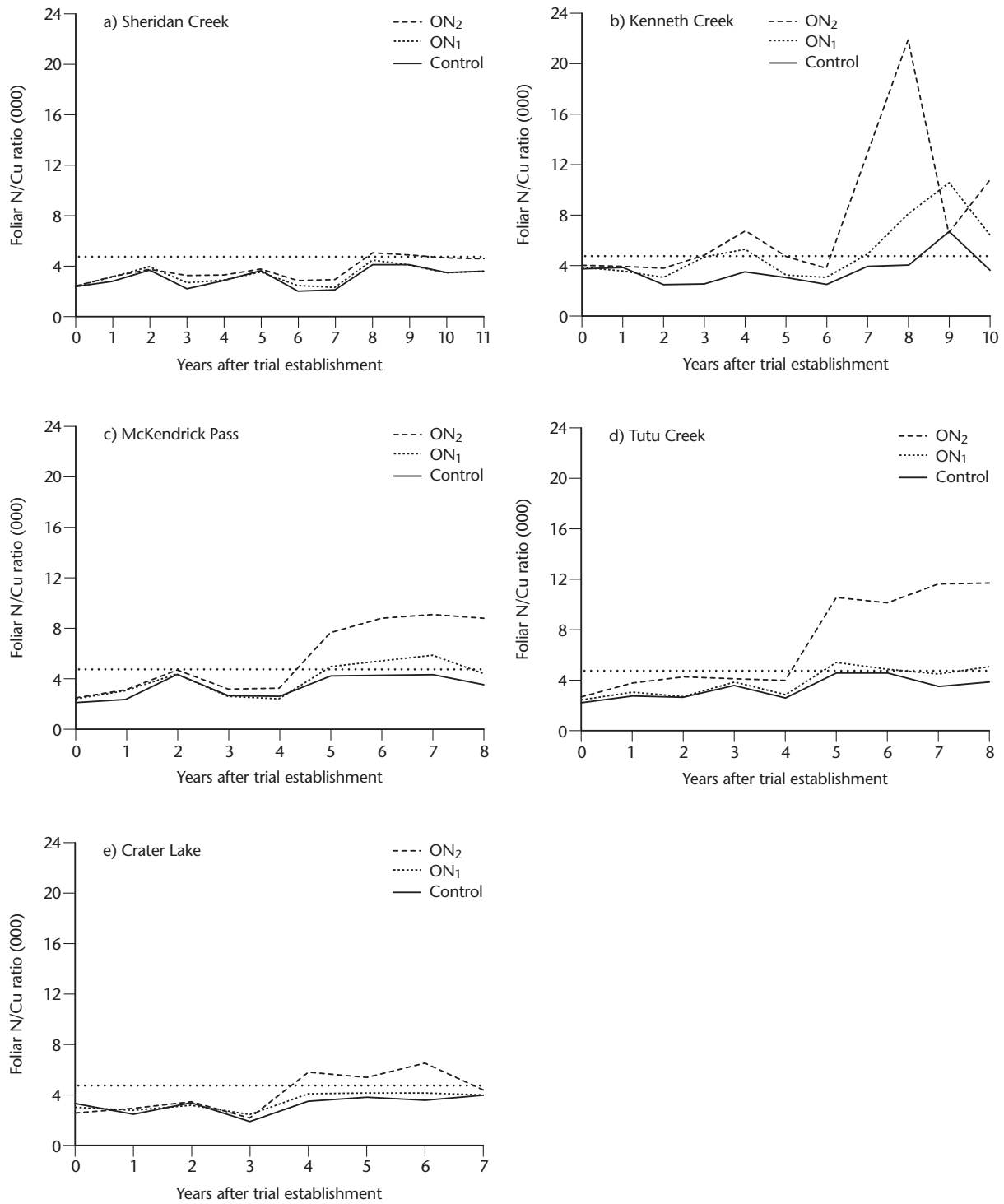


FIGURE 17 Foliar nitrogen:copper (N/Cu) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

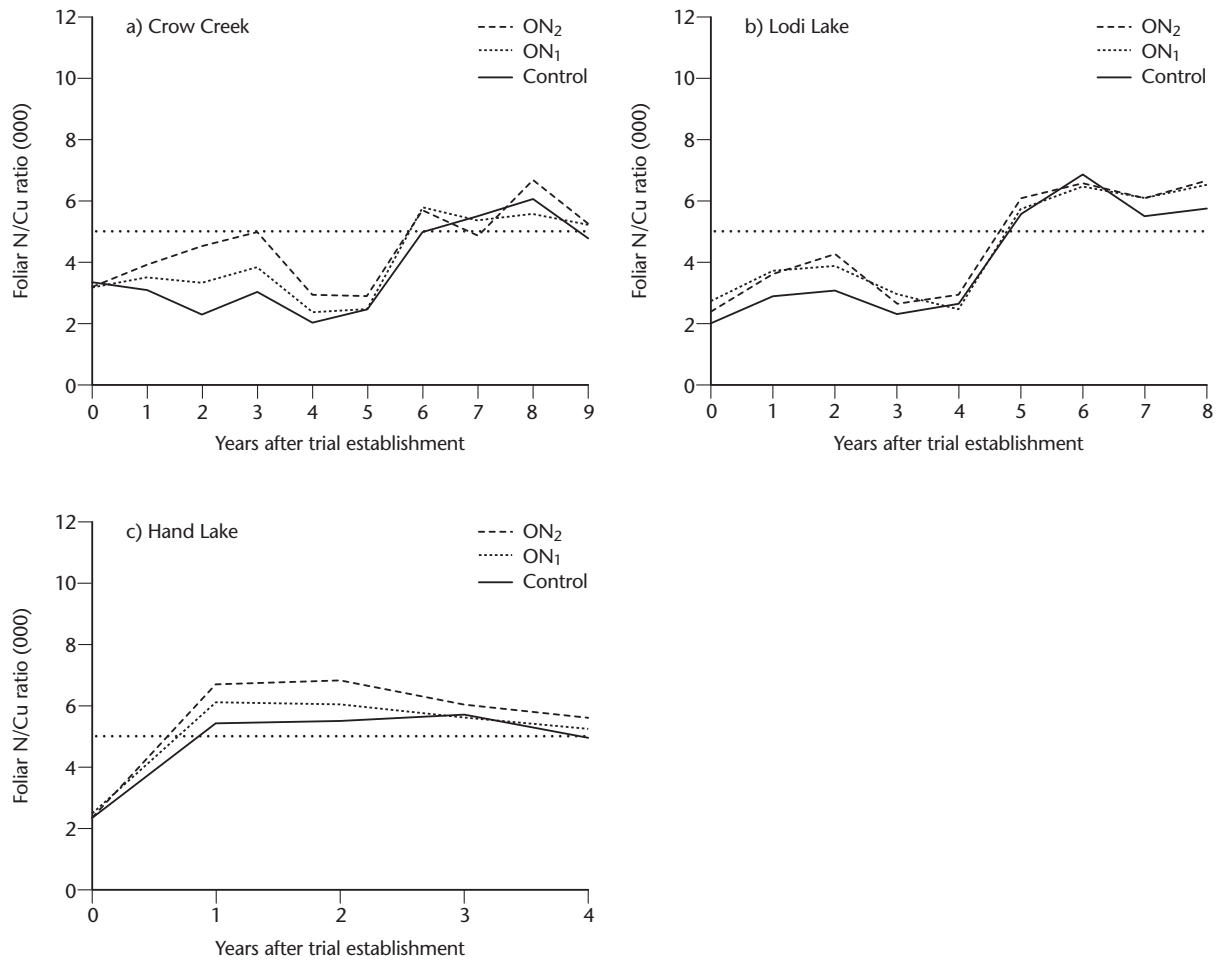


FIGURE 18 Foliar nitrogen:copper (N/Cu) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

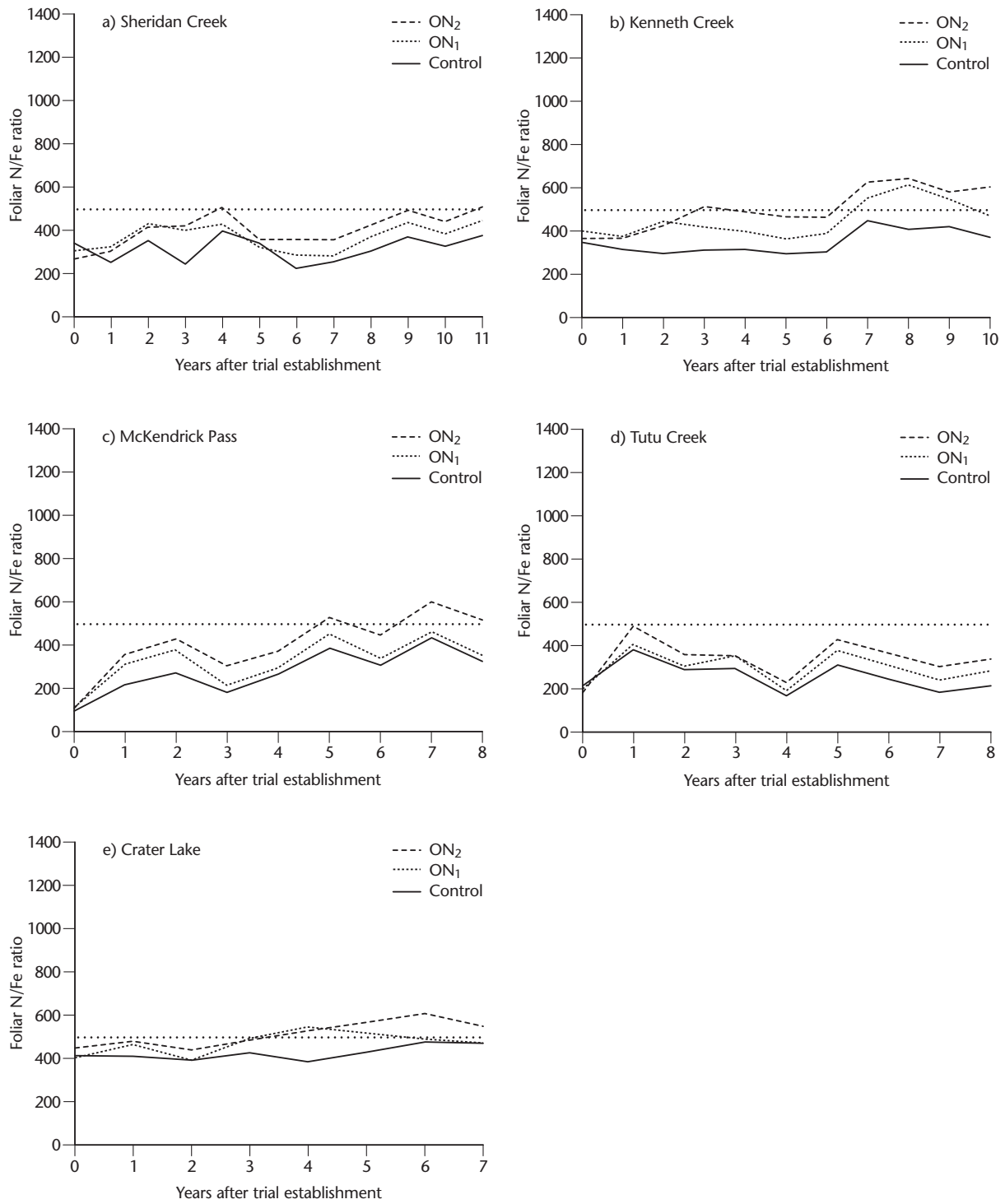


FIGURE 19 Foliar nitrogen:iron (N/Fe) ratio by treatment and year in lodgepole pine "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

