Characterization of Soil Nitrogen and Sulfur Availability in Relation to Volume Response of Douglas-fir (*Pseudotsuga menzesii* Mirb. Franco) in Western Oregon and Washington

by

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Abstract

CHARACTERIZATION OF SOIL NITROGEN AND SULFUR AVAILABILITY IN RELATION TO VOLUME RESPONSE OF DOUGLAS-FIR (*PSEUDOTSUGA MENZESII* MIRB. FRANCO) IN WESTERN OREGON AND WASHINGTON

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Volume response to urea nitrogen was examined on fifty-one Douglas fir installations in western Oregon and Washington. Response was significantly related to stand and soils variables at each location. Site index was negatively related and age was positively related to response. The correlation between response and mineralizable nitrogen from incubation tests was low. It was significantly improved by adjusting the test for gravel content of the soil and the mean annual air temperature at the site. The adjusted mineralization values were also shown to significantly improve the prediction of the net live foliage biomass increment in the control plots. The best predictive model of nitrogen response included site index, mineralizable nitrogen and sulfur indices. The sulfur indices consisted of A horizon sulfate sulfur, age weighted subsoil sulfate sulfur, and the ratio of sulfur to nitrogen in the soil. Canonical analysis demonstrated that age was strongly associated with mineralizable nitrogen (negative) and sulfur availability (positive).

Sulfur availability was examined further in three separate experiments. Douglas fir seedlings showed sulfur responses in greenhouse trials on soils with less than 14 mg kg^{-1} using Morgan's solution. Relative basal area responses in paired fertilization plots of nitrogen only and nitrogen plus sulfur were correlated significantly to indices using sulfate sulfur in the A horizon and the subsoil. Field trials with nitrogen and sulfur were established in a range of young Douglas fir plantations. Growth responses and foliage

analysis after treatment suggest that complex interactions with litter - humus immobilization of sulfur and enhanced nitrogen uptake by the trees may strongly affect responses at specific locations. Genuine sulfur deficiencies appeared to occur when sulfate sulfur in the foliage was reduced below 80 to 100 mg kg^{-1}.

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INTRODUCTION

Douglas fir has been shown to respond to nitrogen (N) fertilization in the Pacific Northwest (Heilman 1974, Regional Forest Nutrition Research Project 1976, Handley and Pienaar 1972). While site index has been proven to be a useful predictor, the responses have not been found to be consistent with respect to easily measurable soil variables (Gessel et al. 1969, Peterson et al. 1984). A very good correlation between response and mineralizable N was produced by Shumway and Atkinson (1977). Evidence exists that N responses in the region may be limited by sulfur (S) (Reimer and Tartar 1916, Olsen and St. John 1921). S deficiencies are also believed to affect conifer responses to N (Turner 1968, Cockran 1978, Will and Youngnerg 1978).

The basic objectives of the study were to:

1) Develop biologically sound stand and soil indices which can be used to improve N response prediction.
2) To refine the soil mineralizable N index.
3) To determine the relationship between N response and S availability, and the effects of S fertilization.

The objectives were achieved, firstly, by quantifying the proportion of the explainable variation attributable to stand and soil variables using an independent study population. Secondly, regression techniques were used to derive statistical measures of the importance of other soil variables, gravel content and temperature to the N mineralization test. Finally, an independent examination of soil S was conducted. Responses to N and NS were evaluated in pot and field tests and related to levels of available S.

Chapter I

LITERATURE REVIEW

Volume Response of Conifer Stands to Fertilization

Northern and Central Europe

Early studies in forest nutrition were able to demonstrate responses to most of the major nutrients. Mayer-Krapoll (1956) summarized work on established stands. Measurements in several trials with Norway spruce showed total growth responses to N of 8 to 38 m^3 ha^{-1}. In general, N appeared to give the largest increase although P and K are important locally. A great amount of interest has been focused on fertilization at planting and during the establishment phase (Baule and Fricker 1967). At this stage, responses to P and occasionally K are more important than N. Everard (1974) reported absolute height increases of 1 to 5 m following treatment with P at various ages in young plantations. Renewed interest in established stands was indicated in a review by Le Tecon (1970). He reported average volume gains due to N fertilization in Scots pine of 1 to 2 m^3 ha^{-1} $year^{-1}$ and up to 4 m^3 ha^{-1} $year^{-1}$ in certain instances.

Deficiencies of N in older sitka spruce stands have become apparent on Calluna dominated sites and certain peats after years of treatment with P and K fertilizers (McIntosh 1980). Binns and Grayson (1967) listed a total growth increase due to NP treatments of 12 to 17 m^3 ha^{-1} in seven years. In pine and spruce stands in Bavaria response to N ranged from 2 to 3 m^3 ha^{-1} $year^{-1}$ over a five year period depending upon the level of fertilization (Laatsch 1962). In Belgium (Weissen and Roisin 1971), growth increments in twenty to forty year old Norway spruce varied between 2 to 4 m^3 ha^{-1} $year^{-1}$ following treatment with urea. Hagner and Leaf (1973) indicated that average responses of 1 to 2 m^3 ha^{-1} $year^{-1}$ from N fertilization could be realized in spruce and pine stands in Sweden. Slightly higher responses were reported by Gustavsen and Lipas (1975) for pine and spruce in Finland, ranging from 1 to 4 m^3 ha^{-1} $year^{-1}$.

North America

Krause et al. (1982) summarized the results of five year growth responses to N in central and eastern Canada. Total volume increase on responsive stands, primarily jack pine, ranged from 4.2 to 19.9 m^3 ha^{-1}.

Early studies of Heiberg and White (1951) drew attention to K deficiencies in red pine in the northeast. The response increment has persisted for 20 years (Heiberg et al. 1964), resulting in a total volume increase of 80 to 90 m^3 ha^{-1}.

In the southeastern U.S., growth responses to P fertilization on poorly drained coastal sands is supported by a number of reports. Substantial work on P fertilization at establishment has shown that growth can be increased by as much as 1600 percent (Pritchett and Smith 1968). In one to eight year old stands of loblolly pine responses to P were found to be as much as 14 m^3 ha^{-1} over a five year period. N produced a similar level of response where P was not limiting (North Carolina State Forest Fertilization Co-operative 1980). Much higher levels of response to N and P can be found in older stands. The range is from 8.5 to 27.6 m^3 ha^{-1} to a combined application of 112 kg ha^{-1} of N and 56 kg ha^{-1} of P. Fisher and Garbett (1980) summarized an extensive series of trials with southern pines. In their work, responses to P only were limited to poorly drained sites, ranging up to 3.2 m^3 ha^{-1} $year^{-1}$. N responses were more consistent across sites but varied from 0 to 4.5 m^3 ha^{-1} $year^{-1}$ over the eight year study period. The average response to N and P in combination was larger, varying from 1.6 to 4.5 m^3 ha^{-1} $year^{-1}$. Stand age in their study ranged from nine to eighteen years.

Early work in the northwest United States indicated that both height (Gessel and Walker 1956) and diameter growth of Douglas-fir (Gessel and Shareeff 1957) could be increased by the addition of N.

Heilman (1971) reported the results of several early trials in southwestern Washington. Between nine and twelve years after treatment growth increases from 224 kg ha^{-1} and 448 kg ha^{-1} of N were 31 and 38 m^3 ha^{-1} respectively. Crossin et al. (1966), in a summary of early studies on Vancouver Island, reported a doubling of height growth increment in ten to fifteen year old stands following treatment with various rates of N. The growth increments appeared to persist on sites in which the stocking was reduced. In a more recent analysis of this data Handley and Pienaar (1972) calculated total average increment due to fertilization ranging from 8.6 to 45 m^3 ha^{-1} over a five year period. The greatest variation in increment resulted from N dosages of 112 to 336 kg ha^{-1}.

The most comprehensive series of trials to date have been conducted by the Regional Forest Nutrition Research Project (1981). In this group of trials, urea was found to produce a mean increase of 21.7 m^3 ha^{-1} at an N rate of 224 kg ha^{-1} in eight years, over a wide range of stand and soil conditions. However, the range of response was considerable, 0 to 45 m^3 ha^{-1}. No other major nutrients appear to affect growth in the Northwest although P and S may be locally important (Cockran et al. 1979, Heilman and Ekuan 1980). Growth response to major nutrients during the establishment phase has been disappointing, apparently a result of the suppression caused by competing vegetation (Austin and Strand 1960).

Australia and New Zealand

In 1950, Stoate summarized Australian experience with several pine species. It was discovered that P was normally deficient, and therefore required at establishment to produce a satisfactory crop. The importance of the practice has been quantified by Waring (1973) who showed that the increase in production persisted even through crown closure. Differences at twenty-years of 100 m^3 ha^{-1} could be expected (Flinn et al. 1979). Both N and P appear essential for continuous production (Waring 1960). But, production gains from N fertilization in older established stands does not appear to be as dramatic. Crane (1982) reported responses of 4.2 to 5.9 m^3 ha^{-1} $year^{-1}$ in 20 year old stands.

Mead and Gadgil (1978) reported on the results of several trials with *Pinus radiata* in New Zealand. In agreement with the Australian results, fertilization with P at an early age or repeatedly throughout the rotation can increase growth by as much as 12 to 30 m^3 ha^{-1} $year^{-1}$. Volume responses to N alone, where P does not appear to be limiting, are substantially less, averaging 3.6 to 8 m^3 ha^{-1} $year^{-1}$. Ballard (1978) indicated that while P is essential at establishment on certain New Zealand soils, volume increments in very young stands are difficult to assess because of the effect of planting density prior to crown closure. Total volume additions within a short period of establishment were about 40 m^3 ha^{-1}.

It is important to note that whereas the growth responses to P and K during establishment appear to persist for long periods, circa twenty years or more (Pritchett and Comerford 1982), the growth increment to N is generally short lived, ranging from three to ten years, depending partially upon the level of application. Exceptionally large and prolonged responses to N occasionally occur on very deficient sites (Miller and Tarrant 1983).

A possible explanation for the variation in the persistence of the various nutrients was put forth by Switzer and Nelson (1972). They believe that P is more efficiently redistributed within the foliage than N prior to needle senescence. In the case of K, the latter appears to be more rapidly released from the litter than N during decomposition.

The primary interest of this review has been volume responses to the major nutrients in conifer stands, there are numerous citations of micronutrient effects in conifers (e.g., Schutz 1976). Boron, especially, has been found to result in improved shoot growth. In a similar fashion both zinc and S have been related to shoot deformities. The quantitative results of these elements in terms of improved volume growth has not been well documented. Boron, S, and molybdenum have received widespread interest in agriculture and horticulture practices in the Northwest. The degree to which they might influence N metabolism in fertilized stands of Douglas-fir is unknown at this time (Gessel et al. 1979).

Response as Affected by Stand Conditions; Age, Site and Stocking

In the Pacific Northwest, the Regional Forest Nutrition Research Co-operative (1976) reported that treatment effects up to six years after fertilization with urea, increased with decreasing site quality in Douglas-fir. This relationship was not detected at 8 years following application (1981). In the same report, a separate analysis of Co-operative and company data by the Weyerhaeuser Company produced a similar effect of site quality on five year data. A positive age x fertilizer interaction found in their own trials did not persist in the combined data analysis.

Crown Zellerbach (Lin et al. 1978) in an analysis of three year response data for Douglas-fir in British Columbia indicated that a positive age x N and age x site interaction existed. In this instance, response increased with site quality, although it should be noted that the highest sites in this study were nearly equivalent to the lowest in the Regional Co-operative. Handley and Pienaar (1972) reported a similar relationship in a separate series of trials by McMillan-Bloedel on Vancouver Island. More recently Strand and Debell (1979) completed analysis of Douglas-fir response on Crown Zellerbach holdings in western Washington and Oregon. In this report, a positive age x N and negative site x N interaction were found. In addition, very low and very high stocking levels were found to reduce response, a phenomenon not previously reported. With the exception of the results from the Regional Co-operative program, N response appears to be influenced by both site quality and stand age in Douglas-fir.

In the southern United States, a large regional study (North Carolina State Co-operative 1980) has elucidated many stand characteristics which appear to influence response. In older stands, volume growth increment from N increases with higher site quality. Response also appears to be sensitive to stocking levels. In older stands, better total response was realized at lower stocking levels regardless of site index. In contrast, when P and N are applied at establishment, the optimum increment does not accrue until stands reach a minimum basal area stocking.

In both Finland (Gustavsen and Lipas 1975) and Sweden (Hagner and Leaf 1973) results clearly showed that growth responses to both urea and ammonium nitrate were positively related to existing stand growth in spruce and pine. Gustavsen and Lipas further showed that the additional increment was positively correlated to site quality. In their results, response declined with age between forty and one hundred and forty years. Malkonen (1979) indicated that response increased with age up to about forty years.

Measures of Nutrient Availability in Forest Stands

Measurements of nutrient availability in forest stands should correlate well with responses to the particular element. Van den Burg's review (1976) listed few successful studies using soil analysis. Similar conclusions were reached by Leaf (1973) for foliar analysis, even considering the tremendous literature available on forest trees (van den Driessche 1974, Turner et al. 1978). It is noteworthy, in this respect, that traditional soil and foliage analysis has proved indispensable in the determination of nutrient disorders in conifer seedlings (Benzian 1965, van den Driessche 1969, Knight 1978).

For P and K and probably such micronutrients as B, values of soil or foliage concentrations which reasonably reflect deficiency levels in certain tree species have been established. Walker (1955) and later Stone and Leaf (1967) established guidelines for K deficiency in red pine stands in the Northeast. Krauss (1967) reported similar evidence for assessing the K status on two soils in Germany. In Zech's (1967) study both foliar and soil analysis were valuable in diagnosing K deficiencies. Both parent materials and vegetation have proven to be useful diagnostic indicators of most elemental deficiencies except N. Will (1978) drew attention to the fact that parent materials and specific nutritional disorders of Pinus radiata were closely correlated. Similar patterns apparently exist in Australia (Turner and Lambert 1980). Baule and Fricker (1967) were able to define nutrient disorders for K, Mg and Ca in terms of geomorphology and geologic formations. Everard (1974) used vegetation and species to discriminate among P deficient sites in Great Britain as did Holmen (1969) in Sweden when considering afforestation on peatlands.

Satisfactory foliar levels for predicting phosphorus response in loblolly pine were produced by Wells et al. (1973). Soil test values were developed by Ballard and Pritchett (1975). They found stronger extractants gave better correlations with response. Ballard (1974) also found good correlations between P response and soil test values in New Zealand.

Direct measures of N availability have presented a more formidable task. Often methods used to establish a relationship between availability and potential response are questionable. As Armson et al. (1973) stated, many studies which have only compared changes in N status after fertilization are more useful in explaining the results than predicting future growth (van den Dreissche and Webber 1977, Miller et al. 1976, Popović 1967).

The weakest link in the understanding N availability in forest stands is the precision to which we understand the N cycles under specific stand and soil conditions. Gessel et al. (1972) presented data on N accumulation in Douglas fir stands that shows the substantial variation between forest sites and ages that exists. Miller (1978), drawing upon many previous studies, theorized that N availability was strongly affected by temporary storage and mobilization within tissues, and therefore complicated analysis. Miller (1981) believed nutritional demand as being highest during the earliest stages of growth, peaking just prior to, or during canopy closure. On low quality sites a progressive development of N deficiency may occur due to immobilization of N in the forest floor and biomass, but on better sites demand should fall progressively with age. The latter notion is supported by several studies with various conifers in which calculated net N uptake peaked at very young ages, about the time of canopy closure (Ovington 1959, Madgwick et al. 1977, Turner 1975). After crown closure net N uptake either remains constant or declines slightly (Cole 1981). Based upon their own data, Switzer and Nelson (1972) stated that following canopy closure in loblolly pine, crown biomass was at a maximum, and that cycling through litterfall was sufficient to supply annual needs. However, limited mobilization of litter N was also reported to be responsible for increasing N deficiencies in young plantations of Scots pine (Malkonen 1975) and sitka spruce (Carey and Farrell 1978) following crown closure.

A number of workers have infered the N available to stands by comparing their inherent productivity to various levels of N in either the soil or foliage. Wehrmann (1959) showed a very good positive correlation between site quality production classes and percent needle N for Scots pine, as did Strebel (1960) for Norway spruce. Zöttl (1960b) correlated site quality production with mineralizable N derived from soil incubations. Shibanoto (1961) also reported a good correlation between height growth and N foliar levels from various sites. Kawana (1966) found a moderate degree of correspondence between total soil N and site quality for two species in Japan. Powers (1980) also correlated site index in ponderosa pine with mineralizable N in the mineral soil horizon at 18 to 22 cm.

Gessel et al. (1969), in an early study of N response, found total N and occasionally C/N ratios to give significant improvement in response prediction. Correlations were felt to be too low to be of immediate practical significance. Shumway and Alkinson (1978) noted a good correspondence between diameter response and mineralizable N from the 0 to 15 cm layer of mineral soil for Douglas-fir stands. Turner et al. (1977) reported a study in which foliar

SO_4-S levels provided a guide to discriminating between high and low responding installations of Douglas-fir. High levels of SO_4-S above 200 mg kg^{-1}, presumably occurred only sites in which available N was insufficient. Finally, Lea and Ballard (1982) found no correlation between mineralizable N in the surface soil and volume response, site quality or foliage N in loblolly pine, however, foliage N and site quality were positively correlated.

Nitrogen Mineralization and Nitrification in Forest Soils

Relationship to Stand Conditions

Some of the earliest work on N mineralization was conducted by Zöttl (1960a, 1960b, 1960c). His work produced good correlations between the site productivity of spruce and pine stands and the N released from the humus layer after incubation for six weeks at 23°c. N release based upon the whole soil profile gave the best results. C/N ratios of the humus fraction appeared to explain a substantial amount of variability in mineralization from the humus. Total N provided a much less satisfactory explanation of the results.

Cunningham (1962) evaluated mineralization under mixed forest and cacao stands. Mineralizable N in the surface mineral soil was correlated well with total N and organic C content but not to C/N ratios. Management activities which caused soil exposure decreased both the organic content and the N released during incubation.

Van Pragg and Weissen (1967), in an intensive study of several hardwood and conifer soils, found field and laboratory incubations to give inconsistent results especially when environmental conditions at the forest site varied. Nitrification proceeded more rapidly in the mineral soil fractions than in the humus or litter layers in beech soils. The proportion of N mineralized to total N was always higher in the surface layers than in the mineral soils. Mineralization was only vaguely related to productivity in the beechwood soils. They also indicated that laboratory incubations of mineral soils showed little seasonal variation when compared with incubations of the humus and litter layers.

Le Tecon (1973) reported that mineralizable N from the surface soil layer was well correlated with site quality in spruce. Neither nitrification nor total N were similarly correlated. N mineralization was positively related to extractable P and pH but not to C/N ratios or total N in the surface mineral soil.

In situ studies of mineralization and nitrification were first suggested by Eno (1960). Despite the drawbacks in the methodology many valuable insights into the process in the field were found. Lemee (1967) made estimates of mineralizable N in the field. His work and others (Remacle 1977) have provided apparently reasonable estimates of N release under field conditions. Melillo (1981) stated that these estimates were surprisingly close to N uptake values calculated from biomass increment studies on similar stands. Most studies, at least in central Europe, show that temperature plays a dominant role in regulating N release. Moisture appears important only for short periods in the summer.

Powers (1980) completed an intensive study of N mineralization in forest soils of northern California. Temperature in the field was the key variable controlling the amount of N mineralized under forest conditions, although moisture was maintained artificially high by the sample bags. N mineralization was correlated with foliar N and site quality in ponderosa pine on certain parent materials. Correlations with site for mesic and frigid zone soils appeared to be different. Lea and Ballard (1982) were unable to find any significant relationship between N mineralization in southeastern soils and stand characteristics. They did feel that the variation in the amount of N mineralized could be explained by the soil pH and initial total N content.

Effects of Soil Factors

Kawahara (1970) found both total N and C/N ratios useful in explaining N mineralization values from forest soils in Japan.

Substantial rates of nitrate formation were noticed in several soils. The quantities of nitrate were partially related to total N released. Nitrification was strongly related to C/N ratios. He also found that the fraction of N released in relation to total N was greater in the surface soil, in agreement with van Praag and Weissen.

Ohita and Kumada (1978a) found almost identical results. They reported differences in nitrate formation between wet and dry forest types and a tendency for nitrate formation, as a proportion of total N, to be higher in the surface mineral horizons than in the litter or humus layers. A more complex relationship was shown to exist between the C/N ratio and mineralization. The rate increased to about 30:1 and then decreased thereafter.

With respect to other studies which have examined controls on the release of N, Nomnik's (1976) work showed that the C/N ratio of a readily exidizable fraction of the organic matter was closely related to N mineralization. This was a better variable than the C/N ratio of the whole organic fraction used by Zöttl (1960b). Shumway and Atkinson (1978) also demonstrated a fair correlation between C/N ratios and net mineralization as part of their study with Douglas fir fertilizer response. Youngberg (1978), who measured N release from various Douglas-fir litter types, found total N content to explain only a portion of the variability. With litter types Berg and Staaf (1981) found total N important after adjusting the lignin content. For fresh litter materials both C/N ratios (e.g., Edmonds 1980) and lignin (e.g., Fogel and Cromack 1977) can regulate decomposition and therefore nutrient release in Pacific Northwest soils. Lamb's (1975) evaluation of N mineralization from radiata pine litter produced anomalous results. His laboratory incubations showed no significant effect on N mineralization from either total N or C/N ratios. He interpreted the variable rates of mineralization as due to polyphenol contents, although P content of the litter was directly related to mineralization.

Higher rates of N release from the humus layers were reported in the vast majority of research cited previously. However, the larger numerical impact of the humus layers arises from the expression of absolute N production as a fraction of the dry weight. If the importance of the humus is expressed on as area bases, its contribution to the total release potential is less than half of the mineral horizon, as noted by Runge (1971) and Popović (1980). Richards (1981) reported on a study by Jeanes that compared N mineralization from different litter and soil layers in undisturbed blocks. Although litter and humus released more on a weight bases, the surface soil was quantitatively more important on a whole soil or volume bases.

Seasonal Variability

Popovic (1971) analyzed the seasonal variability in mineralization values derived from laboratory incubations. His conclusion that incubation values are consistently more variable than other chemical analysis is certainly in agreement with other work in agriculture (Beckett and Webster 1971). Much greater variability (C.V. ~ 30%) was noted in the humus layer than in the mineral soil. Other workers have shown similar variability with season or between years (van den Driessche and Webber 1977). Zöttl (1960a) did not find as much variability although his incubation periods were much longer.

Fertilization Effects

In the examination of fertilizer effects on mineralization, a great deal of attention has been drawn to the impact of liming on N release. It was generally perceived that acid-mor type humus soils have restricted rates of decomposition as a result of their acid condition. However, Tamm and Pettersson (1969) demonstrated that liming actually reduced mineralization, but stimulated nitrification. Similar results were found by Viro (1963) and Williams (1972). Apparently, liming does favor rapid decomposition, but as a result N is immobilized by the active microbial population (Adams and Dickson 1973). Nitrate formation is probably stimulated by the improved pH status of the soil.

Heilman (1974) found nitrification to be considerably enhanced by the addition of urea in incubation tests. Nitrate formation in the untreated samples was correlated with total N and inversely related to C/N ratios. He related specific changes in nitrification to factors affecting the population of nitrifiers, particularly available N. Popović (1977) demonstrated that the tendency to stimulate nitrification in humus samples varies with the N source. Urea greatly stimulates production when compared with either ammonium nitrate or ammonium sulfate. Experiments by Overrein (1970) indicated a fundamental difference in the reaction of various fertilizers with the soil humus. Urea, in contrast to the other mineral fertilizers was rapidly incorporated into the humus layer. Dangerfield and Brix (1978) also reported rapid immobilization of urea by the soil microorganisms. The result is a greater availability of N from the ammonium nitrate source which probably accounts for better tree growth in their studies.

In general, fertilization with N appears to stimulate mineralization of N. In incubation studies, Williams (1972) showed this effect with Scots pine humus. Both Roberge and Knowles (1966) and Nakos (1976) found that urea treated soils had enhanced mineralization, however, exceptions were found. Westman (1974) reported this effect to be true following incubation of the humus layer but not the mineral soil. Ohita and Kumada (1979) reported that the addition of ammonium sulfate to fresh litter stimulated immobilization but accelerated mineralization in other soil layers. Popović (1967) was also able to relate the changes affected by fertilization on the mineralization of N to the growth response of the trees and their N status. In general, results from field trials indicated that fertilizer effects are more pronounced on the surface litter and humus layers than on adjacent mineral horizons.

Sulfur Response and Sulfur Availability in Forest Soils

Many studies with seedling crops, such as those summarized by Beaton (1966) and Ojo and Jackson (1972) have found that fertilizer applications containing sulfate as a component often give greater growth responses than additions lacking this nutrient. Treatment differences are usually confounded with other factors which make it impossible to assess the role of S alone. Will and Youngberg (1978) found consistently higher diameter responses in a forty-five year old stand of ponderosa pine in central Oregon when S was included with N. They also reported significant S responses in pot trials with Monterey pine seedlings on a wide range of central Oregon soils. In a similar study, Cochran (1978) reported larger, but not quite significant, responses to an N plus S treatment in ponderosa pine. Turner (1968) demonstrated that young Douglas-fir in Christmas tree plantations displayed a greater height growth when sulfate in various forms was included along with N. The latter occurred on glacial soils of the Puget Sound.

Two studies utilizing pot cultures found increases in seedling size due to S (Youngberg and Dyrness 1965, Strand 1964). Strand's study produced significant S effects on a western Oregon forest soil using both Douglas-fir and Monterey pine. Meurisse (1972), also in pot tests, reported that chlorotic symptoms similar to an S deficiency developed following N fertilization in radiata pine seedlings growing in an acid Hembre soil. No data on the levels of available soil S were presented in any of these studies.

In Australia, foliar sulfate S levels have been used to assess the potential for N fertilization response, excess S being considered a better indicator of N deficiency than total foliar N (Kelly and Lambert 1972). Humphreys et al. (1980) summarized additional information on the potential for an actual S deficiency responsible for a dieback disease and poor response to N on certain sites occupied by radiata pine. As with most of the studies cited, gross treatment observations are merely suggestive of a S deficiency.

Kang et al. (1981) evaluated the S status of forest and savanna soils in Nigeria. In pot tests, all the soils showed significant responses to S, with the savanna soil generally lower in available S. Good correlations with uptake were found with a wide variety of common extractants. Poorest correlations were noted with total organic S. Hesse (1957) studied S distribution in East African forest soils. He noted that surface soils contained little SO_4-S but high levels of organically bound S. High levels of SO_4-S were found in the subsoil, which he hypothesized as being extracted by the deep-rooted trees and then recycled through the litter. He also found little of the organically bound S to be released during incubation. A similar distribution of SO_4-S was found by Johnson and Henderson (1979) in a highly weathered Utisol in Tennessee under a mixed deciduous forest. In this respect it is of interest to report Storey and Leach's observations (1933), that S deficiency in tea decreased with crop development presumably due to increased access of the roots to the subsoil. This same developmental pattern was also found by Gosnell et al. (1964) with wattle.

The percentage of S in the organic fraction greatly exceeds the mineral fraction, at least in the surface soil (Biederbeck 1978). However, both uptake and response studies have found the mineral fraction to have a dominant influence on the results (Probert and Jones 1977). Studies by White (1959) pointed to the influence of pH and C/N/S ratios as factors controlling mineralization in situ. Data collected by Williams (1967) and many others certainly substantiate the belief that low pH and high C/N/S ratios result in decreased mineralization or rapid immobilization of S. Organic S is probably of tremendous importance to long term fertility, especially on deficient soils, however, its availability to the crop may be less important in short term evaluations than mineral S.

Turner et al. (1977) utilized SO_4-S to separate high and low N responding stands of Douglas-fir. Low levels of SO_4-S were associated with low response to N. It was not altogether clear whether low values of SO_4-S (< 200ppm) represented high levels of available N or low levels of available S. Later refinements (Turner et al.

1979) appeared to indicate an absolute deficiency of S occurred when SO_4-S was less than 80 mg kg^{-1} in radiata pine and perhaps Douglas-fir. Low levels of S have also been associated with a dieback disease in exotic plantations of radiata pine (Lambert and Turner 1977). More recently several workers have proposed that the N/S ratio would be a reliable criterion for measuring S availability. Stewart (1969) suggested a ratio of 15:1 for plant material and 10:1 for soil humus if the crop is not to be critically short of S. This is in agreement with Dijkshoorn and van Wijk (1967) who reported a fairly constant ratio between the two elements in a wide range of crop crude protein, ranging from 14:1 to 17:1. A close ratio of about 15:1 has been reported for radiata pine (Kelly and Lambert 1972).

Summary of Literature

Reported volume responses to N for Douglas fir in the Pacific Northwest appear to be higher than in other conifers. The range in response is also very large. Stand conditions which affect volume response are site quality, age and possibly stocking.

In comparison with P, K and several micronutrients, measures of N availability appear difficult to define precisely. This is believed to result from variable inputs to the stand from the soil, litter, internal redistribution and storage. Several authors emphasized that N demand on the soil system is highest prior to crown closure. Others believe that N is withdrawn from the soil, followed by gradually immobilization in the forest floor and biomass. This can lead to increasing N deficits. Total N in the foliage and site quality are often reported to be positively correlated.

