SOYBEAN (GLYCINE MAX L. MERRILL) NODULATION, GROWTH AND GRAIN YIELD AS INFLUENCED BY N FERTILIZER, POPULATION DENSITY AND CULTIVAR IN SOUTHERN QUEBEC

by

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ABSTRACT

M.Sc. Z.Q. CHEN Renewable Resources

SOYBEAN (*GLYCINE MAX* L. MERRILL) NODULATION, GROWTH AND GRAIN YIELD AS INFLUENCED BY N FERTILIZER, PLANT POPULATION AND CULTIVAR IN SOUTHERN QUEBEC

Soybean growth with respect to N fertilizer rates, plant population densities and two cultivars was investigated on three Quebec soils at four sites. Soybean nodulation, growth, grain yields and nutrient uptake at three developmental stages were investigated. Soil nitrate levels after harvest were also studied.

N fertilizer application depressed soybean nodulation consistently, but improved soybean growth where initial soil nitrate levels were low. Grain yield was increased at one site with added N, where soybean growth was stressed by low initial soil nitrate levels (below 17 kg N/ha) and severe summer drought. Soybean N and K uptake were increased with increased N fertilizer but P uptake was not affected. Residual soil nitrate content in the 0-50 cm depth in the fall of the crop year increased linearly and this effect carried over to the following spring.

Plant population had little effect on individual plant nodulation but increased fresh nodule mass per unit area. Plant biomass, grain yield and nutrient uptake were increased with increased population densities.

The cultivar Apache had better nodulation potential and grain yield potential and was better adapted to intensive management practices with high plant populations than the cultivar Maple-Arrow.

RESUME

M.Sc. Z.Q. CHEN Ressources renouvelables

LA NODULATION, LA CROISSANCE ET LE RENDEMENT DU SOYA TELS QU'INFLUENCES PAR LA FERTILISATION AZOTEE, LA DENSITE DE LA POPULATION ET LE CHOIX DE CULTIVAR

La gestion intensive de la fève soya (Glycine max L. Merrill) a été étudiée avec la fertilisation azotée, differentes densités de populations et cultivars sur trois différents types de sols québecois afin d'améliorer la production de la fève soya au Québec. La formation de nodules, la croissance, le rendement ainsi que l'assimilation des éléments nutritifs ont été investigués à certains stades du développement du soya. Le niveau de nitrate du sol après la récolte a aussi été étudié.

L'application d'engrais azotées a causé une dépression de la formation de nodules de façon consistante mais a amélioré la croissance lorsque le soya était semé sur sol ayant un niveau faible de nitrates. L'assimilation de l'azote et du potassium a augmenté avec l augmentation d'azote utilisé, mais le phosphore n'a pas été affecté. De plus, les taux de nitrates du sol, de 0 à 50 cm de profondeur, ont augmenté de façon linéaire avec l'apport d'azote. Cet effet s'est maintenu jusqu au printemps suivant.

La densité de population n'a eu que peu d'effet sur la formation de nodules par plant mais a causé une augmentation de la masse de nodules par unité de surface. La croissance de la plante, la production de grains ainsi que l'assimilation des éléments nutritifs ont augmenté de

façon consistante avec l'augmentation de population.

Le cultivar Apache a demontré un meilleur potentiel de nodulation et un meilleur rendement et semblé mieux adapté à la gestion intensive que le cultivar Maple-Arrow.

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CHAPTER I. INTRODUCTION

Soybean production is expanding in Quebec due to the introduction of early maturing cultivars. The seeded area was estimated at 10,500 ha in 1988 (Statistics Canada, 1988) and is likely to expand further, creating a demand for comprehensive agronomic techniques for optimum production.

Conventional soybean production usually employs a plant population of 430,000 plant/ha, and wide row spacing, with recommended fertilizer rates of 45-60-120 ($N-P_2O_5-K_2O$) kg/ha. To expand soybean production, information on soybean production needs to be re-evaluated for new cultivars and new growth patterns. At Macdonald College, Mackenzie and Kirby (1979) reported a linear yield response to N fertilizer up to 60 to 90 kg N/ha, but not for P or K fertilizers, using narrow row growth patterns on some major Quebec soils. According to Costa et al. (1980), early maturing cultivars have greater yield potential in narrow row growth patterns. Use of narrow row growth patterns is likely to expand if better soybean production is expected in Quebec. Special attention should be given to soybean N nutrition in narrow row growth patterns as early maturing soybean cultivars often have reduced N fixation ability and a shorter N fixation period than full season cultivars (Peterson and LaRue, 1983) and N stress may be a yield-limiting factor in narrow row growth patterns (Cooper and Jeffers, 1984). In general, information on soybean production is very limited in Quebec, and a more detailed evaluation of agronomic practices is required.

It is assumed that intensive crop management research will supply the most useful information for maximum economic yield. Practical agronomic factors have been tested in the United States for maximum soybean production. In Ontario, similar research has been conducted for soybean. Soybean yield records of 7.4 and 6.5 t/ha have been reported in New Jersey (Flannery, 1982) and in Ontario (Stevenson, 1988) respectively. The Ontario results indicated the most yield-responsive factor was cultivar, while population density, nutrient levels and irrigation generally had no effect. But the Ontario results can not be transfered to Quebec due to cultivar differences. It is also noted that soybean yields in Quebec are generally lower than those in Ontario (Statistics Canada, 1987) and this is related to fertilization practices (Vigier et al., 1989). Studies with basic agronomic factors are necessary if optimum soybean yields are to be achieved in Quebec where unique climatic and soil conditions exist (relatively short growing seasons and acid soils). The research reported here concerns intensive soybean management practices with regards to N fertilization, high plant population and their interactions with two selected soybean cultivars.