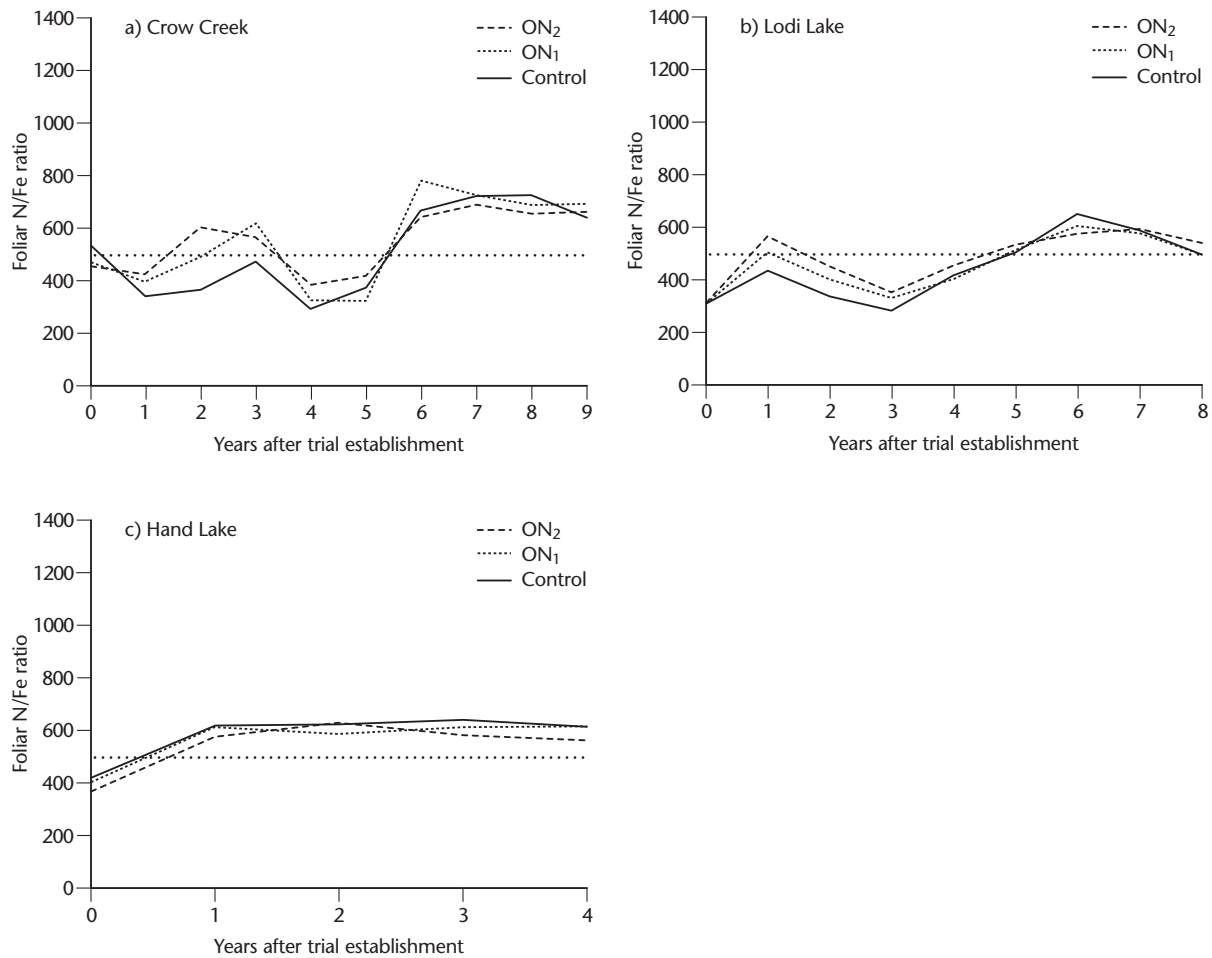


FIGURE 20 Foliar nitrogen:iron (N/Fe) ratio by treatment and year in spruce "maximum productivity" installations. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the upper threshold target value.

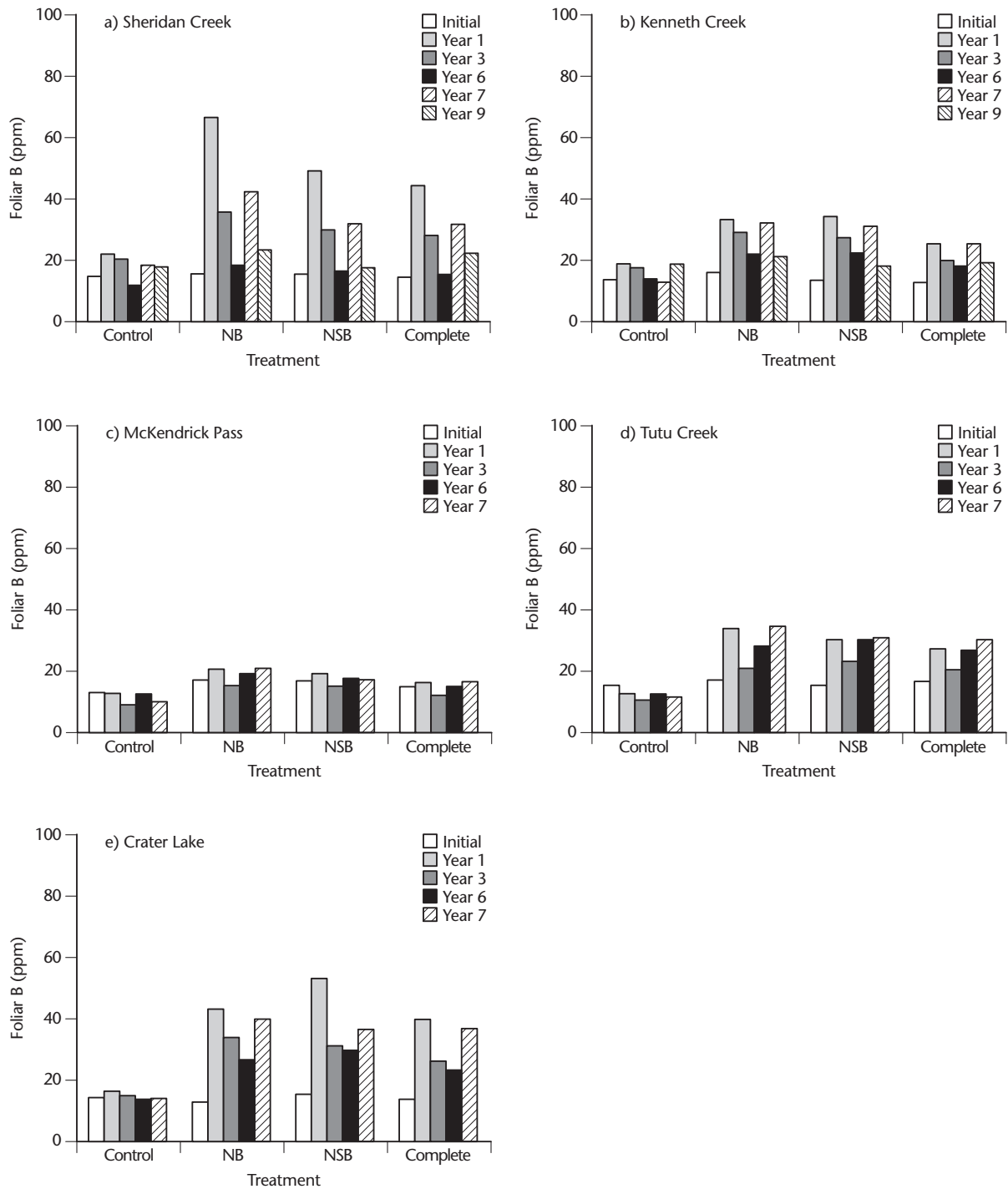


FIGURE 21 Foliar boron concentration by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite).

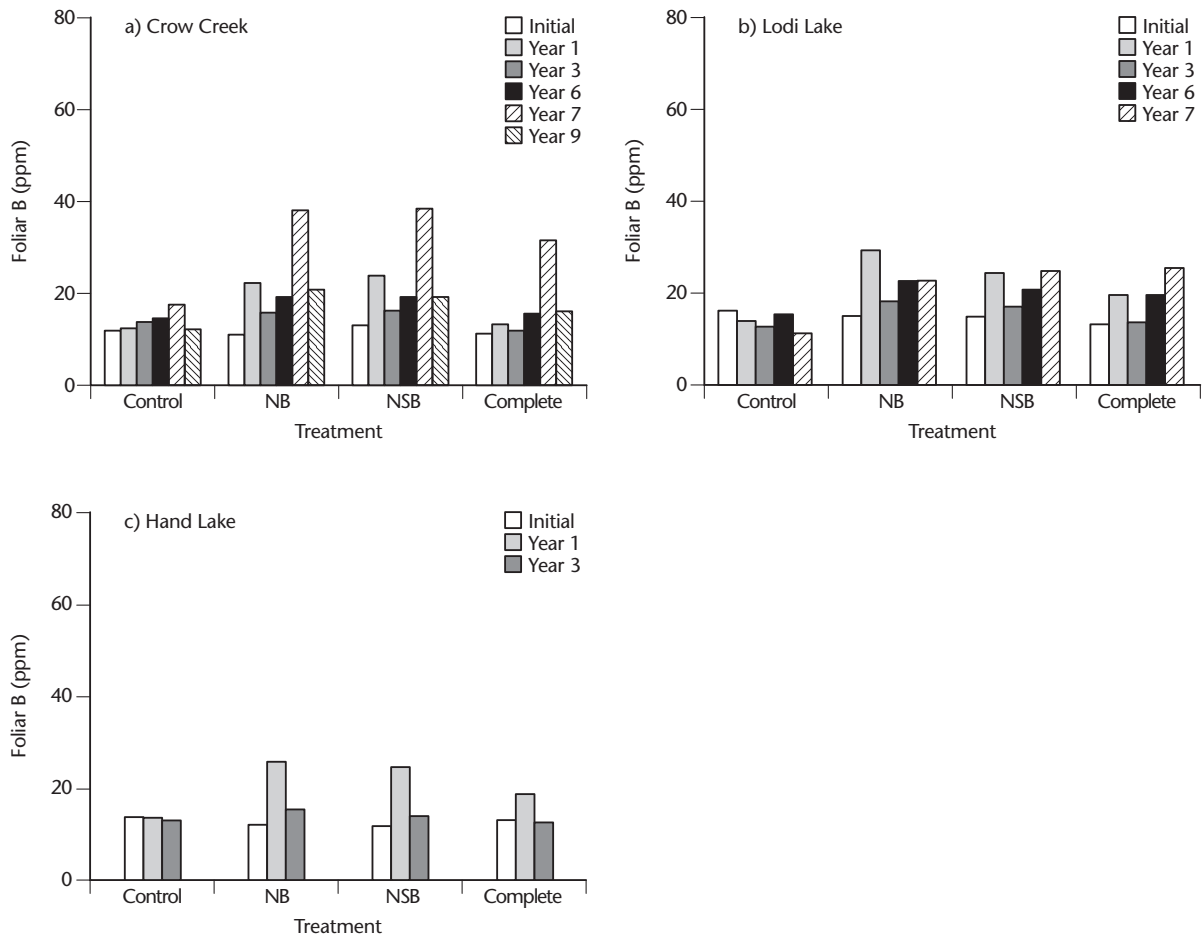


FIGURE 22. Foliar boron concentration by treatment and year in spruce "maximum productivity" installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite).

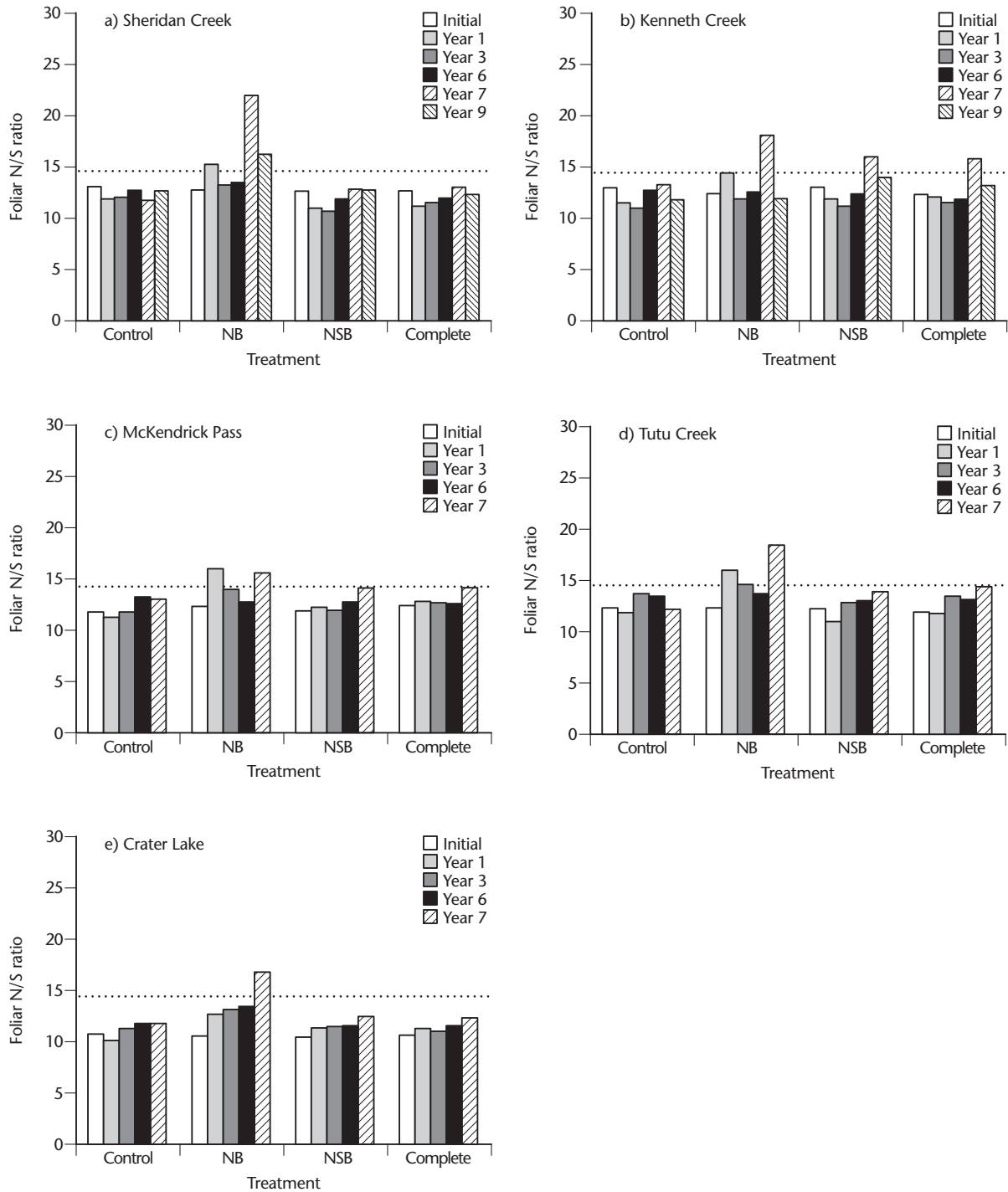


FIGURE 23 Foliar nitrogen:sulphur (N/S) ratio by treatment and year in lodgepole pine “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents a “critical” level above which a probable nutrient imbalance (i.e., deficiency) relative to N is indicated (Brockley 2001b).