Mineralization studies in forest soils reported variable relationships to other soil properties, stand conditions and treatments. Rates of N release during incubation are generally related to C/N ratios in the humus layers, and total N in the mineral soil. The release of N from the mineral soil is smaller when expressed on a weight basis, however it is generally larger when expressed on an area or volume basis. Mineralization in the field has been shown to be highly sensitive to temperature. N mineralization has been positively correlated to site quality in many studies. N fertilization appears to enhance mineralization for short periods following application. Nitrification is especially sensitive to N fertilization.

The analysis of several field fertilization trials suggest that N responses in certain regions may be limited by S. Critical quantities in the soil have not been established for conifer crops. Low levels of SO_4-S in the foliage (< 200 mg kg^{-1}) have been used to discriminate between high and low N responses in Douglas fir. In highly weathered soils, substantial quantities of S are accumulated in the subsoil. This pattern is believed to be important to assessing S availability to perennial crops.

Chapter II

METHODS

Soil Collection and Preparation Procedures

The published sample variation estimates of Shumway and Atkinson (1977) were used to determine the number of cores per plot. According to their work twenty-five cores would be required to be within ten percent of the true mean and four to be within twenty percent at a critical N concentration of 42 mg kg^{-1}. Appendix A lists coefficients of variation for a wide range of soil properties measured.

The least intensive sampling scheme called for a systematic sample of sixteen cores from the control plots to a depth of 15 cm and a composite of sixteen cores from the buffer zones between plots. The buffer sample was used to test for bias in the use of control plot data. Based upon standard variance estimates from intensively sampled plots, the sixteen cores will produce a 95% confidence interval around a mean of 42 mg kg^{-1} of ± 5.2 mg kg^{-1} N. This corresponds to a C.V. of 12.4%. The exception to this sampling procedure was followed on extremely gravelly soils, such as those of the Everett series, in which six large cores to 15 cm were collected using a hand trowel. At the time each surface core was collected the litter and decomposed humus layers were separated.

Subsoil samples, primarily designed to provide estimates of available S at depth, were collected in the upper third of the textural B-horizon at each site. Depth varied from a minimum of 35 to 45 cm to a maximum of 75 to 85 cm. Four cores were extracted with either a bucket auger or shovel just off the perimeter of each control plot.

Almost all samples were collected from November to April, with the heaviest concentration in the period of January through

March. During the initial collection phase six installations had frozen soil (Appendix B).

Following field collection, soils samples were processed within a few days as follows: The material was first passed through a 12 mm^2 mesh sieve in a moist state. The remaining material was then placed on aluminum trays in a large oven, which was held at 30°C. The time needed to reduce moisture content to an air dry state varied from three to five days. Occasionally samples were allowed to dry at room temperature.

Immediately following drying, samples were crushed with a wooden mortar to pass a 2 mm^2 sieve. The excess material above 2 mm^2 (gravel) was weighed. The fraction below 2 mm^2 as a proportion of the total weight was designated as the specific fraction or active fraction.

Incubation Procedure

Samples were incubated in an essentially identical manner to the methods proposed by Bremner (1965). For anaerobic conditions, 5 g of dry soil were poured into a 20 cm^3 test tube containing 12 cm^3 of distilled water passed through a H^+ saturated exchange resin to remove traces of ammonium. No special procedures were used to submerge organic material which tended to float on the surface. The tubes were then capped with serum stoppers and placed in an incubator for fourteen days at 30°C.

Aerobic incubations were created by mixing 5 g of dry soil with 15 g of acid washed silica sand (ASTM Grade) followed by the addition of 3 cm^3 of water. This mixture was placed in a 1x6 cm polystyrene petri dish, covered and the entire group of samples sealed inside a six mil polyetheylene bag.

Extraction was carried out with 1N KCL using a 1:5 soil: solution extraction ratio. The supernatant was filtered through Whatman #42 to produce a clear solution for analysis of ammonium and nitrate. Duplicate incubations were run for each sample. Samples were stored frozen (-20°C) for short periods prior to analysis (2-4 weeks). Tests of both standards and samples during prolonged freezer storage showed no significant change in ammonium concentration. No comparable analysis was conducted on nitrate.

Analytical Methods

Ammonium

The ammonium ion was determined with either an HNU or Orion ammonium specific-ion electrode in conjunction with a Leeds and Northrup pH/specific ion meter (Model 1401) (Banwart et al. 1972). Five cm^3 of extract were added to 43 cm^3 of water and the latter treated with 2 cm^3 of ten percent NaOH solution. A linear output was found between 0.1 mg kg^{-1} and 10 mg kg^{-1}, which represents the general limits of the sample results. Standards were checked using the standard addition technique since the output of the ammonium electrode is very near the theoretical voltage calculated with the Nernst equation. Sample concentrations were read from a calibration curve and are reported as elemental N per gram oven dry (105°C) soil.

This technique is relatively insensitive to organic or metallic ion interference with the exception of amines. A good correlation between this method and traditional steam distillation procedure was found for anaerobic samples which should theoretically be free of nitrites and nitrates (Figure 1).

Nitrate and Nitrite

The procedure of Shinn (1941) was used to screen samples for the presence of nitrite, both before and after incubation. Only trace quantities were detected. The maximum quantity in any sample was 0.05 mg kg^{-1}.

Nitrate was calculated as the difference between total N, determined by using Devarda's alloy and steam distillation and ammonium N measured by the electrode method. The sensitivity of

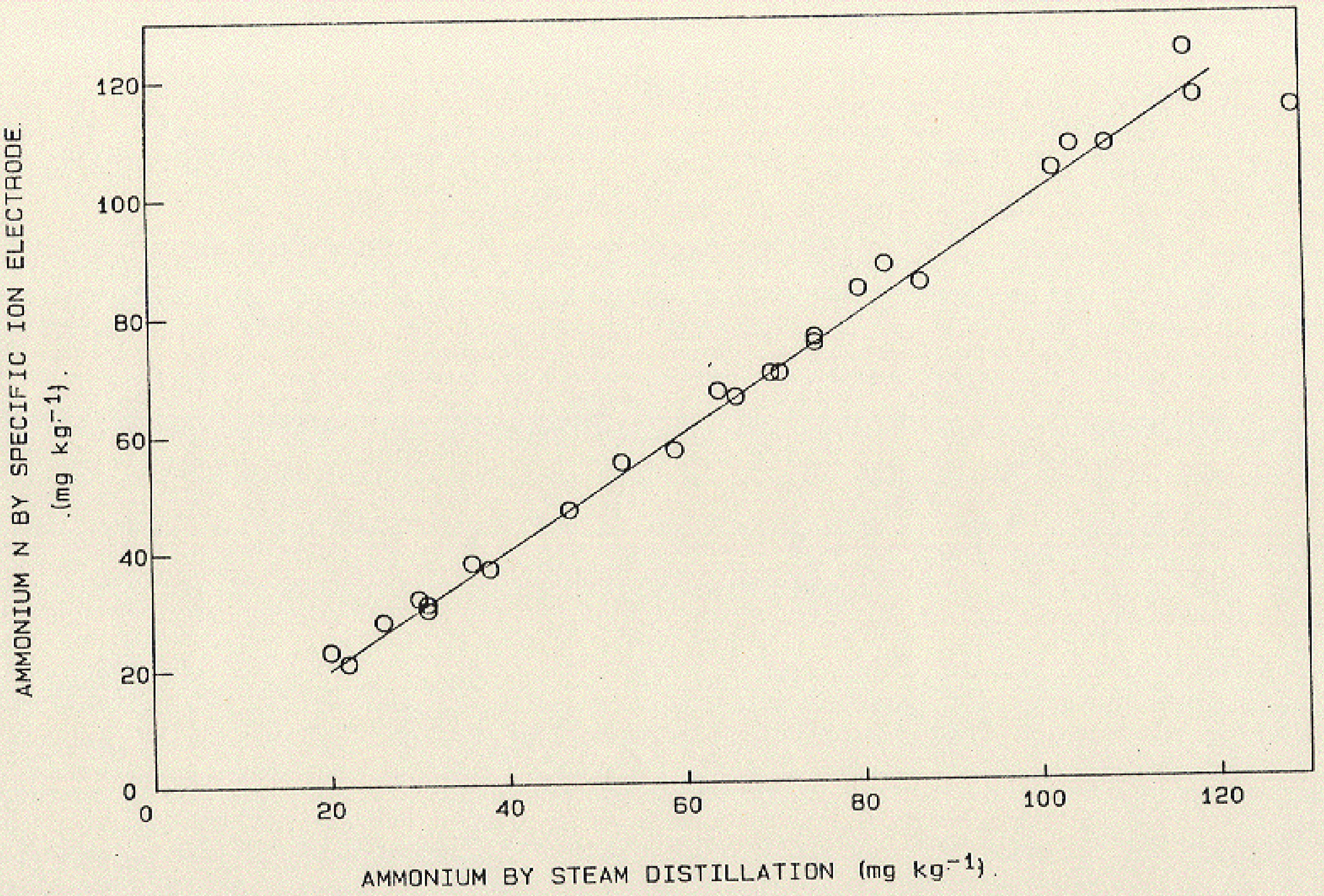

FIGURE 1: AMMONIUM ANALYSIS BY STEAM DISTILLATION VS. SPECIFIC ION ELECTRODE. Determination of ammonium N from 1N KCL extracts of anaerobically incubated. soils using an HNU specific ion electrode and steam distillation with MgO..

this technique was partially limited by the errors in titration, since one drop of titrant is equal to 0.7 mg kg^{-1} of N. An alternative procedure was developed using chromotropic acid (CTA) (Clarke and Jennings 1965, Sims and Jackson 1971). This method is insensitive to chloride interference encountered in the standard phenoldisulfonic acid method (Appendix C). A notable limitation with this method is its apparent sensitivity to low molecular weight organics in solution which complex with the CTA to form a deep purple color. This color complex was only a problem in pre-incubation extracts, presumably due to the metabolism of these compounds during the incubation processes. Nitrates could not be adequately quantified in the pre-incubation samples by either technique, therefore nitrate values reported include the quantities present prior to incubation.

A poor correlation was observed between the two methods used to determine nitrate. The problem may be the result of a long period of frozen storage, up to eighteen months in some cases between the use of the steam distillation-electrode and CTA procedures. Recent results reported by Breuer (1984) indicated nitrate may be relatively unstable even during freezer storage. The CTA method gave consistently lower values.

Total Nitrogen

Total N was determined using a standard micro Kjedhal procedure (Oregon State University 1978).

Phosphorus

Available P was estimated by extraction of a 2 g soil sample with 15 cm^3 of a Bray #1 solution. P was determined colorometrically with the molybate-vanadate reagent at 420 nm (Oregon State University 1978).

SO_4-Sulfur

Available S was determined by extracting with Morgan's solution (1N Na-acetate at pH 4.5) and measuring SO_4-S by the technique of

Johnson and Nishita (1952). The procedure also removes a significant amount of organic S, which is digested during the analysis.

The acetate ion is not a strong competitor for sulfate absorption sites (Chao 1964) and as such only displaces sulfate anions which are weakly coordinated or have only a single bond with iron or aluminum oxides.

Organic Matter

Levels of organic matter in each sample were measured by ignition in a furnace at 400°C. This is less than the critical temperature needed to expel intercrystalline water from most clays (Grimm 1968) yet high enough to destroy most organic compounds. Ball (1964) found the ignition method to give satisfactory results after an extensive examination of many soils. Soils were ignited for twenty-four hours, which appears optimum (Appendix D). A substantial portion of native charcoal was also consumed by this method.

A comparison of ignition vs. the Walkley-Black procedure (Figure 2) shows that the former method gave values approximately two-fold greater. The fact that the regression line passes through the origin, indicates that the techniques are comparable. There is no clear evidence to explain the two-fold difference, although there are many assumptions in the wet digestion method, percent recovery and carbon-organic ratio that may not be valid in this instance. It is also possible that not grinding the soil to 0.5 mm lessened the access of the dichromate to the organic matter. A similar correlation was found by Storer (1984) between the Walkley-Black method and ignition.

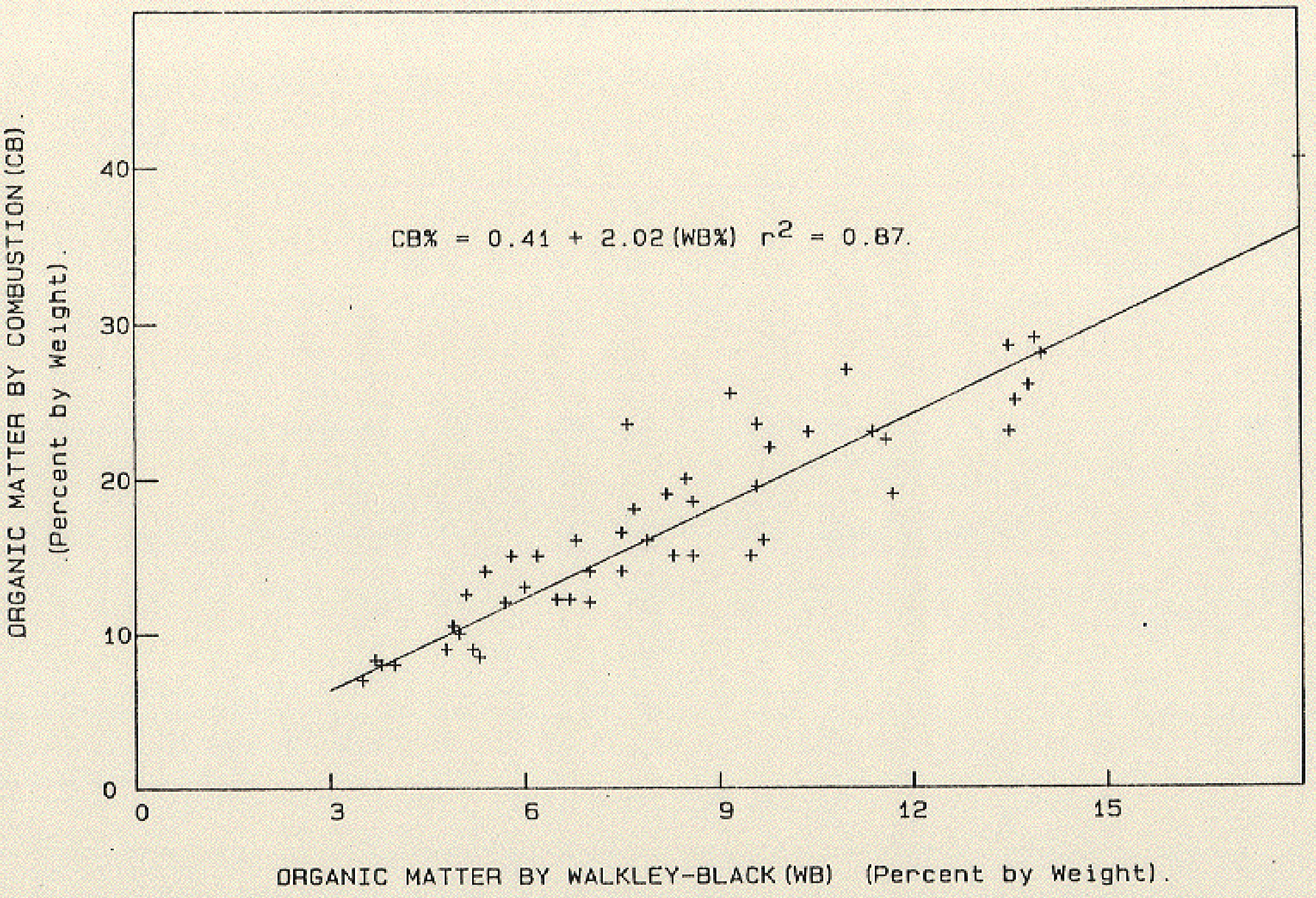

FIGURE 2: ORGANIC MATTER ANALYSIS BY COMBUSTION VS. THE WALKLEY-BLACK METHOD. Organic matter determined on 2 mm soil fraction by ignition at 400°C for 24 hours. and by dichromate oxidation using the Walkley-Black method.

Chapter III

GROWTH RESPONSE OF DOUGLAS-FIR TO UREA NITROGEN

Installation Selection and Response Measures

The entire population was chosen from stands which were part of the Weyerhaeuser Company's Empirical Fertilization Trials and the University of Washington Regional Forest Nutrition Fertilization Cooperative (Phase I and II). From the combined population of slightly over one-hundred Douglas-fir sites, 51 were selected. All of the installations comprising three or more soils of the same soil series were selected (Appendix E). This selection criterion resulted in twenty-eight sites, representing seven soil series. The second independent criterion depended upon the presence of a "complete" fertilizer treatment plot at the installation. These were all derived from the Weyerhaeuser EFTs. These included some of the previous group and, in addition, twenty-three new stands.

The selection method resulted in nineteen Regional and thirty-two EFT sites in the final study population. Figure 3 shows the distribution of these installations in western Oregon and Washington. There is a fairly heavy concentration along the foothills of the Willamette valley and in southwest Washington between Mt. St. Helens and Olympia. Very few coastal sites were included. Major industrial sources of S are also identified. In Washington the ASARCO Smelter in Tacoma, the Centralia Steam plant and the pulp and paper mills near Longview represent the most significant sources of contamination in relation to their proximity and the predominant air flow in the direction of the sites used. In Oregon, the pulp and paper mill at Albany is possibly the only significant source that could affect the study results.

Table 1 gives a two way distribution of sites by age and site quality at the time of initial fertilization. This distribution can be

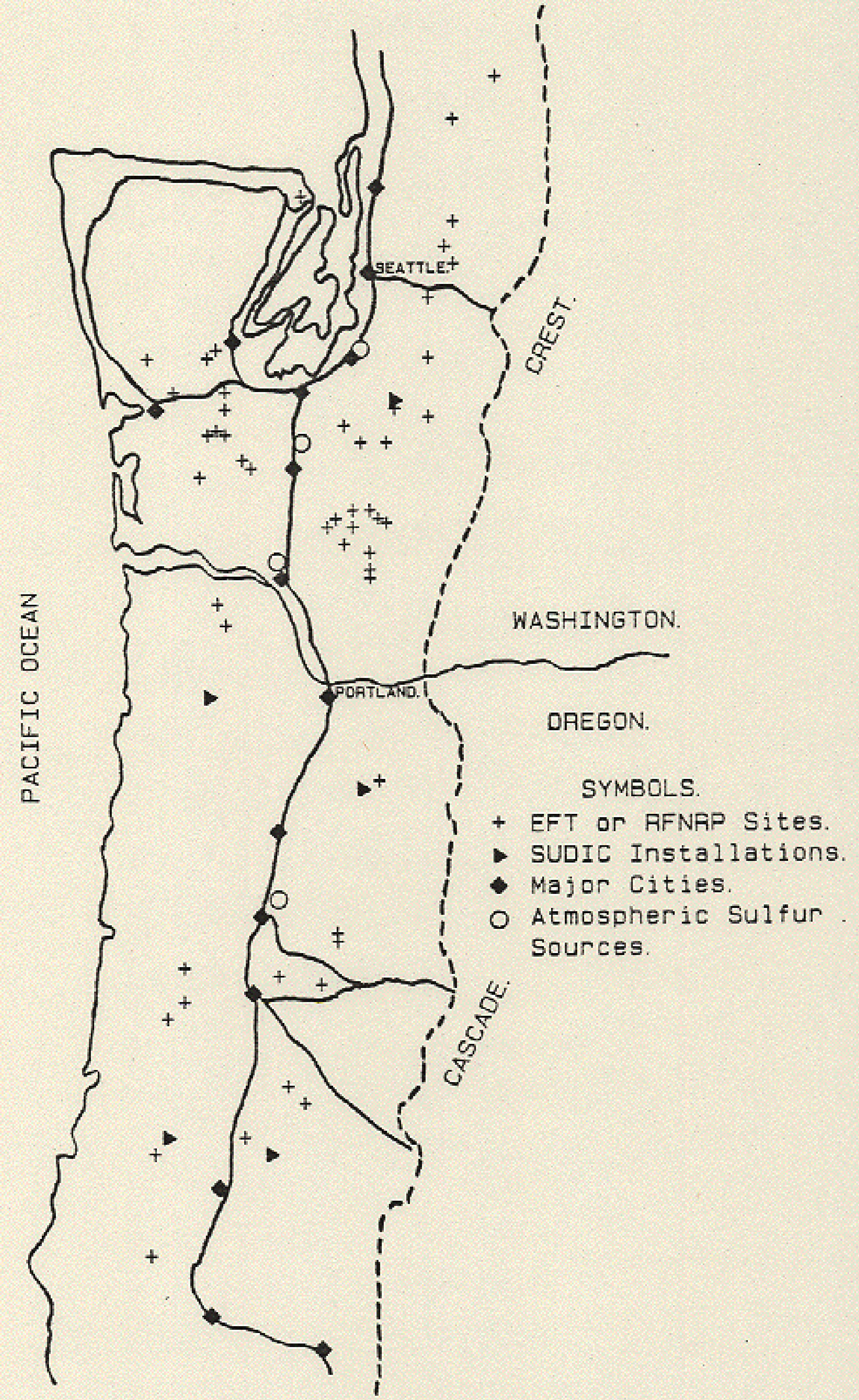

FIGURE 3: GEOGRAPHIC DISTRIBUTION OF INSTALLATIONS.
EFT, RFNRP and SUDIC stands sampled in western Oregon and Washington..

Table 1: Distribution of Sampled Installations by Age and Site Quality.

	Breast Height Age at Fertilization						
Site Index	0-10	10-20	20-30	30-40	40-50	50-60	Total
40-44m	3	2	6	2	3	0	16
35-40m	0	2	5	4	3	1	15
30-35m	0	1	4	8	2	1	16
25-30m	0	0	0	3	1	0	4
Total	3	5	15	17	9	2	51

be compared with the one published by the Regional Co-operative (1978). In general, this study contains a larger proportion of very high site quality stands.

Mean volume response for each location was estimated by averaging the calculated or adjusted response for either the 336 and 560 kg ha^{-1} N treatments, in the case of the EFTs, or the two 224 and 448 kg ha^{-1} N treatments for the RFNRP installations.

The model used to compute the calculated response has been reported elsewhere (Regional Forest Nutrition Research Project #39, 1981). The reported mean for this combined analysis, 21.7 m^3 ha^{-1} 5 $years^{-1}$, is very close to the mean of the selected population (22.2 m^3 ha^{-1} 5 $years^{-1}$). An advantage of using the combined analysis is in the lower standard error of the estimate surrounding the calculated response (±13 vs. 21 m^3 ha^{-1} 5 $years^{-1}$).

An alternative method for determining a relative apparent response was proposed by Gagon (1975) and used by Shumway and Atkinson (1978) and Olsen (1982). The paired tree analysis was used to estimate biological response on a large number of sites. Unfortunately, only a third or less of the sites actually met the pairing criteria. The values correspond in a general manner to calculated volume estimates (Appendix F).

Stand Structure and Volume Response

Within the population of stands used in this analysis, volume response was significantly related to both stand B.H. age and site index (Table 2). Growth response increased linearly with increasing age and decreased with increasing site. A composite equation using both variables had an r^2 value of 0.46. The overall F-value was significant at $P < \alpha = 0.001$.

Volume Response (m^3 ha^{-1} 5 $years^{-1}$) = 43.77 + 0.39 (B.H. Age) -0.91 (Site Index)

Figure 4 shows the general relationship between age, site quality and volume response.

Effect of Age

The residuals, following removal of linear site index effects, are shown plotted against stand B.H. age in Figure 5. The data were split by site quality into two groups, those representing typically very high sites, greater than 38 meters at 50 years, and those representing average sites for the region, less than 38 meters.

While the composite model suggests an overall positive relationship with age, splitting the populations reveals a more complex pattern. On the high sites the deviations become consistently more positive with age. On the average sites, within a narrower age range, there appears to be both positive and negative trends. There is either no general effect or a very complex relationship to age on the average sites.

Positive effects of age on N response have been reported in several other studies. Lin et al. (1978) found linear effects of age on volume response of Douglas fir in S.W. British Columbia as did Strand and Debell (1979) on Crown Zellerbach holdings in western Oregon and Washington. A similar pattern was reported by Gustavsen and Lipas (1975) for Scots pine in Finland. While the Regional Co-operative study did not report a linear age effect, it is

Table 2: Simple Correlation Matrix Between Stand and Soil Variables.

Values derived from 51 EFT and RFNRP installations.

	Soil and Stand Variables										
Variables	1	2	3	4	5	6	7	8	9	10	11
2. Site Index	-0.56										
3. B.H. Age	0.57	-0.39									
4. Spec. Frac.	-0.43	0.57	-0.32								
5. Nitrate N	-0.31	0.37	-0.22	0.33							
6. N Aerobic	-0.44	0.35	-0.31	0.36	0.42						
7. N Anaerobic	-0.27	0.15	-0.29	0.22	0.46	0.86					
8. SO_4-S 0-15cm	0.04	0.19	-0.02	0.31	0.03	0.37	0.20				
9. SO_4-S Subsoil	-0.13	0.39	0.00	0.36	0.14	0.36	0.15	0.55			
10. Phosphorus	0.04	-0.29	0.06	-0.33	-0.10	0.31	0.33	-0.34	-0.28		
11. Foliage Biomass[a]	0.35	-0.14	0.68	-0.16	-0.11	-0.21	-0.20	0.07	-0.09	-0.20	
12. Foliage Increm.[a]	-0.37	0.34	-0.67	0.37	0.60	0.63	0.58	0.18	0.25	-0.09	-0.66

Variable 1 is equal to Calculated Volume response

[a] Calculated for control plots using the equations of Snell and Anholt (1981)

$r = 0.275$ for $P < \alpha = 0.05$; $r = 0.354$ for $P < \alpha = 0.01$

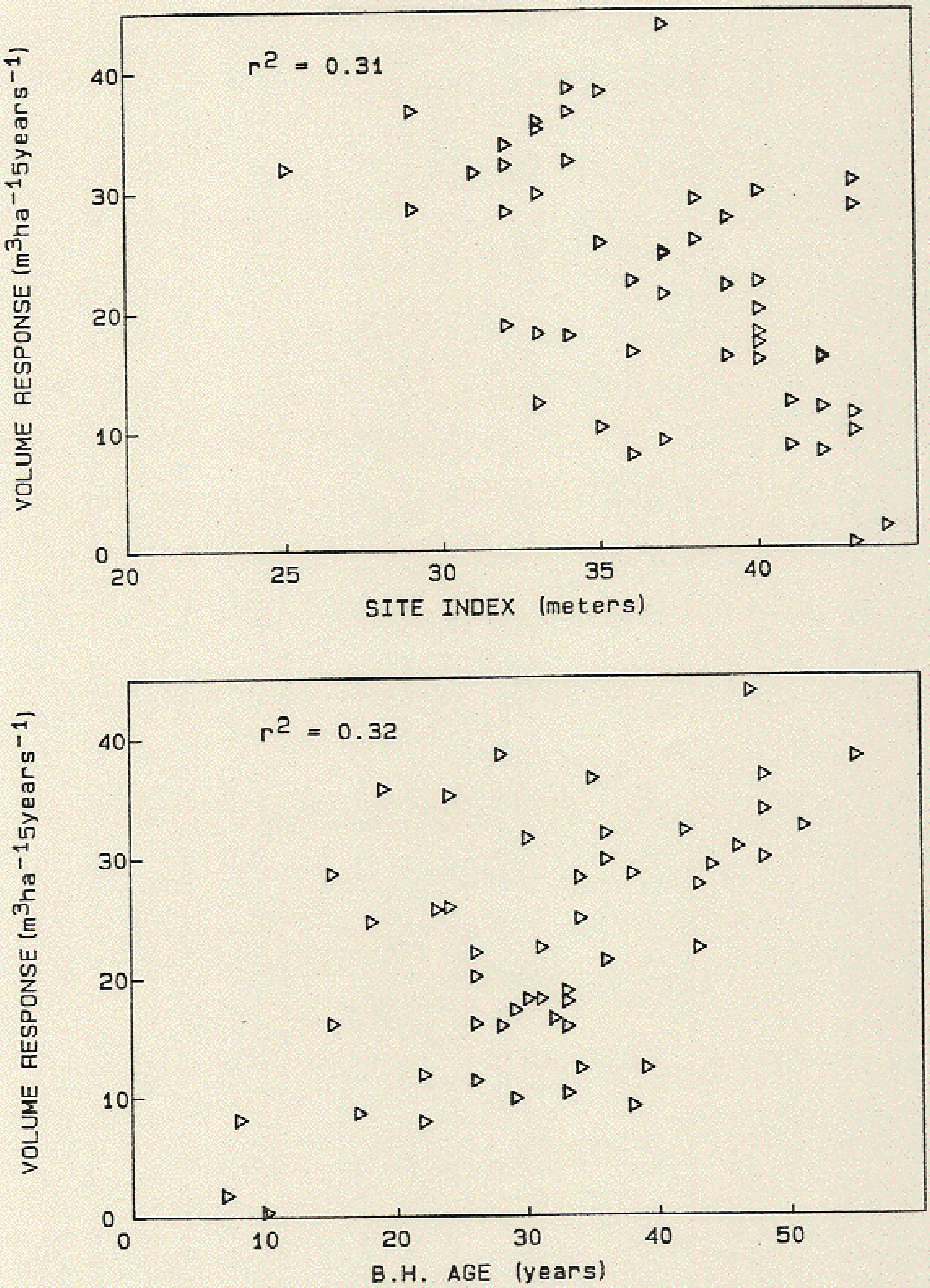

FIGURE 4: RELATIONSHIP OF AGE AND SITE INDEX TO VOLUME RESPONSE Age is B.H. age at the time of fertilization. Site index is determined at 50 years using the tables of King (1966).