The objectives of this experiment were:

1. to investigate soybean grain yield response to N fertilizer and the nature of the responses;

2. to investigate population effects on soybean growth, management and yield;

3. to assess early maturing cultivars for yield; and

4. to investigate interactions among these management factors.

CHAPTER II. LITERATURE REVIEW

The soybean is an important crop as a food legume for both human and animal consumption. It has high protein levels in the grain and is distributed world-wide. As a leguminous plant, soybean has the capacity to fix atmospheric N_2 through a symbiotic relationship with Azotobacter species. Soybean crops fix more N than many other agricultural legume crops (Thornton, 1946; Allos and Bartholomew, 1959; Smith and Hume, 1985) and also use soil and fertilizer N (Norman, 1944a,b; Weber, 1966b; Harper, 1987). In this review, soybean N nutrition at certain development stages, N fertilization practices and soybean response, and soybean N nutrition in intensive management practices will be discussed.

1. Soybean N nutrition at main development stages

After germination, soybeans have a slow vegetative growth stage, followed by rapid growth from bloom to pod-filling stages and then growth declines during late seed-filling to maturity stages (Hanway and Weber, 1971a; Fehr and Caviness, 1977).

Nitrogen stored in cotyledons is the first N nutrition source (McAlister and Krober, 1951) during soybean germination and early vegetative growth, followed by soil N as the principal N source after root formation but before functional nodule systems have been developed. This may require about 35-40 days after planting (Harper, 1974; Obaton et al., 1982). Improved nodule initiation with short-term N supply over the control (Hatfield et al., 1974) and improved nodulation and plant vigor with small doses of fertilizer N (45 kg N/ha) at early vegetative growth periods (Harper, 1974) indicates the importance of soil N supply after the depletion of cotyledon N. Nitrogen derived from symbiotic fixation by soybean contributes to reproductive growth mainly from bloom to seed-filling stage, with a N fixation peak at pod-filling (Hardy et al., 1968; Harper, 1974; Zapta et al., 1987). Using ^{15}N techniques and nodulating and non-nodulating cultivars, Zapta et al. (1987) reported soil N was the most important N source in soybean vegetative growth and in the construction of vegetative organs. Symbiotically fixed N was the main source for reproductive growth and seed N supply, while fertilizer N was generally not efficient relative to the other two sources. Soybeans have highest N demands during seed-filling stage and N stored in vegetative parts is translocated and redistributed to pods to maintain seed growth (Borst and Thatcher, 1931; Hanway and Weber, 1971b). This process was found to be enhanced when soybeans were under N stress and earlier leaf senescence occurred (Egli et al., 1978).

2. Nitrogen fertilization and soybean response

Information on soybean N fertilization is relatively limited compared with other agricultural crops. Yield responses have been affected by forms of fertilizer, time and methods of application, cultivars, growth patterns and climatic conditions. In the United States, the world's predominant soybean production area, soybeans are usually grown in rotation with corn, using the residual fertilizer after corn (Martin et al., 1976). In practice, N fertilizer is usually banded or broadcast on the soil and then incorporated with the soil during tillage in the fall, or during planting in spring (de Mooy et al., 1973). In most soybean fertilizer studies, N fertilizer is applied at planting to the soil surface or in the rooting zone.

Thornton (1946) reported N fertilizer applied at planting resulted in greater N recovery in the vegetative organs, and a greater decrease in nodule number than did midseason applications which resulted in greater N recovery in seeds. Using both nodulating and non-nodulating cultivars, Deibert et al. (1979) reported a greater N fertilizer efficiency in grain and dry matter yield response by the non-nodulating cultivar when fertilizer was applied at full-bloom than at planting, and a moderate rate (89 kg N/ha) of N fertilizer did not depress N fixation of the nodulating cultivar, although no yield response occurred. Afza et al. (1987) confirmed this effect of delayed N fertilizer at the pod-filling stage on N fixation and further obtained a positive dry matter yield (27%) and a grain yield response of 37% over N applied at planting. This indicated a higher efficiency may exist for delayed N application than applications made at planting. But N fertilization during the growing season is usually inconvenient and not practical as the plant canopy is usually closed by midseason, especially in narrow-row planting patterns. Other limited research indicated that N fertilizer applied at planting does not necessarily depress soybean nodulation and N fixation if N fertilizer is placed away from the rooting zone (Harper and Cooper, 1971). Unfortunately, in practice, most N fertilizer is placed in the rooting zone (0-20 cm), where most root nodules are located (Harper, 1987).

Sinclair and de Wit (1975) compared the production physiology of twenty-four crops with respect to C and N and proposed that soybeans were "self-destructive" in the seed-filling period due to excessive depletion of N from vegetative organs. They concluded only delayed N fertilization would result in yield response. Contradictory results of delayed N application with foliar fertilization indicated this technique is not feasible for agronomic use in soybean production (Garcia and Hanway, 1976; Parker and Boswell, 1980; Vasilas et al., 1980; Poole et al., 1983a,b; Afza et al., 1987;). Thus early N application to soil is a practical choice in soybean production.

The depressive effect of N fertilizer on soybean nodulation (Lyons and Earley, 1952; Allos and Bartholomew; 1959, Vest et al., 1973) resulting in reduced soybean N fixation (Norman and Krampitz, 1945; Thornton, 1946; Weber, 1966b; Johnson et al., 1974; Harper, 1987) has been well documented. Beard and Hoover (1971) reported an inverse linear relationship between N rates and soybean nodule numbers per plant. Uziakowa (1959) reported a reduction of nodule number and nodule weight with four N forms. Harper and Cooper (1971) reported greater reduction of nodule weight than nodule number. Harper (1987) concluded that at least four aspects of nodulation (root hair infection by Rhizobia, nodule development, nitrogenase activity of developed nodules, and nodule bacterioid integrity) were affected with added N.