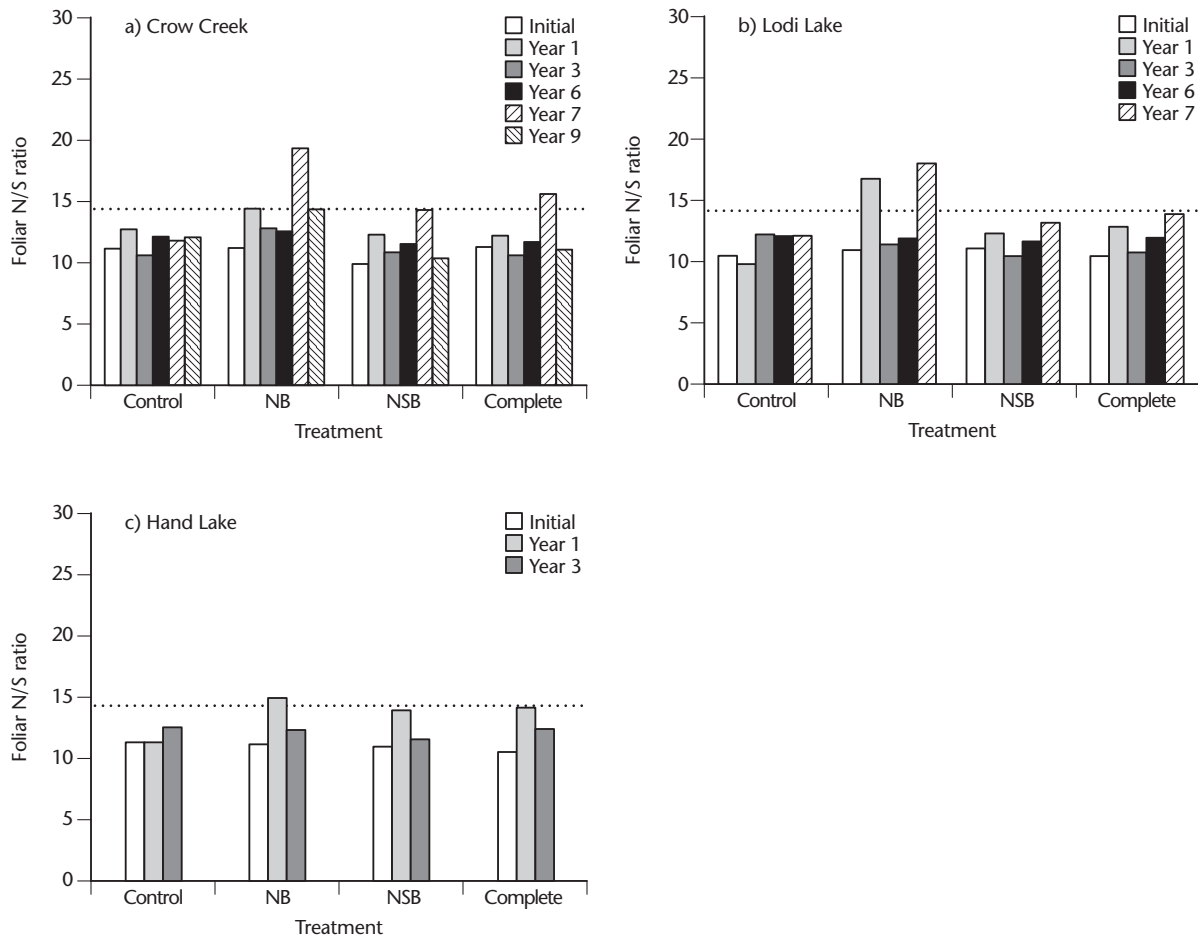


FIGURE 24 Foliar nitrogen:sulphur (N/S) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents a “critical” level above which a probable nutrient imbalance (i.e., deficiency) relative to N is indicated (Brockley 2001b).

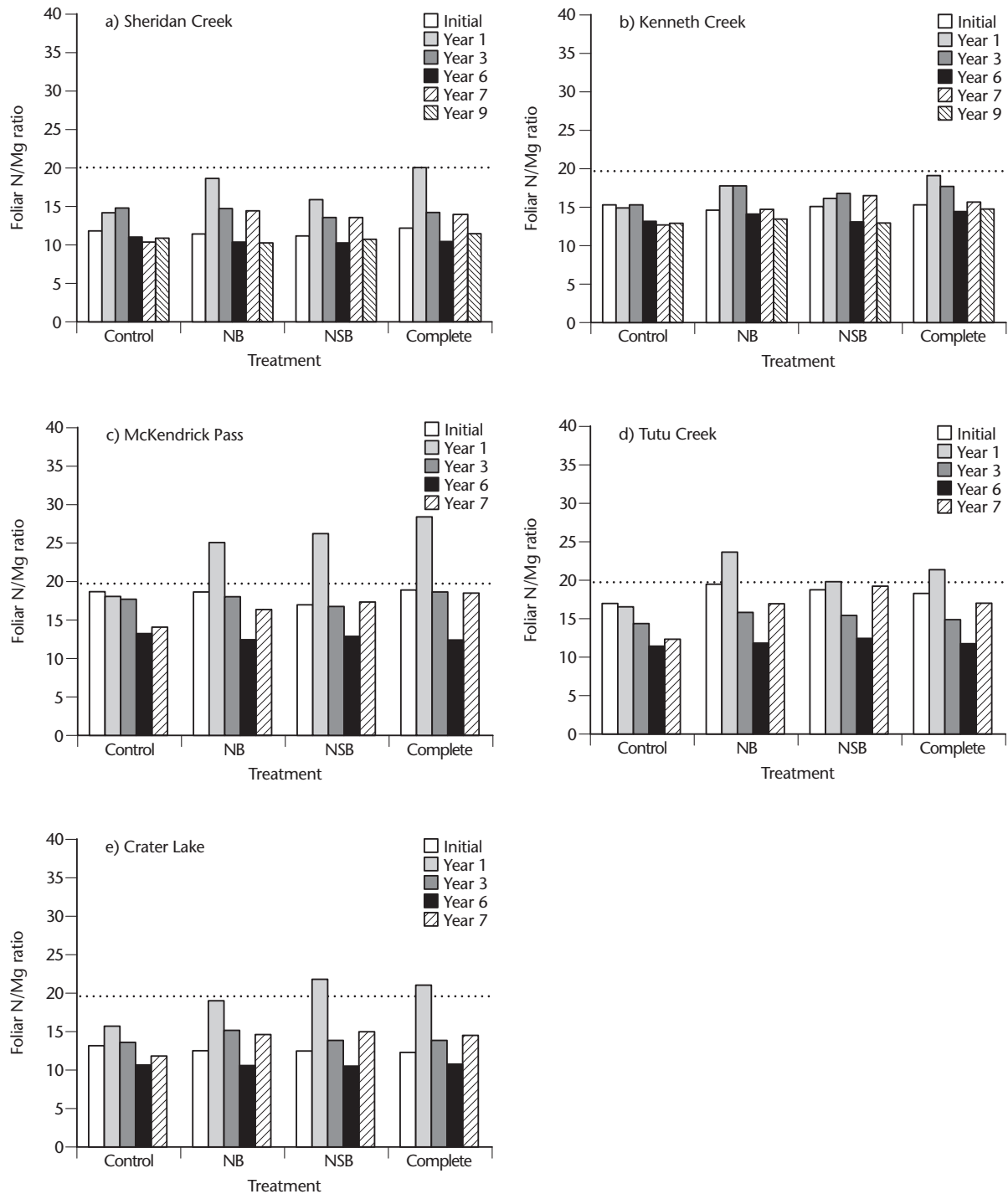


FIGURE 25 Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year in lodgepole pine "maximum productivity" installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents a "critical" level above which a probable nutrient imbalance (i.e., deficiency) relative to N is indicated (Brockley 2001b).

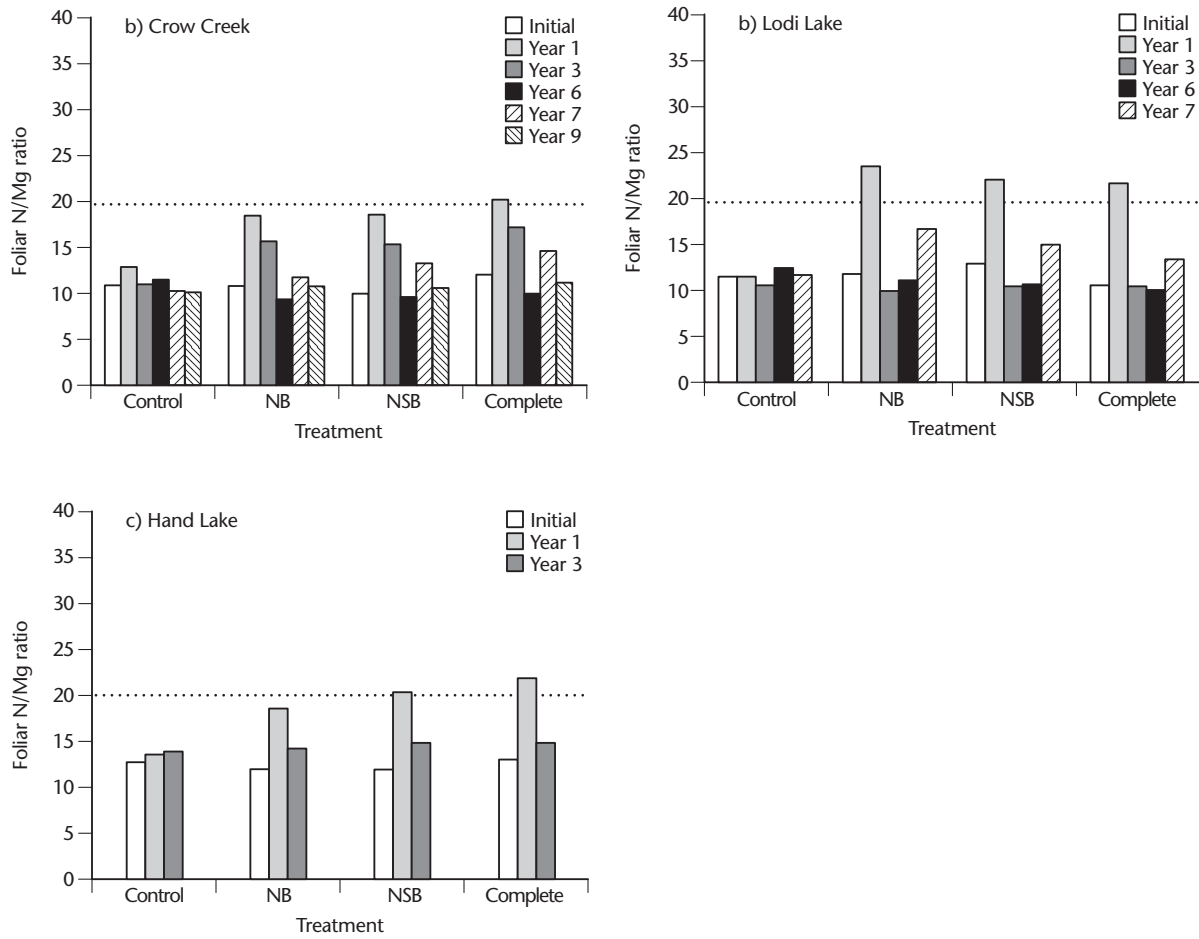


FIGURE 26 Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year in spruce “maximum productivity” installations. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents a “critical level” above which a probable nutrient imbalance (i.e., deficiency) relative to N is indicated (Brockley 2001b).