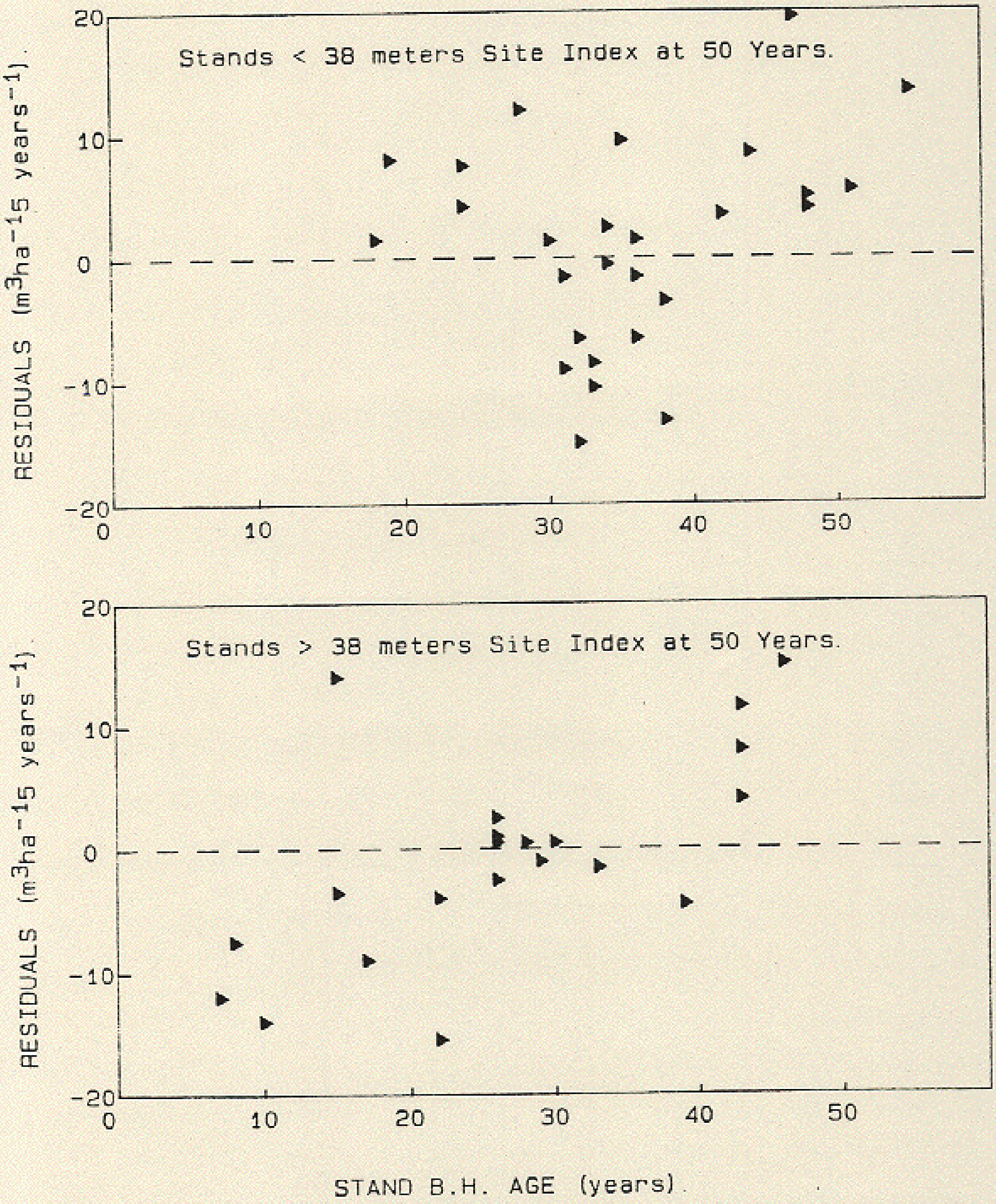

FIGURE 5: SITE INDEX REGRESSION RESIDUALS VS. B.H. AGE. Values derived from simple linear regression of site index on volume response. Figure split to show high and low sites.

possible that the age x site interaction suggested in this analysis is responsible. Their study did not include as large a proportion of younger, high site stands.

There is evidence to support a biological rationale for age effects on N availability. Early studies in Douglas fir established the distribution of N in a wide range of natural stands less than 100 years old (Gessel et 1. 1972). Most of the N in the system was concentrated in the mineral soil profile, especially within the more youthful glacial soils. The amount of N in the above ground portions was about equally distributed between the forest floor and standing crop. The authors hypothesized that during establishment of the stand, N was withdrawn from the soil reserves and either immobilized in the standing crop or forest floor, since both these compartments were found to have a net accrual.

Others (Heilman 1966, Viro 1967, Williams 1972) have also suggested a continuous withdrawal from the N pool in the mineral soil coupled with gradual immobilization in the humus and standing crop could lead to an increasing N deficit, and presumably larger N fertilizer response. In contrast, Miller (1981) and also Switzer and Nelson (1972) envisage N response potential to follow net N immobilization by the standing crop. The latter is usually highest just at crown canopy closure because a large percentage of the N is concentrated in the foliage. Most studies report that total crown biomass stabilizes after closure (Tadaki 1966, Ovington 1959, Miller 1978, Madgwick et al. 1977, Satoo 1968). At that point N cycling through litter fall and decomposition is believed to supply demand (Gosz 1981) until an advanced age is achieved. The strongest evidence for this reasoning is the fact that in natural stands N uptake in the crown is balanced by N return through litter fall. It is assumed that rapid decomposition of the litter will release the remaining N to supply crop demand if there are no significant N losses through leaching or denitrification. This leads to the notion that cycling enables the stand to become independent of the nutrient status of the mineral soil.

Clearly, a continuous increase in N response as seen on the high sites is at odds with the rapid cycling hypothesis. The disparity can be reconciled if one assumes a fairly constant N demand on the system by the crop, beyond the period of establishment. Therefore, changes in response reflect a decrease in either N availability in the soil system or decreased N mobilization from the forest floor. Although, net N uptake and immobilization certainly decrease after crown closure, gross demand on the soil system may actually continue to increase. This takes place if litter fall increases with crown biomass (Figure 6), requiring a greater amount of total N to be replaced by the stand. Assuming the crown continues to expand with age (Figure 7), the estimated net increment is in fact only a fraction of the total foliage replaced by the stand annually.

If annual litterfall is generally between 20 to 30 percent of the existing foliage biomass following crown closure (approximately 15,000 kg ha^{-1}), then, based upon an N content of 0.7 percent, the total N which must be replaced may range from 21 to 32 kg ha^{-1}. This value is about ten times the estimated net uptake that occurs in Douglas fir.

This interpretation does not infer that decomposition and N release from the litter is unimportant to the N economy of the stand. Under N limiting conditions any change in the mineralization/immobilization rates of the litter can affect significant changes in the stand N status (Piene 1978, Williams 1972, Mahendrappa 1978). Several studies have shown age dependent fluctuations in forest floor accumulation and decomposition (Page 1968, Jose and Koshy 1972, Turner and Long 1979, Edmonds 1979). Rapid initial rates of decomposition, corresponding to increased soil exposure following stand removal, are generally followed by accumulations as a result of ground flora inputs and tree litterfall. A similar trend can be seen in the surface soil (Figure 8) on the high sites. In many studies, the rate of decomposition is not a constant, but appears to be a maximum at or just after crown closure. The latter appears to

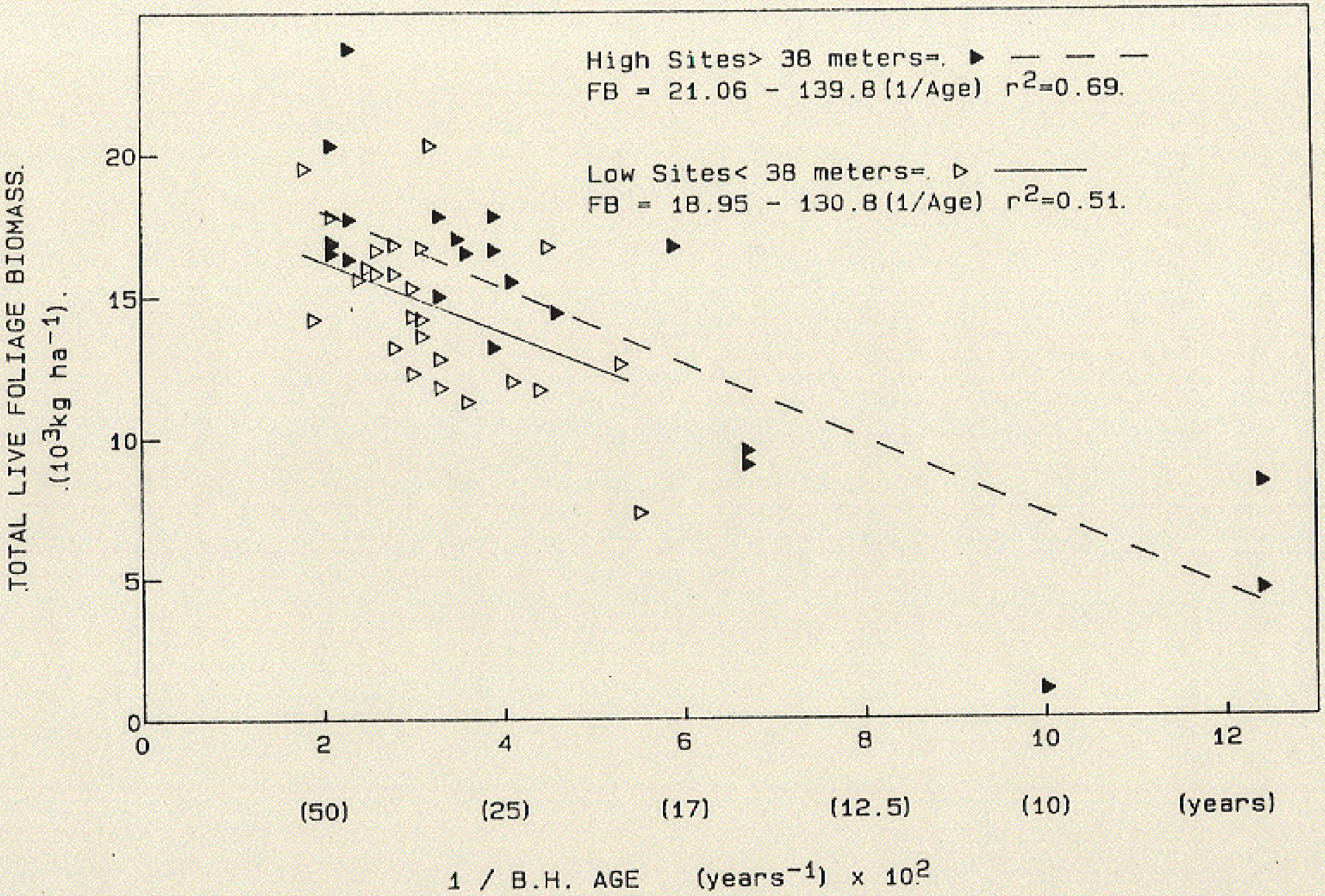

FIGURE 6: TOTAL ESTIMATED LIVE FOLIAGE BIOMASS VS. THE INVERSE OF STAND B.H. AGE . Values calculated for control plots at the beginning of the treatment period using the equations of Snell and Anholt(1981).Intercepts significantly different at $p=0.026$..

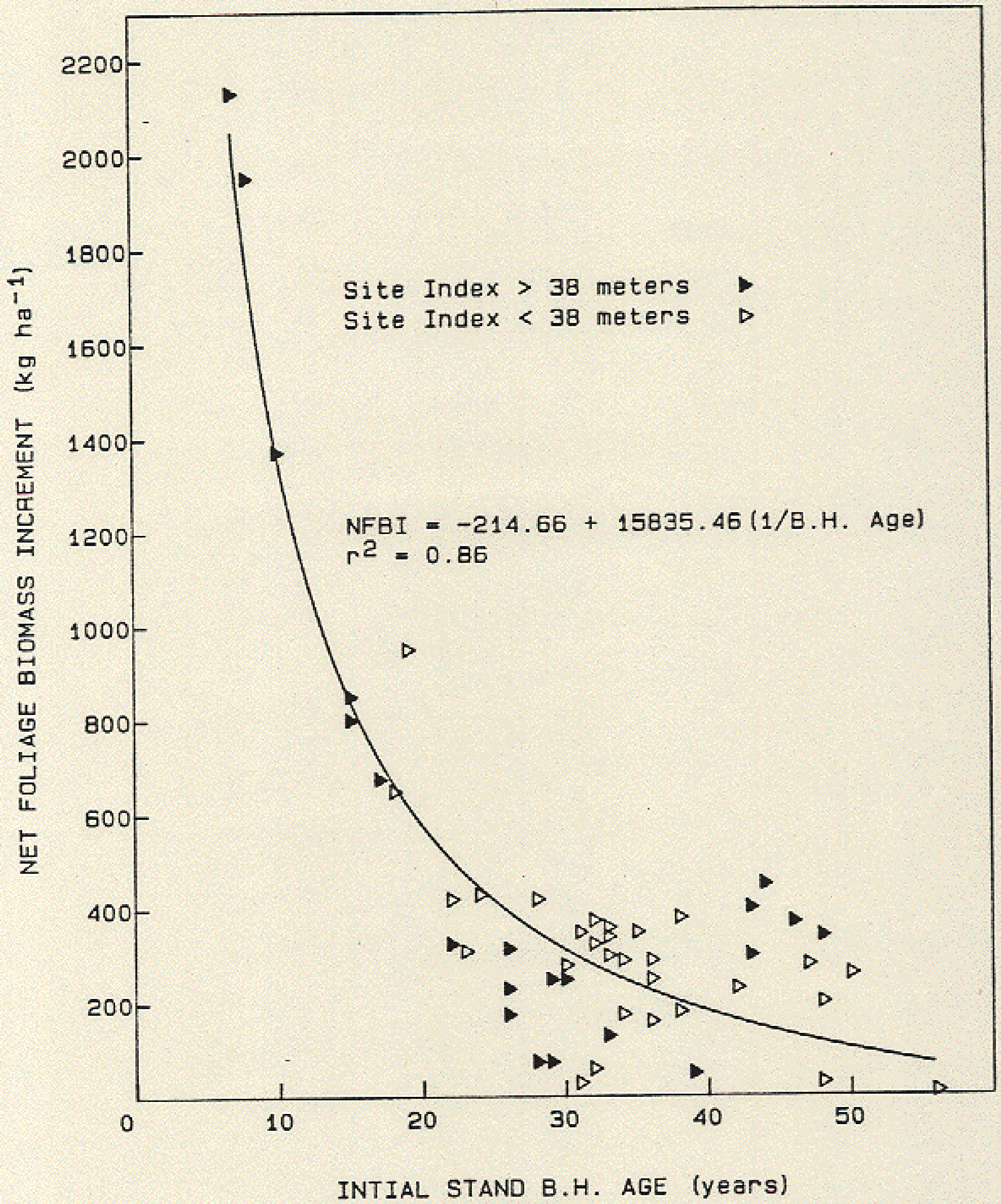

FIGURE 7: CHANGES IN NET FOLIAGE BIOMASS INCREMENT IN RELATION TO STAND AGE. Calculated for initial five seasons on control plots using the equations of Snell and Anholt (1981). Points are idenified by site quality class.

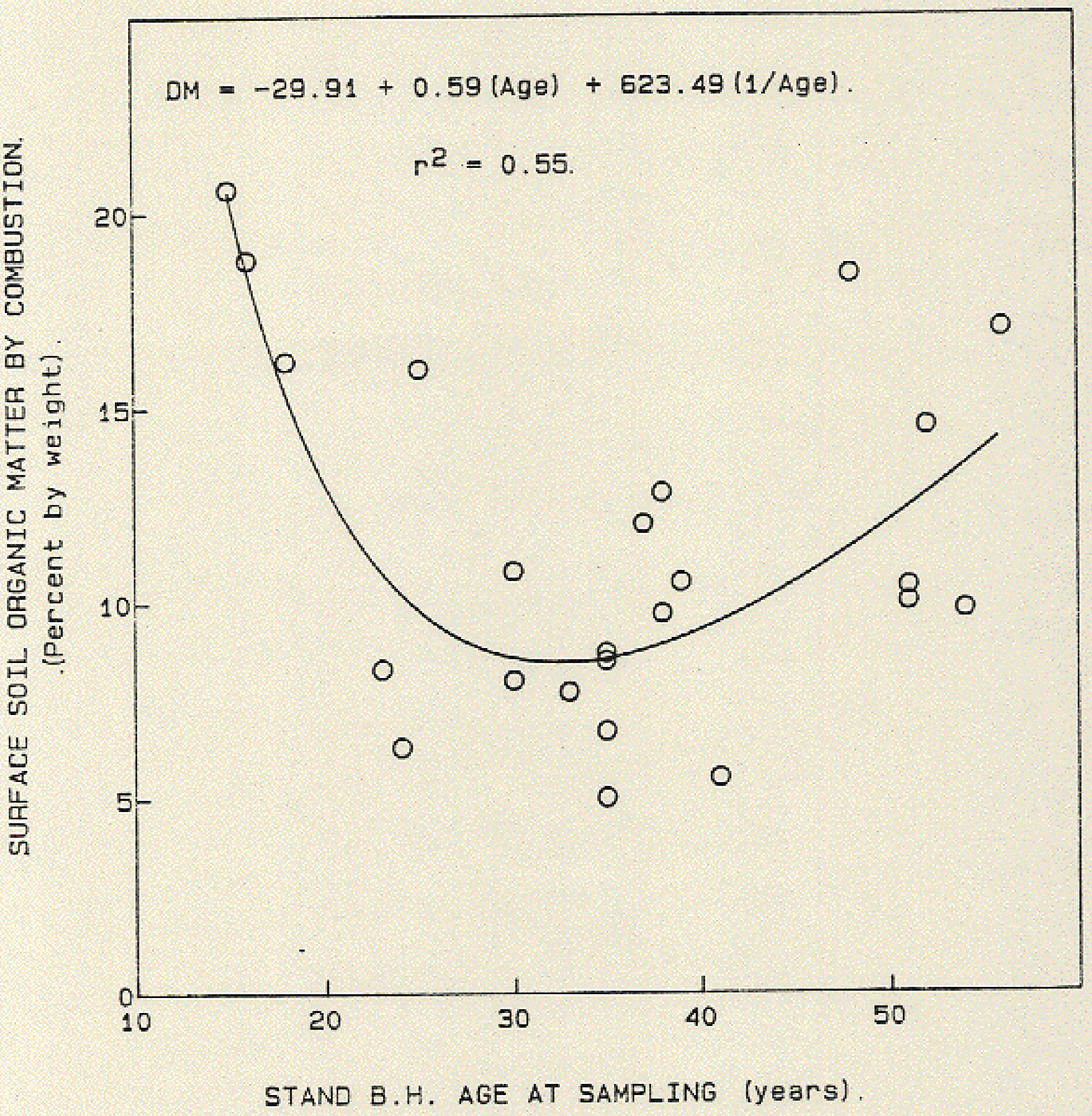

FIGURE 8: CHANGES IN SURFACE SOIL (0-15cm) ORGANIC MATTER CONTENT IN RELATION TO STAND B.H. AGE.
Samples from control plots on stands with site index > 38 meters. Organic matter based upon < 2 mm soil fraction. Values adjusted for gravel content by weight..

be related to a more favorable environmental condition (Edmonds 1979) and may be responsible for temporarily enhanced N status. Whether this accounts for the negative response deviations in the 30-40 year old age group on the average sites is uncertain. The time frame is beyond the period of crown closure. If N availability is increased during the period of crown closure, then N uptake and utilization by the stand may actually lag release by the forest floor.

The large responses on the young, less than 30 year old stands on average sites when compared with high sites is indicative of limited N availability. This tendency agrees more with the concepts proposed by Miller (1981). In general, the superficial pattern on the average sites conforms to his expectations. His specific propositions relating N response to N cycling may be valid when applied to situations in which available N in the soil system is clearly insufficient to support potential crown formation.

Effect of Site Quality

Site index effects are displayed as residuals from the age regression in Figure 9. Response to N fertilization is negatively related to site index at the time of treatment. A strong negative correlation with site index has also been reported in other analysis (Regional Forest Nutrition Research Project Biennial Report 1976, Strand and Debell 1979) within the Douglas fir region. However, a positive relationship was found by Lin et al. (1978) for stands in British Columbia. The highest sites in the latter study were nearly equal to the lowest sites in the former two studies. Similar effects were noted in loblolly pine (North Carolina Co-op 1980) and Scots pine (Malkonen 1979). It is apparent that a universal trend with site quality does not exist.

Within a regional context, the correspondence suggests that N availability decreases with decreasing site quality. The N content of conifer foliage has been positively related to site quality in a number of reports (Strebel 1960, Wehrmann 1967, Hohne 1967, Ito et al. 1972, Lea and Ballard 1982). However, it is unclear as to

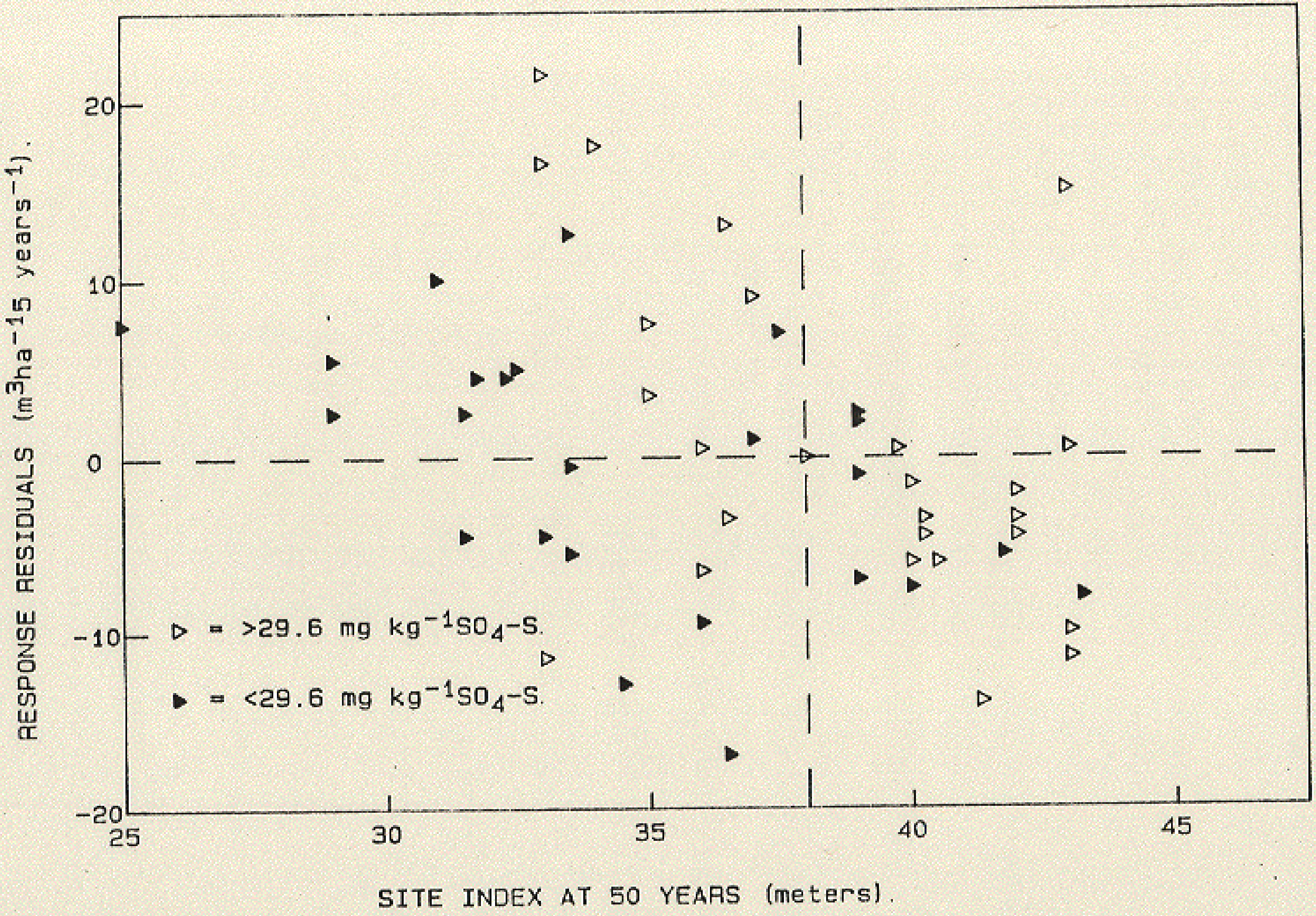

FIGURE 9: STAND B.H. AGE REGRESSION RESIDUALS VS. STAND SITE INDEX.
Values derived from simple linear regression of age on volume response..
Available S level determined as = A horizon SO_4-S +[Age x 10^{-2}x Subsoil SO_4-S]..

which factors may contribute to lower N availability on inherently less productive sites. In some cases, lower N availability may be related to lower total N in the soil (Gessel et al. 1969, Kawana 1966) as a result of limited soil development or site degradation. Zöttl (1960b) was able to demonstrate that N mineralization in the humus layer was highly correlated with site quality in pine. These values were in turn correlated with C/N ratios. Similar results were reported by Le Tacon (1973).

Direct comparison of specific N cycling processes between site classes with similar stand characteristics are rare. Edmonds et al. (1981) examined decomposition rates both within and between productivity classes. No significant differences in needle decomposition could be detected between site classes. Differences within age and site classes appeared to be a result of environmental conditions. The effect of site quality on N availability represents apparently complex interrelationships between soil characteristics and stand development.

Soil Test Variables and Volume Response

Nitrogen Mineralized

The correlation between soil N mineralized and volume growth (Table 2, page 30) accounts for only 20 percent of the variation in response. This value is less significant than either site index or age and is comparable to the less involved measures of N using either total N or C/N ratios (Peterson et al. 1984). An even poorer r^2 was realized with the anaerobic test values.

Two additional variables were tested, specific fraction (i.e., 1- gravel fraction of soil by weight) and the estimated mean annual air temperature at the installation. Several detailed experiments (Waring and Bremner 1964, Chichester 1971, Robinson 1967) have demonstrated that the larger particle size material does not contribute to the mineralization potential. Adjusting the N release rate by this relatively inactive fraction should balance differences in rock content so that a more realistic estimate of the N mineralization potential per unit of soil area or volume can be obtained. A similar effect was reported by Shumway (1984) using bulk density and gravel content per unit volume to adjust his N incubation results. Using proportional weights probably underestimates the volumetric importance of the 2 mm fraction because of the normally higher mineral densities of the unweathered rocks. Mean annual air temperature estimates for each site were derived from elevation using weather station temperatures in Oregon and Washington (Appendix G). The assumption that air and soil temperatures are highly correlated has been validated (Bouyoucous 1913). Temperature within the soil has been demonstrated to be important by a number of experimenters (Lemee 1967, Ellis 1974, Powers 1980).

In the final regression model both variables significantly improved the prediction of volume response (Table 3, Model 1). In the analysis, the overall F-value was found to be slightly better when each factor was included separately, rather than using them to directly transform or weight the N mineralization results. This was very evident with the specific fraction, and suggests that the equations were improved when more weight was applied to this variable.

The specific fraction variable may provide more information about the stand N status than the proportional reduction in the mineralization values. Perhaps moisture availability or root development is adversely affected to the extent that N availability is further reduced. The adjustment for gravel in terms of nutrient dilution can be questioned on theoretical grounds. Research with K by Heiberg and White (1951), P (Ballard 1974) and S in this study have not shown any significant effect of gravel content on nutrient deficiencies. Neither have significant effects been reported in agriculture. The effectiveness of temperature was probably due to the wide range in elevations and latitudes among the sampled stands. A number of installations above 600 m had unexpectedly

Table 3: Multiple Regression Models for Volume Response of Douglas fir to Urea Nitrogen

	Variables	Coefficients	F-Value	Rank	P Level
Model 1: Soil Variables					
Volume Response ($m^3 ha^{-1} 5\ years^{-1}$)	Constant	$b_0 = 70.741$	33.07		0.000
$b_0 + b_1$ (N Mineralized Aerobically)	N Mineral.	$b_1 = -0.253$	29.43	1	0.000
$+ b_2$ (Specific Fraction) +	Fraction	$b_2 = -11.811$	4.11	5	0.048
b_3 (Mean Ann. Air Temperature)	Temperature	$b_3 = -3.561$	8.66	4	0.005
$+ b_4$ (S Index) + b_5(S/N Ratio)	S Index	$b_4 = 1.259$	29.32	2	0.000
$r^2 = 0.596$	S/N Ratio	$b_5 = -5.084$	14.04	3	0.001
Model 2: Stand and Soil Variables					
Volume Response ($m^3 ha^{-1} 5\ years^{-1}$)	Constant	$b_0 = 59.026$	60.08		0.000
$b_0 + b_1$ (Site Index) + b_2 (N	Site Index	$b_1 = -0.822$	13.32	1	0.001
Mineralized Aerobically x Mean	N Index	$b_2 = -0.233$	25.74	3	0.000
Annual Air Temperature x 10^{-1}) +	S Index	$b_3 = 1.258$	34.09	2	0.000
b_3 (S Index) + b_4 (S/N Ratio)	S/N Ratio	$b_4 = -5.325$	17.81	4	0.000
$r^2 = 0.657$					

S Index = [A horizon SO_4-S + (Subsoil SO_4-S x B.H. Age x 10^{-2})] / Log_e (N Mineralized x Specific Fraction x Mean Annual Air Temperature x 10^{-1})

S/N Ratio = (A horizon SO_4-S + Subsoil SO_4-S) / (N Mineralized Aerobically) high N mineralization values in view of their low site quality and high volume response. The simple adjustment for temperature appeared to reduce these outliers. It seems reasonable that cooler sites would not only have low rates of mineralization, as has been demonstrated in many experiments, but that higher levels of soil organic matter would accumulate. The latter may be readily released upon incubation at a higher laboratory temperature, resulting in large apparent N mineralization rates.