Soybean distributes large amounts of photosynthate to nodules to maintain symbiotic N fixation (Brun, 1976). Added N fertilizer reduces translocation of photosynthate to nodules (Brun, 1976, Rabie et al., 1980) and growth and activity of nodules are restricted. Short-period depression of nodule function by N fertilizer can be recovered while long term depressions are detrimental and nodules may lose N fixation ability (Gibson, 1976). By comparing the energy cost per mole to assimilate N from nitrate-N and symbiotic N fixation, Ryle et al. (1979) and Finke et al. (1982) suggested N fixation costs more energy, which may be why soybeans depress or delay fixation when there is adequate external N available. This adverse effect of N fertilization on soybean nodulation and N fixation leads to a waste of soybean genetic advantage in N fixation and low efficiency of N fertilization. Efforts concerning the inverse effects of N fertilizer on soybean nodulation and N fixation have been made through genetic improvement and fertilization improvement. Tolerant cultivar selection (Harper, 1987), deep N fertilization (Harper and Cooper, 1971), delayed application (Deibert et al., 1979; Afza et al., 1987), and irrigation (Smith and Hume, 1985) have shown positive results in nodulation, N fixation or yields.

3. Soybean N nutrition and intensive management for optimum yield

Cooke (1982) pointed out that "In highly developed agriculture, large increases in yield will mostly come from interaction effects. Researchers and farmers must be ready to test all new advances that may raise yield potential of their crops and be prepared to try combinations of two or more practices". Leibig's "Law of the Minimum" indicates most yield increase should come from an increased supply of the nutrient that is limiting yields. If two nutrients are limiting, adding either one alone will have no effect on yield, but adding both together will increase yields, providing a positive interaction. Similarly, Prevot and Ollangier (1961) expressed a "law" of the minimum and balanced nutrition which can be applied to any factor that limits yields. Simply stated, when one factor that influences growth becomes optimum, one or several other factors will become limiting. Thus greatest benefits are likely to occur with multiple factor studies by exploring not only main effects, but also interactions between and among growth factors (Dibb, 1983).

Fifty-two factors have been identified affecting crop growth and fourty-five of these are said to be controlled by growers. These factors have to operate in union since many of them are interrelated (Tisdale et al., 1985). Sanders and Usherwood (1984) have listed thirteen factors in intensive management for maximum yield. They are: optimum soil fertility, proper inoculations of legume, high plant population, superior variety selection, proper row spacing, optimum planting dates, proper tillage operations, good drainage, supplemental irrigation, pest control, crop rotation, multiple cropping and good harvesting techniques. In current intensive management studies with corn and soybeans in the United States and Ontario, combinations of population density, cultivar, nutrient level and irrigation are most often considered (Flannery, 1982; Stevenson, 1985; Remillard, 1987).

Soybean yield factors may be related to soybean N nutrition in intensive management. In Ontario, Stevenson (1988) indicated that cultivar was the main factor for yield based on a five-year study. Soybeans have been divided into 10 maturity groups from 00 to VIII (Martin et al. 1976, Hartwig, 1973) and the first two groups are adapted to the northern United States and Canada. Peterson and LaRue (1983) investigated N fixation ability of twenty-one soybean cultivars and found that early maturing cultivars, with lower N fixation rates and shorter N fixation periods, fixed less N than late maturing cultivars. Nodulating soybean cultivars when not inoculated in virgin soil behave like non-nodulating cultivars (Pal and Saxena, 1976), which depend on soil N and need large amounts of N fertilizer to produce similar yields to nodulating cultivars (Weber, 1966a; Deibert et al., 1979). This implies that when nodulation or nodule functions are depressed by environmental factors such as Al and Mn toxicity in acid soil, or under severe drought disturbance (Raper and Kramer, 1987), nodulating soybean cultivars may behave like non-nodulating cultivars and N fertilizer application may improve soybean growth and grain yields. As acid soils are wide-spread in Quebec, and early maturing cultivars are used, the N fertilization of soybeans may need investigation before an optimum yield system can be established.

Cooper and Jeffers (1984) showed that N stress could eliminate the yield advantage of narrow rows as more soil N was depleted than in the wide rows and they proposed N fertilization or enhanced inoculation to deal with this problem. Pello et al. (1980) reported increased N fixation per unit area in narrow row systems with increased population but grain yields were not increased due to the decrease of N fixation for individual plants. Little is known for the effects of plant population and its interaction with N fertilizer on root nodulation in narrow-row growth patterns.

At Macdonald College, MacKenzie and Kirby (1979) reported linear soybean grain yield responses to added N fertilizer up to fertilizer rates of 60 to 90 kg N/ha with narrow row patterns. They attributed this effect to poor nodulation but no further information was supplied.

Soybean N fixation and nitrate ultilization are affected by climatic conditions during the growing season. N fixation appears to be more sensitive to cold (10°C) (Matthews and Hayes, 1982) and hot temperatures (40°C) (Munevar and Wollum, 1981) than nitrate utilization. Plants obtain mineral N from soils through mass-flow and diffusion (Barber, 1984) thus field water deficit is bound to affect soil mineral N and fertilizer N availability. However, soybean N fixation is more profoundly affected by soil water deficits than is nitrate utilization (Obaton et al., 1982; Harper, 1987). Improved water supply with irrigation increased soybean N fixation two to four times and reduced the N fertilizer depressive effects on nodulation and on N fixation (Smith and Hume, 1985). This suggested that the detrimental effect of drought was a strong yield limiting factor. Taylor (1980) has reported that dry climates can diminish the yield advantage of soybeans in narrow rows which is otherwise attainable in growing seasons with adequate rainfall. Soybeans are particularly sensitive to water stress during reproductive growth (Shaw and Laing, 1966) and a major portion of variation in yield can be attributed statistically to seasonal variation in rainfall during flowering and fruiting (Runge and Odell, 1960; Thompson, 1970).