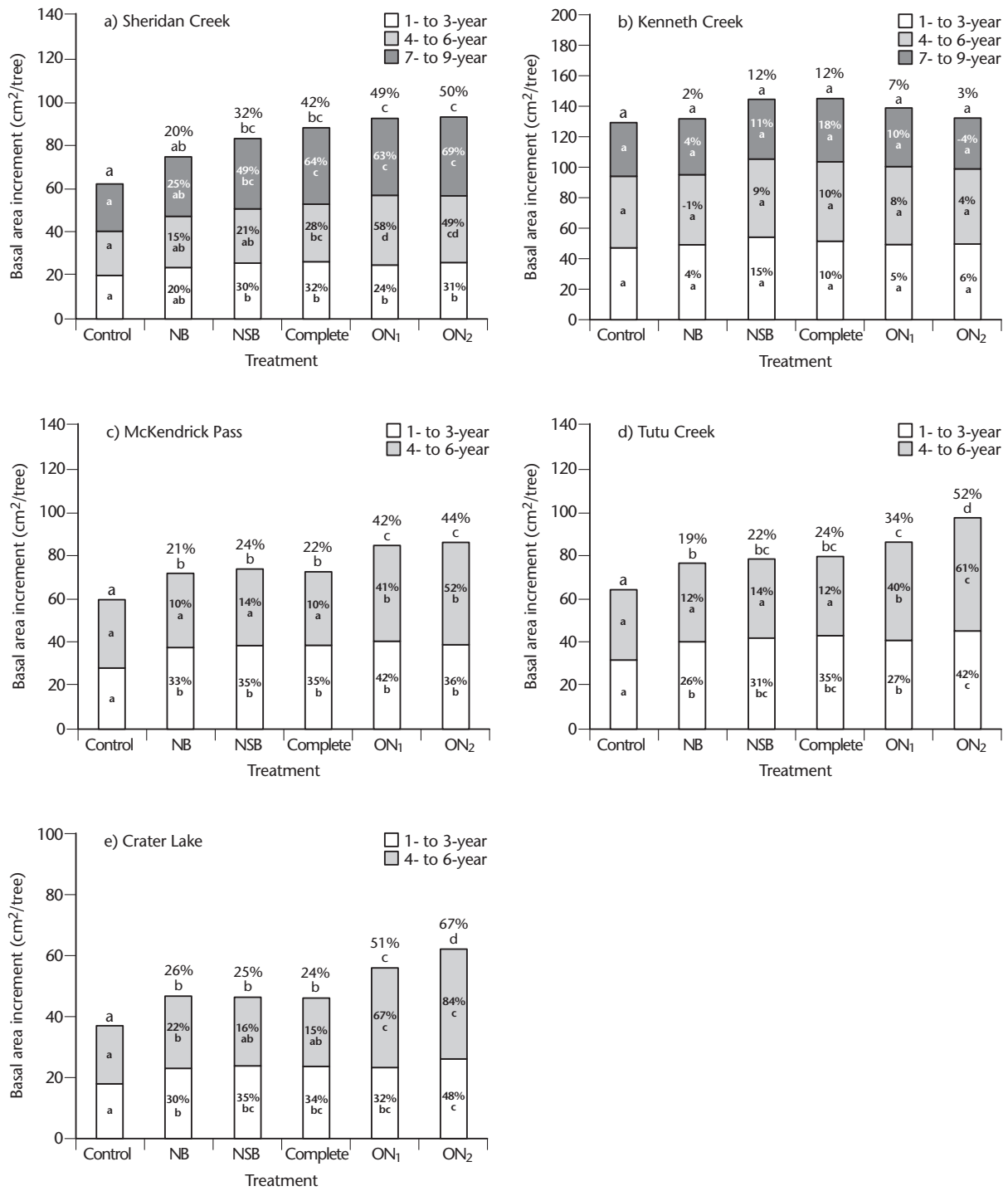


FIGURE 27 Mean tree basal area increment by measurement period and treatment in lodgepole pine “maximum productivity” installations. Numbers inside each bar indicate change relative to the control treatment for each measurement period. Numbers above each bar indicate change relative to the control treatment over all response periods. For each measurement period, bars with different letters are significantly different ( $p < 0.05$ ).

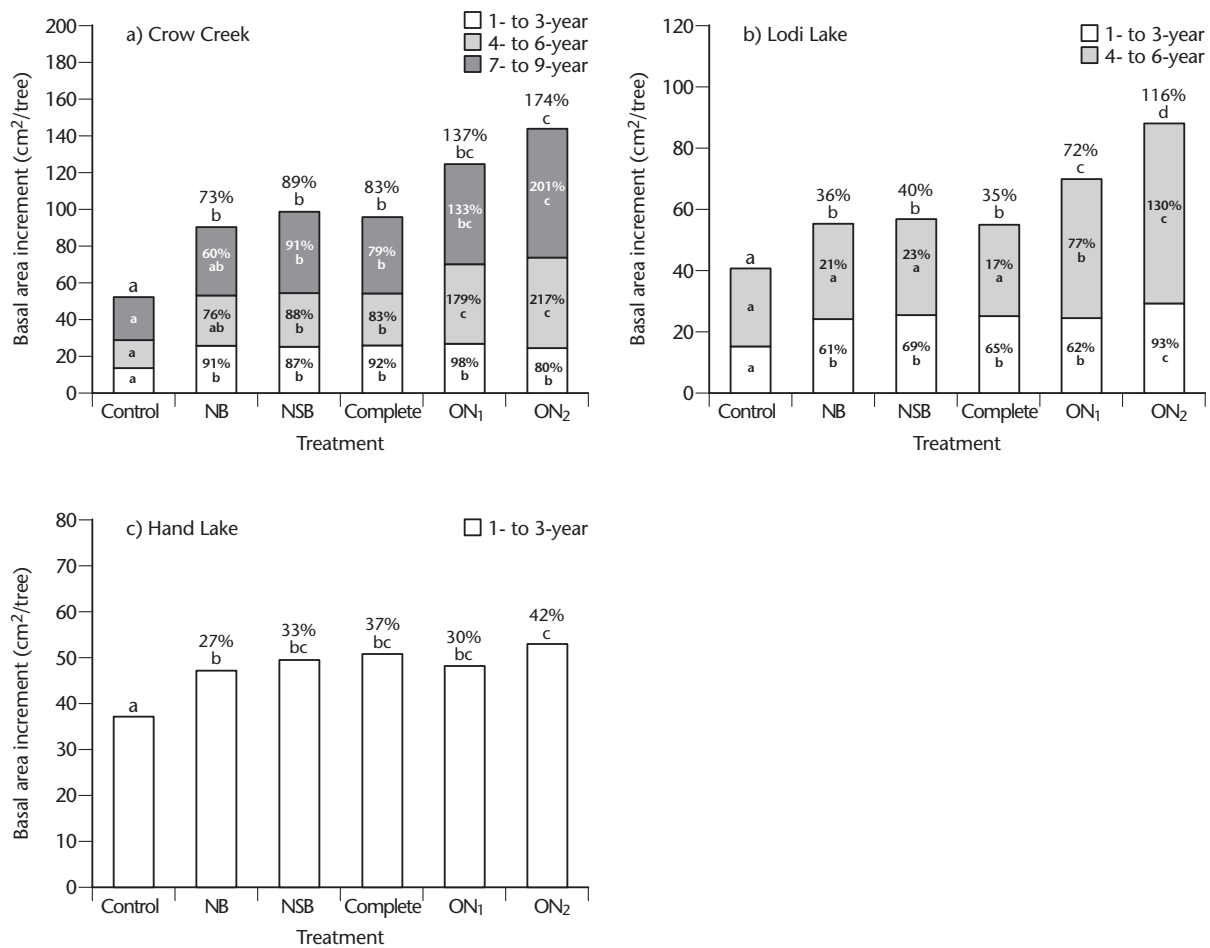


FIGURE 28 Mean tree basal area increment by measurement period and treatment in spruce "maximum productivity" installations. Numbers inside each bar indicate change relative to the control treatment for each measurement period. Numbers above each bar indicate change relative to the control treatment over all measurement periods. For each measurement period, bars with different letters are significantly different ( $p < 0.05$ ).

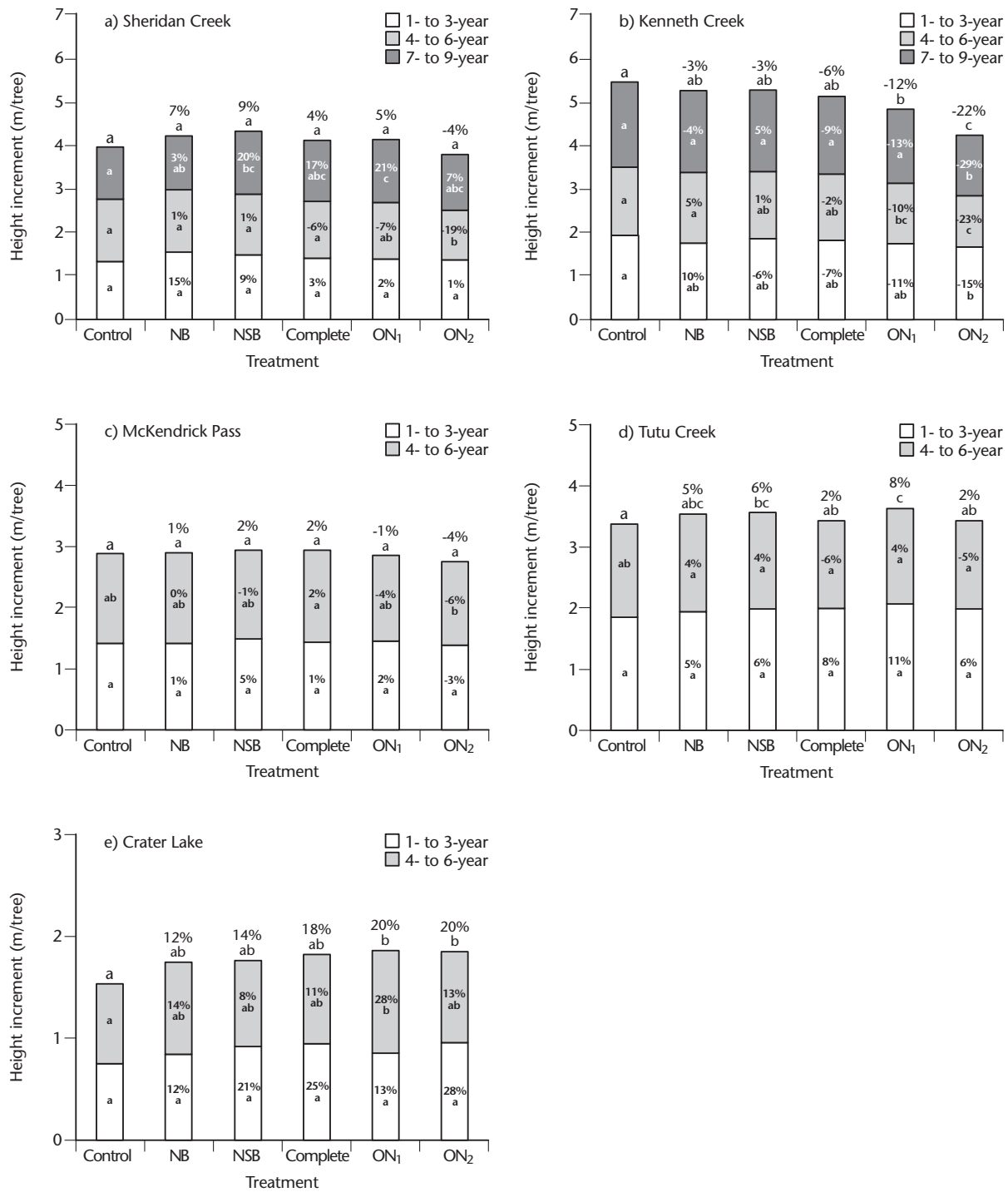


FIGURE 29 Mean tree height increment by measurement period and treatment in lodgepole pine "maximum productivity" installations. Numbers inside each bar indicate change relative to the control treatment for each measurement period. Numbers above each bar indicate change relative to the control treatment over all response periods. For each measurement period, bars with different letters are significantly different ( $p < 0.05$ ).