Deviations in the relationship between volume response and N mineralization, when adjusted for gravel and temperature (Figure 10), indicate that at least two additional factors are contributing to the scatter of data points. Soils low in available S appear to have a lower mean response. In addition, regardless of S status, stands in the age group between 22 to 36 years fall consistently below the mean trend line. Arguments put forth in the previous section suggest that age related deviations during this period may be the result of greater imputs of N being generated from litter decomposition.

The results of the multiple regression analysis support the notion that surface mineral N is important to the N economy of Douglas fir stands. Evidence is also provided by examining the proportional release of N throughout the whole profile (Appendix B, Figure B4). In addition, its influence on N nutrition can be seen in its relationship to foliage biomass. By combining age with the previous N index, the variation between stands in net foliage biomass increment is reduced substantially (Figure 11). The possibility that variations in soil N availability regulate the rate of crown formation at any point in the development of the stand agrees with the experimental work of Brix (1981, 1983) and Albrektson et al. (1977), in which the mechanism of response to N fertilization was related to changes in foliage biomass.

Sulfur Availability Relationships

The analysis of the importance of soil S to the N response estimate was examined in a mnner similar to soil N mineralization.

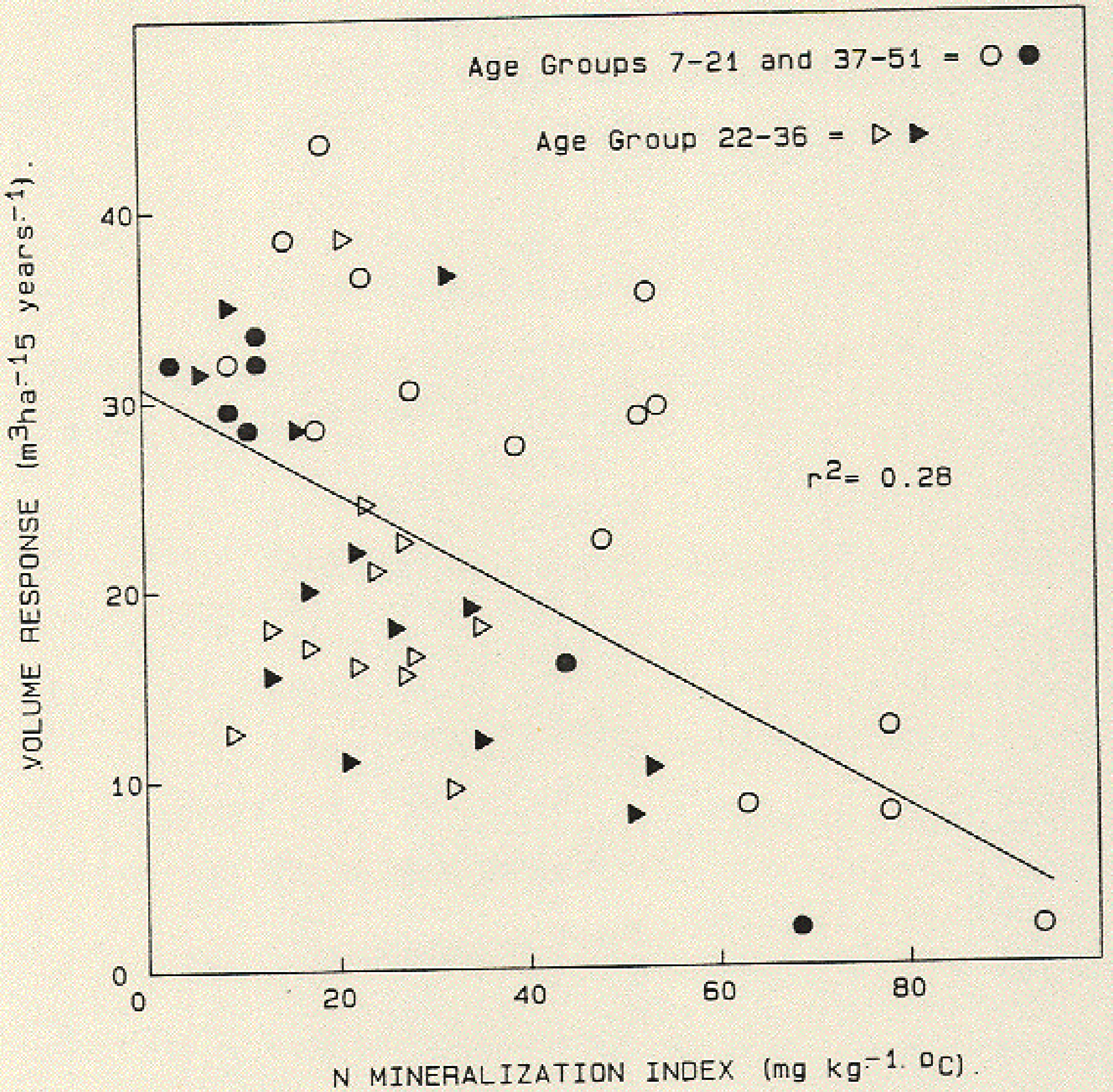

FIGURE 10: CORRESPONDENCE BETWEEN INITIAL FIVE YEAR VOLUME RESPONSE AND THE N MINERALIZATION INDEX.
N Index = [Net Aerobic N x Specific Fraction x Mean Annual Air Temperature x 10^{-1}]. Soil SO_4-S levels calculated as [A horizon SO_4-S + (Subsoil SO_4-S x B.H. Age x 10^{-2})]. Solid points are soils containing < 29.6 mg kg^{-1} SO_4-S. Points are identified by age groups at the time of fertilization.

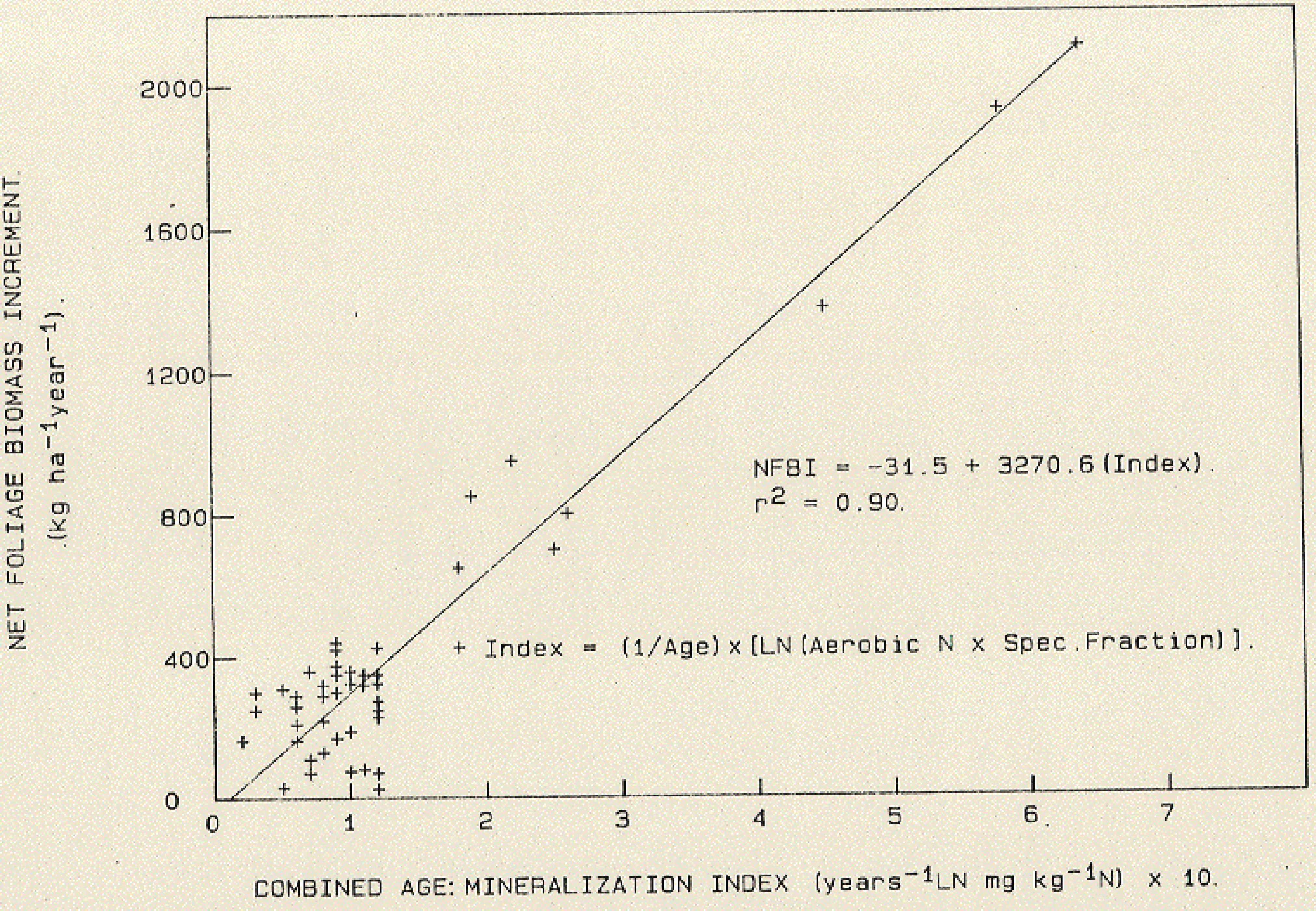

FIGURE 11: COMBINED EFFECT OF AGE AND N MINERALIZATION ON CROWN BIOMASS INCREMENT. Values of net live foliage biomass increment calculated using the equations of Snell and Anholt (1981) on control plots for five years after treatment.

Variables, either unmodified or transformed, were incorporated into the multiple regression equation used to predict gross volume response. The simplest expression of the variable which gave the largest improvement in F values was selected for the final model. Individually, only the A-horizon SO_4-S caused a significant reduction in the residual variance.

Two generally accepted relationships were examined to determine if the S availability index could be improved.

The first has been defined by both early and current research (Storey and Leach 1933, Ensminger 1954, Pawluk and Bentley 1964, Kamprath et al. 1957). In deeply weathered soils, S characteristically leaches from the surface horizon and accumulates in the subsoil in quantities exceeding the surface amounts by several fold. This extractable SO_4-S has been shown to be quantitatively important to the crop and is believed to be a function of rooting intensity in the various horizons (Probert and Jones 1977). A similar distribution of SO_4-S was present in many of the forest soils in the study (Appendix B, Table B3). The most dramatic differences between horizons were in the ultisols and alfisols.

Simple addition of the surface and subsoil values did not improve the model beyond that achieved by using the A horizon values alone. A gross estimate of available S being utilized by the stand from the subsoil was made by weighting the subsoil values by two factors which were thought to be related to rooting development in the subsoil. Predictability was significantly improved by weighting the subsoil values by either stand B.H. age or the mean height of the dominant site index trees at the time of fertilization. Stand age has been quantitatively related to the intensity of root development in the surface and subsoil in several studies (Kalela 1950, Bowen 1964, McMinn 1963, McQueen 1968). Because of the wide disparity in rock content and bulk density, it was anticipated that stand dominant height would be a better index of root development as it might integrate both site quality and age. This did not occur.

The second relationship deals with the interaction between the N status and the S requirement. It can be stated in general terms that the S requirement is a direct function of the available N in the system. The close relationship is believed to result from the balance of N to S atoms which is normally maintained in plant protein (Dijkshoorn and Van Wijk 1967, Stewart 1969). The latter has been documented in many types of studies, including microbial processes (Stewart et al. 1966a, Kowalenko and Lowe 1978) and plant growth (e.g., Jordan and Bardsley 1958, Golden 1979, Janzen and Bettany 1984). As shown in Table 3 (page 42), a natural log transformation of the mineralization value times the specific fraction provided the best index to adjust the SO_4-S availability. Stands growing on soils with moderate to low levels of mineralizable N would not be expected to have the same S requirement as those with high levels of available N. Reserve levels of SO_4-S in the foliage of the latter sites would be expected to be low (Turner et al. 1977).

A final variable, expressing the gross soil S/N ratio was incorporated into the response equation. In this case, the new variable had a negative coefficient. It remains difficult to find biological interpretation of this factor. The inclusion of this factor reduced most of the outliers existing after the development of the main S index. The summation of the A and B horizon values characterizes soil series or soil groups more than S availability. Those having high values are typically the alfisols and ultisols with large accumulations of S in the subsoil. The inverse relation to mineralizable N corresponds to the installations on low sites in the 30 to 40 year age group. While its meaning is uncertain, the variable probably represents a real factor of a physical or chemical nature which is influencing response.

The results of this analysis (Table 3, Model 1, page 42) support previous conclusions concerning the role of subsoil S in regulating the S status of perennial crops such as tea (Storey and Leach 1933) and wattle (Gosnell 1964). It suggests that the likelihood of S deficiencies will decrease with age on certain soil types provided that the rooting system can rapidly absorb the S in proportion to the N additions. The influence of N on the S requirement has also been substantiated.

Canonical Analysis of Soil and Stand Variables

The particular goal of this analysis was to determine the underlying structure, if any, between the two data sets, one representing soil-environmental variables and the other stand variables, which effectively predicted response to N.

Canonical analysis can be viewed as the general case of multiple linear regression in which two or more sets of presumably interdependent variables are correlated. The numerical properties of the correlation are such that the intra-set covariance is minimized and the canonical weights chosen to maximize the interset correlations. The data sets normally express some sort of hypothetical relations, e.g., dependent vs. independent, biological vs. physical.

In general, canonical analysis produces K pairs of canonical weights which in the case of standardized variables, will be a measure of the importance of each in producing the correlation. As Gittins (1979) has noted the value of the canonical weights is limited, since they are unstable and at times represent rather complex interrelationships that have no meaningful interpretation. However, the sign and magnitude are often useful in assessing the contribution of each variable.

The results of the canonical analysis are shown in Table 4. The first correlation accounts for almost 50% of the variation between the data sets. The list of variables shows that age is heavily weighted in the first case to the exclusion of site index. Of the soil variables, S availability receives the greatest weight. The main S index is positively related to stand age whereas the secondary variable, denoting largely the S/N ratio of the soil system is negatively correlated. Mineralizable N receives a negative weight in relation to stand age.

In a strict sense, a cause and effect relationship between age and the above soil variables should not be assumed. The inference to be drawn from the first canonical variate is that the age

Table 4: Canonical Correlation Analysis of Stand and Soil Variables Used to Predict Volume Response of Douglas fir.

Canonical Variate	Eigenvalue (R^2)	Chi-Square	D.F.	Significance
1	0.521	51.553	8	0.000
2	0.302	16.891	3	0.001

Set	Variables	Canonical Variate #1	Canonical Variate #2
1	Site Index	-0.115	-.081
(Stand)	B.H. Age	0.949	0.529
2	N Mineralized	-0.630	-0.001
(Soil)	Specific Fraction	-0.288	0.792
	S Index	1.423	0.869
	S/N Ratio	-1.050	-0.421

component appears to integrate corresponding soil values of S and N. Discussions in the previous sections have suggested some rational interpretations for a close association between these variables. Age is believed to positively influence the S nutrition of the stands through increased rooting in the subsoil. Age can be negatively related to the N mineralization index as a result of the decrease in mineral soil N that occurs during the period subsequent to stand conversion. The meaning of the negative weight applied to the S/N variable is more obscure.

The second canonical correlation accounts for an additional 30% of the variation between data sets. In this case site index is weighted about twice as heavily as age. Among the soil variables both the S index and the soil specific fraction are about equally weighted.

The correspondence between site quality and the specific fraction is consistent with the regional pattern found between Douglas fir site quality and gravel content (Steinbrenner 1979). While several direct biological reasons for this good correlation can be suggested, such as water availability, the significance of this in terms of N response is not clear. Gravel or rock content can simply adjust the N mineralization values to a whole soil basis or it may directly influence a rate controlling N transformation process in the soil. Of interest, is the fact that the N mineralized in the 2 mm fraction receives no weight at all in the second canonical variate. The laboratory incubation per se does not appear to generally reflect the site quality of the originating stand.

The second factor, the S index is also positively weighted. This suggests that decreases in S availability correspond to a decline in site quality once age effects are removed. To some degree this trend can be seen in the response deviations in Figure 9. In all probability it reflects the sample distribution of stands, where many average to low site quality units had coincidentally low levels of available S.

In summary, canonical analysis of the two data sets has illuminated certain relationships that exist between the stand and soil variables. Stand age has been shown to be strongly tied to both the mineralizable N in the surface mineral soil and to S availability. Site index appears to be less strongly related to the soil nutritional factors measured. The correspondence between site index and gravel content accounts for a large proportion of the co-variance. Because of the minimal weight applied to mineralizable N, it is suggested that the "whole" soil concept may be an over-simplification of a more complex relationship between Douglas fir site quality and N status. These patterns indicate that there exists more real information concerning the stand N status in the site index variable than what may be reflected by the N mineralization index developed in this analysis.

The Best Predictive Model

A hybrid model of response was constructed using stepwise multiple linear regression of the previously defined stand and soil variables. An improved level of predictability was achieved with this approach over the separate use of either data set.

Table 3 (Model 2, page 42) lists the variables selected for the final model of response. The results are consistent with the canonical analysis. Site index was selected from the stand variables, whereas age was dropped as a result of its strong co-variance with the soil variables. Of the latter, only mineralizable N, the S index and ratio of S to N were included. The specific fraction variable was rejected because of a similar co-variance relation with the site index.

The hybrid model provided additional predictability not available when using either stand or soil variables alone. The relative improvement can be seen in relation to the best stand (page 29) or soil (Model 1, Table 3) model. Nearly two-thirds of the variation in response can be explained by the hybrid equation. Although the stability of the coefficients can be questioned because of the limited size and method of site selection, the significance of the variables should not be altered. Because of the uncertain biological nature of the gross S/N ratio, further investigation of its meaning seems justified before too much reliability is placed upon it. Identical results were found with Discriminant Analysis of response groups (Appendix H).

Chapter IV

EXPERIMENTAL STUDIES OF NITROGEN AND SULFUR RESPONSES

Greenhouse Growth of Douglas-fir Seedlings

Experimental Design

The overall objective of this experiment was to investigate whether or not a valid response to S could be found in selected forest soils, and secondly, to partition the response by a single measure of availability. To accomplish this objective, a simple pot test to examine the interaction of S and N on seedling growth was initiated, utilizing a wide range of forest soils from selected Weyerhaeuser EFT installations.

The statistical design was a blocked split-plot with five replications, using soils for the major plots, and fertilizer effects (Control, N, N+S), as minor plots. An analysis of variance was conducted on height, stem caliper, and shoot and root weight. Details of experiment are given in Appendix I.

Treatment Effects Related to Seedling Growth

The four growth variables measured; height, diameter, root and shoot weight all show significant effects of N and NS (Table 5) (Appendix J). Growth between the various soils was also significantly different when averaged across all treatments (Appendix K). It was clear that attempts to balance the nutritional status by moderate supplements of other elements did not totally remove important factors in the root environment affecting growth.

Fertilization x soil interaction terms were generally significant, except for height. This term was particularly important, as it suggests treatment effects are not uniform across all soils.

Table 5: Summary of Seedling Responses to N and NS Treatments in Greenhouse Pot Trial with Various Pacific Northwest Forest Soils.

Analysis of variance based upon five replications of 21 soils, using a split plot design with fertilization as minor plots.

	Treatment Means			F-Values for Various Factors and Contrasts[c]			
Variable	Control	N	NS	Soils	Soils x Fert.	N vs. NS	C vs. (N+NS)
Height (cm)	10.8	18.90	20.20	4.38[a]	0.66	13.6[b]	798.0[b]
Diameter (mm)	1.53	2.19	2.41	9.31[a]	7.39[b]	133.6[b]	1,946.8[b]
Root Weight (g)	0.47	0.77	0.92	60.1[b]	1.92[b]	929.0[b]	14,700.0[b]
Top Weight (g)	0.41	1.00	1.16	11.7[b]	2.13[b]	1,470.6[b]	8,879.3[b]
Total Weight (g)	0.87	1.77	2.08	30.7[b]	2.01[b]	987.0[b]	10,241.0[b]

[a] $P < \alpha = 0.05$

[b] $P < \alpha = 0.01$

[c] Orthogonal Contrasts based upon treatment means

Mean response to NS was greater than for N alone, but varied by the individual type of measurement. Height was least affected (6.9%) and root weight the most (19.5%). Diameter and shoot weight were intermediate.

The universal response to N on these soils suggests that sufficient S can be obtained from the soil, even at quite low levels of extractable S. This could be anticipated, partially as a result of the large unoccupied rooting volume that was available for the exploration and uptake of soil solution or water extractable S. Additionally, inputs of S from decomposing organic matter could offset extreme mineral soil deficiencies. This effect was suspected to have occurred during the latter half of the test when sunlight caused a noticable warming of the black pots. During this period, some soils, demonstrating chlorosis in the N only treatments, dramatically improved in color. This agrees with the observations of Lee and Speir (1979) on the effect of soil temperature in regulating the importance of organic S.

The question can be raised as to which of the growth variables is the most appropriate measure of S deficiency. Mead and Pritchett (1971) made a careful examination of relative growth responses in field and pot trials where P deficiencies were evident. They concluded that seedling weight was much more sensitive to detecting deficiencies and in predicting field responses, than was height. Diameter was somewhat less significant than weight. As in this experiment, relative growth increases were greatest for weight and least for height. Individual soil or site anomolies were also present.

The S response study reported by Will and Youngberg (1978), using radiata pine in a pot trial, showed exceptionally large increases for both height and weight. It is possible that this result was related to the extremely low levels of Morgan's extractable SO_4-S (3.1 mg kg^{-1}). Heilman and Ekuan (1980) also reported large increases in height and weight on P deficient soils. While height responses were substantially less than weight, height appeared to be more sensitive, statistically, to detecting deficiencies.

While the general trend for growth response is similar to Mead and Pritchett's, the S data suggest that diameter growth is the more sensitive. This is based on F-values for treatment effects rather than the magnitude of the percent increase. Critical levels of S availability also appear to be better defined using stem caliper (see Table 6, page 56).

Estimates of Critical Levels of Availability

Determining the relationship between some measure of nutrient availability and response is essential to the validation of soil tests. The two most common approaches are the linear or non-linear regression of a transformed soil test variable, and the Cate-Nelson procedure (Cate and Nelson 1971).

Table 6 shows the results of using a standard rectangular hyperbola model in terms of the correlations between the soil test for Morgan's extractable SO_4-S and absolute growth increases. A number of transformations were attempted, including logs, square root and polynomial. These were found to produce similar or inferior correlation coefficients. The height and caliper response variables were also transformed to percentage yield estimates. Using the data in this form did not alter the form or improve the quality of the regression.

Figure 12 demonstrates the scatter of data from the regression estimate for height and diameter. The estimated critical level of available S needed to generate a response was calculated as that level at which the 95% confidence interval for the true mean did not include zero. The mean value of 18.1 mg kg^{-1} includes a very wide range (11.5 mg kg^{-1} to 22.0 mg kg^{-1}). Restricting the confidence interval to 99% would lower the critical level even further.

The mathematical version of the Cate-Nelson procedure was applied to the same data set. It is essentially a non-parametric use of the chi-square procedure. It has distinct advantages over linear models in that it makes no assumption concerning the shape

Table 6: Determination of Soil SO_4-S Critical Levels Using Various Measures of Douglas fir Seedling Growth.

Values derived from seedling growth on 20 Northwest forest soils in the greenhouse pot test.

Growth Variable	Linear Regression Model[b]	r^2	Critical Level[a]	Cate-Nelson ANOVA r^2	Critical Level[a]
Height	$Y = 1.067 - 24.33\ (1/SO_4\text{-S})$	0.47[d]	11.5	0.32[d]	13.0
Diameter	$Y = 0.0104 - 2.236\ (1/SO_4\text{-S})$	0.39[d]	20.0	0.49[d]	15.0
Root Weight	$Y = 0.0162 - 1.318\ (1/SO_4\text{-S})$	0.19[c]	16.0	0.24[c]	14.2
Shoot Weight	$Y = 0.0464 - 2.130\ (1/SO_4\text{-S})$	0.31[c]	22.0	0.16	---
Total Weight	$Y = 0.0042 - 3.242\ (1/SO_4\text{-S})$	0.24[c]	21.0	0.19[c]	14.2
	Average Critical Level		18.1 mg kg^{-1}		14.1 mg kg^{-1}

[a] Morgan's Solution Extractable SO_4-S (mg kg^{-1})

[b] Y = Growth response as absolute difference between N and NS treatments. Critical levels estimated as concentration at which the 95% C.I. does not include zero.

[c] $P < \alpha = 0.05$

[d] $P < \alpha = 0.01$

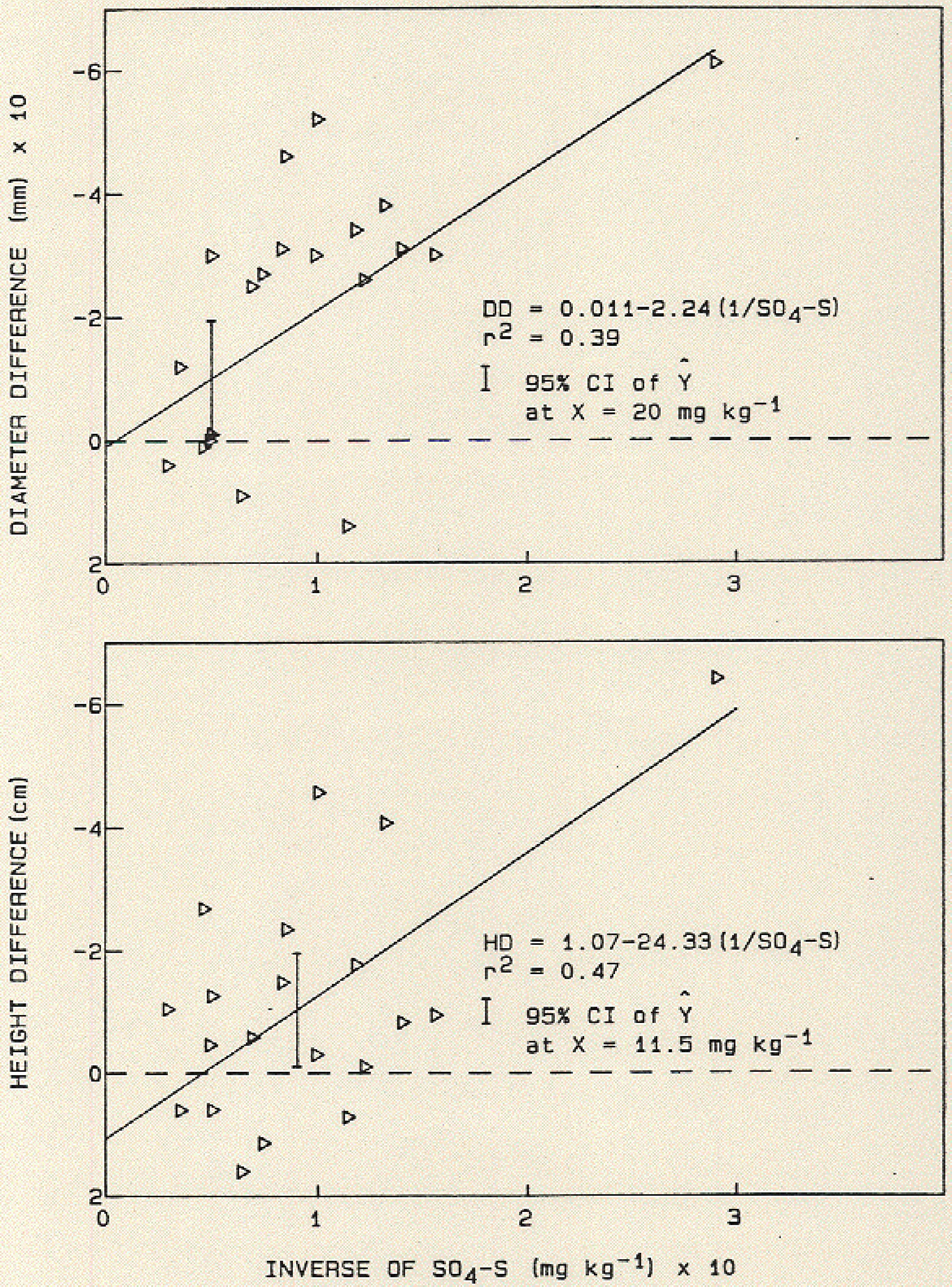

FIGURE 12: RELATIONSHIP OF SEEDLING STEM HEIGHT AND DIAMETER TO THE INVERSE OF SOIL SO_4-S. Growth expressed as the difference between N and NS fertilizer treatments. SO_4-S derived from soil extractions using Morgan's solution.

of the soil test response functions. It therefore avoids the problems of achieving a suitable fit to the data. Higher r^2 values were reported by Cate and Nelson. The performance of this test procedure compares favorably with the reciprocal value function. Although, the shoot weight data was non-significant, the range of critical values is much narrower and the mean lower (14.1 mg kg^{-1}).