Acid soils are detrimental to soybean nodulation. According to Loneragan and Dowling (1958) a media pH greater than 4.5 is needed for <u>Rhizobium trifoli</u> to grow. Holding and King (1963) found a large proportion of <u>Rhizobium trifoli</u> in acid soil were ineffective for nodulation. Nodule number, nodule weight and N uptake can be depressed in acid condition (Mengel and Krampiath, 1978). Thus acid soil conditions are likely to depress soybean N fixation potential through adverse effects on nodulation.

Use of high plant populations has been identified as a highly productive practice. For soybeans, high populations can be achieved by decreasing distance between rows or decreasing plant distance within the row. Experimental modelling suggests an equidistant planting pattern gives optimum individual plant light interception and individual plant yield (Willey and Heath, 1969). Early studies by Wiggans (1939) and later studies by Parks et al. (1983) indicated narrow inter-row spacing (narrow-row) was more effective in increasing soybean yield than reduced intra-row spacing. Narrow-row patterns more closely approach the ideal equidistant patterns while achieving high population rates (Duncon, 1986). Highest grain yields were achieved in 20-cm row systems with a population rate at around 45 to 98 plant/m^2 (450,000 to 980,000 plant/ha) (Wiggans, 1939). Cooper (1977) has proposed a rate of 37.5 plant/m^2 as an optimum seeding rate to avoid lodging since lodging increases as population increases. His proposal was based on soybean maturing groups II to IV, which may not be optimum for early maturing cultivars in groups 00 to I used in Quebec. A row spacing by cultivar effect was reported by Costa et al (1980) and Cooper (1977), where early maturing cultivars had greater row spacing response than late cultivars. Use of narrow-row growth patterns is likely to expand in Quebec if better yields are expected with the early maturing cultivars.

Munson and Nelson (1973) pointed out crop nutrient uptake should be constantly investigated when improvements in varieties and management practices are made. Hanway and Weber (1971b) showed soybean dry matter accumulation and N, P and K uptake were parallel. Generally speaking, high yield growth patterns and productive cultivars remove more nutrients from soils. This may enhance depletion of soil nutrients and consequently decrease soil fertility. The addition of N fertilizer may affect relative availability and uptake of other nutrients such as P and K in the soils (Olsen and Kurts, 1982). Thus the uptake of N as well as other nutrients should be investigated to improve fertilizer efficiency and to maintain long-term soil fertility.

The effects of intensive management of crops on environmental degradation have been discussed by Cooke (1982). A main concern was possible nitrate contamination of ground water. Fertilizer N not taken up by plants can readily accumulate in soil as nitrate (Olsen et al., 1970), which is subject to leaching when there is adequate precipitation or irrigation (Allison, 1966). Adverse effects of nitrate in drinking water for humans and livestock have been reviewed by Keeney (1982) and it is generally accepted that N fertilizer should be applied at a rate similar to the amount of N removed in harvest.

As a result of the above review, it seemed pertinent to study the effects of the unique agricultural conditions of Quebec, N fertilizer, plant population, and cultivar as well as their interactions on

1. soybean nodulation;

2. soybean growth and grain yield;

3. soybean nutrient uptake and its relation with soybean growth and grain yield; and

4. soil mineral N levels after soybean harvest.

CHAPTER III. MATERIALS AND METHODS

1. Experimental design

Due to space limitations in the field, a 2*2*4 balanced partial confounded design was used, with three replicates, each containing two blocks with blocks of eight plots. The factors and rates involved were plant population (430,000 and 650,000 plant/ha), cultivar (Apache and Maple-Arrow), and N fertilizer (0, 45, 90, and 180 kg N/ha). This resulted in 16 treatment combinations, which were further divided into two groups according to the levels of the three-way interaction. The three components of the population-cultivar-N fertilizer interaction were confounded with block effects, each component per replicate. The design plan was constructed as that by Cochran and Cox (1968). Randomization was carried out for each site and each year so that the soil effects could be evaluated. Four levels of N fertilizer were used so that the nature of possible N fertilizer responses could be determined.

2. Field preparation and management

Three soil series, Chicot (Gray-brown Luvisol), Ste-Rosalie (Humic Gleysol) and Ormstown (Orthic Humic Gleysol) (Canada Soil Survey Committee, 1978) were used. Two sites were established each year. Plots were 5 by 1.5 m in 1987 and 6 by 1.5 m in 1988, with six rows, spaced at 20 cm and a tractor-way of 30 cm between each plot. The distance between each block and each replicate was 3 m. Border strips were used at the edge of the plots. Soils were ploughed 20 cm deep in the fall and disked to the same depth in the spring before planting.

Soybean seeds pre-treated with fungicide were inoculated with powder inoculant containing Bradyrhizobium japonicum. Seeding depth was approximately 5 cm in 1987 and 3 cm in 1988. Triple-super phosphate at a rate of 120 kg P_2O_5/ha was placed equidistant between the rows at planting depth to ensure the plant P supply. K fertilizer as potassium chloride was used at a rate of 240 kg K_2O/ha, broadcast together with N fertilizer as ammonium nitrate immediately after planting. Herbicide as Basagran (containing Bentazon 480 g/L, BASF Canada Inc.) was sprayed on the soil surface at a rate of 2L/ha with the surfactant Assist (containing 83% paraffin base mineral oil and 17% surfactant blend, BASF Canada Inc.) one or two days after planting. Weeds were further removed by hand at approximately the bloom-initiation (R1) stage before the plant canopy closed. In 1987 the plants were thinned to the desired population during the second to third trifoliate stages. In 1988 the plant number per plot was determined. Development stages were determined as outlined by Fehr and Caviness (1977).