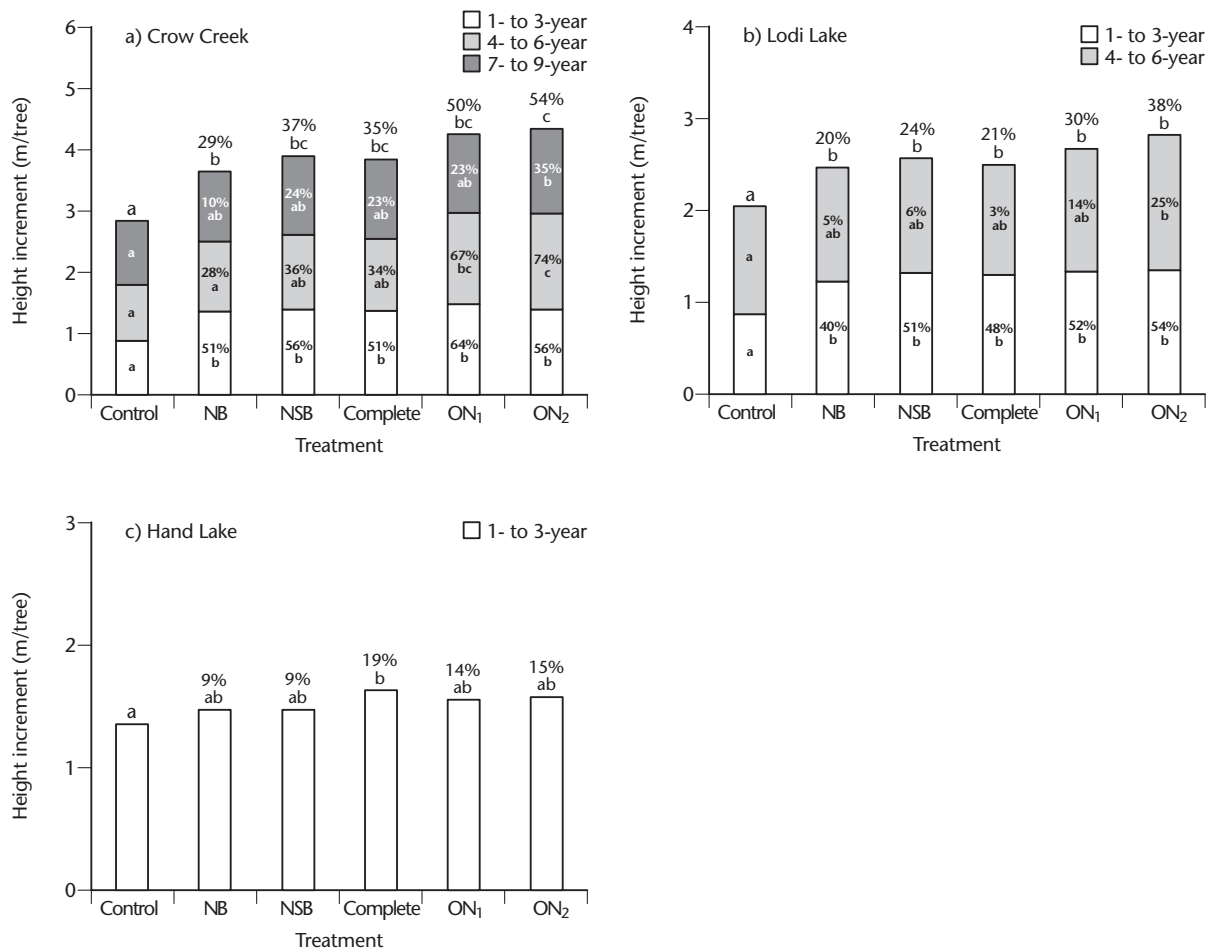


FIGURE 30 Mean tree height increment by measurement period and treatment in spruce "maximum productivity" installations. Numbers inside each bar indicate change relative to the control treatment for each measurement period. Numbers above each bar indicate change relative to the control treatment over all measurement periods. For each measurement period, bars with different letters are significantly different ( $p < 0.05$ ).

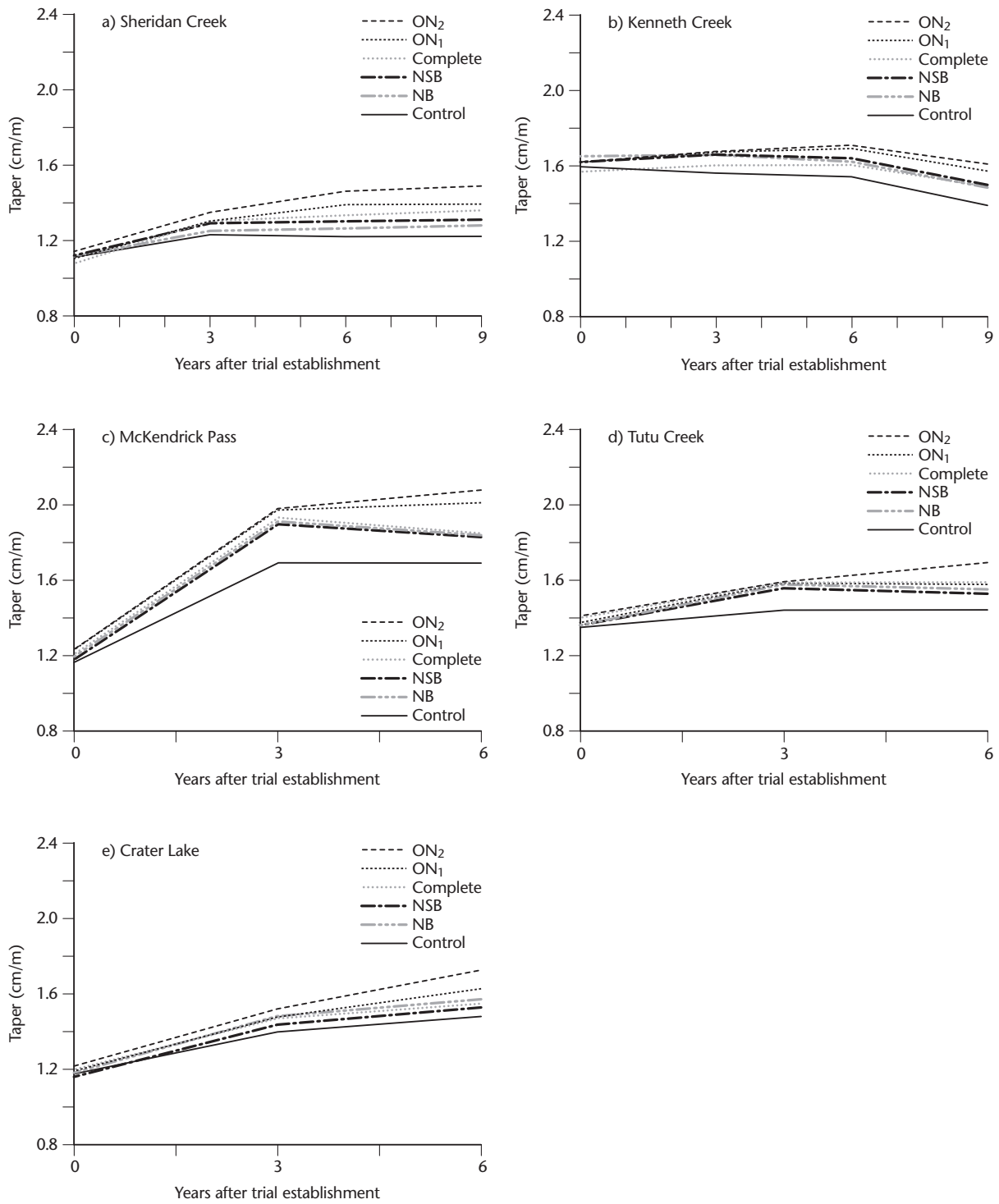


FIGURE 31 Mean tree taper by year and treatment in lodgepole pine "maximum productivity" installations.

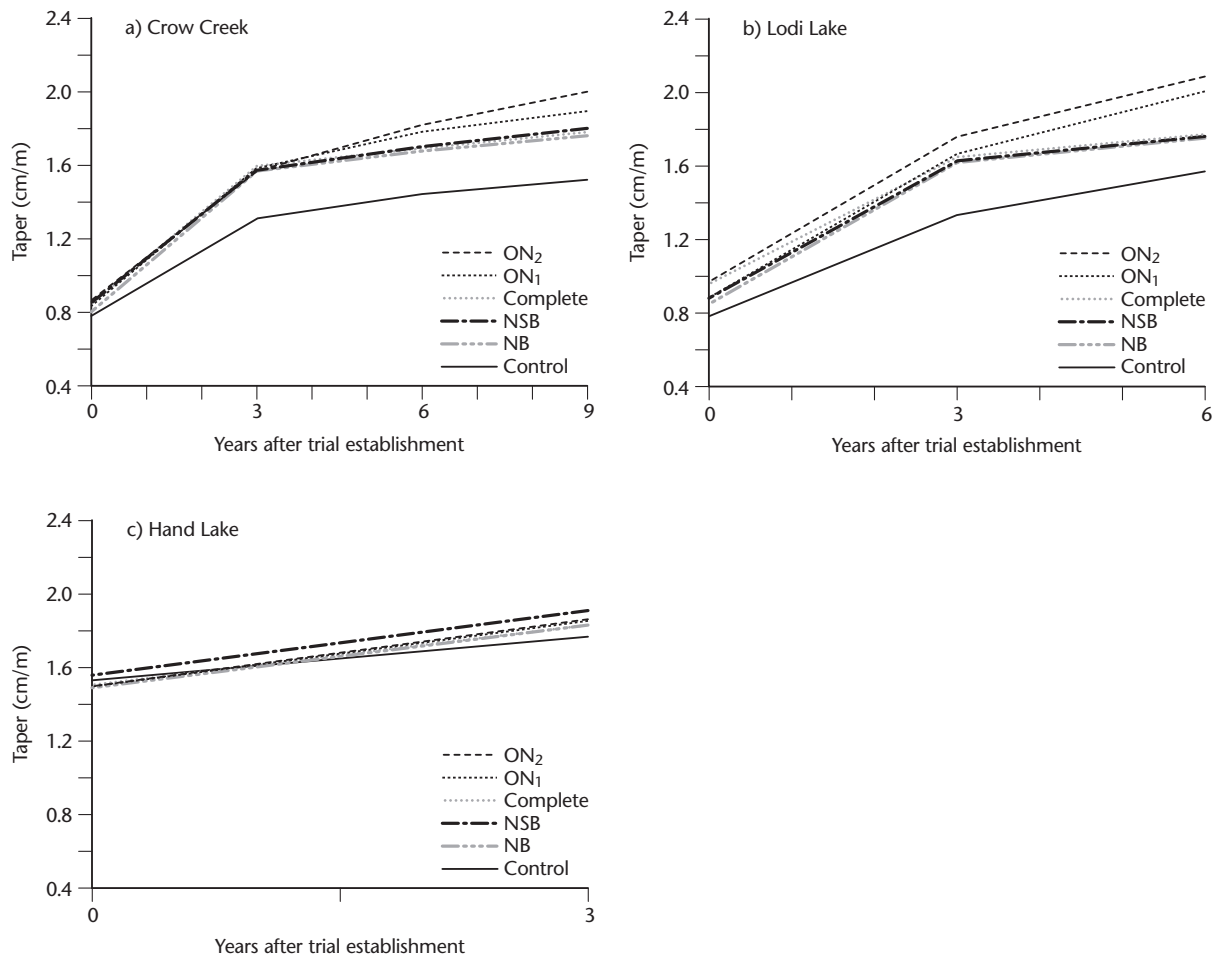


FIGURE 32 Mean tree taper by year and treatment in spruce "maximum productivity" installations.