This value is similar to the critical level of 12 mg kg^{-1} estimated by Harward et al. (1962) using Morgan's extract with alfalfa on Pacific Northwest soils. It is lower than the value reported by Handley (1972) for white clover (20 mg kg^{-1}).

With the exception of the top weight data, the r^2 values of the Cate-Nelson and regression method are similar. With either model, both caliper and height are the best variables to choose. Problems with the use of weight were noted previously.

The greenhouse study has shown that Douglas-fir is sensitive to soil S levels at concentrations which are similar to agricultural crops. From the standpoint of the stability of the critical levels, the Cate-Nelson procedure appears to be the preferred method. Averaging the values may give a suitable approximation to the critical level of extractable S in the surface mineral horizon needed to sustain a response to N.

EFT Sites Retreated With Nitrogen and Sulfur

Original Plot Design and Retreatment Plan

Twenty-eight of the EFT installations, which had included in their original plot system an additional "complete" fertilizer treatment, were retreated with NS. The purpose of the original complete plot was to assess the impact of additional nutrients on growth.

The original complete plots received urea N (336 kg ha^{-1}) and additional amounts of P, K, Ca, Mg, S and micronutrients. S was added as $CaSO_4$ in an amount equal to 56 kg ha^{-1} of S. Each installation also contained a control and urea N treated plots at 112, 336 and 556 kg ha^{-1}.

The scheme for retreatment called for retention of the original control as untreated, retreating the 112 kg ha^{-1} plot at the same rate, and randomly assigning the 336 kg ha^{-1} rate to one of the higher N only plots. The "complete" plot was fertilized with 336 kg ha^{-1} of N and 100 kg ha^{-1} of S, using urea (248 kg ha^{-1}) and ammonium sulfate (88 kg ha^{-1}).

Only gross basal area growth was monitored after the initial five seasons. These values were adjusted for basal area/age (Appendix L). Of the initial 28 installations retreated after eight growing seasons, only 20 remain. Several were destroyed in the St. Helens eruption, clearcut or operationally fertilized. The survivors were measured for three seasons after retreatment.

Initial Five Year Growth

The initial analysis focused on paired percent response of the N (average of the 336 and 556 kg ha^{-1} plots) and NS treatments at each installation in relation to available soil S. Data analysis in relation to soil S was based upon the Cate-Nelson procedure (Cate and Nelson 1971).

Several estimates of available soil S were constructed. From the initial multivariate analysis conducted in Chapter III, three obvious choices were: 1) A horizon SO_4-S; 2) A horizon plus age weighted subsoil SO_4-S; and 3) Option #2 adjusted for mineralizable N. Table 7 lists the results of the Cate-Nelson analysis for the various soil S availability estimates. While all are significant, the best separation of values resulted from the inclusion of age weighted subsoil SO_4-S.

Figure 13 demonstrates the scatter in the data resulting from the use of surface alone and combined surface and subsoil S values.

The critical quantity of 20 mg kg^{-1}, using only the A horizon SO_4-S is substantially higher than the 14 mg kg^{-1} derived from the pot study with the same technique. A few installations with very

Table 7: Critical Soil SO_4-S Values by the Cate-Nelson Procedure for Several Periods and Composite Soil S Variables.

Values based upon growth for "complete" or NS plot in relation to N only plots using periodic annual gross basal area adjusted for initial basal area/age.

	Growth Period After Initial Fertilization					
	0-5 Years		8-11 Years		0-11 Years	
Soil S Variable	Value ($mg\ kg^{-1}$)	r^2	Value ($mg\ kg^{-1}$)	r^2	Value ($mg\ kg^{-1}$)	r^2
A horizon (0-15 cm) SO_4-S	20.2	0.26^a	20.2	0.29^a	20.2	0.44^b
A horizon (0-15 cm) + Subsoil SO_4-S	69.2	0.32^b	62.5	0.37^b	62.5	0.47^b
A horizon (0-15 cm) + (Subsoil SO_4-S x Age x 10^{-2}) SO_4-S	32.1	0.35^b	29.6	0.38^b	29.6	0.47^b
Above S Variable/Log_e (N Mineralized x Temp. x 10^{-1} x Spec. Fraction)	12.0	0.37^b	12.0	0.34^b	12.0	0.46^b

$^a P < \alpha = 0.05$

$^b P < \alpha = 0.01$

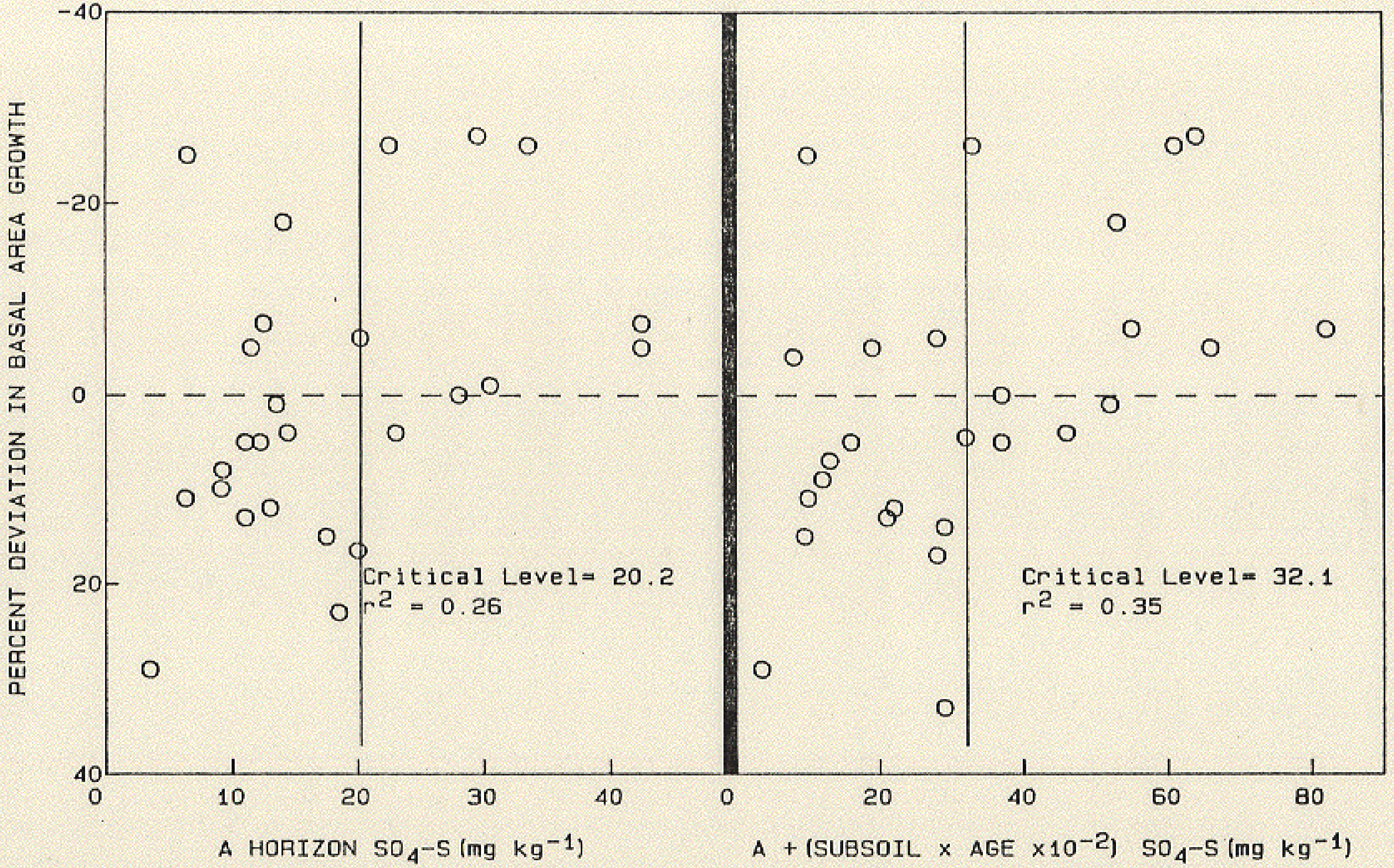

FIGURE 13: PERCENT CHANGE IN INITIAL FIVE YEAR ADJUSTED GROSS BASAL AREA GROWTH IN RELATION TO SOIL SO_4-S LEVELS. Critical level estimated using Cate-Nelson method. Percent change estimated as the growth of (Complete-N only)/N only plots. SO_4-S derived from soil extractions using Morgan's solution.

strong positive deviations near the critical point appear to be responsible. The limited replication in these trials decreases the value associated with any individual installation.

An improved r^2 value resulted from use of a number of procedures which included subsoil SO_4-S. Comerford and Fisher (1982) have recently pointed to the importance of subsoil rooting in relation to P availability in slash pine fertilizer trials. K deficiency was also influenced by deep soil layers in red pine (White and Wood 1958).

Below the critical levels (Figure 13) there is little suggestion of a continued trend in response. This variability may be caused by S interactions with N availability.

Figure 14 demonstrates the approximate gains due to N fertilizations on high and low S soils. The lower mean response of the N only treatments on the low S soils might be a result of another factor, such as site quality. However, the average response on the "complete" plots is identical to the N only response on the high S sites. This is exactly what would be expected if S deficiency was affecting the growth. The anomalous growth depression on the complete treatment plots on the high S soils is largely the result of several extreme negative deviations on four very young, high site (I) stands. The cause for this is unknown. With the possible exception of B, other nutrients are probably not limiting enough on these soils to influence N response. P concentrations are all sufficient based upon reported deficiency levels (Appendix M).

Three Years Growth Following Retreatment

Results from the retreatment period are in most respects similar to the initial five year period. In this case, growth response on the plots receiving S is not confounded by the possible effects of the other nutrients. The initial rate of S application (56 kg ha^{-1}) may also not have been adequate to saturate the S demand of the system. Since only the 112 kg ha^{-1} and one of the

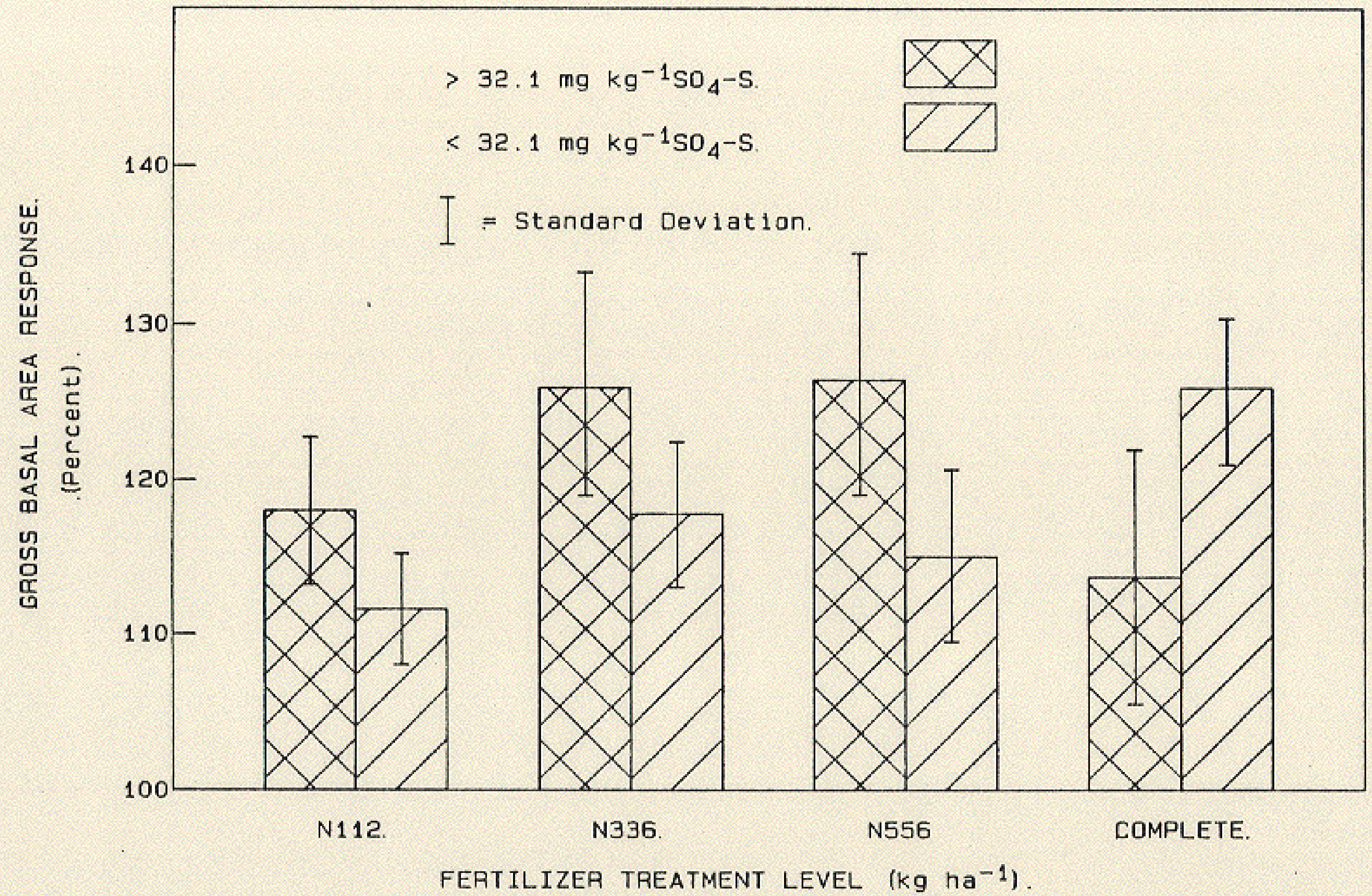

FIGURE 14: PERCENT ADJUSTED GROSS BASAL AREA RESPONSE ON N ONLY AND COMPLETE PLOTS. Initial five year basal area response of EFT stands in relation to control plot growth. Soil S values = A horizon SO_4-S + (Age x 10^{-2}x Subsoil SO_4-S) .N = 28..

higher rates of N alone were retreated, comparisons refer only to retreated plots.

Table 7 shows that the r^2 values are greater following retreatment than during the first phase of fertilization. This occurred despite the reduced number of installations. As in the first period, inclusion of subsoil SO_4-S values substantially improved the separation of points. Critical soil SO_4-S levels are reduced slightly, based upon the growth analysis. Figure 15 shows the amount of growth deviation by soil S availability level. There are fewer strong negative deviations, probably the result of using N and S without the confounding effects of other nutrients.

Figure 16 represents the average adjusted gross basal growth over the control following retreatment. Again, the low S soils have much lower N only responses, whereas the response with the combined NS treatment is identical to the average effect of N on the high S soils.

Conclusions

The analysis of the comparative growth of the "complete" or NS plots and the N only treatments provides strong support for the hypothesis that S is limiting response to N. The results are consistent with the multivariate analysis of Chapter III. The critical A horizon values are higher than those derived from the pot trial. The calculated critical levels from the field plots are strongly influenced by two points very close to the value of 20 mg kg^{-1}. Most of the other points are visually much less than 14 mg kg^{-1}. As with the study of gross volume response, the current results support the belief that the availability of SO_4-S in the subsoil can directly influence the need for additional S.

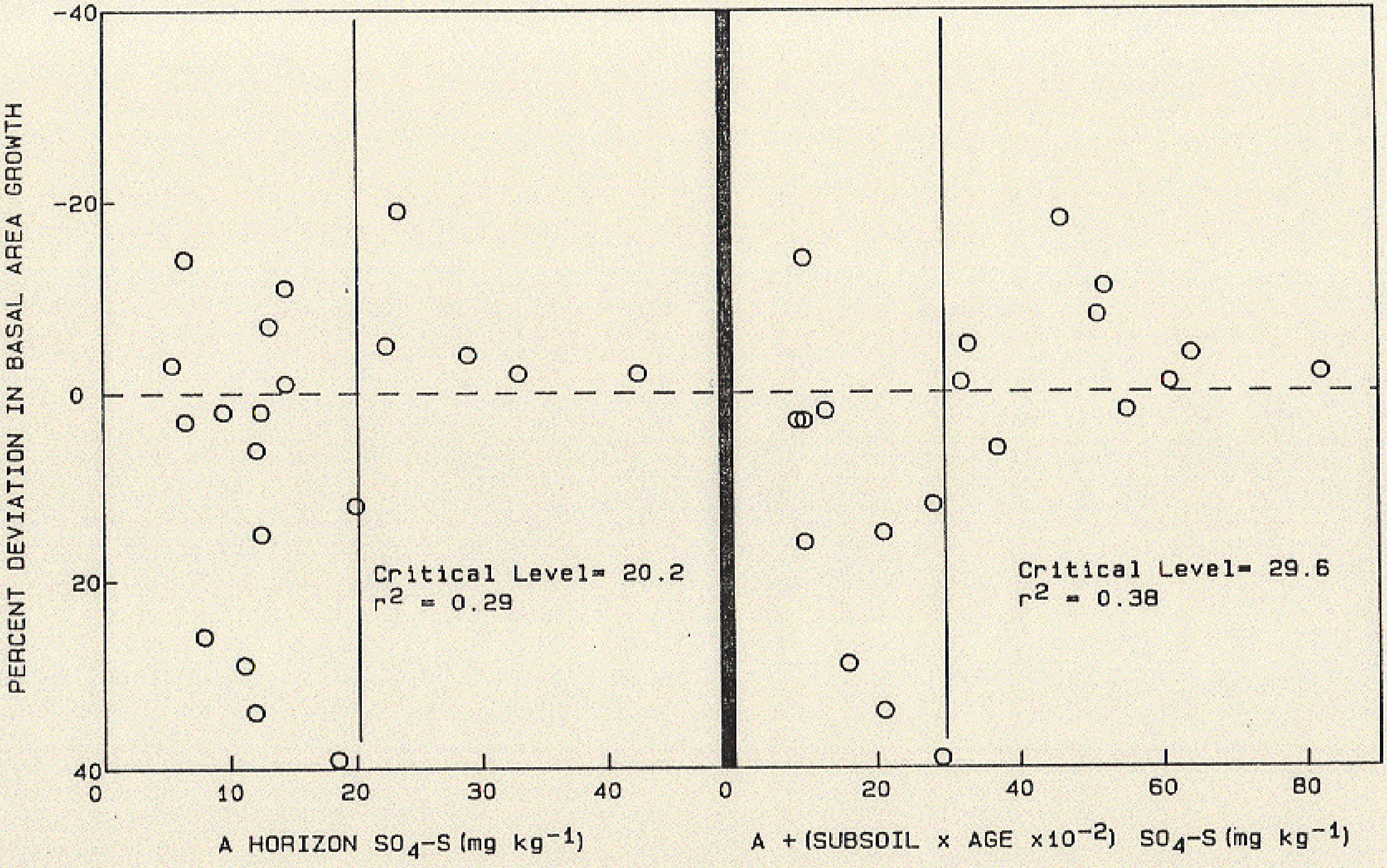

FIGURE 15: PERCENT CHANGE IN THREE YEAR ADJUSTED GROSS BASAL AREA GROWTH AFTER RETREATMENT IN RELATION TO SOIL SO_4-S LEVELS. Critical level estimated using Cate-Nelson method. Percent change estimated as the growth of (NS - N only)/N only plot. SO_4-S derived from soil extractions using Morgan's solution.

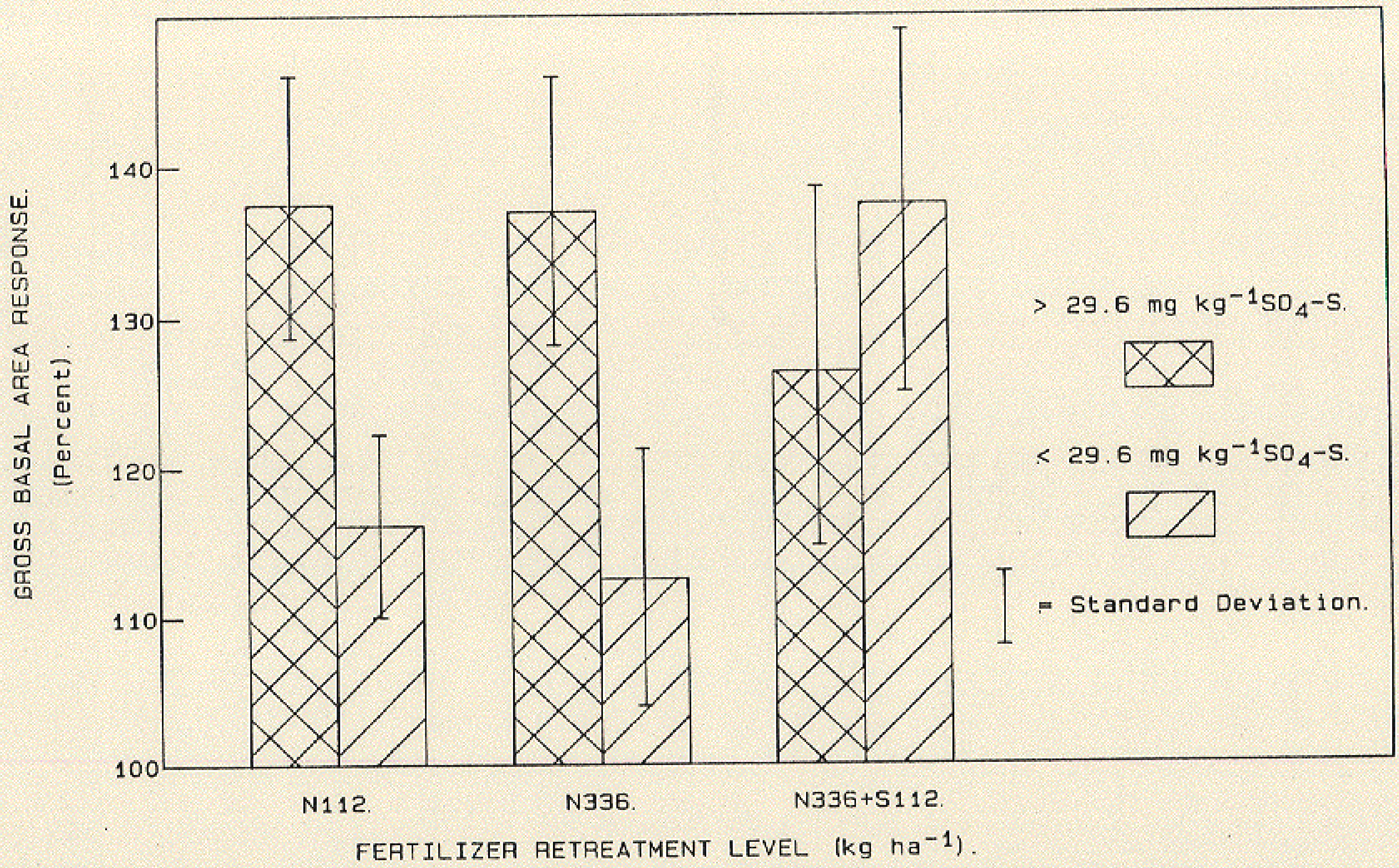

FIGURE 16: PERCENT ADJUSTED GROSS BASAL AREA RESPONSE FOLLOWING RETREATMENT. Three year basal area response of retreated plots in relation to control plot growth. Soil S values = A horizon SO_4-S + (Age x 10^{-2}x Subsoil SO_4-S) . N = 20 . .

SUDIC Installations

Experimental Design

In order to overcome some of the limitations in the correlation methods used to analyze the EFT and RFNRP plots for S effects, independent trials of N and NS were established in the field. The goal of this new study was to characterize the potential volume gain from NS fertilization over a series of Douglas fir stands and to determine if methods used to establish critical levels of S availability were consistent with the site specific growth responses.

Five areas were located, four in Oregon, and one in Washington which had moderate to low levels of soil available S in the A horizon (Table 8). Four stands were precommercially thinned plantations, the fifth was a natural stand which was thinned to balance stocking. Three treatments were used: control, N only as urea at 224 kg ha^{-1} and NS at 224 kg ha^{-1} of N and 112 kg ha^{-1} of S. The latter was supplied by mixing urea (127 kg ha^{-1}) and ammonium sulfate (97 kg ha^{-1}).

Samples were taken to estimate nutrient levels in current foliage prior to fertilization. Post-treatment samples were taken in September of 1981 from the upper third of the crowns of three trees adjacent to each other from three randomly selected blocks. Current shoots were analyzed for total N and S on all plots and P, K, Mg plus micronutrients on the N only plots.

Growth Response

Growth, for both volume and basal area, was calculated for each treatment after the second growing season. Statistical comparisons of treatment effects were made using predetermined orthogonal contrasts if the overall treatment F-value was significant at $P \leq 0.05$. In some cases covariance analysis by means of linear regression of certain variables on control plot growth was used to reduce plot growth variability. In the latter case, the F-test was reduced

Table 8: Selected Stand Characteristics of SUDIC Installations.

	Installation Number				
	#227	#228	#229	#230	#231
Owner	Weyerhaeuser Company	Publishers Paper Co.	Champion Timberlands	Oregon State Forestry	International Paper Co.
Location	McKenna, WA	Mollala, OR	Sutherlin, OR	Forest Grove, OR	Elkton, OR
Legal	3-16N-3E	12-6S-2E	18-24S-3W	14-1N-6W	33-22S-8W
B.H. Age	17	16	26	22	12
Site Index	36 m	41 m	32 m	38 m	45 m
Replications	5	5	3	6	5
Plot Size	0.062 ha	0.062 ha	0.083 ha	0.062 ha	0.062 ha
Date Fert.	March 1980	February 1980	January 1980	March 1981	March 1981
Soil Series	Kapowsin	Honeygrove	Freezner	Hembre	Batemen/Rendhaven
Classification	Typic Dystrochrept	Typic Haplohumult	Ultic Haploxeralf	Typic Haplohumult	Ultic Haploxeralf

by one d.f. for each parameter estimated. Tables 9 and 10 list the analysis of periodic annual increment for each site.

Significant growth responses occurred only at the McKenna and Sutherlin installations. N treatments improved growth at both sites, but S was effective only at the McKenna plantation. Because of the large number of replications in each treatment it is instructive to examine the treatment means. In this case, there is an indication that N and NS improved growth at Mollala and Elkton. In the former case, S effects are not evident. At Elkton, the large mean effect of NS suggests that S may be important at this site. A close examination of the Elkton installation revealed that three blocks were on the Rendhaven soils series, which initial sampling had shown to be low in available S. Two blocks were on the Bateman series which later sampling established as having higher concentration of available S. When analyzed separately, the plots on the Rendhaven series showed a considerable improvement in growth on the NS plots (Figure 17), although the difference is still not significant. Finally, the treatment responses to both N and NS appear to be negligible at the Forest Grove site.

Certain treatment effects are evident in the post-treatment foliage analysis (Table 11). With the exception of Mollala, the NS treatment has enhanced the total N content of the current foliage. The total S content has been increased only slightly by the heavy application of S. This is also reflected in the moderate reserves of SO_4-S in the foliage following treatment with NS. Levels in the N treatment are consistently depressed. The N/S ratios between the N and NS treatments show only modest differences. No other major nutrients appear to be low enough to limit response. At Mollala, the B levels are low (9 to 12 mg kg^{-1}) in the foliage. These are near the limits suggested by Will (1978) as being critical. Using either normal stocking tables or the relative density index (Drew and Flewelling 1979) does not indicate that any of the stands are overstocked.

Table 9: Two Year Periodic Volume Growth for SUDIC Study Plots.

Installation	Treatment	Site Index m=50 yrs.	Volume m^3ha^{-1}	Volume Growth (m^3 ha^{-1} $year^{-1}$) Unadjusted	F-Value	Significance	Adjusted[d]	F-Value	Significance
#227 McKenna	Control	32	151.4	28.2	4.59[a]	<0.05	0.01	10.58[a]	<0.01
	Nitrogen	32	153.3	31.1	15.28[b]	<0.01	2.70	30.39[b]	<0.01
	Sulfur	32	140.6	31.0	-----	----	4.30	7.15[c]	<0.04
#228 Mollala	Control	40	204.1	30.9	1.50[a]	----	0.00	2.25[a]	<0.20
	Nitrogen	42	208.6	33.4	----	----	2.80	----	----
	Sulfur	40	211.9	33.6	----	----	2.54	----	----
#229 Sutherlin	Control	35	224.9	25.5	6.96[a]	<0.05			
	Nitrogen	36	217.4	31.3	13.65[b]	<0.02			
	Sulfur	36	240.6	30.4	0.41[c]	----			
#230 Forest Grove	Control	38	293.6	32.5	0.14[a]	----			
	Nitrogen	40	296.2	33.2	----	----			
	Sulfur	37	291.1	32.8	----	----			
#231 Elkton	Control	45	124.7	24.2	1.87[a]	----			
	Nitrogen	47	134.2	25.9	----	----			
	Sulfur	44	128.9	27.2	----	----			

[a] F-value of treatments

[b] Contrast: Control vs. Nitrogen and Nitrogen plus Sulfur

[c] Nitrogen Only vs. Nitrogen plus Sulfur Contrast

[d] Predicted Growth - Actual Growth based on control plots growth equation

Table 10: Two Year Basal Area Growth for SUDIC Study Plots.