3. Sampling procedures

3.1. Soil sampling

Two sets of soil samples were collected. One set was collected before planting for soil characterization. The samples were collected at two depths, 0-20 and 20-40 cm in 1987 and 1988. One composite sample from three points per block was collected for each depth, respectively. The fresh soil samples were then extracted with 1M KCl for extractable soil nitrate and ammonium and then oven-dried at 105° C for moisture content.

The dry soil was ground to pass a 1-mm sieve and stored in sealed glassware for soil pH and extractable P and K. A subsample of about 30 g was ground to pass a 0.25-mm sieve for soil organic carbon determination. After harvest, another set of soil samples was collected from each plot at 0-25 and 25-50 cm depths to determine soil mineral N levels. These depths were felt to be preferable for nitrate movement estimates. To test the residual effect of N fertilizer on soil mineral N levels, soil samples were also collected in the spring of 1989 from the two sites used in 1988.

A composite sample for each block was collected from each depth per site and dried, crushed and sieved to pass 2 mm for soil texture determination. Soil core samples for each depth were collected from each replicate to determine the soil bulk density for each sample set. Differences between the spring and the fall mineral soil N levels for the controls were considered as N released through mineralization and nitrification from the soil organic N pool and crop residues.

3.2. Plant sampling

3.2.1. Nodulation

Root samples were collected at the mid-bloom (R2) stage in 1987 and at mid-bloom and seed-initiation (R5) stages in 1988. A soil core method adapted from Weber (1966b) was used to collect root samples. An aluminum cylinder, 7 cm in diameter and 10 cm high was centred over the plant root mass, hammered 10 cm into the soil and then removed. Three soil cores per plot were collected. The sample was then washed with a hydro-pneumatic root-washing machine. Soil-root suspensions were collected on a 1-mm soil sieve and roots and nodules were washed with a high pressure water flow. Root and nodule samples were placed on brown paper towels to drain residual water, nodule number counted, and fresh nodules from three root samples removed and weighed. Mean nodule size (weight/nodule) was determined by dividing the total fresh weight of the nodules from three root samples by the total nodule number.

3.2.2. Dry matter

Five normal plants per plot were harvested (cut at the soil surface) at mid-bloom (R2) and seed-initiation (R5) stages. Samples were dried at 70°C for 48 hours and weighed for dry matter determination. Dried samples were ground in a Wiley mill to pass a 2-mm sieve for chemical analyses. Plant dry matter yield (kg/ha) was determined by converting the dry weight of the samples to the designed population rates per hectare.

3.2.3. Grain yield

Soybeans were harvested after full maturity stage (R8) when they were dry enough to thresh. Whole plots were harvested since field observations indicated no obvious border effect. Harvest areas were smaller at one site (S-87) due to poor germination and storm damage. Grain was kept in paper bags and dried at 60°C for 48 to 72 hours until dry. The empty pods and soil particles mixed with seed during harvesting were separated with a seedburo (5/64" x 3/4", No 19L, Seedburo Equipment Company, 1022 W. Jackson Blvd. Chicago, Illinois 60607) and further removed with a laboratory aspirator (Bates, H.T. McGill, 584 N. Milby St. Houston, Texas), and the grain yield determined.

A grain subsample of approximately 50 g was collected for each plot and ground in a Wiley mill to pass a 2-mm sieve for chemical analyses.

4. Laboratory analyses

4.1. Soil analyses

The soil particle size was determined using the hydrometer method described by Bouyoucos (1951).

Soil pH in distilled water and in 0.01 M $CaCl_2$ was determined with the glass-electrode method outlined by LRRI (1984) with 1:1 and 1:2 soil:solution ratios for pH in water and in $CaCl_2$, respectively.

Soil extractable P and K were measured in the Mehlich-III extractant (Mehlich, 1984) with a 1:5 soil:solution ratio. P in the extractant was determined with the ascorbic acid-ammonium molybdophosphate blue method (Watanabe and Olsen, 1965) using a "Technicon" auto-analyser. K in the extractant was determined using a flame-photometer with $LiNO_3$ as the internal standard (Chapman and Pratt, 1961).

Soil organic carbon was determined using the Walkley-Black procedure (Nelson and Sommer, 1982).

Soil nitrate and ammonium were extracted from fresh soil with 1 M KCl. Ammonium in the extractant was determined with the indophenol blue method (Keeney and Nelson, 1982) and nitrate was determined with copperized cadmium reduction method (Keeney and Nelson, 1982) using the "Technicon" auto-analyser system (O'Brien and Fiore, 1962; Kamphake et al., 1967).

4.2. Plant analyses

About 0.250 g tissue samples or 0.125 g grain samples were digested with concentrated sulfuric acid and 30% hydrogen peroxide following the procedures outlined by Thomas et al. (1967). The digest was diluted to 250 ml before chemical analysis.

The NH_4-N, P and K content in the digest were determined using the same techniques as those used for soil analyses, after appropriate modification to adjust for acidity and concentrations.

Seed protein content was obtained by multiplying the seed N% content by 6.25.

5. Data analysis and presentation

Data for soil characterization were not statistically analysed. The mean values averaged over blocks and replicates were used for each depth at each site.

Results of residual soil nitrate and ammonium content and grain yield, nodulation, dry matter yield, and nutrient uptake were analysed with SAS mainframe computer system (SAS Institute Inc., 1985) using the "General Linear Model" (GLM). Where a statistically significant effect was observed, the LSD test, outlined by Steel and Torrie (1980) was used to compare plant population or cultivar effect, and single-degree of freedom contrasts outlined by Little and Hills (1978) for the unequal spaced design were determined for polynomial trend analyses for added N. Where the interaction between factors was significant, single-degree of freedom contrasts were used to locate mean differences.

Correlation and regression analyses were conducted according to Gomez and Gomez (1984).