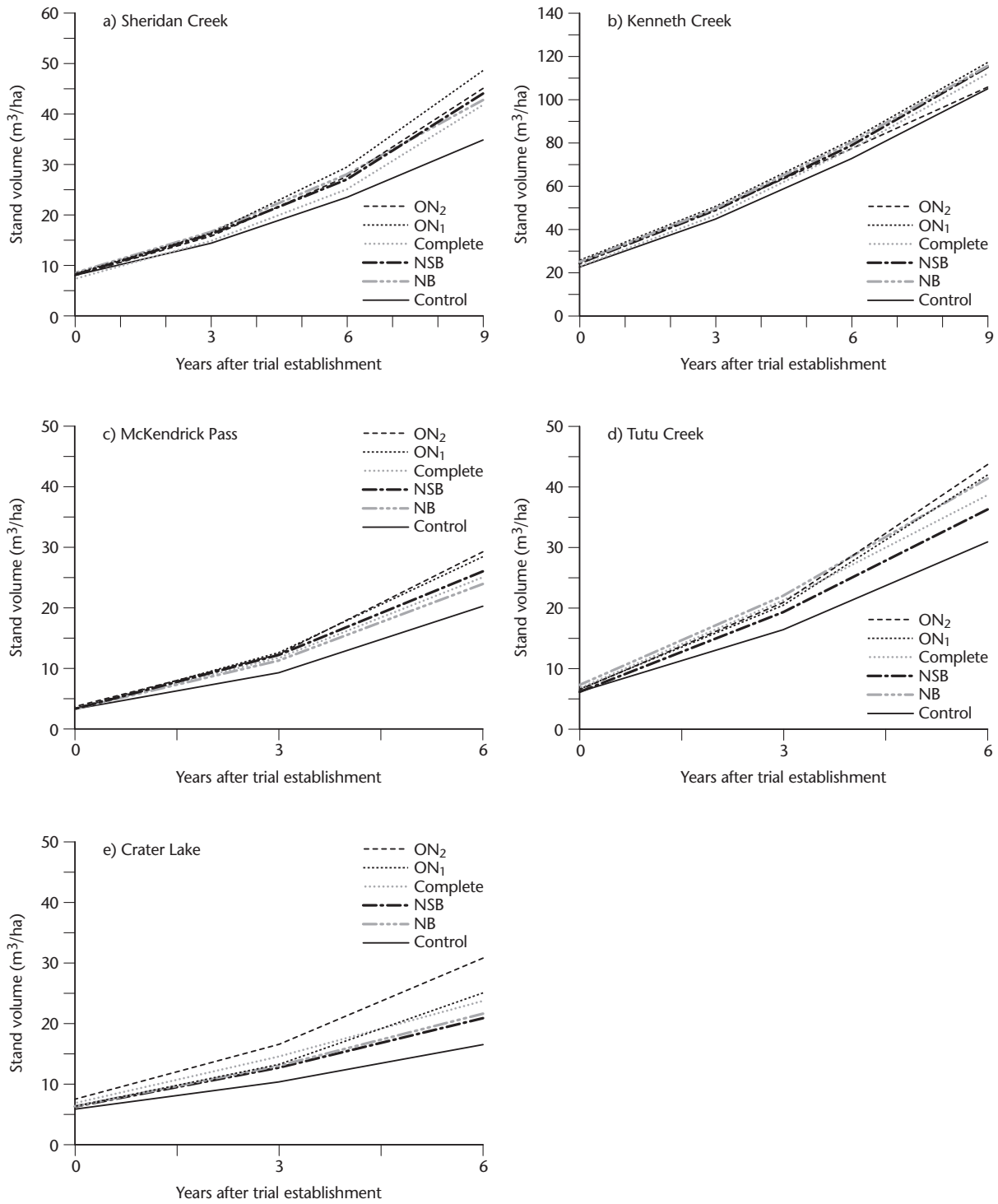


FIGURE 33 Stand volume development in lodgepole pine “maximum productivity” installations. Plotted points represent the mean of three replications.

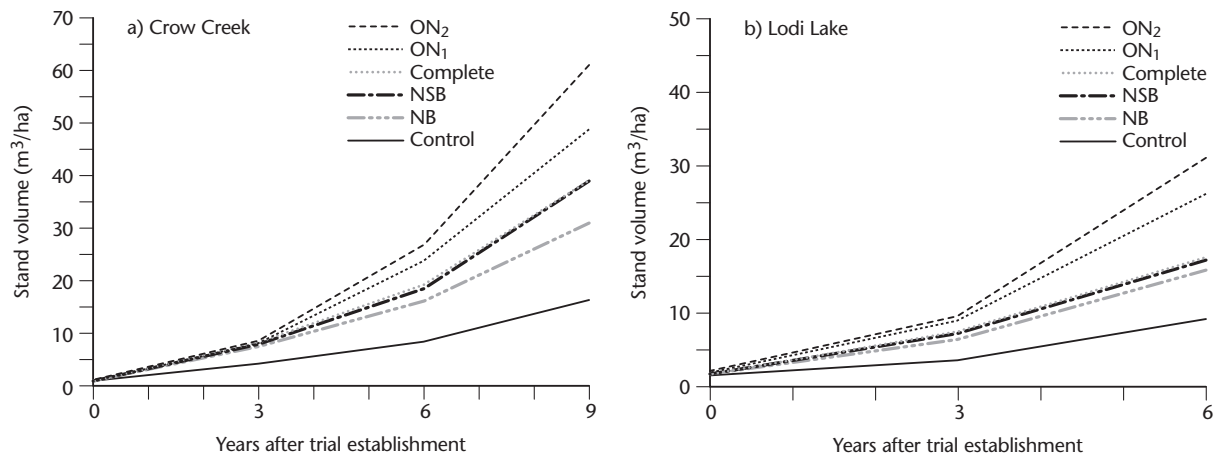


FIGURE 34 Stand volume development in spruce "maximum productivity" installations. Plotted points represent the mean of three replications.

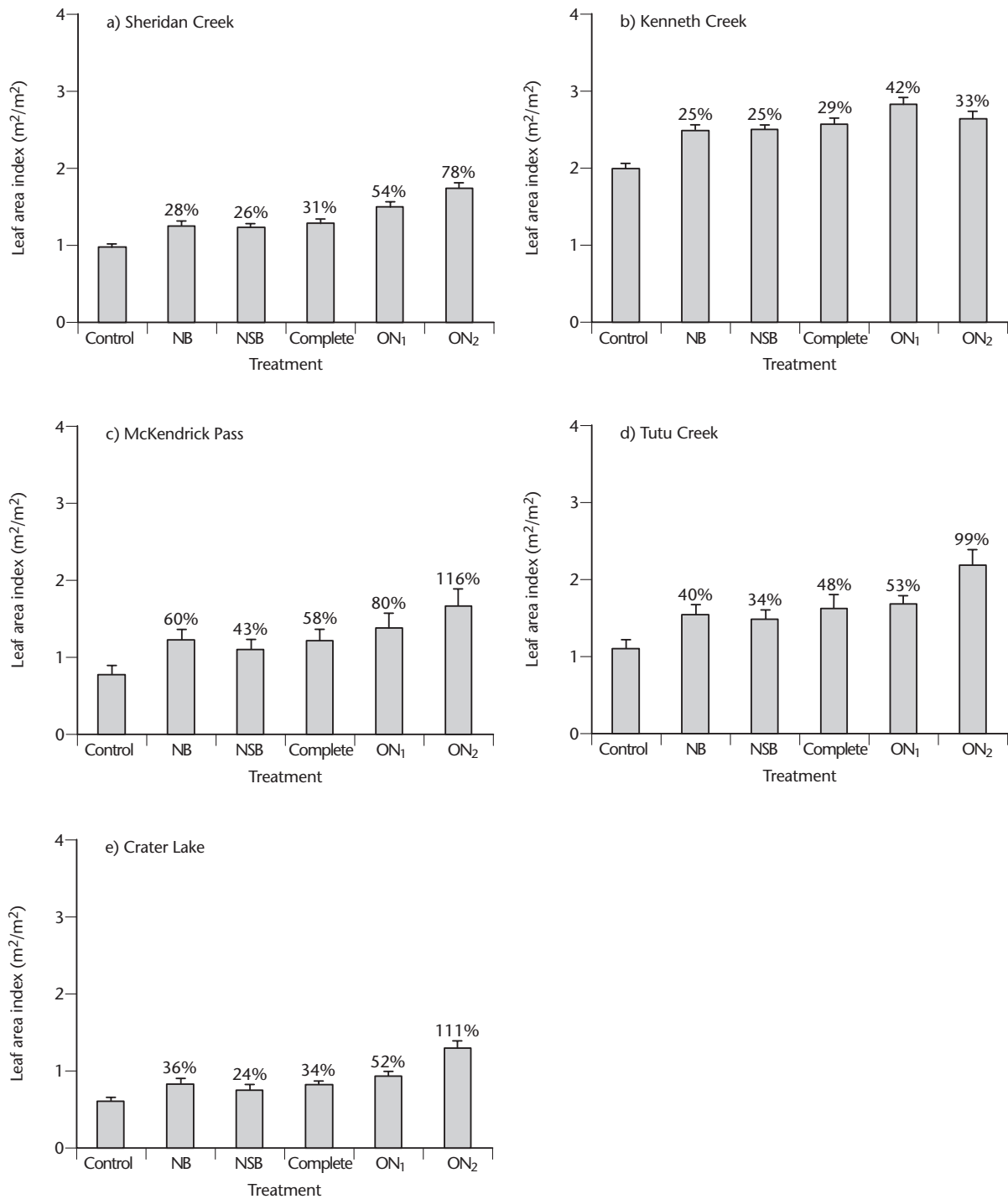


FIGURE 35 Leaf area index by treatment in lodgepole pine “maximum productivity” installations. Measurement of leaf area coincided with 9-year remeasurement at Sheridan Creek and Kenneth Creek and 6-year remeasurement at McKendrick Pass, Tutu Creek, and Crater Lake. Numbers above each bar indicate change relative to the control treatment. Error bars represent standard error.

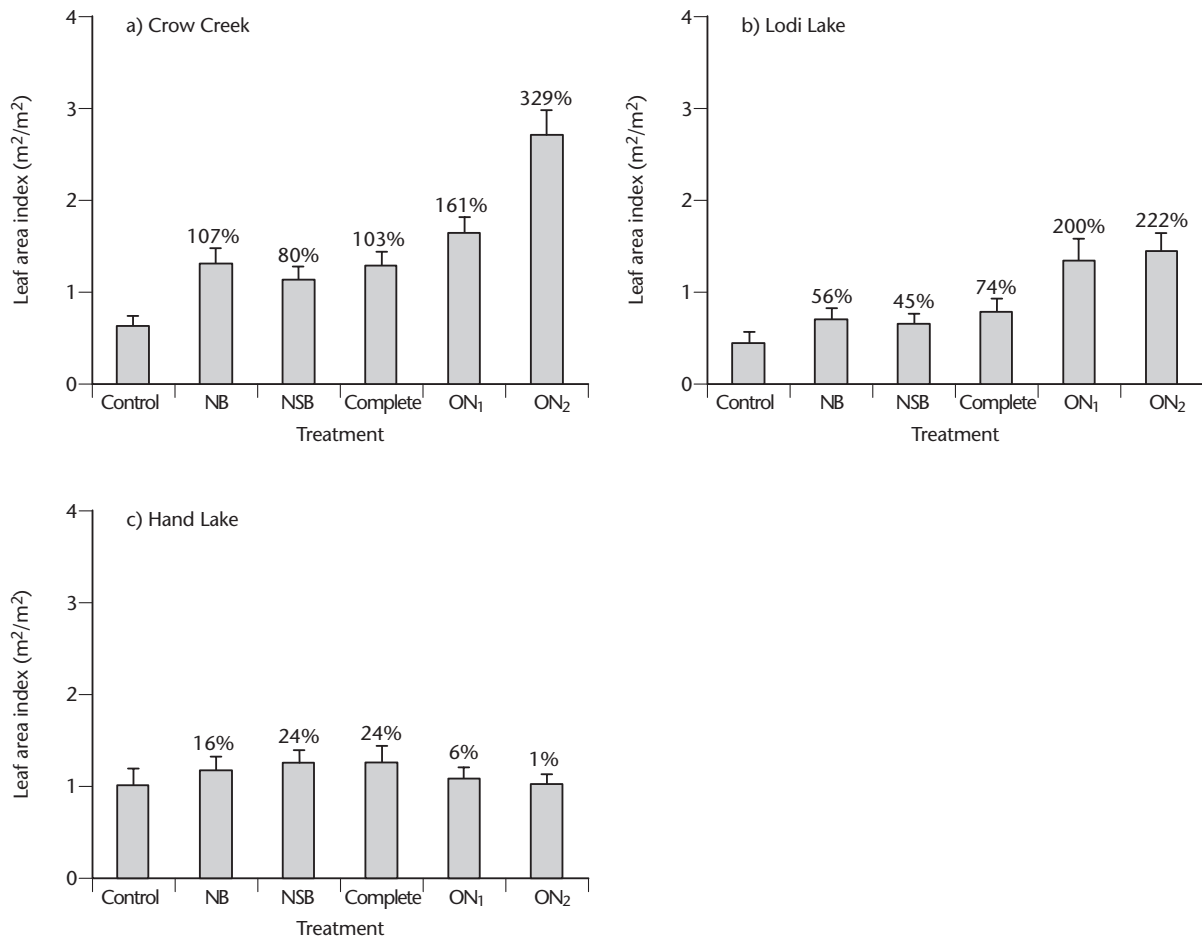


FIGURE 36 Leaf area index by treatment in spruce “maximum productivity” installations. Measurement of leaf area coincided with 9-year remeasurement at Crow Creek, 6-year remeasurement at Lodi Lake, and 3-year measurement at Hand Lake. Numbers above each bar indicate change relative to the control treatment. Error bars represent standard error.