Installation	Treatment	Stocking Stems ha^{-1}	Basal Area m^2ha^{-1}	Basal Area Growth (m^2 ha^{-1} $year^{-1}$)					
				Unadjusted	F-Value	Significance	Adjusted[d]	F-Value	Significance
#227 McKenna	Control	1039	26.7	2.73	9.24[a]	<0.01	0.00	9.92[a]	<0.01
	Nitrogen	909	25.8	3.09	27.06[b]	<0.01	0.34	29.14[b]	<0.01
	Sulfur	985	27.2	3.28	5.31[c]	<0.05	0.53	5.86[c]	<0.05
#228 Mollala	Control	816	32.6	2.87	3.75[a]	<0.08	0.00	0.20[a]	----
	Nitrogen	803	32.1	3.02	----	----	0.14	----	----
	Sulfur	833	32.8	3.10	----	----	0.23	----	----
#229 Sutherlin	Control	984	24.2	1.73	8.21[a]	<0.03			
	Nitrogen	1000	24.3	2.35	11.57[b]	<0.03			
	Sulfur	905	23.2	2.02	7.14[c]	<0.06			
#230 Forest Grove	Control	828	38.7	2.37	0.48[a]	----			
	Nitrogen	842	37.7	2.33	----	----			
	Sulfur	883	38.1	2.55	----	----			
#231 Elkton	Control	1052	24.0	2.70	2.35[a]	<0.15			
	Nitrogen	1019	24.6	2.86	----	----			
	Sulfur	957	24.6	3.14	----	----			

[a] P-value of Treatments

[b] Contrast Control vs. Nitrogen and Nitrogen plus Sulfur

[c] Nitrogen only vs. Nitrogen plus Sulfur Contrast

[d] Predicted Growth - Actual Growth based on control plots growth equation

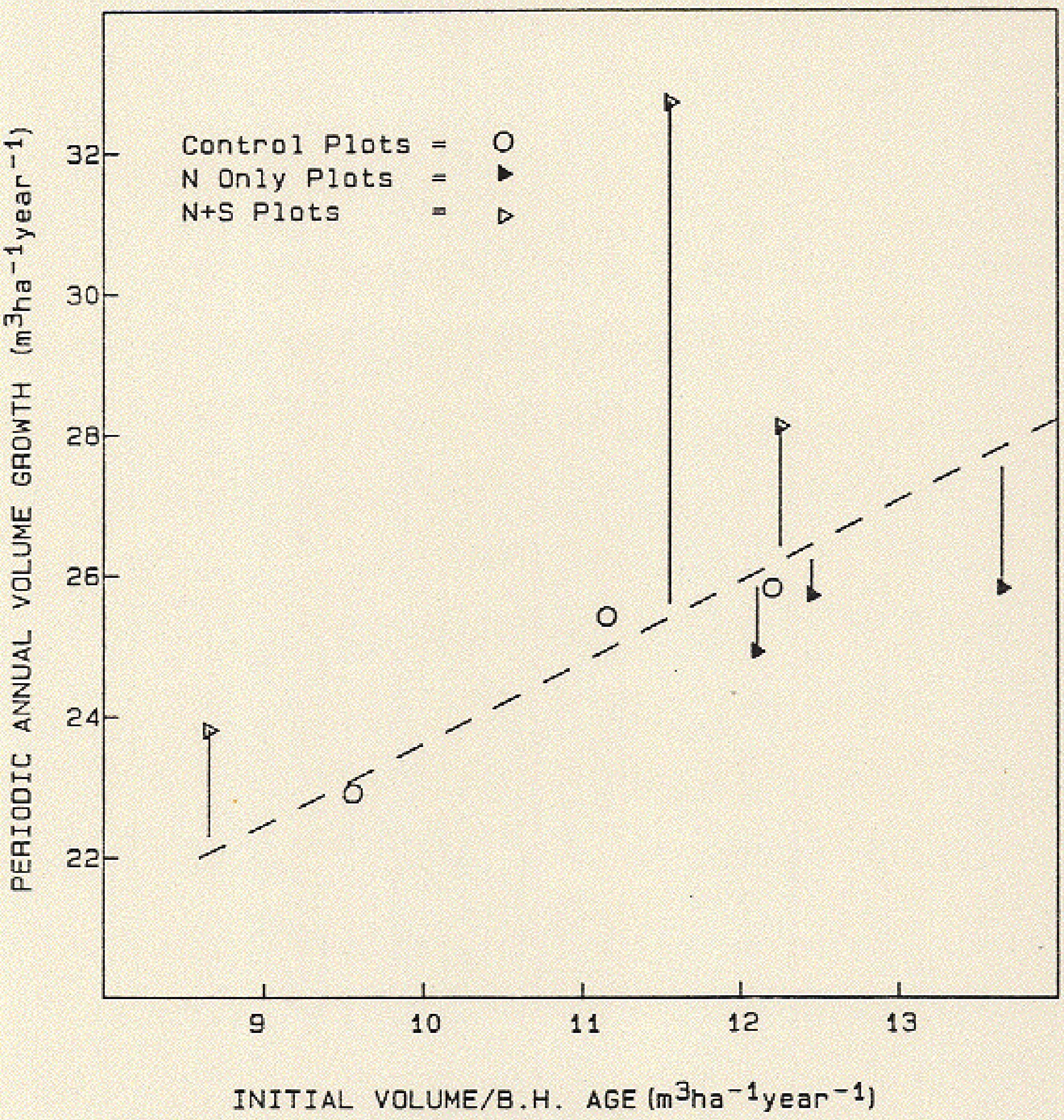

FIGURE 17: VOLUME GROWTH AT THE ELKTON PLANTATION ON THE RENDHAVEN SOIL SERIES IN RELATION TO VOLUME/AGE
Growth measured for two seasons after treatment. Baseline derived from control plot regression.

Table 11: Comparative N Response and Nutrient Characteristics of SUDIC Stands.

		Nutrient Characteristics and Response							
Installation	Treatment	Volume[a] Response	Soil N Nitrate	N Mineral. Aerobic[b]	A horizon/ Subsoil S[c]	Foliage N %	Foliage S %	Foliage SO_4-S[d]	Foliage N/S Ratio
#227	Control	---	16.9	18.5	6.0/5.5	1.17	0.140	626	8.4
McKenna	Nitrogen	2.7	---	----	-------	1.45	0.135	389	10.7
	+Sulfur	4.3	---	----	-------	1.61	0.148	408	10.9
#228	Control	---	1.9	20.0	13.8/78.7	1.33	0.116	273	11.5
Mollala	Nitrogen	2.8	---	----	-------	1.65	0.126	158	13.1
	+Sulfur	2.5	---	----	-------	1.43	0.115	202	12.4
#229	Control	---	0.0	15.8	7.6/11.6	1.00	0.107	403	9.3
Sutherlin	Nitrogen	5.8	---	----	-------	1.31	0.104	168	12.6
	+Sulfur	4.9	---	----	-------	1.35	0.127	373	10.6
#230	Control	---	1.5	28.7	19.2/36.9	1.16	0.112	352	10.4
Forest	Nitrogen	0.7	---	----	-------	1.54	0.109	67	14.1
Grove	+Sulfur	0.3	---	----	-------	1.68	0.114	26	14.7
#231	Control	---	1.6	37.6	6.4/16.0	1.35	0.116	263	11.6
Elkton	Nitrogen	1.7	---	----	-------	1.58	0.108	30	14.6
	+Sulfur	3.0	---	----	-------	1.79	0.132	130	13.6

[a] Gross mean adjusted response (Control-Treated) $m^3ha^{-1}year^{-1}$

[b] Adjusted for Specific Fraction following aerobic incubation, 0-15 cm mineral soil (mg kg^{-1} N)

[c] Morgan's Solution, 1:5 soil:solution extraction ratio, SO_4-S (mg kg^{-1}), (0-15 cm layer)/(Subsoil layer)

[d] Calculated based upon an organic N/S ratio of 15

Discussion and Conclusions

From the examination of the results from these five stands, none of the methods proposed as indicators of N status was totally satisfactory in explaining the relative or absolute growth response. Site index and foliage N were generally correlated. The general trend in response was for the highest response to be associated with the lower sites in agreement with the Regional Cooperative data. The exception to this is the Forest Grove installation. The potential for response was indicated by the mineralization test at all sites.

Differential treatment responses were not adequately predicted by the soil S extraction and N mineralization indices derived from the multivariate analysis. Only the McKenna, Mollala and Elkton sites correspond to the expected pattern. The overall high volume response at Sutherlin was predictable, however it was expected that there would be some positive effect of the S addition. The variability in response using only soil S extraction values is typical of other studies (Saunders and Cooper 1975). Similarly, neither the initial N/S ratio nor total S adequately projected the response pattern observed between treatments. Incomplete analysis of the foliage SO_4-S prior to installation of the plots was made at three sites. All three showed values less than the 200 ppm suggested by Turner et al. (1977) as the critical value needed for adequate N response. Only the Forest Grove site confirms this prediction.

The foliage analysis after treatment provide a more consistent pattern, in line with the mean observed response. In conjunction with the measured total N/S ratio, the amount of reserve sulfate S was estimated by assuming an average organic N/S ratio of 15 (Dijkshoorn and Van Wijk 1967, Stewart 1969). Although there are no published analysis of Douglas fir protein fractions to support this value, Kelly and Lambert's (1972) study of radiata pine reported a ratio of approximately 15.

Using this technique, it is clear that treatments which reduced SO_4-S below 100 mg kg^{-1} generated very low or no response to N.

This is evident, in particular, at Forest Grove and Elkton. The moderate reserve quantities at Mollala and Sutherlin probably lead to higher volume responses and no effect of S. These results also indicate that uptake of additional soil S in the N only plots might be sufficient to offset additional requirements. Therefore, in conflict with the suggestion of Turner, the existing SO_4-S foliar level does not have to be quantitatively adequate in itself to balance fertilizer N uptake.

The response to NS at McKenna is not indicative of a real S deficiency in the trees. Here, although response between treatments was significantly different, neither the N/S ratio nor the calculated SO_4-S reserve supports the notion that S was limiting in the conifer foliage (Kelly and Lambert 1972, Turner et al. 1977). It is conceivable that the real effect is solely the result of the difference in N status following fertilization.

A number of patterns require further elaboration, these include: 1) the generally enhanced foliage N contents on the NS treated plots; 2) the minimal uptake of the applied S; 3) the reduced efficiency of added N when reserve SO_4-S was severely reduced.

The observation that S supplements can enhance N content is not uncommon. Walker and Evans (1958) reported this effect in certain legumes. It was found in peanuts by Richards (1972), also a legume. In these cases, the result is believed to be an effect of S on the efficiency of N fixation by rhizobia. Increased N contents have also been found in other non-legumious crops (Richards 1972, Dabin 1972), such that other explanations may also be plausible.

Limited information suggests that microbial transformations in the litter and humus fractions may be limited by other nutrients (Stotzky and Norman 1961). Munevar and Wollum (1977) were able to demonstrate a strong effect of P on N mineralization. Mahendrapha and Solonious (1982) listed higher N contents in black spruce treated with P and N compared with N alone. Stewart et al. (1966b) demonstrated that S availability in decomposing substrates could affect microbial activity and N utilization by the competing field crop. Saggar et al. (1981) also reported S limited metabolism in incubated soil samples. It is conceivable that N mineralization on most of these stands is S limited and that the excess S added to the soil enhanced the availability of N through increased decomposition of soil organic matter.

An alternative explanation is based on the findings of Dangerfield and Brix (1978). They found mineral fertilizers especially ammonium nitrate to have greater N efficiencies in some Douglas-fir stands. This pattern was originally discovered in Northern Europe (Møller 1974). Overerin (1970) explained the effect as due to the larger rate of incorporation of urea into soil organic fractions, therefore decreasing its short term availability. Because only about half of the treatment was ammonium sulfate, the potential influence of this factor would not be expected to be as dramatic. The proportion of urea used in the NS plots would be expected to raise the pH and solubolize some organic fractions, both of which contribute to high microbial activity.

The minimal uptake of the applied S was unexpected. In most agricultural systems 100 kg ha^{-1} of S could be expected to saturate even the most limiting sites. Based upon foliage increment estimates, the amount of S needed to raise the levels by .03% is only 5 kg ha^{-1}, and for the entire plant system probably no more than 15 kg ha^{-1}. Yet, the foliage concentrations seem to indicate very poor uptake, particularly at Forest Grove, when compared to N. In agricultural systems rates of immobilization of S amendments appear to vary between 50-80% (Freney and Swaby 1975). Given the heavier accumulations of litter and humus in the forest floor, and the fine particle size of the ammonium sulfate used, immobilization by the microbial population could be responsible for the low fertilizer efficiency (Kowalenko and Lowe 1978).

As no substantial growth increases were found when reserve SO_4-S was reduced below 80 to 100 mg kg^{-1}, the implication that a physiological deficiency of S has occurred, seems tenable. The effective level of N based on an N/S ratio of 15 was still high at both Forest Grove and Elkton, yet there has been no improvement in growth over the controls. This result is in contrast to the classic pattern of increasing N efficiency with increasing increments of S until SO_4-S begins to accumulate in the foliage (Bouma 1975, Delock 1960). This result suggests the possibility of a physiological role for the sulfate ion per se. Disease interactions, as suggested by the results of Beaton et al. (1971) and Lambert and Turner (1977) do not appear applicable. In sampling the foliage at each stand, it was very easy to identify the N and NS treatments through their effect on foliage color and needle length. No disease problems were evident. The NS treated foliage was consistently dark green, with very long needles in comparison with the N only treatment at all sites. Neas (1953) reported similar dramatic improvements in apparent color of S treated tobacco, without a corresponding increase in dry weight yield.

Chapter V

CONCLUSIONS

The first objective was to provide biologically sound stand and soil indices to predict N response. This was completed by using stand, soil and combined variables. In this study response was related to both age and site index. The degree of predictability was highest (r^2=0.657) when both stand and soil variables were combined in the same equation. The latter consisted of site index, aerobic mineralizable N and S availability index variables. Further, it was shown that among the stand variables, age was strongly related to N mineralization and S availability.

The second objective was to refine the N mineralization index. Both gravel content and temperature were found to improve the predictive value of the N mineralization test when related to N volume response. These adjustments may represent factors which directly influence N availability in the field. In addition, deviations occurred in the relationship between the mineralization test and volume response in the age range from 22 to 36 years. This is believed to result from higher inputs of N from decomposing litter.

The third objective was to determine the relationship between N response and S availability and the effects of S fertilization. The regression of gross volume response on soil variables showed that S significantly improved response prediction. This was supported by pot and field tests showing a positive growth response to NS treatments. Pot and field studies suggest that Douglas fir may be sensitive to S deficiencies when extractable SO_4-S in the A horizon is less than 14 and 20 mg kg^{-1}, respectively. Levels of extractable SO_4-S in the subsoil were shown to dramatically improve S availability estimates.

NS fertilization at specific locations indicated that responses may be affected by complex interactions due to an enhanced N status of the trees and immobilization of S in the forest floor. Pretreatment soil or plant analysis were not effective predictors of treatment response. Genuine S deficiencies may have occurred when foliage SO_4-S levels were reduced below 80 to 100 mg kg^{-1}.

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Appendix A

SOIL VARIABILITY FOR SELECTED PROPERTIES AND INSTALLATIONS

Installation	No.[a] Subsamples	Percent Organic	Initial NH_3-N	Mineralized Anaerobic N	Mineralized Aerobic N	Nitrate N-Aerobic	SO_4-S[b] A Horizon
576	5(12)	12.55 ± 0.85	11.4 ± 2.3	44.8 ± 4.4	52.1 ± 10.3	0.74 ± 0.07	29.38 ± 2.61
577	5(12)	12.29 ± 1.42	10.2 ± 2.4	42.7 ± 13.8	66.7 ± 24.1	6.97 ± 1.56	12.55 ± 0.72
532	5(12)	15.48 ± 0.54	6.5 ± 0.4	24.2 ± 6.1	29.0 ± 4.9	3.25 ± 0.94	47.8 ± ----
551	4(12)	9.87 ± 0.38	8.4 ± 2.1	31.5 ± 5.4	48.9 ± 5.8	0.88 ± 0.15	14.55 ± 1.13
602	4(12)	12.30 ± 0.56	9.8 ± 2.2	43.0 ± 1.8	40.5 ± 5.6	0.68 ± 0.18	12.10 ± 1.10
599	4(12)	12.99 ± 1.22	11.1 ± 0.5	22.0 ± 3.7	43.5 ± 3.9	0.80 ± 0.08	22.43 ± 3.61
606	5(12)	23.2 ± 1.23	8.2 ± 1.1	68.4 ± 9.9	80.7 ± 5.9	1.90 ± 1.41	46.17 ± 10.68
10	5(12)	16.48 ± 1.16	8.1 ± 0.6	43.5 ± 4.6	59.3 ± 2.8	1.84 ± 0.04	6.03 ----
26	5(12)	14.70 ± 1.65	8.9 ± 0.6	24.2 ± 3.9	21.4 ± 5.0	2.28 ± 0.35	10.40 ----
30	5(12)	18.07 ± 1.35	6.4 ± 0.8	53.1 ± 5.0	48.2 ± 6.4	2.01 ± 0.22	19.00 ----
7	5(12)	26.27 ± 2.71	26.99± 3.8	61.1 ± 7.6	127.1 ± 6.1	2.95 ± 0.84	36.3 ----
54	5(12)	17.67 ± 1.53	17.2 ± 3.6	45.4 ± 5.7	52.8 ± 8.1	1.17 ± 0.16	14.2 ----
	Average	15.99 ± 1.22	11.1 ± 1.7	42.0 ± 5.99	55.9 ± 7.4	2.12 ± 0.50	22.86 ± 3.31
	Coefficient of Variation	7.6%	15.3%	14.3%	13.3%	23.6%	14.5%

Values are reported in mg kg^{-1} for Nitrogen and Sulfur ± Standard Deviation

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[a] Number in parentheses are the cores taken for each composite subsample.

[b] SO_4-S values are the average of 3 subsamples.

Appendix B

INTERRELATIONSHIPS BETWEEN VARIOUS SOIL PROPERTIES

Comparisons were made between various soil properties, their distribution and the effects of specific treatments in order to relate the behavior of the soils used to known characteristics reported by others. Differences or similarity in behavior are related to specific properties of the soils sampled.

Aerobic vs. Anaerobic Incubations:

A comparison was made between N mineralized under aerobic and anaerobic conditions for the same period and temperature (Figure B1). Both methods give similar ranks to a wide range of soils in agreement with Keeney and Bremner (1966). The variation about the regression line is large enough to suggest that there are real differences in the microbial populations ability to metabolize substrates when the oxygen supply is altered.

The slope of the line indicates that when N release is low, the anaerobic test exceeds the aerobic. The reverse trend appears at high release rates. Tusneem and Patrick (1971) found an identical pattern in incubated agricultural soils, which they attributed to variations in the C/N ratio. Moraghan and Ayotade (1968), in a study of anaerobic C metabolism, suggested a means for interpreting this phenomenon. They concluded that under conditions of limiting oxygen supply, most carbon compounds are incompletely metabolized to organic acids. For soils high in organic N compounds, incomplete product metabolism would lead to a reduction in the amount of N mineralized. When organic N substrates were low, reduced C metabolism under anaerobic conditions would decrease immobilization of the limited N supply.

Although neither ammonia volatilization nor denitrification were measured during the incubation, it is doubtful that these processes could account for the observed trend. Few soils demonstrated

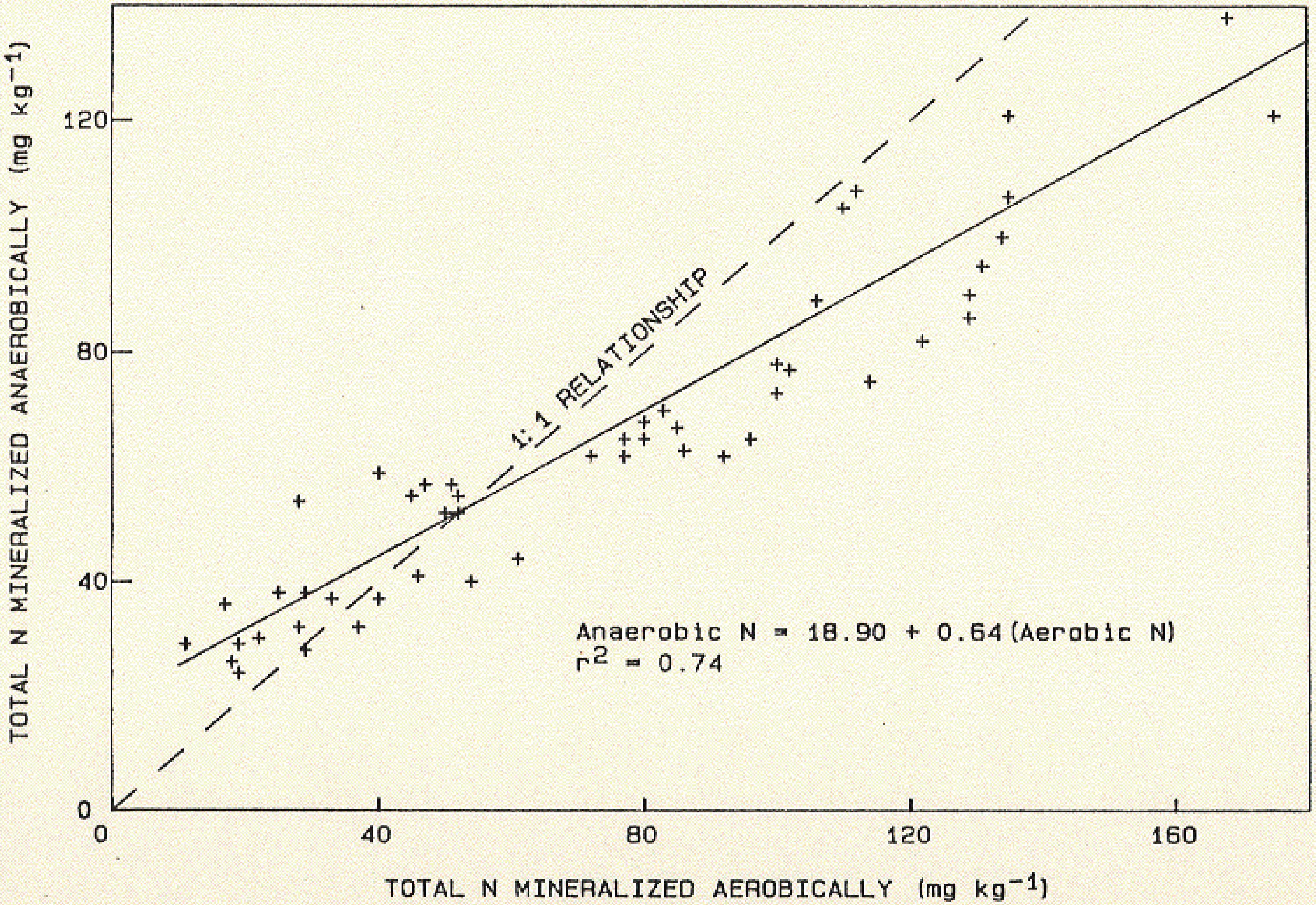


FIGURE B1: COMPARISON OF N MINERALIZED DURING AEROBIC AND ANAEROBIC INCUBATIONS
Values derived from incubations of 51 soils at 30 °C for 14 days.

significant nitrification capacity and the correlation patterns (Table B1) showed that higher soil pH was usually associated with lower N mineralization rates. If pH was influencing volatilization, the aerobic values should be higher than the anaerobic when mineralization was low.

Effect of Organic Matter, Total Nitrogen and C/N Ratio:

As is evident from the correlation matrix (Table B1), most of the variables are interrelated in such a fashion that an independent evaluation of their influence cannot be attained.

Among the variables tested, organic matter followed by total N produced the best correlation with N mineralized (Figure B2). Neither of these produced very high r^2 values.

$$N(\text{Aerobic}) = 23.25 + 2.26(\text{Organic Matter}\%) - 1.61(\text{Moisture Content}\%)$$

$$r^2 = 0.35$$

The effect of organic matter is consistent with the studies of Redman and Patrick (1965), Cunningham (1962) and Powers (1980), whereas Nommik (1976), Zottl (1960c) and Kawahara (1970) reported a stronger effect of total N on N mineralization. Most of the previous authors also found an apparent relation with C/N ratios, which was not evident in the current data set.

The negative effect of air dry moisture content on mineralization is in agreement with most research showing a stimulation of mineralization upon drying. The effect is both continuous and nonlinear as demonstrated by Munro and MacKay (1964). It is therefore not surprising that slight differences in the degree of air drying can contribute to significant changes in N mineralization.

The influence of C/N ratios appears clouded by the study results. The vast majority of soil profiles examined show C/N ratios decline with depth. The lower ratios in the mineral horizons can often be associated with an advanced degree of humus decomposition making it resistant to further breakdown. Ohita and Kumada (1978b) in combined litter and soil samples beneath plantations

Table B1. Simple Correlation Matrix Between Soil Variables and the N Mineralization Indices. Values from control plot samples of the 0-15 cm of the mineral soil horizon, n = 51 Installations.

	N-Mineral. (Anaerobic)	N-Mineral. (Aerobic)	Organic Matter	Soil pH	Total Soil N(Percent)	Nitrate-N by CTA	C/N Ratio	Initial NH_3-N Content
N Mineralized[a] (Aerobic)	0.80							
Organic Matter[a]	0.54	0.52						
Soil pH[a]	-0.34	-0.42	-0.52					
Total Soil N[b]	0.48	0.39	0.76	-0.45				
Nitrate N[a]	0.41	0.45	0.33	-0.17	0.27			
C/N Ratio[b]	0.10	0.18	0.27	-0.07	-0.36	0.11		
Initial NH_3-N[a]	0.32	0.42	0.47	-0.30	0.30	0.04	0.22	
Moisture Content[a]	0.03	-0.07	0.37	0.02	0.40	0.23	-0.07	-0.04

[a] $R = 0.28 > \alpha\ 0.05$ $R = 0.37 > \alpha\ 0.01$

[b] $R = 0.30 > \alpha\ 0.05$ $R = 0.38 > \alpha\ 0.01$

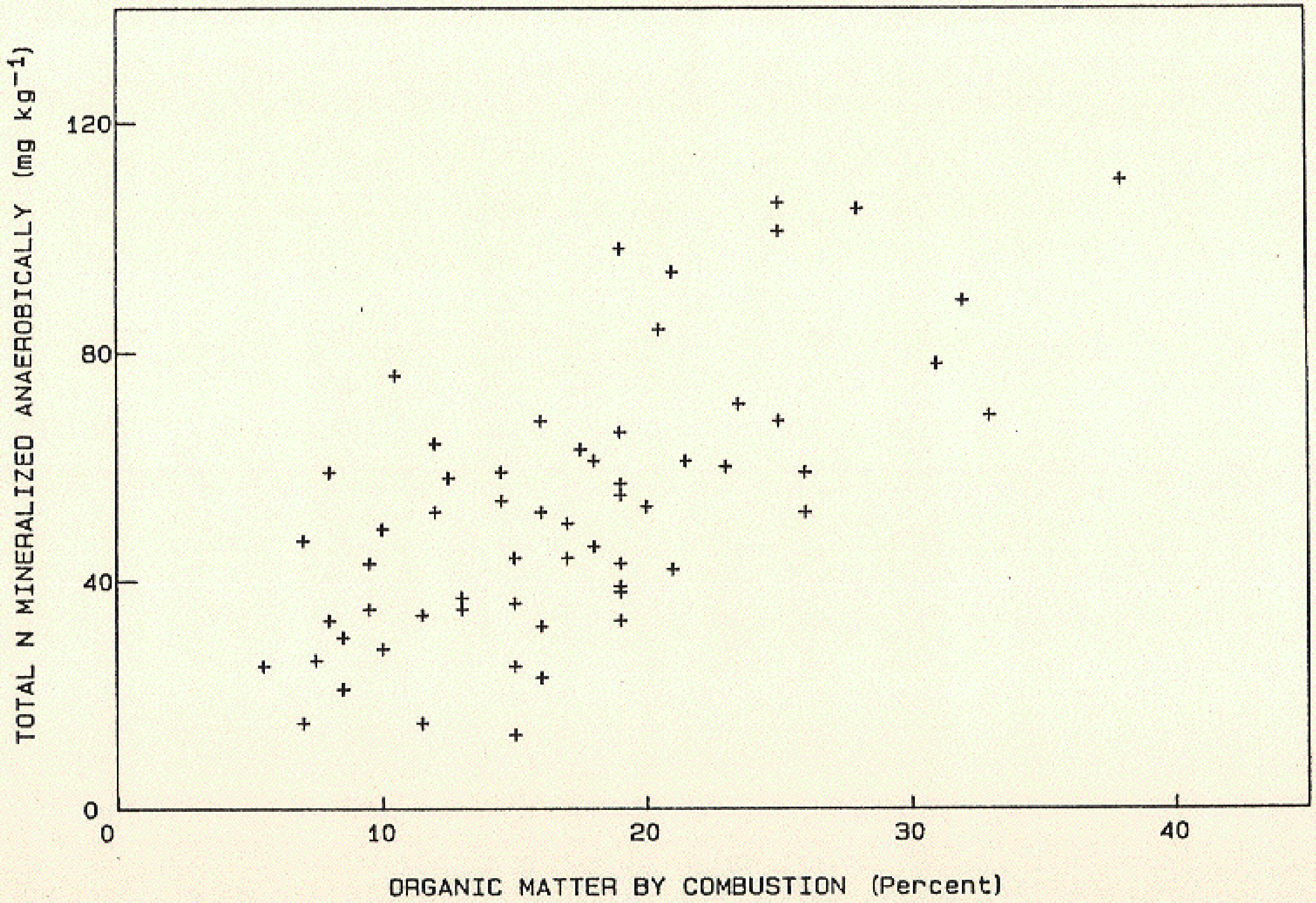


FIGURE B2: N MINERALIZED DURING ANAEROBIC INCUBATION VS. ORGANIC MATTER CONTENT Organic matter determined by combustion. Values derived from incubations of 51 soils at 30 °C for 14 days.

reported a much more complex pattern of mineralization related to C and N. Their results showed an increase up to a value of 30 and a decrease thereafter. It is notable that most of the authors who have found C/N ratios valuable were dealing with humus or partially decomposed litter. Nommik (1976) listed good correlations with mineralization for humus, but not mineral soil samples.