6. Soil properties and meterological information of experimental sites

The four experimental sites belong to three soil series. Sites S-87 and S-88 were on Ste-Rosalie soils, located on the Quinn Farm, Ile Perrot, P.Q.. Site C-87 was on Chicot soil, located on the Macdonald College Farm. Site O-88 was on Ormstown soil, located on the Dupond Farm near Ormstown.

The Ste-Rosalie soils were clay soils low in soil test N and P but medium in K (Table 3.1). The Ormstown soil was a silt clay loam with high soil test N, and medium P and K contents. The Chicot soil was a sandy clay loam with low soil test N, high soil test P and low K supply. All soils were slightly acid (Chicot) or acid (Ste-Rosalie and Ormstown) (Table 3.1).

Table 3.1. Initial properties of soils at the experimental sites

Soil	Site	Depth	Texture	O.C.	NO_3-N	NH_4-N	M3-P	M3-K	pHw
		cm		%	kg/ha				
Ste-Rosalie	S-87	0-20	c	2.56	46	3.3	21	175	5.40
		20-40	c	0.45	15	1.4	9	289	6.98
Chicot	C-87	0-20	scl	1.63	38	2.5	75	78	6.48
		20-40	scl	0.66	23	2.6	46	93	6.37
Ste-Rosalie	S-88	0-20	c	2.03	17	23	13	249	4.88
		20-40	c	0.77	8	3	11	312	5.68
Ormstown	O-88	0-20	sicl	2.08	91	5	41	154	5.35
		20-40	sicl	1.90	110	7	43	169	5.38

O.C.: organic carbon. pHw: soil pH in H_2O.
M3-P, M3-K: soil P and K extracted with Mehlich-III extractant.

Monthly rainfall statistics (Environment Canada, 1989; Gouvernment du Québec, 1989) for each site showed that there was low precipitation in August, 1987 at sites S-87 and C-87, a severe drought in July, 1988, at site S-88 and low precipitation at site O-88 in July and September, 1988, compared to normal levels (Table 3.2).

Results from the Chicot site (C-87) for 1987 should be treated cautiously since there was poor germination at that site, and a storm in July 14, 1987, resulted in considerable damage to the crop.

Table 3.2. Monthly precipitation in 1987 and 1988 and normal precipitation during growing seasons at the experimental sites

Month	Precipitation							
	Site							
	S-87		C-87		S-88		O-88	
	1987	Normal	1987	Normal	1988	Normal	1988	Normal
	mm							
May	102.2	83.4	72.6	61.6	44.2	83.4	50.6	60.1
June	111.0	85.9	114.7	77.3	89.0	85.9	92.2	73.3
July	105.2	98.9	125.4	93.9	22.8	98.9	51.2	82.2
Aug.	49.8	101.3	58.3	92.6	133.6	101.3	102.9	99.1
Sept.	115.6	100.0	150.6	88.2	88.2	100.0	49.0	82.3
Oct.	61.4	82.9	66.1	71.2	86.0	82.9	70.7	75.0

CHAPTER IV. RESULTS AND DISCUSSION

1. Soybean nodulation, dry matter yield and grain yield as influenced by N fertilizer, plant population density and cultivar

1.1. Nodulation

Nitrogen fertilizer affected all nodulation values, including nodule number, nodule weight and mean nodule size although mean nodule size was not affected by added N rate at the C-87 and O-88 sites, at the R2 stage (Table 4.1).

Added N reduced nodule number, nodule weight and mean nodule size and the reduction generally followed a linear trend (Tables 4.2, 4.3, 4.4), suggesting the effect of N fertilizer on nodulation was additive. Exceptions were found in the Ste-Rosalie soil (S-87 and S-88 sites), where reduction followed a quadratic trend for nodule number and nodule weight at the S-87 site, R2 stage (Table 4.2), and a cubic trend for nodule weight and quadratic trend for mean nodule size at the R5 stage, for the S-88 site (Table 4.3). Quadratic responses were a result of a larger decrease in values for the first 45 kg of fertilizer N, compared to the final 90 kg of added N. The cubic trend for nodule weight at the R5 stage, S-88 site, was consistent with this effect to the extent that the lower rates of added N depressed nodule weight more than the higher rates per unit of added N. Lower initial soil N contents in those sites (Table 3.1) may have encouraged better nodulation when no N fertilizer was added. When N fertilizer was added, relatively larger depressions in nodulation occurred with initial N rates and quadratic or cubic effects occurred. However, nodule number and nodule weight remained relatively high at the Ste-Rosalie sites even at high N rates. Thus it appears the

Table 4.1. Analysis of variance of soybean nodule number per plant, nodule weight per plant and mean nodule size at mid-bloom (R2) and seed-initiation (R5) stages

Treatment	df	Stage: R2 stage, Site: S-87	C-87	S-88	O-88	R5 stage, Site: S-88	O-88
		Significance of F-values					
		Nodule number					
N fertilizer (N)	3	**	**	**	*	**	**
Population (Pop)	1	ns	ns	ns	*	ns	ns
Cultivar (Cul)	1	*	ns	**	ns	**	**
Pop x Cul	1	ns	ns	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	*	ns
		Nodule weight					
N fertilizer (N)	3	**	**	**	**	**	**
Population (Pop)	1	ns	ns	ns	ns	ns	ns
Cultivar (Cul)	1	**	ns	ns	ns	*	ns
Pop x Cul	1	ns	ns	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	*
Cul x N	3	**	ns	ns	ns	*	ns
		Mean nodule size					
N fertilizer (N)	3	**	ns	*	ns	**	**
Population (Pop)	1	ns	ns	ns	ns	*	ns
Cultivar (Cul)	1	ns	ns	ns	ns	ns	ns
Pop x Cul	1	ns	ns	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant.