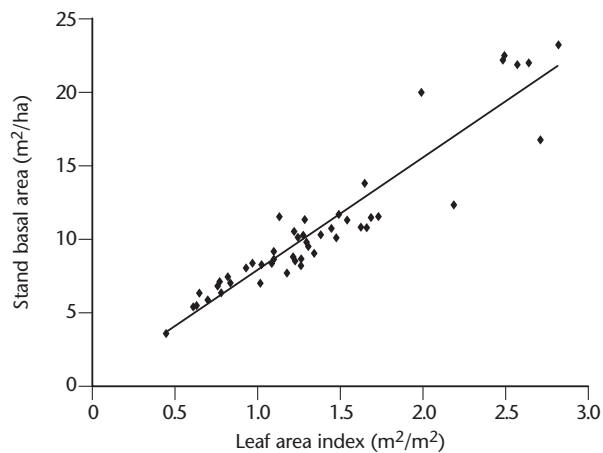


FIGURE 37 Relationship between stand basal area (BA) and leaf area index (LAI) ( $n=48$ ). The regression line is fit from the following equation:  $BA (m^2/ha) = 7.67 \times LAI (m^2/m^2) + 0.22$ ,  $R^2 = 0.88$ .

#### 4 DISCUSSION

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After 6 years, BA responses to single applications of NB, NSB, and Complete fertilizers indicated generally positive growth responses to N additions, but only marginal incremental gains to added S and other nutrients in pine and spruce “maximum productivity” installations. These results differ from those reported previously for several lodgepole pine and spruce “conventional” and “single-tree” fertilizer research trials, in which larger growth responses were obtained by combining S (and other nutrients) with N in fertilizer prescriptions (Swift and Brockley 1994; Brockley 2000, 2004). At the McKendrick Pass and Tutu Creek study sites, positive growth responses to added S were expected, given low pre-treatment foliar  $\text{SO}_4$  levels ( $< 60$  ppm) (Brockley 2000). However, neither of these S-deficient lodgepole pine stands responded incrementally to S additions. Actual Mg deficiencies, or N:Mg imbalances following N fertilization, may have precluded S response at both sites. Post-fertilization foliar N/Mg ratios in NB, NSB, and Complete treatments temporarily exceeded the threshold level of 20, above which visual symptoms of Mg deficiency (chlorosis) have been reported (Cape et al. 1990). Interestingly, the incremental benefits of added S and other nutrients on tree growth were more pronounced following re-fertilization (in year 7). At Sheridan Creek, smaller BA responses in NB than in NSB or Complete treatments in the 3-year period following re-fertilization can almost certainly be attributed to S deficiency induced by the NB re-fertilization. One year after re-fertilization, the foliar N/S ratio in NB-treated lodgepole pine foliage was 22, whereas ratios in NSB and Complete treatments remained below the threshold value of 14.5. Although BA differences were not statistically significant, similar trends in growth and foliar N/S levels in NB, NSB, and Complete treatments were evident following re-fertilization of lodgepole pine at Kenneth Creek and of spruce at Crow Creek. These results indicate that the likelihood of N-induced nutrient deficiencies in pine and spruce forests in central British Columbia may increase with the frequency of N application unless S (and possibly other nutrients) is included with N in fertilizer prescriptions. Similarly, Jacobson and Nohrstedt (1993) suggested that induced deficiencies of non-added nutrients were likely responsible for the relative ineffectiveness of repeated N application compared to initial fertilization at improving the growth of Scots pine and Norway spruce in Sweden. However, findings from a subsequent study did not support this hypothesis (Jacobson and Pettersson 2001).

The general inability of NB, NSB, and Complete fertilizers to stimulate lodgepole pine height increment is consistent with results previously reported following single fertilizer applications to non-repressed lodgepole pine in British Columbia and to young lodgepole pine and Scots pine in Sweden (Pettersson 1984; Brockley 2001a). Yearly nutrient additions also failed to stimulate height development at four of the five lodgepole pine “maximum productivity” sites. In fact, height increments in repeatedly fertilized  $\text{ON}_1$  and  $\text{ON}_2$  treatments at Kenneth Creek were significantly smaller than in the control treatment over 9 years, with the largest height reductions achieved with the highest fertilization intensity ( $\text{ON}_2$ ). Similarly, Kishchuk et al. (2002) reported that four applications of N and N + “Complete” fertilizers had either a minimal or negative impact on the height of lodgepole pine after 14 years. Repeated fertilization also inhibited height development of Scots

pine in Swedish “optimum nutrition” experiments (Tamm et al. 1999). Studies with Scots pine indicate that increased N supply stimulates crown and stem radial growth more than height growth (Albrektson et al. 1977; Malkonen and Kukkola 1991; Tamm et al. 1999). Amponsah et al. (2004a) reported evidence of increased branch diameter and branch mass following repeated fertilization at two lodgepole pine “maximum productivity” sites (Sheridan Creek and Kenneth Creek). In a companion study, the crown widths of fertilized lodgepole pine trees were 17–33% larger than unfertilized trees across a range of post-thinning densities after 10 years (R. Brockley, unpublished data). At Kenneth Creek, repeated fertilization increased the hydraulic conductivity, sapwood permeability, and leaf specific conductivity of lower branches of lodgepole pine (Amponsah et al. 2004a). It was hypothesized that the higher flow capacity of lower branches may reduce the availability of water to support the growth of the terminal leader and upper branches of repeatedly fertilized trees.

Induced micronutrient deficiencies (B and/or Cu), and associated top-dieback, were suggested as possible reasons for height disruptions in repeatedly fertilized Scots pine trials (Tamm et al. 1999). Similar acute symptoms of B deficiency were documented following N fertilization of lodgepole pine in the British Columbia interior, and inadequate B nutrition was shown to inhibit lodgepole pine height increment in the absence of acute symptoms of B deficiency (Brockley 1996, 2003). Because it is included in fertilizer prescriptions, B is almost certainly not the causal agent for small, or negative, height increments in fertilized treatments at the lodgepole pine “maximum productivity” sites. However, inadequate Cu nutrition may have played a role in disrupting height development in at least one pine installation. Twisting of stems and branches and rosetting of terminal shoots are clearly evident in ON<sub>2</sub> treatment plots at the Kenneth Creek site, where foliar Cu levels (1–2 ppm) are within the range associated with visual symptoms of Cu deficiency in *Pinus radiata* (Will 1985; Turvey and Grant 1990). Induced Cu deficiency was hypothesized as a factor in the premature loss of foliage at this site (Amponsah et al. 2004b). Foliar N/Cu ratio decreased, at least temporarily, following supplemental addition of 3 kg Cu/ha to ON<sub>2</sub> plots at Kenneth Creek. It will be interesting to observe whether the added Cu will have beneficial effects on tree form and height development at this site.

Positive height responses were documented in periodic (NB, NSB, Complete) and annual (ON<sub>1</sub>, ON<sub>2</sub>) fertilizer treatments at all spruce “maximum productivity” study sites. At Lodi Lake, substantial height responses were obtained in fertilized trees despite increased incidence of leader damage from the white pine weevil. During the 5 years following trial establishment, more than twice as many trees sustained weevil damage in the ON<sub>2</sub> treatment (54% attacked) than in the control treatment (24% attacked) (vanAkker et al. 2004). Although the incidence of weevil attack increased with fertilization intensity, the height losses were not as great as the height gains due to fertilization. Only small amounts of weevil damage were recorded at Hand Lake and Crow Creek (L. vanAkker, unpublished data). At these locations, heat sums were likely below the threshold required for successful weevil brood development (McMullen 1976). The positive height responses in the spruce “maximum productivity” installations are consistent with published results from *Picea* spp. fertilization studies. Brockley (1992) reported that height increment of N-fertilized Engelmann spruce (*Picea engelmannii* Parry) was 0.5 m (84%) greater than the growth measured in unfertilized trees over a

3-year period. In Sweden, height gains following a single fertilizer application to young stands were significantly larger in Norway spruce than in either lodgepole pine or Scots pine (Pettersson 1984). In Swedish “optimum nutrition” experiments, large height gains were reported following repeated fertilization of young Norway spruce (Tamm 1985).

The higher stem taper of pine and spruce in ON<sub>1</sub> and ON<sub>2</sub> treatments than in unfertilized trees is consistent with results reported for repeatedly fertilized Scots pine and Norway spruce (Mead and Tamm 1988; Tamm et al. 1999). At the lodgepole pine study sites, repeated fertilization has generally produced shorter, fatter trees. Even though height responses in repeatedly fertilized spruce have been positive, there has been proportionally greater radial growth response than height response. Large increases in tree taper may have undesirable effects on stand volume and lumber recovery at harvest (Middleton et al. 1995). Also, the accuracy of stem volume estimations is affected by stem shape (Meng 1981; McTauge 1992). Future measurements of bole form will be required to accurately report the effects of fertilization on stem and stand volume. The relatively low density (i.e., 1100 sph) of these young pine and spruce stands has likely exacerbated the conical shape of fertilized trees. In most cases, the large live crowns of fertilized trees have receded slowly, which has likely shifted radial growth response downwards on the stem. It will be interesting to observe future taper differences between fertilized and unfertilized treatments as crown expansion continues and inter-tree competition causes tree crowns to lift. It will also be interesting to document the effects of the recent pruning in two lodgepole pine installations on future taper development.

To date, the relative and absolute tree- and stand-level growth responses in ON<sub>1</sub> and ON<sub>2</sub> treatments have been much smaller in lodgepole pine than in spruce “maximum productivity” installations. These species differences are consistent with those reported from Swedish “optimum nutrition” studies, in which stand volume gains following intensive fertilization have been considerably better in Norway spruce than in Scots pine (Tamm 1985, 1991; Tamm et al. 1999).

The relative stand volume gains reported to date from most lodgepole pine “maximum productivity” installations are within the range of those previously reported for similar response periods from intensive fertilization studies with young (12- to 20-year-old) Scots pine and lodgepole pine. In Sweden, two “optimum nutrition” fertilization studies were established in young Scots pine stands at Lisselbo (~15 years old) and Norrliden (~20 years old) in 1969 and 1971, respectively. At both locations, four levels of N (N<sub>0</sub>, N<sub>1</sub>, N<sub>2</sub>, N<sub>3</sub>), with and without periodic PK supplements, were applied annually for 20 years. Annual N application rates ranged from 20–60 kg/ha for N<sub>1</sub> to 60–180 kg/ha for N<sub>3</sub>. The N<sub>2</sub>+PK and N<sub>3</sub>+PK regimes in the Swedish experiments are very similar to the ON<sub>1</sub> and ON<sub>2</sub> treatments included in the British Columbia “maximum productivity” studies. At Lisselbo, 6-year (1972–1977) relative stand volume responses were approximately 50%, 20%, and 9% larger than control growth in the N<sub>1</sub>+PK, N<sub>2</sub>+PK, and N<sub>3</sub>+PK treatments, respectively (Tamm 1985). Growth responses at Norrliden were considerably larger, with corresponding relative gains of about 45%, 42%, and 27% over 8 years (1972–1979). A negative dose-response relationship was documented at both sites. After 18–20 years, the largest stand volume responses were achieved at the N<sub>1</sub> level, with total volume gains of about 40–50 m<sup>3</sup>/ha (Tamm et al. 1999). Similar fertilizer regimes applied four times over a

6-year period produced substantial growth gains in 7-year-old lodgepole pine in south-central British Columbia. After 14 years, stand BA in the  $N_3$ +PK treatment was 48% larger than in the control (Kishchuk et al. 2002). Repeated fertilization with N alone had a negative effect on mean tree basal area and volume. In Finland, two Scots pine stands (12–16 years old) were fertilized five or six times over a 26- to 30-year period. Nitrogen fertilization increased 10-year relative stand volume responses by 22 and 67% more than control growth at the two sites (Malkonen and Kukkola 1991). Over the entire study period, absolute volume gains were 54 and 45  $m^3/ha$ , representing relative increases of 22% and 35%, respectively. In Quebec, “optimum nutrition” fertilizer regimes were applied six times over a 10-year period in an unthinned, 45-year-old jack pine (*Pinus banksiana* Lamb) stand. At the  $N_1$  level, net increments up to 49  $m^3/ha$  (163%) higher than control values were reported over 10 years (Weetman and Fournier 1984). However, repeated fertilization at the  $N_3$  level killed trees and reduced growth relative to unfertilized trees. Large N inputs also resulted in heavy mortality and significant reductions woody biomass production in a red pine (*Pinus resinosa* Ait.) stand in the northeast United States (Magill et al. 2000, 2004).