When the data are examined in terms of the percentage of total N in the sample that is mineralized during incubation, then C/N ratio is found to be positively correlated (Figure B3) and total N negatively related.

$$\text{Percent N} = 1.08 + 0.0528(\text{C/N Ratio}) - 2.67(\text{Total N})$$
$$r^2 = 0.39$$

This is not what would be expected intuitively. This result is reasonable only if one relies upon the hypothesis that in the mineral soil profile, the humus fractions with low C/N ratios represent more resistant material. Higher values represent soils with more liable compounds, which have been leached or mixed with the surface horizon. From the standpoint of the current study, bulk C and N values are not as meaningful for biological evaluations as for pedogenic interpretations. Closer attention to readily oxidizable or water soluble fractions may have been of greater value for the particular soils in this study. This is supported by the fact that only 0.5-5.0 percent of the total N was subject to mineralization during the incubation period.

Nitrate Production and Soil Properties:

Nitrate production has received considerable attention in agriculture because of its association with high levels of available N (Eagle and Mathews 1958, Hanway and Dumenil 1955). It has received attention in forest soils because of the concern about nitrate contamination of ground and surface waters (Tamm et al. 1974, Moore 1974). Many of the environmental parameters affecting nitrification and nitrifier populations have been examined (Belser 1979).

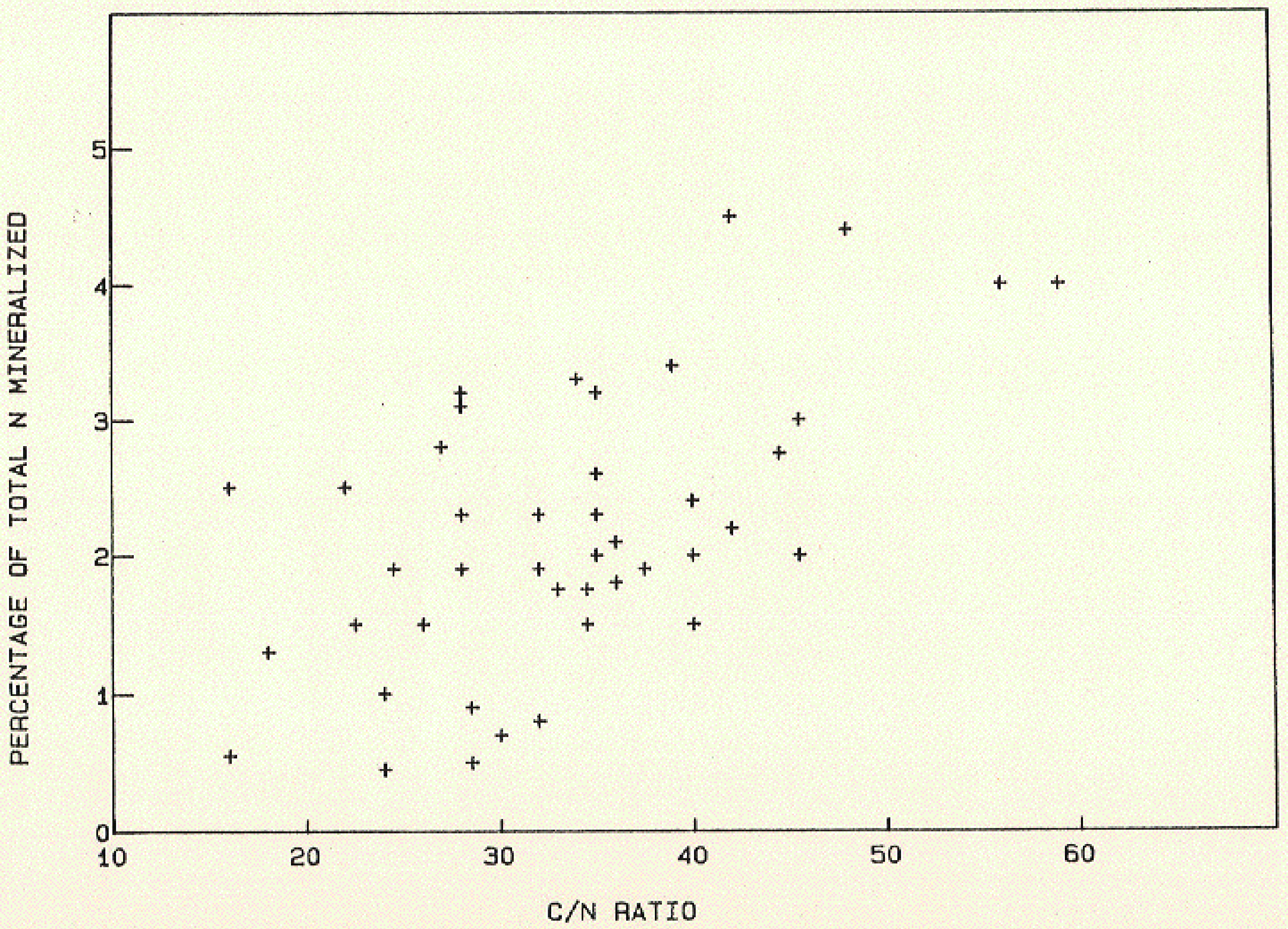


FIGURE B3: EFFECT OF THE C/N RATIO ON THE PERCENTAGE OF TOTAL N RELEASED DURING INCUBATION
Total N determined by micro Kjedhal. C estimated from combustion at 400 ^{o}C.
Soils incubated aerobically for 14 days at 30 ^{o}C. n = 45.

As with the release of ammonia N, many factors apparently correlated to nitrate production are interrelated. The best single variable was total N released during aerobic incubation (Table B1). Multiple regression did not reveal any combination of variables or interactions which could significantly explain additional variation. Since it is known that autotrophic nitrifiers are dependent upon ammonium as an energy source it is not surprising that activity increases with increasing substrate level. The latter has been demonstrated by Stojanovic and Alexander (1958), Ohita and Kumada (1979) and Robertson and Vitousek (1981). Heilman (1974) reported a good correlation with total N and organic C in incubated samples but apparently did not measure mineralized N.

Numerous reports also support a positive effect of pH on nitrification (Kivekas and Kirinen 1959, Chase et al. 1964). Apparently the effect is due to growth limitations on nitrifying bacteria, possibly the result of inhibition of substrate-enzyme formation needed to sustain population growth. No statistical effect was noticed in this data set over the pH range of 4.9 to 6.2.

Because a great deal of unexplained variation remains, it is conceivable that additional controls may arise from the presence of tannins and phenolic compounds (Bollen and Lu 1969, Basaraba 1964).

Comparison of Nitrogen Released on Fertilized and Unfertilized Plots:

Samples that were taken from the EFT complete treatment installations included the plot previously treated with NPKS, and either one of the 336 or 560 kg ha^{-1} plots, which was to be refertilized with 336 kg ha^{-1} of N.

Because the mean level of organic matter in the 0 to 15 cm layer was slightly higher in the fertilized plots, an ANOVA was run with organic content as a covariate. No significant differences in net mineralization between control, N only and NPKS plots were detected 8 years following the initial treatment (Table B2). The N only plots showed a slight enhancement and it is possible that in individual cases, especially at the 560 kg ha^{-1} rate this does occur.

Table B2. N Mineralization and Nitrification on EFT Complete Treatment Installations 8 Years After Initial Fertilization.

Installation	Soil Series	Total N Mineralized (mg kg^{-1})[1]			NO_3-N Released (mg kg^{-1})[2]		
		Control	N-Only	NPKS	Control	N-Only	NPKS
562	Kapowsin	57.8	77.1	60.0	1.5	12.1	4.3
503	Klaus	54.2	73.5	66.8	5.5	2.3	6.5
568	Jonas	79.7	65.8	74.2	2.9	12.0	3.8
572	Olympic	69.7	80.2	55.3	1.6	34.0	25.0
601	Gurney	45.6	50.5	42.3	1.5	4.8	11.8
551	Melbourne	55.4	55.2	80.9	0.9	0.5	8.5
553	Melbourne	22.9	28.8	17.0	1.4	2.1	2.1
602	Nekia	42.6	47.3	60.3	0.7	1.3	2.0
588	Dunnigan	80.3	67.3	70.1	2.0	9.5	17.0
579	Leavell	70.2	86.3	99.3	1.5	33.0	4.8
578	Raught	87.0	81.6	80.6	1.8	21.5	21.0
580	Ariel	96.7	107.3	64.5	25.0	30.0	32.0
527	Lytell	75.3	71.6	54.5	5.3	2.8	1.5
596	Toutle	49.2	30.1	60.1	1.8	19.0	14.0
501	Skykomish	50.4	76.4	53.3	5.4	50.0	20.0
577	Morgan	71.9	110.4	87.4	7.0	25.0	9.5
514	Astoria	74.0	106.3	67.0	3.3	9.0	10.5
594	Goble	136.7	150.4	125.8	5.5	8.5	44.0
563	Baumgard	61.1	128.8	85.7	7.0	36.0	42.0
599	Hawkins	41.5	40.7	78.8	0.8	11.0	5.8
597	Ryan	49.9	56.7	86.4	4.8	30.0	27.0
500	Klaus	55.9	30.1	65.2	2.7	17.5	15.5
508	Barnston	28.1	47.4	50.4	1.5	15.5	3.0
576	Morgan	50.9	85.2	79.5	0.7	1.5	4.5
544	Clemmons	101.4	110.8	94.2	4.3	4.0	8.3
	Mean	64.3	74.6	70.4	3.8	15.7	13.8

[1] Results from Aerobic Incubation Adjusted for Initial Organic Matter Content
Treatment Means Not Significantly Different ($F = 2.94 < F_{\alpha} = 0.05 = 3.40$)

[2] Results from Aerobic Incubation (Chromotropic Acid Method)
Treatment Means Significantly Different ($F = 22.37 \gg F_{\alpha} = 0.01 = 5.61$)

Immediate effects can be expected as a result of the priming effect (e.g., Williams 1972) and through an increase in the general decomposition of the humus (Viro 1963). Since urea is quickly immobilized by the humus a decrease in the C/N ratio could also be expected (Overrein 1970, Popović 1977). Ohita and Kumada (1979) reported that the largest effects of fertilization on mineralization were manifest in the partially decomposed litter and humus layer and not in the mineral horizon.

The effects of fertilization on nitrification are more pronounced and also highly significant. Reports of enhanced nitrification potential in forest soils are frequent as a result of fertilization (e.g., Popović 1977, Heilman 1974, Roberge and Knowles 1966, Robinson 1963). All of these studies were done with samples treated within a few months to two years, none as long as 8 years, as in this study. The former results are often interpreted in light of the hypothesis that substrate (ammonium ions) availability controls activity (Verstraete 1981). The slight difference in total N mineralization cannot account for the observed differences. Inclusion of total N released as a covariate did not significantly change the results. It is possible that the environment needed to sustain higher populations had been improved. Chase et al. (1964) clearly showed that certain fertilizer effects sustained higher populations for as long as 8 years under maple. Garbosky and Giambiagi (1962) have found nitrifiers to survive exceptionally well as spores for many years under a wide range of conditions, particularly where other nutrients, excluding ammonium, are high. N availability was not found to influence survival and subsequent nitrification potential following long term storage in their experiments.

From the standpoint of fertilizer response, the lack of a significant change in readily mineralizable N, indicates that response to the second dosage should be similar. This presumes that the original N dose is not cycled efficiently enough in either the litter/humus layers or within the tree to reduce the N demand.

The latter proposition is supported by the apparent growth increase following retreatment reported by the Regional Co-operative.

Finally, nitrification appears to be sensitive to urea applications, however, environmental conditions in situ and plant uptake of the readily mobile nitrate ion make it difficult to assess its importance in the field.

Distribution of Nitrogen and Sulfur Quantities Within and Between Soils:

Changes in N mineralization potential with depth were studied on six installations. Sites were selected to sample a common soil series, representing the range of ages in the fertilizer installations. Three soil series pairs were chosen in close proximity to each other to avoid gross climatic differences (Figure B4).

An attempt was made to derive an estimate of the N mineralization in the humus and partially decomposed litter by mixing the latter materials thoroughly before drying and sieving with the 0 to 15 cm mineral soil fraction. The difference in N release are presumably a result of the humus input.

The percentage contribution of the 0 to 15 cm layer to the overall N release potential in the profile ranges from 28-69 percent with an average of 50±14. Only in the older installations did the surface layers contribute significant amounts of reserve potential. The particular sample plot on installation 515 had a large amount of animal burrowing activity which could have resulted in significant mixing of horizons. It is reasonable that both the absolute levels of mineralization potential and the relative contribution of the humus layers would increase with stand age, but the pattern is confounded by the results from installation 515. On podzolized soils Tamm and Pettersson (1969) reported greater N release in the A_0 vs. A_1 horizon in several older pine stands. Ohita and Kumada (1978a) reported a similar pattern but the differences in % total N mineralized were smaller in a wide range of conifer plantations. The larger numerical impact of the humus layers arises from the

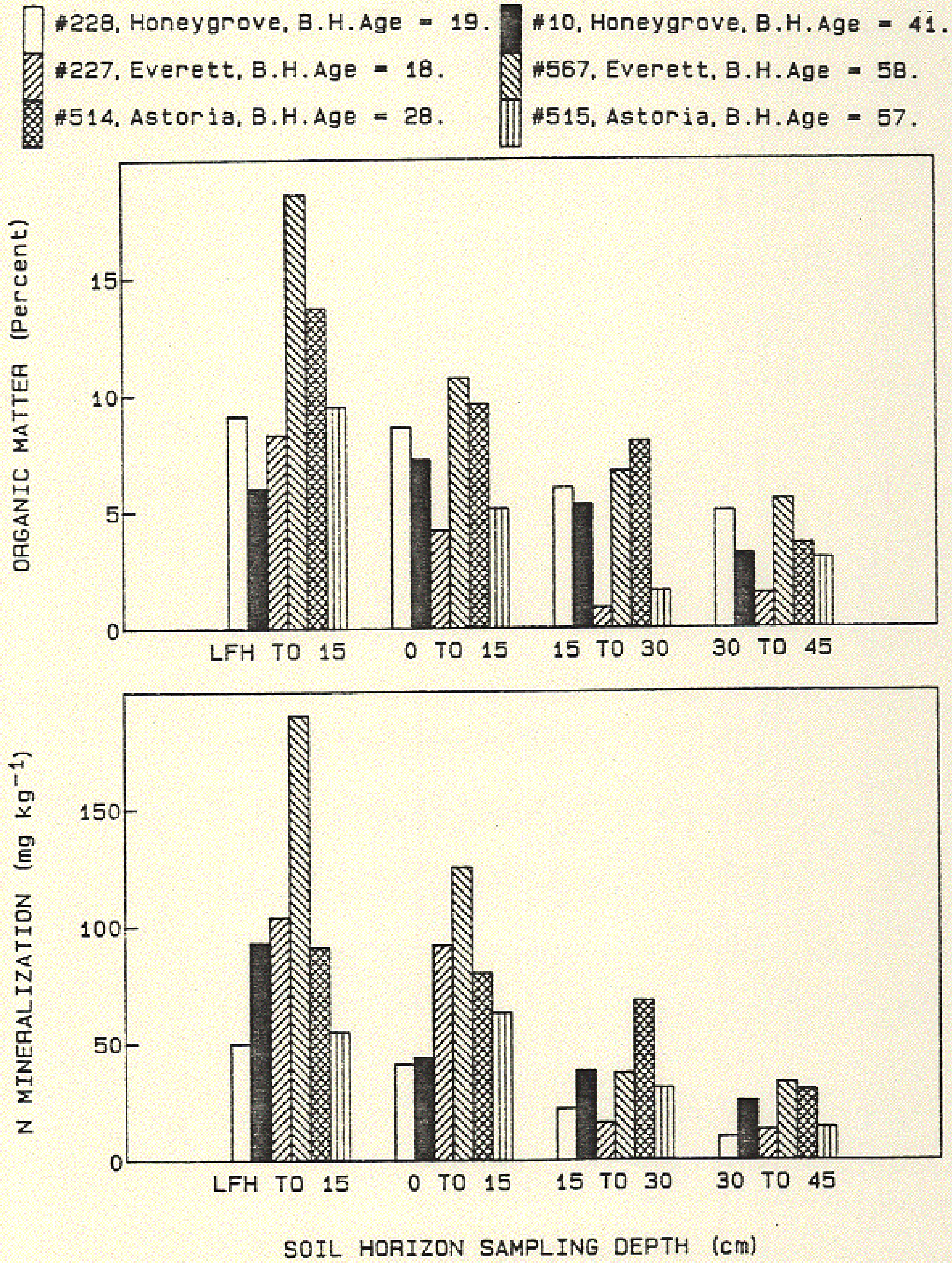


FIGURE B4: N MINERALIZATION AND SOIL ORGANIC MATTER WITHIN THE PROFILE OF SEVERAL INSTALLATIONS. Organic matter determined by combustion. N mineralization derived from aerobic incubation. LFH represents the litter and humus layers combined.

expression of absolute N production as a fraction of the dry weight. If the contribution of the humus layer is expressed on an area basis, its contribution to the total N release potential is less than half of the mineral horizon, as noted by Runge (1971) and Popović (1980). Popović's values in older mature beech stands are similar to the 26 to 31 percent "apparent" contribution on Installations 567 and 10. Jeanes, in a study discussed by Richards (1981), noted that N mineralized per unit area was greatest in the surface mineral horizon, not in the litter or humus, when bulk soil blocks were incubated in the laboratory.

Below the 0 to 15 cm layer, the N released during incubation declines. Significant quantities are produced by soil horizons at almost fifty centimeters. Similar results were reported by Kawahara (1970) with generally 74-86% of the mineral N produced in the upper 20 cm of soil. Shumway and Atkinson (1978) also found much less total N released below 15 cm. Although variation in the distribution among soils was evident, the contribution below 15 cm was one-third or less. The decline in mineralization with depth in Figure B4 is generally proportional to changes in organic content. A number of studies report that C/N ratios decline with depth (Young 1962, Kononova 1975).

Several recent studies, including this one, support the belief that the surface mineral horizon is of equal importance to the N economy of the stand, when compared with forest floor layers. The variable nature of its contribution under static conditions makes it doubtful that a precise measure of N availability can be made. Furthermore, the dynamic nature of the temperature and moisture conditions at the soil surface will complicate the real contributions of each layer.

The distribution of SO_4-S across a range of soils and parent materials and by sampling depth is listed in Table B3. With few exceptions, there is a consistent trend showing an increase in Morgan's extractable SO_4-S with depth. The most dramatic increases are in those soils with a typically well developed cambic B horizon.

Table B3. Comparison of SO_4-S Distribution in the Soil Profile of Several Common Soil Series (< 2 mm fraction).

Soil Series	No. Sites	Sample Depth	Concentration	Sample Depth[a]	Concentration
Astoria	6	0-15 cm	39.8 ±38	45-76 cm	87.4 ± 70.8
Honeygrove	6	0-15 cm	9.9 ± 3.5	45-68 cm	42.0 ± 31.0
McCully	4	0-15 cm	25.0 ±14	45-60 cm	103.0
Evere H	5	0-15 cm	7.8 ± 1.6	30-45 cm	27.4 ± 21.6
Grove	3	0-15 cm	10.6 ± 4.8	30-40 cm	31.7 ± 31.4
Morgan	3	0-15 cm	19.5 ± 8.8	45-70 cm	86.2 ± 18.5
Melbourne	3	0-15 cm	13.6 ± 0.8	45-60 cm	74.3 ± 32.6

[a] Samples were selected from the upper third of the textural B-horizon. Depth varies considerably with site.

The variability among sites was large, but more noticeable in soils which were sampled from a very wide geographic range (Honegrove and Everett vs. Melbourne and Morgan).

Surface quantities are fairly constant within certain soil series. Both the McCully and Astoria profiles normally have a high level of available SO_4-S. No trends within parent materials with respect to S availability have been noted which would point to geochemical deficiencies.

The enhanced levels of mineral S in the subsoil are characteristic of the deeply weathered alfisols and ultisols of the region. The surface values are consistent with other studies in Oregon (Harward et al. 1962). Hesse (1957) found that in deeply weathered forest oxisols of East Africa nearly all of the S in the surface soil was organically bound whereas the subsoil S was entirely in the sulfate form. The same pattern was evident in oxisols and ultisols from the southeastern agricultural region (Sanford and Lancaster 1962).

Larson (1980) followed sulfate movement in residual forest soils in the western Olympics. There was a net movement of sulfate from the surface horizon, followed by nearly total adsorption in the subsoil. Stream sulfate was derived entirely from bedrock weathering.

Probert (1977) proposed that this differential distribution is caused biopedogenic weathering, where organic anions complete effectively for anion ligand adsorption sites in the surface soils. Where the subsoil clay mineralogy contains a significant level of free or amorphorous iron and aluminum oxides, the sulfate is concentrated by adsorption (Chao et al. 1962, Black and Waring 1979, Parfitt and Smart 1978).

Inverted sulfate distributions were found on two sites which showed clear evidence of severe soil disturbance as a result of previous tractor logging activity. A few clay textured soils concentrated little sulfate S in the subsoil. The latter is presumably a result of the clay mineralogy developed in the lower horizon which does not favor the existence of anion exchange sites, or which may also lead to illuviation of the oxide clays.

Roberts and Koehler (1968) sampled agricultural soils in Washington. Many were low in extractable sulfate. They suggested that the pattern of increase with depth was primarily caused by calcareous horizons or accumulations of fertilizer sulfate, however few agricultural activities were located on the more highly weathered soils common in this study.

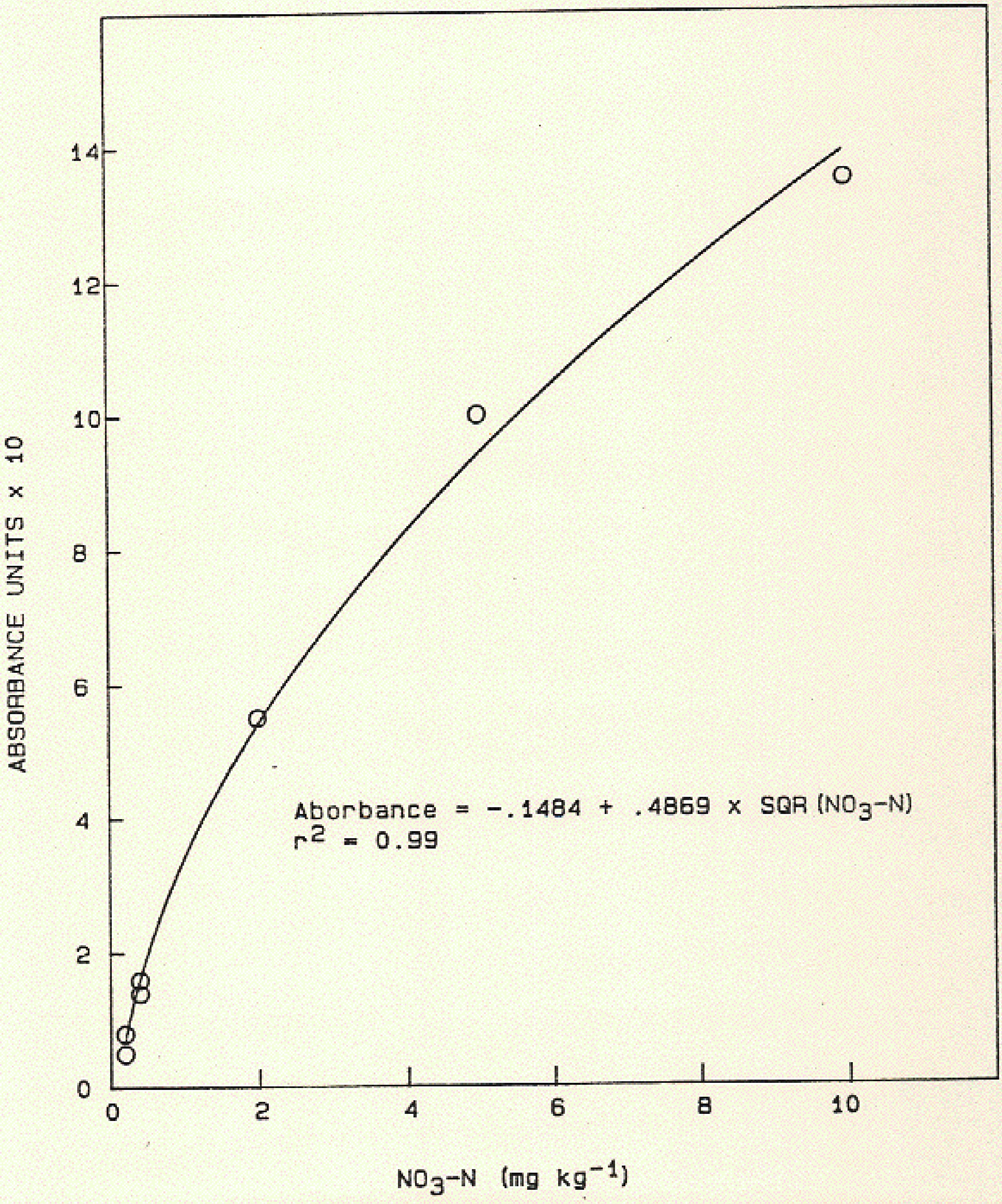
Only the coarse sandy or gravelly soils of the Puget Sound had consistently little accumulation of extractable SO_4-S in the subsurface horizon. Most of these soils are a result of recent glacial action and would not be expected to develop a strong enough anion adsorption capacity to prevent leaching losses in the profile under high rainfall conditions (Ensminger 1954).

Hesse suggests that the organic/inorganic distributions of S with depth are a significant factor in regulating the nutrient cycling of S following the establishment of perennial crops. The latter is consistent with the studies of Greenland and Nye (1960) on nutrient cycling and fertility in Africa and undoubtedly have applications to situations in western Oregon and Washington.