Table 4.2. Soybean nodulation as a function of N rate, population density, and cultivar at mid-bloom (R2) stage at the S-87 and C-87 sites

Treatment	S-87			C-87		
	Nodulation			Nodulation		
	number	weight	mean size	number	weight	mean size
	number/plant	mg/plant	mg/nodule	number/plant	mg/plant	mg/nodule
N rates (kg N/ha)						
0	27.1	1031	41	15.2	127	9
45	18.6	542	29	10.4	66	6
90	9.7	248	21	9.6	75	8
180	10.8	143	12	4.6	23	5
Trend	Q**	Q**	L**	L**	L**	ns
Population (plant/ha)						
430,000	15.4	469	26	10.2	85	8
650,000	17.7	512	25	9.7	60	6
Cultivar						
Apache	19.3a	582a	27	9.7	60	6
Maple-Arrow	13.8b	399b	24	10.1	85	8
C.V.%	44.4	41.9	42.2	32.9	66.3	65.7

Means of cultivar and population followed by different letters are significantly different at P<0.05 level.
L, Q: linear and quadratic trend, respectively.
**: significant at P<0.01 level. ns: not significant.

stimulation of nodule formation with low initial soil N was evident even at high fertilizer N rates.

There was generally no effect of population density on soybean nodulation (Table 4.1). Where population effects occurred, nodule

Table 4.3. Soybean nodulation as a function of N rate, population density and cultivar at mid-bloom (R2) and seed-initiation (R5) stages at the S-88 site

Treatment	Stage					
	R2 stage			R5 stage		
	Nodulation			Nodulation		
	number	weight	mean size	number	weight	mean size
	number/ plant	mg/ plant	mg/ nodule	number/ plant	mg/ plant	mg/ nodule
N rates (kg N/ha)						
0	14.1	160	12	12.1	384	38
45	11.1	150	13	11.9	344	29
90	7.7	67	9	5.9	100	15
180	4.8	32	7	5.3	76	16
Trend	L**	L**	L**	L**	C**	Q**
Population (plant/ha)						
430,000	9.0	99	11	9.1	205	20b
650,000	9.8	106	10	8.5	247	28a
Cultivar						
Apache	11.6a	120	10	11.0a	261a	21
Maple-Arrow	7.2b	85	10	6.5b	191b	27
C.V. %	40.8	66.0	59.5	51.5	48.3	46.0

Means of cultivar and population followed by different letters are significantly different at $P<0.05$ level.
L, Q, C: linear, quadratic and cubic trends, repectively.
*, **: significant at $P<0.05$ and 0.01 levels, respectively.

Table 4.4. Soybean nodulation as a function of N rate, population density and cultivar at mid-bloom (R2) and seed-initiation (R5) stages at the O-88 site

Treatment	R2 stage Nodulation number	R2 stage Nodulation weight	R2 stage Nodulation mean size	R5 stage Nodulation number	R5 stage Nodulation weight	R5 stage Nodulation mean size
	number/ plant	mg/ plant	mg/ nodule	number/ plant	mg/ plant	mg/ nodule
N rate (kg N/ha)						
0	13.8	87	7	17.3	237	15
45	10.4	57	6	14.7	114	11
90	9.8	47	9	12.7	111	8
180	7.8	25	3	6.4	27	4
Trend	L**	L**	ns	L**	L**	L**
Population (plant/ha)						
430,000	8.9b	60	8	13.0	111	9
650,000	12.0a	49	6	12.5	134	10
Cultivar						
Apache	10.4	51	7	15.5a	138	10
Maple-Arrow	10.5	58	6	10.0b	107	9
C.V.%	42.1	51.4	129.9	42.8	59.3	45.1

Means of cultivar and population followed by different letters are significantly different at P<0.05 level.
L: linear trend. ns: not significant.
*, **: significant at P<0.05 and 0.01 levels, respectively.

number (O-88, R2 stage, Table 4.4) and mean nodule size per plant increased at high populations (S-88 site, Table 4.3). Fresh nodule mass per unit area (kg/ha) significantly increased with high populations at certain stages at the S-87, S-88 and O-88 sites (Table 4.5). This effect of plant population on nodule mass was due primarily to increased plant numbers per unit area. Weber (1966b) reported a close correlation between total nodule mass per acre and soybean N fixation. Thus greater

N fixation may have occurred with high populations, as has been observed by Hardy et al. (1973) and Bello et al. (1980).

Table 4.5. Effect of plant population on soybean fresh nodule mass at the mid-bloom (R2) and seed-initiation (R5) stages

	Stage					
	R2 Stage				R5 Stage	
	Site				Site	
Population	S-87	C-87	S-88	O-88	S-88	O-88
(plant/ha)	kg/ha					
430000	206b	36	42b	25	88b	47b
650000	322a	39	68a	31	160a	87a

Means followed by different letters in the same column are significantly different at P<0.05 level.

A population by N rate interaction on nodule weight per plant was observed at the O-88 site, R5 stage. When no N fertilizer was added, soybean plants had greater nodule weights in high populations compared to the low populations (Table 4.6), indicating the nodulation advantage with high populations was diminished with added N.

Table 4.6. Effect of population by N rate interaction on nodule weight per plant at seed-initiation (R5) stage for the O-88 site

Population	N rate (kg N/ha)				
	0	45	90	180	Trend
(Plant/ha)	mg/plant				
430,000	172b	108	125	36	L**
650,000	302a	119	97	17	Q**

Means followed by different letters at the same column were significantly different at P<0.01 level.
L, Q,: linear and quadratic trend, respectively.
**: significant at P<0.01 level.