The poor growth response to periodic and repeated fertilization at Kenneth Creek is an interesting anomaly among the lodgepole pine installations. The BA and height responses to NB, NSB, and Complete fertilization at this site are much smaller than those normally obtained for lodgepole pine in the central British Columbia interior (Brockley 2001a). Moreover, and despite large increases in foliar N levels, the radial and height responses to annual fertilization (especially the  $ON_2$  treatment) are nonexistent or negative. This negative growth trend is apparently worsening over time. There are several possible hypotheses for these results. As discussed previously, the higher flow capacity of lower branches may reduce the availability of water to support upper crown development of repeatedly fertilized trees at Kenneth Creek (Amponsah et al. 2004a). Also, induced Cu deficiency (or other foliar nutrient imbalances) may be associated with distorted crown development and significantly reduced needle longevity in  $ON_2$  treatment plots (Amponsah et al. 2004b). Lower needle longevity, leaching of nitrates and cations, and foliar nutrient imbalance have been linked to reduced growth and acute mortality following large N additions to red pine in the northeastern United States (Minocha et al. 2000; Bauer et al. 2004; Magill et al. 2004). Despite much higher foliar N levels, heavily fertilized red pine had significantly lower photosynthetic capacity than control trees (Bauer et al. 2004). Because a disproportionate amount of the surplus foliar N accumulated as free amino acids (i.e., predominantly arginine), little of the excess N was used to produce photosynthetically active metabolites.

The large relative and absolute growth responses reported to date for the spruce “maximum productivity” installations are consistent with the large growth gains reported for Norway spruce intensive fertilization studies in Sweden (Tamm 1985, 1991; Bergh et al. 1999a). The Strasan “optimum nutrition” experiment was established in 1967 in a 12-year-old Norway spruce plantation. Four levels of N ( $N_0$ ,  $N_1$ ,  $N_2$ ,  $N_3$ ), with and without periodic P or PK supplements, were applied annually for 21 years. Magnesium and several micronutrients were also included in the PK treatment. Annual N application rates ranged from 30–60  $kg/ha$  for  $N_1$  to 90–180  $kg/ha$  for  $N_3$ . At Strasan, 6- and 10-year relative stand volume responses in excess of 400% were recorded (Tamm 1985). Over 10 years, 40–50  $m^3/ha$  of “extra” wood were

produced in fertilized treatments. After 20 years, standing volume in the most intensively fertilized treatments was more than four times larger than in control treatments (Tamm 1991). Absolute volume gains at Strasen totalled about 250 m<sup>3</sup>/ha over this period. Sophisticated “fertigation” experiments, established in northern (Flakaliden) and southeastern (Asa) Sweden in the mid-1980s, also produced impressive stand volume responses (Bergh et al. 1999a). These studies tested the effects of both water and nutrients on limiting the growth of young Norway spruce. The treatments consisted of control (C), irrigation (I), solid fertilizer (F), and irrigation combined with liquid fertilizer (IL). Small, balanced supplies of nutrients were injected into irrigation water throughout the growing season at rates consistent with estimated demand. Solid fertilizers used in F treatments were applied at the beginning of each growing season. After 10 years, the volume growth in fertilized stands (F and IL) at the northern site (Flakaliden) was almost four times higher than that in stands without fertilization (C and I), and standing volume had almost tripled (~ 98 m<sup>3</sup>/ha vs. 35 m<sup>3</sup>/ha). At the more fertile southern site (Asa), standing volumes in the control, F, and IL treatments were 80, 131, and 163 m<sup>3</sup>/ha, respectively, after 10 years. A similar “fertigation” experiment with 15-year-old Scots pine also yielded impressive growth responses. After 11 years of nutrient and water additions, standing BA in F and IL treatments was 120 and 163% higher, respectively, than in control plots (Linder 1987).

Because light interception is principally a function of the amount of foliage production, a strong relationship between forest productivity and leaf area has been demonstrated for many species (Linder 1987; Vose and Allen 1988; Albaugh et al. 1998). Increased leaf area has been identified as the primary “engine” driving fertilization growth response (Fagerstrom and Lohm 1977; Brix 1983). The strong relationship between stand BA and LAI that has been observed in “maximum productivity” installations, and the large increases in LAI following fertilization (especially in ON<sub>1</sub> and ON<sub>2</sub> treatments) at most study sites, are consistent with these findings. The prospects for continuing rapid growth of fertilized trees is very good, given the higher LAI levels in fertilized treatments.

After several years of annual fertilization, foliar N levels in repeatedly fertilized treatment plots have more-or-less stabilized in several “maximum productivity” installations. However, yearly N additions to ON<sub>1</sub> treatment plots (50–100 kg N/ha) and ON<sub>2</sub> treatment plots (100–200 kg N/ha) have so far failed to achieve, and maintain, the target foliar levels of 1.3% and 1.6%, respectively, at most study sites. This failure can be partially explained by dilution caused by large increases in above-ground biomass (boles, branches, and foliage) in fertilized trees. The foliar N targets could likely be attained if annual N application rates were increased. However, preliminary results indicate that large N additions may potentially create foliar N imbalances relative to other macro- and micronutrients. For example, the maintenance of a favourable foliar N:Mg balance has necessitated large supplementary Mg additions at several study sites. Despite the frequent use of multi-nutrient fertilizer prescriptions, thresholds for foliar N/P, N/K, and N/S ratios have also been exceeded in some of the lodgepole pine installations. Foliar nutrient imbalance was hypothesized to be a probable factor contributing to the negative impact of heavy N additions on the growth of *Pinus* in previously reported studies (Tamm et al. 1999; Kishchuk et al. 2002; Bauer et al. 2004). Given these concerns, the foliar N target levels for ON<sub>1</sub> and ON<sub>2</sub> treatments

were recently lowered to 1.2 and 1.4%, respectively, for all “maximum productivity” installations. This decision will likely make it easier to maintain (or restore) favourable foliar nutrient balance, and will likely necessitate smaller yearly additions of N and other nutrients.

## 5 SUMMARY

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At least 6 years of growth measurements have been obtained from seven of the eight “maximum productivity” installations. These preliminary results indicate that the repeated fertilization of young managed forests may be a potentially viable strategy for addressing timber supply challenges in the interior of British Columbia. Young spruce plantations are apparently particularly well suited to intensive forest management. Although four of the five lodgepole pine installations have produced significant growth gains following periodic (every 6 years) and yearly fertilization, the responses to date have been more variable and consistently smaller than those obtained at the spruce study sites. In the lodgepole pine installations, annual applications of N and other nutrients produced 6-year relative stand volume increments that ranged from 2% lower to 120% higher than control values. In contrast, 6-year stand volume increases of 213–280% were obtained from yearly fertilization at the spruce study sites. In one spruce stand, 9-year stand volume increment in the most intensively fertilized treatment was almost four times larger than in the unfertilized stand. This represented an absolute volume gain of 45 m<sup>3</sup>/ha. These species differences are consistent with those previously reported from “optimum nutrition” and “fertigation” studies with Scots pine and Norway spruce.

Lodgepole pine growth responses appear to be inversely related to fertilization intensity. Foliar nutrient imbalances and growth disruptions have apparently been induced by large, and frequent, N additions at some lodgepole pine study sites, despite the frequent inclusion of other macro- and micronutrients in fertilizer prescriptions for repeatedly fertilized treatment plots. It is hypothesized that large N additions may lead to accumulation of free amino acids in the foliage of heavily fertilized lodgepole pine, thereby diverting N away from photosynthesis and reducing carbon assimilation. Conversely, the largest spruce responses have been associated with the most intensive fertilization treatments.

It is too early to reliably predict the potential impacts of intensive fertilization on harvest yields and/or rotation length of managed interior spruce and lodgepole pine in the interior of British Columbia. However, preliminary responses from “maximum productivity” research installations appear to be tracking along pathways similar to the Scots pine and Norway spruce “optimum nutrition” studies in Sweden. The Swedish results suggest that the growth of Norway spruce can potentially be doubled in southern Sweden, and more than tripled in the north, by frequent application of balanced fertilizers (Bergh *et al.* 1999b). Growth projection models estimate that the rotation length for Norway spruce can be shortened by 20–30 years in the south and by 40–60 years in the north. In the interior of British Columbia, productivity gains and accelerated stand development of similar magnitude would be of huge benefit in addressing timber supply challenges such as the amount, and timing, of future harvests.

It is important to continue monitoring stand development in all “maximum productivity” treatments to see whether these early species growth trends continue, and to determine how closely growth gains from periodic fertilization (i.e., every 6 years) of spruce and pine will approximate the responses achieved by yearly nutrient additions. Judicious monitoring of foliar nutrient levels in ON<sub>1</sub> and ON<sub>2</sub> treatments at all study sites will continue,

and adjustments will be made to fertilizer regimes, as required, in order to maintain a favourable foliar nutrient balance.

The “maximum productivity” project is an excellent example of an interdisciplinary approach to forest research and of how long-term growth and yield field experiments can be used to achieve multiple objectives. In collaboration with other scientists, several companion studies have been undertaken (or are planned) at selected “maximum productivity” sites to document the potential long-term ecological consequences of repeatedly fertilizing interior forests and to determine the effects of large nutrient additions on wood quality and value. As in many other long-term growth and yield field experiments, the “maximum productivity” installations will also likely be used for purposes beyond the original study objectives. For example, the Swedish “optimum nutrition” installations have contributed valuable information regarding the potential effects of atmospheric N inputs on boreal forest ecosystems. Similarly, the lodgepole pine and spruce “maximum productivity” installations may provide a glimpse into the future regarding the long-term effects of atmospheric nutrient input on the health and sustainability of interior forest ecosystems. Also, by increasing biomass production and increasing carbon reserves in soil, repeated fertilization has the potential to enhance the capability of managed forests to act as carbon sinks, and thus positively affect net carbon sequestration. By providing strictly controlled experimental treatments, the “maximum productivity” installations provide an excellent opportunity to quantify these changes.

**APPENDIX 1** Fertilization regimes by treatment and year at Sheridan Creek (EP 886.13 Installation #1)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
1993	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
1994				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
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	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N	100N
2000				100N, 50P, 50K, 63S, 32Mg	150N, 50P, 50K, 63S, 32Mg
2001				50N	100N
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50P, 50K, 50S, 25Mg

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

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

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
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, 10Fe, 3Cu, 2.4S	100N, 50Mg, 11S, 10Fe, 3Cu
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

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

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
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, 10Fe, 3Cu, 2.4S	150N, 10Fe, 3Cu, 2.4S
2002				50N, 1.5B	100N, 1.5B
2003				100N, 50S	150N, 50S

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

**APPENDIX 4** Fertilization regimes by treatment and year at McKendrick Pass (EP 886.13 Installation #4)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
1996	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
1997				50N, 50P, 50K, 100Mg, 50S	100N, 50P, 50K, 100Mg, 50S
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63Mg, 32Mg	150N, 50K, 63S, 32Mg
2001				50N, 50Mg, 8S	100N, 100Mg, 17S
2002	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50S

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

**APPENDIX 5** Fertilization regimes by treatment and year at Lodi Lake (EP 886.13 Installation #5)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
1996	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
1997				50N, 50P, 50K, 100Mg, 50S	100N, 50P, 50K, 100Mg, 50S
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63Mg, 32Mg	150N, 50K, 63S, 32Mg
2001				100N	150N, 50Mg, 8S
2002	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50S

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

**APPENDIX 6** Fertilization regimes by treatment and year at Tutu Creek (EP 886.13 Installation #6)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
1996	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
1997				50N, 50P, 50K, 100Mg, 50S	100N, 50P, 50K, 100Mg, 50S
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63Mg, 32Mg	150N, 50K, 63S, 32Mg
2001				50N	100N, 50Mg, 8S
2002	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50P, 50K, 50S, 25Mg

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

**APPENDIX 7** Fertilization regimes by treatment and year at Crater Lake (EP 886.13 Installation #7)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
1997	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 107Mg, 64S, 1.5B	200N, 100P, 100K, 107Mg, 64S, 1.5B
1998				50N, 50P, 50K, 50S, 50Mg	100N, 50P, 50K, 50S, 50Mg
1999				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
2000				100N, 50K, 63S, 32Mg	150N, 50K, 63S, 32Mg
2001				50N	100N
2002				50N, 1.5B	100N, 1.5B
2003	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 50S	100N, 50S

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

**APPENDIX 8** Fertilization regimes by treatment and year at Hand Lake (EP 886.13 Installation #9)

Year	Treatment				
	NB	NSB	Complete	ON <sub>1</sub>	ON <sub>2</sub>
2000	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 100Mg, 62S, 1.5B	200N, 100P, 100K, 100Mg, 62S, 1.5B
2001				100N, 50P, 50K, 63S, 32Mg	150N, 50P, 50K, 63S, 32Mg
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50S

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; B = boron. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

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