Appendix C

ABSORBANCE VS. CONCENTRATION OF NO_3-N IN 1N KCL BY CHROMOTROPIC ACID

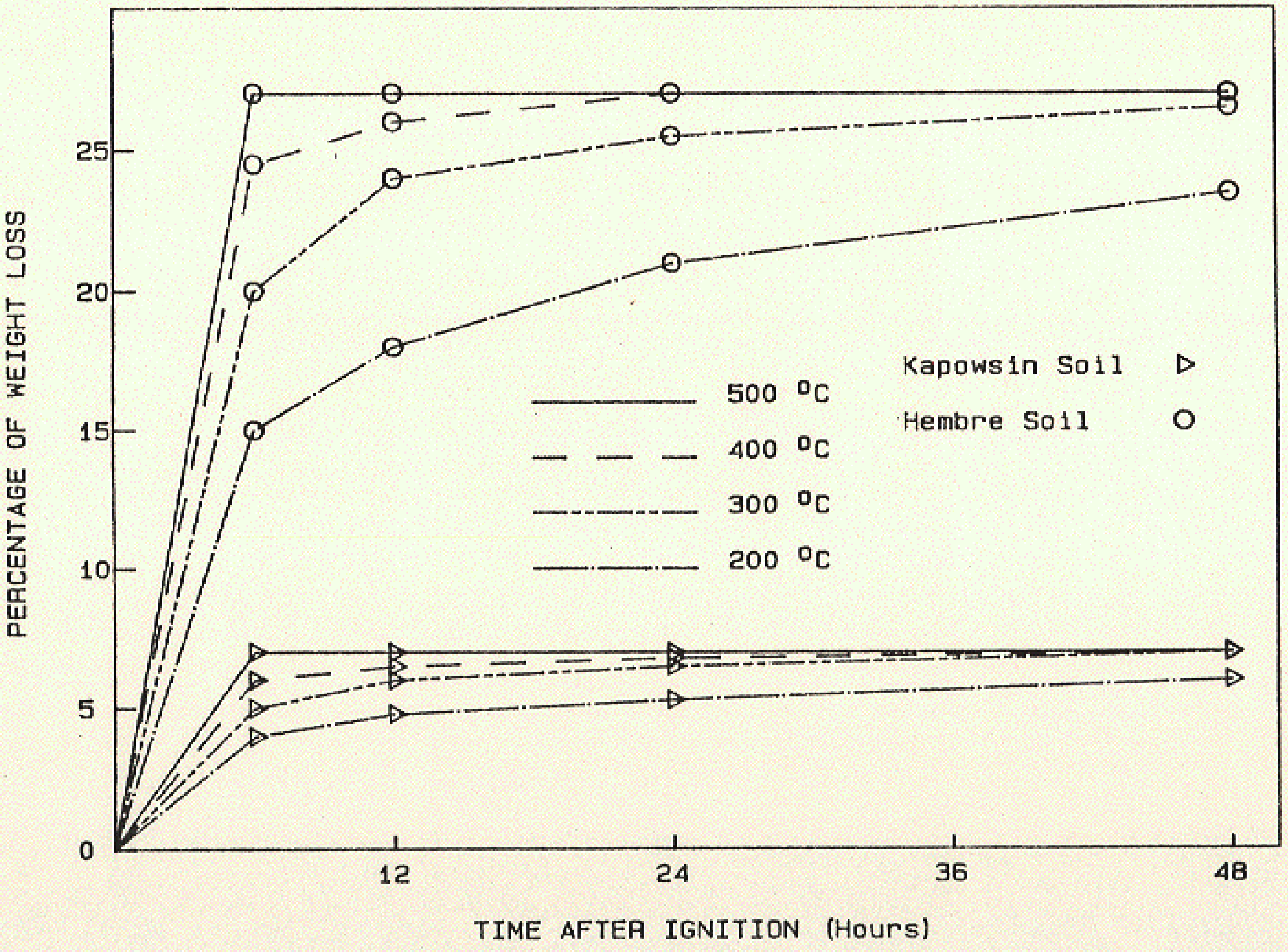
Absorbance measured in 1N KCL solutions at 357 mm.



Appendix D

EFFECT OF COMBUSTION TIME AND TEMPERATURE ON THE DETERMINATION OF ORGANIC MATTER

Percentage of weight loss during ignition used to estimate organic matter.
Soil samples derived from the surface to 15 cm layer of two installations.



Appendix E

ANALYSIS OF SITE QUALITY AND SOIL SERIES EFFECTS ON VOLUME RESPONSE OF PAIRED[a] SITES

Soil Series	Volume Increment (m^3ha^{-1} 5 year^{-1}		Total
	Higher Site	Lower Site	
1. Everett	30.0	31.9	61.9
2. Everett	23.0	33.8	56.8
3. Astoria	9.1	8.3	17.4
4. Astoria	38.2	30.7	68.7
5. Honeygrove	12.7	20.0	32.7
6. Honeygrove	22.1	18.4	40.5
7. Klickitat	20.8	35.1	55.9
8. Wilkinson	14.6	23.2	37.8
9. McCully	9.0	15.0	24.0
10. McCully	33.1	35.7	68.8
11. Bromo	2.3	26.4	28.7
12. Hembre	14.6	17.6	32.2
13. Grove	27.4	25.8	53.2
14. Oso	24.7	24.2	48.9
15. Kapowsin	13.2	28.6	41.8
16. Raught	21.2	24.4	45.6
17. Goble	8.1	26.0	34.1
18. Lytell	22.0	28.5	44.5
19. Melbourne	5.4	19.7	25.1
20. Morgan	22.3	29.1	51.4
21. Biegle	7.5	29.5	37.0
22. Alderwood	13.5	21.7	35.2
23. Baumgard	21.0	28.9	49.9
24. Jory	25.7	27.1	52.9
Total	441.60	603.6	1,045.2

ANOVA

Df	Source	TSS	MS	F-Value	Significance
47	Total	3,487.07	--	--	
23	Soil Series	2,177.27	94.66	2.85	$P < \alpha = 0.01$
1	Site Quality	546.75	546.75	5.78	$P < \alpha = 0.05$
23	Error	763.05	33.18		

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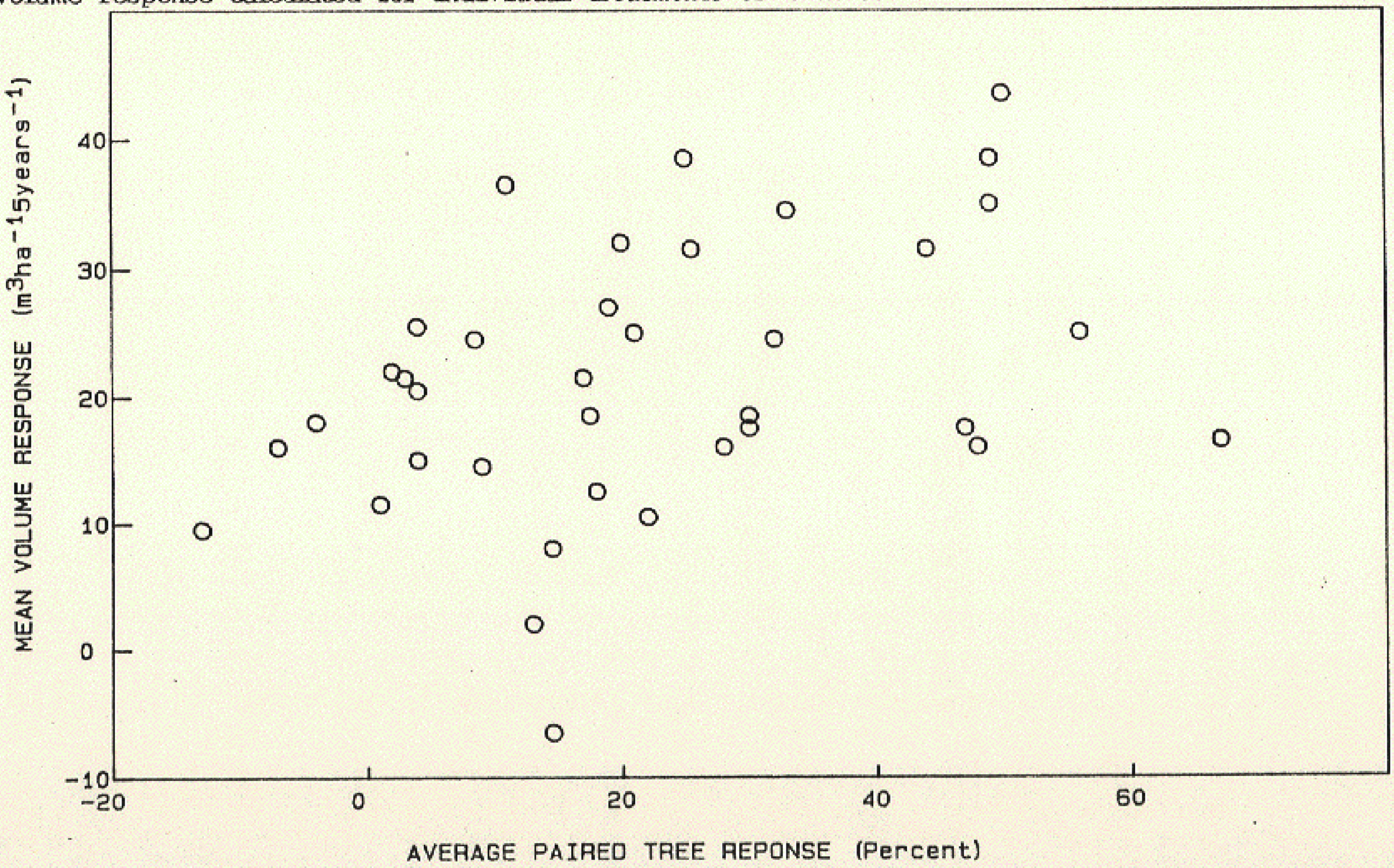
[a] Paired sites randomly selected from list of all installations on the same soil series.

Appendix F

RELATION BETWEEN PAIRED TREE INCREMENT AND VOLUME RESPONSE

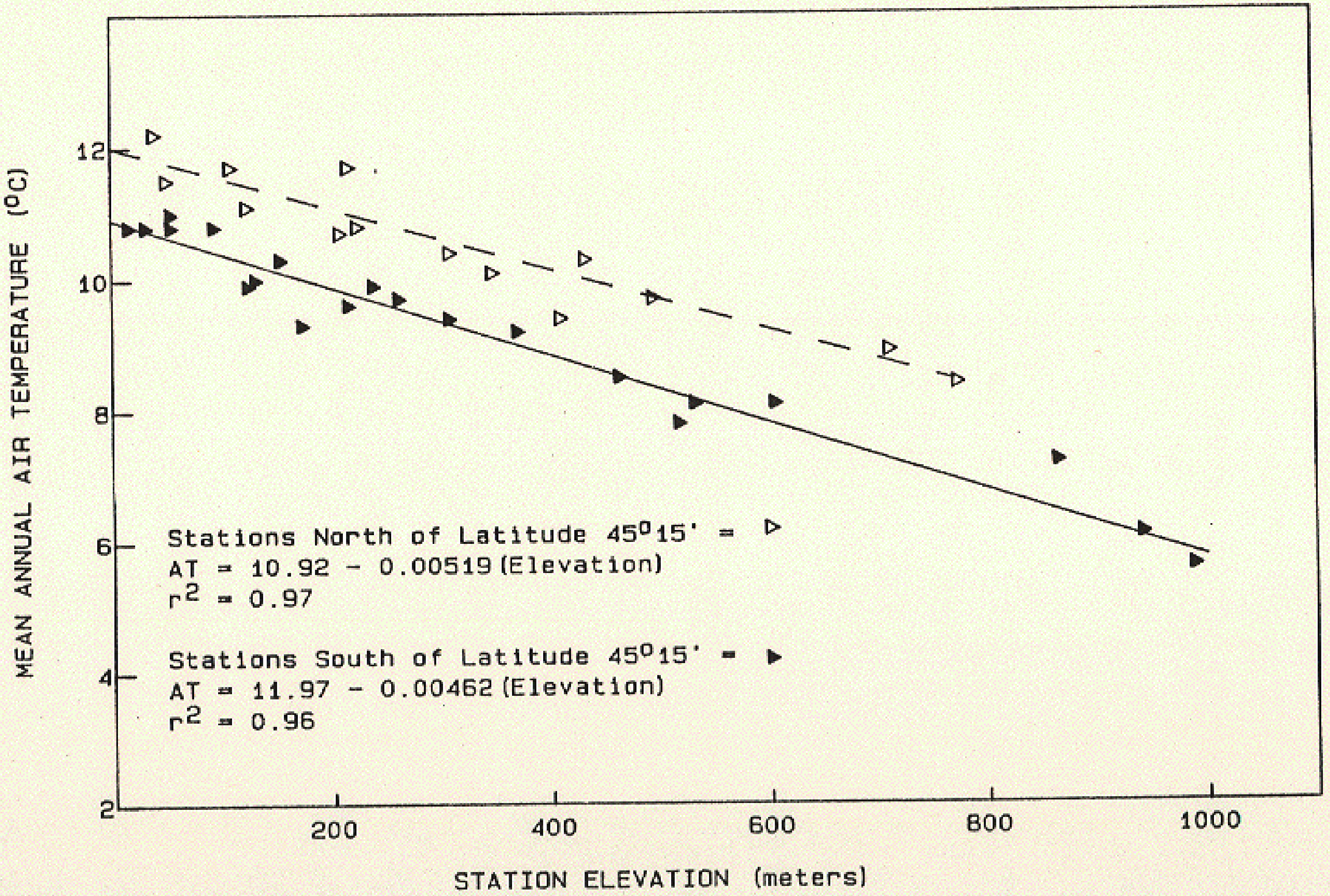
Paired tree growth analysis based upon the method of Gagon (1975).
Volume response calculated for individual treatments of N on 36 installations.



Appendix G

MEAN ANNUAL TEMPERATURE FOR SELECTED WEATHER STATIONS IN WESTERN OREGON AND WASHINGTON

Stations are from west of the Cascade crest. Points are shown split by latitude at Portland, Oregon.



Appendix H

CANONICAL DISCRIMINANT ANALYSIS OF RESPONSE GROUPS IN RELATION TO STAND AND SOIL VARIABLES

Canonical Discriminant Analysis was applied to the data set to compare the effectiveness of the stand and soil variables in separating response groups. This type of analysis affords a slightly different perspective since it deals with the separation of groups with dissimilar characteristics. The boundaries of each group can be used to delimit additional response properties.

Initially the response data was divided into three groups representing three response ranges: 1 = 0 to 15 m^3 ha^{-1} 5 $years^{-1}$, 2 = 15 to 28 m^3 ha^{-1} 5 $years^{-1}$ and 3 $>$ 28 m^3 ha^{-1} 5 $years^{-1}$. Group 2 represents approximately one standard deviation around the mean response, the others, response extremes. Soil, stand and combined variable sets were incorporated in a stepwise manner. Rao's V was selected as the generalized distance measure.

When utilizing soil variables separately, all those found to be significant in the multiple regression approach were also found to be useful in separating groups (Table H1). In the selection sequence, N mineralization and mean annual temperature were significant in separating groups 1 and 2 only. The S index provided significant separation of groups 2 and 3. These results support Shumway and Atkinson's (1977) original contention that N mineralization may be a useful means to separate average to high response areas from low ones, however the precision the classification system using only this variable is poor (52 percent). The S status of the soil appears to influence the differences between average and high response stands. Seventy-five percent of the sites were correctly classified with the soil variables alone.

When stand age and site index were incorporated, only groups 2 and 3 and 1 and 3 were significantly separated. Neither variable provided separation of the low and average response groups. Overall classification efficiency was 59 percent.

Table H1. Canonical Discriminant Analysis of N Response Group Based Upon Analysis of Soil Variables[a]

Actual Group	Number Cases	Classification Results (Percent Predicted Group Membership) 1	2	3
1(0-15 $m^3ha^{-1}5$ $year^{-1}$)	12	83.3	16.7	0.0
2(15-28 $m^3ha^{-1}5$ $year^{-1}$)	20	5.0	80.0	15.0
3(>28 $m^3ha^{-1}5$ $year^{-1}$)	19	10.5	26.3	63.2

Percent Correctly Classified = 74.5

Variable	Standardized Canonical Discriminant Function Coefficients Function 1	Function 2
N-Mineralized[b]	1.326	0.869
Mean Temperature	0.669	0.472
S-Index	-1.579	0.453
S/N Ratio	1.381	0.273
Specific Fraction	0.313	-0.688
Group Centroids		
1	1.848	0.390
2	-0.108	-0.718
3	-1.054	0.509
Characteristics of Functions		
Eigenvalue	1.299	0.356
Canonical Correlation	0.751	0.512
Significance	0.000	0.007

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[a] Stepwise selection of variables using RAO's V generalized distance.

[b] Adjusted directly for temperature.

A combination of both variable sets gave the best classification (82 percent correct). The two indices, site and N mineralization, significantly separated all three groups. The other variables (S-index and S/N ratio) provided further refinement. Specific fraction or gravel was not important in the combined analysis. A complete breakdown is shown in Table H2. The soil only analysis, while overall slightly poorer, gave a higher correct percentage classification in group 1.

Table H2 shows that two orthogonal vectors were extracted. The first function, showing the standardized weights applied to each variable in separating the three groups, contrasts the S index with the others. The second function primarily serves to separate the median group from the high and low groups.

The results of the regression (Chapter III, page 50) and discriminant analysis support several general statements. In both cases a hybrid approach provides greater predictability of response. It is hypothesized that while age reflects underlying nutritional patterns evident from the measurement of soil S and N, site quality in Douglas-fir embodies a more complex set of relationships to N. The individual components of surface soil mineralizable N and probably also litter decomposition (Edmonds et al. 1981) do not provide a suitable soil based integration of site effects.

Mineralizable N offers a significant but limited classification of low response stands.

Table H2. Canonical Discriminant Analysis of N Response Groups Based Upon Combined[a] Analysis of Stand and Soil Variables

Actual Group	Number Cases	Classification Results (Percent Predicted Group Membership) 1	2	3
1(0-15 $m^3ha^{-1}5$ $years^{-1}$)	12	75.0	25.0	0.0
2(15-28 $m^3ha^{-1}5$ $years^{-1}$)	20	5.0	85.0	10.0
3(>28 $m^3ha^{-1}5$ $years^{-1}$)	19	10.5	5.3	84.2

Percent Correctly Classified = 82.4

Variable	Standardized Canonical Discriminant Function Coefficients Function 1	Function 2
N-Mineralization[b]	0.905	1.038
Site Index	0.503	-0.435
S Index	-1.663	0.003
S/N Ratio	1.403	0.794
Group Centroids		
1	1.835	0.599
2	0.156	-0.767
3	-1.323	0.429
Characteristics of Functions		
Eigenvalue	1.545	0.408
Canonical Correlation	0.779	0.538
Significance	0.000	0.003

[a] Stepwise selection of variables using RAO's V generalized distance.

[b] Adjusted directly for estimated Mean Annual Air Temperature.

Appendix I

EXPERIMENTAL METHODS FOR GREENHOUSE STUDY OF DOUGLAS FIR SEEDLING RESPONSE TO NITROGEN AND SULFUR

The study was conducted at the Weyerhaeuser Regeneration Center, Rochester, Washington. Initially all Weyerhaeuser EFT installations on which S availability had been previously measured by Morgan's extract were ranked: 5 to 10, 10 to 15, 15 to 20, 20 to 25 and greater than 25 mg kg^{-1}. From each of these groups five sites were randomly selected. Bulk soil samples were collected from the 0-15 cm layer, air dried and screened through a 12 mm^2 sieve. The dried soils were mixed with an equal volume of perilite and then placed in 4 liter black plastic pots. Pure nutrient compounds were dissolved in water (Table I1), then added to each soil and distributed by shaking the soil in a large plastic bag.

Eight new germinants of Douglas fir from the 071-0.5 seed zone in Oregon were planted in each pot. Natural daylight was supplemented by light from high pressure sodium vapor lamps for sixteen hours per day (200 W m^2). The pots were irrigated two or three times per week for ten minutes to give an average rate of 14.5 cm per month. This rate was in excess of plant demands and therefore permitted some leaching. A supplemental application of N, at half the initial rate, was added four months after the study initiation.

The experiment was terminated in August, following seven months of growth. Sufficient biomass had accumulated to facilitate dry weight analysis. The roots had developed sufficiently to keep the soil intact when removed from the pots.

Table I1. Nutrient Levels for Seedling Fertilizer Experiment

Nutrient Source	Control	Fertilizer Treatment Nitrogen	Nitrogen + Sulfur
NH_3 NO_3	-	+	+
$(NH_3)_2$ SO_4	-	-	+
Ca $(NO_3)_2 \cdot 4H_2O$	-	-	+
KH_2PO_4	+	+	+
$CaCl_2 \cdot 2H_2)$	+	+	-
H_2BO_3	+	+	+

Treatment	Concentration Level (mg $liter^{-1}$ of soil mix) N	P	K	Ca	S	B
Control	0	13	17	11	0	2
Nitrogen	41	13	17	11	0	2
Nitrogen + Sulfur	41	13	17	11	19	2

Appendix J

ANALYSIS OF VARIANCE FOR SEEDLING ROOT WEIGHT AND SHOOT WEIGHT, CALIPER AND HEIGHT

Source	df	SS	MS	F	Significance
Root Weight					
Total	314	31.77			
Block	4	0.40	0.1000	3.32	$> \alpha$ at $p = 0.05$
Soils	20	7.04	0.3520	11.7	$> \alpha$ at $p = 0.01$
Error	80	2.41	0.0301		
Fertilization	2	11.55	5.780	141.0	$\gg \alpha$ at $p = 0.01$
Fert x Soils	40	3.49	0.0873	2.13	$> \alpha$ at $p = 0.01$
Error	168	6.88	0.0410		
Contrasts:					
Nitrogen vs. Nitrogen plus Sulfur				1,470.6	$\gg \alpha$ at $p = 0.01$
Control vs. Nitrogen Treatments				8,879.3	$\gg \alpha$ at $p = 0.01$
LSD$_{\alpha = 0.01}$ for fertilizer treatments within soils = 0.124 grams					
Shoot Weight					
Total	314	69.640			
Block	4	0.033	0.00826	0.86	NS
Soils	20	11.53	0.577	60.1	$\gg \alpha$ at $p = 0.01$
Error	80	7.68	0.00960		
Fertilization	2	32.38	16.10	218.0	$\gg \alpha$ at $p = 0.01$
Fert x Soils	40	5.69	0.5310	1.92	$> \alpha$ at $p = 0.01$
Error	168	12.43	0.0740		
Contrasts:					
Nitrogen vs. Nitrogen plus Sulfur				929.0	$\gg \alpha$ at $p = 0.01$
Control vs. Nitrogen Treatments				14,700.0	$\gg \alpha$ at $p = 0.01$
LSD$_{\alpha = 0.01}$ for fertilizer treatments within soils = 0.167 grams					

Appendix J (continued)

Source	df	SS	MS	F	Significance
Seedling Caliper					
Total	314	72.93			
Blocks	4	2.93	0.51	7.72	$>$ α at $p = 0.05$
Soils	20	12.28	0.61	9.31	$>$ α at $p = 0.01$
Error	80	5.24	0.066		
Fertilization	2	44.13	21.65	1,082.5	$\gg$ α at $p = 0.01$
Fert x Soils	40	5.90	0.1476	7.39	$>$ α at $p = 0.01$
Error	168	3.35	0.020		
Contrast:					
Nitrogen vs. Nitrogen plus Sulfur				133.6	$\gg$ α at $p = 0.01$
Control vs. Nitrogen Treatments				1,946.8	$\gg$ α at $p = 0.01$
LSD$_{\alpha}$ = 0.01 for fertilizer treatments within soils =					0.135 mm
Seedling Height					
Total	314	8643.38			
Blocks	4	57.96	14.99	1.34	NS
Soils	20	951.61	47.58	4.38	$>$ α at $p = 0.01$
Error	80	868.26	10.85		
Fertilization	2	5453.04	2726.52	403.9	$\gg$ α at $p = 0.01$
Fert x Soils	40	178.71	4.47	0.66	NS
Error	168	1133.80	6.75		
Contrast:					
Nitrogen vs. Nitrogen plus Sulfur				13.6	$>$ α at $p = 0.01$
Control vs. Nitrogen Treatments				798.0	$\gg$ α at $p = 0.01$
LSD$_{\alpha}$ = 0.01 for fertilizer treatments within soils =					2.46 cm

Appendix K

GROWTH RESPONSE OF DOUGLAS FIR SEEDLINGS IN GREENHOUSE POT TRIAL

		Height (cm)			Diameter (mm)			Root Weight (g)			Top Weight (g)			SO_4-S
Inst.	Soil	C	N	N+S	C	N	N+S	C	N	N+S	C	N	N+S	mg kg^{-1}
--	Shanahan	12.6	18.9	20.3	1.68	1.94	2.25	0.52	0.64	0.75	0.49	0.82	0.94	3.1
596	Toutle	12.7	18.3	25.0	1.75	2.12	2.73	0.50	0.64	1.02	0.49	0.92	1.71	3.5
576	Morgan	12.6	17.5	17.6	1.44	2.53	2.52	0.40	0.91	1.03	0.36	1.11	1.20	21.6
551	Melbourne	12.9	21.1	25.7	1.69	2.56	3.08	0.53	1.10	1.63	0.49	1.31	1.78	9.9
527	Lytell	9.7	19.2	19.5	1.45	2.29	2.59	0.44	0.88	1.03	0.34	1.05	1.22	10.1
568	Jonas	14.9	25.6	24.9	1.87	2.86	2.72	0.67	1.18	1.05	0.63	1.83	1.65	8.8
572	Olympic	11.9	20.9	22.3	1.60	2.47	2.78	0.59	1.01	1.31	0.53	1.26	1.44	12.0
503	Skykomish	9.7	14.3	16.6	1.63	2.13	2.59	0.52	0.74	1.06	0.43	0.74	1.08	11.8
508	Barnston	9.5	18.2	17.6	1.38	2.10	2.40	0.33	0.65	0.78	0.31	0.82	0.92	19.9
602	Nekia	11.2	20.8	21.8	1.58	2.27	2.57	0.53	0.87	1.05	0.46	1.27	1.35	6.4
606	McCully	7.5	18.4	19.7	1.24	2.23	2.24	0.31	0.67	0.80	0.27	0.95	1.15	20.0
577	Morgan	8.8	18.1	20.8	1.61	1.87	2.13	0.48	0.76	0.80	0.50	0.59	0.64	8.2
563	Baumgard	11.8	20.9	19.3	1.63	2.20	2.11	0.55	0.89	0.67	0.46	1.21	0.93	15.6
229	Honeygrove	10.1	19.6	18.5	1.61	2.19	2.46	0.47	0.73	0.96	0.40	0.99	1.08	14.0
544	Clemons	9.7	19.2	20.2	1.47	2.32	2.28	0.45	0.88	0.99	0.40	1.08	1.32	34.0
514	Astoria	9.9	18.7	18.1	1.42	1.93	2.05	0.38	0.56	0.65	0.35	0.82	0.91	28.4
588	Dunnigan	9.6	16.7	17.3	1.35	1.93	2.18	0.39	0.60	0.67	0.36	0.78	0.82	14.4
580	Ariel	11.3	16.9	17.7	1.45	1.79	2.10	0.41	0.51	0.64	0.40	0.74	0.81	7.1
582	Biegle	9.3	16.6	18.4	1.30	1.77	2.11	0.35	0.51	0.71	0.30	0.63	0.81	8.0
578	Raught	10.5	17.6	21.7	1.42	2.23	2.61	0.37	0.82	1.03	0.38	0.94	1.33	7.0
549	Boisfort	9.9	18.7	19.2	1.47	2.29	2.29	0.44	0.82	0.82	0.38	1.02	1.08	20.6

Appendix L

RELATIVE ADJUSTED[a] BASAL AREA GROWTH FOR THE EFT COMPLETE TREATMENT INSTALLATIONS RETREATED WITH N AND NS

		Treatment 0-5 years					Treatment 8-11 years			
Installation	C	N1	N3	N5	N3S	C	N1	N3	N5	N3S
500	1.07	1.15	1.01	1.48	1.63	0.81	0.98	0.65+	1.08	1.33
501	0.90	1.00	1.07	1.02	1.19	0.64	0.72	0.76	0.72+	0.85
514	0.83	0.95	0.83	0.96	0.85	0.49	0.65	0.43	0.52+	0.60
527	1.07	1.02	1.15	1.21	1.35	0.73	0.75	0.89+	0.73	1.23
544	3.58	4.16	2.91	3.26	2.28	2.20	2.60	3.00+	2.47	2.77
568	1.06	1.19	1.45	1.23	1.49	0.96	1.05	1.17	1.13+	1.12
572	0.91	1.04	1.27	1.18	1.29	0.63	0.93	0.94+	0.98	1.32
576	1.05	1.44	1.66	1.56	1.18	0.85	1.35	1.75	1.45+	1.32
577	1.24	1.28	1.35	1.71	1.40	0.99	1.26	1.16+	1.49	1.23
578	1.20	1.33	1.88	1.25	1.13	1.29	1.44	1.91	1.13+	1.08
579	1.29	12.6	1.55	1.27	1.71	1.25	1.00	1.41	1.13+	1.43
588	1.03	1.17	1.52	1.45	1.22	1.00	0.93	1.17	1.30+	0.96
599	1.66	1.96	2.21	1.54	1.34	1.38	1.75	1.86	1.18+	0.87
601	0.88	0.86	1.03	1.22	1.21	0.99	1.10	0.14	1.21+	1.17
602	0.75	0.70	1.05	1.02	1.09	0.46	0.80	0.86+	0.74	0.88
551	1.44	1.74	1.55	1.63	1.66	0.87	1.51	1.28+	1.19	1.38
553	1.02	1.50	1.42	1.50	1.44	1.03	1.54	1.10+	1.25	1.19
561	1.08	1.31	1.24	1.05	1.19	0.78	1.04	1.04+	0.79	0.85
562	0.78	1.08	1.18	1.35	1.20	0.86	1.22	1.04	1.34+	1.31
563	1.27	1.46	1.25	1.20	1.47	1.10	1.34	0.93+	0.94	1.29

[+] Indicates Refertilized N only Plot.

[a] Adjusted by Dividing Gross PAI by (Basal Area/Age).

Appendix M

SOIL P LEVELS FOR VARIOUS INSTALLATIONS

Samples from the 0-15 cm mineral soil extracted with Bray #1 solution. Values of P in mg kg^{-1} oven dry soil.

Installation	P	Installation	P
5	78.8	527	14.3
7	24.0	532	25.5
10	13.1	544	9.4
13	24.8	551	69.8
20	74.3	553	82.5
26	13.5	561	14.3
27	19.5	562	96.8
28	20.3	563	14.3
29	22.5	568	22.5
30	13.0	572	10.5
45	65.3	576	16.8
54	52.5	577	32.3
55	51.7	578	13.1
57	50.6	579	28.2
60	65.6	580	48.0
68	43.5	582	28.5
113	93.0	588	19.5
500	55.5	594	30.0
501	55.5	596	129.8
503	38.3	597	30.0
508	71.3	599	18.0
514	27.8	602	19.5
515	24.0	606	13.5