Cultivar Apache produced more nodules than Maple-Arrow at the S-87 and S-88 sites, R2 stage, and at the S-88 and O-88 sites, R5 stage (Tables 4.2, 4.3, 4.4). Further, Apache plants had greater nodule weight than Maple-Arrow at the S-87 site, R2 stage, and the S-88 site, R5 stage (Tables 4.2, 4.3). This indicated a greater genetic nodulation potential for Apache than for Maple-Arrow.

Several cultivar by N rate interactions occurred with nodule number and nodule weight (Table 4.7). In general, Apache had greater nodule values than Maple-Arrow at low N rates (0, 45 kg/ha), whereas there were no differences at 90 and 180 kg N/ha. Thus, effects were due largely to an abrupt decrease in nodule values with added N in Apache plants whereas Maple-Arrow plant nodule values changed only slightly or not at all with added N. Thus, use of N fertilizer at rates above 45 kg N/ha eliminated the genetic advantage of better nodulation with Apache.

Table 4.7. Effects of cultivar by N rate interaction on nodule number and nodule weight per plant at the S-87 and S-88 sites

Site	Cultivar	N rate (kg N/ha)				
		0	45	90	180	Trend
		number/plant				
S-88 (R5)	Apache	15.3a	17.0a	6.5	5.3	C**
	Maple-Arrow	8.8b	6.8b	5.3	5.2	ns
		mg/plant				
S-87 (R2)	Apache	1358a	569	246	155	Q**
	Maple-Arrow	703b	514	249	129	L**
S-88 (R5)	Apache	413	473a	86	70	C**
	Maple-Arrow	354	215b	113	81	L**

Means followed by different letters at the same site for cultivars were significantly different at $P<0.01$ level.
L, Q, C: linear, quadratic and cubic trend, respectively.
**: significant at $P<0.01$ level. ns: not significant.

Regression equations described the inverse relationship of nodule number, nodule weight and nodule size and N rate (Table 4.8). Nodule growth continued from R2 to R5 stages while there was little or no additional nodule initiation beyond the R2 stage, even at the 0 N rate. Thus the physiological effect of added N on nodule initiation seems to be related to the early stages of growth while the N depression of nodule growth is a longer term effect and consequently may lead to greater reduction at high N rates.

Nodulation differences among soils were obvious. Greater nodule weight per plant and greater total nodule mass in the Ste-Rosalie soils (S-87, S-88 sites) were probably due to low initial soil N levels (Table 3.1). The difference between the two Ste-Rosalie soils was related to precipitation and soil pH. For the S-88 site, a drier growing season and lower soil pH (Tables 3.1 and 3.2) may have restricted nodulation. According to Sprent (1976), water deficits reduce soybean nodule weight and nodule size. Spurway (1941) reported optimum soil pH for nodulation was 6.0. Consequently the low initial soil pH in the S-88 site (pH=4.88) was not favorable for good nodulation.

Taole 4.8. Regression equations for N fertilizer versus nodulation estimates at mid-bloom (R2) and seed-initiation (R5) stages

Site	Stage	Regression equations	R^2
S-87	R2	$Yn=28.3-0.29X+0.0011X^2$	0.98
		$Yw=1008.5-13.1X+0.046X^2$	0.98
		$Ys=37.6-0.15X$	0.94*
C-87	R2	$Yn=14.3-0.055X$	0.95*
		$Yw=112.7-0.51X$	0.85
S-88	R2	$Yn=13.5-0.052X$	0.96*
		$Yw=162.8-0.77X$	0.89*
		$Ys=13.5-0.040X$	0.97*
	R5	$Yn=12.1-0.042X$	0.77
		$Yw=416.9-3.37X+4.4*10^{-5}X^3$	0.89
		$Ys=38.9-0.57X+1.2x10^{-3}X^2$	0.95
O-88	R2	$Yn=12.8-0.030X$	0.87
		$Yw=79.5-0.32X$	0.92*
	R5	$Yn=17.5-0.060X$	0.99*
		$Yw=205.0-1.048X$	0.86
		$Ys=14.1-0.059X$	0.97*

Yn: nodule number/plant. Yw: nodule weight, mg/plant.
Ys: mean nodule size, mg/nodule. X: N fertilizer, kg N/ha.
*: significant at $P<0.05$ level.

1.2. Dry matter yields at R2 and R5 stages

Soybean dry matter yields were affected by N rates at two sites but affected largely by population rates (Table 4.9). Cultivar effects and interaction effects on dry matter yields were each restricted to one site, the O-88 and S-87 sites respectively.

Dry matter yield increases with added N were linear where they were observed (S-87, R5 stage, S-88, R2 and R5 stages) (Table 4.10). At the S-87 site, a cultivar by N rate interaction was observed. Consequently, the regression equations relating N rates to dry matter yield can only

Table. 4.9. Significance of F values from the analysis of variance of soybean dry matter yields at mid-bloom (R2) and seed-initiation (R5) stages at four sites

Source	df	Stage							
		R2 stage				R5 stage			
		Site				Site			
		S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
		Significance of F-value							
N fertilizer (N)	3	ns	ns	+	ns	*	ns	*	ns
Population (Pop)	1	**	**	**	**	**	**	ns	+
Cultivar (Cul)	1	ns	ns	ns	**	ns	ns	ns	ns
Pop x Cul	1	ns	ns	ns	ns	*	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	*	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant.

be calculated for the S-88 site. These relationships are indicated in the following equations,

$Y=993 + 1.04X$, $(R^2=0.65)$, site S-88, R2 stage

$Y=2255 + 2.99X$, $(R^2=0.99, P<0.01)$, site S-88, R5 stage,

where Y is yield (kg/ha) and X is added N (kg/ha).

These responses were related to low initial N contents at the two sites (Table 3.1). Appearance of a N response as early as the R2 stage at the S-88 site indicated soil N was more limiting than at the S-87 site. This coincided with the lowest soil initial N content at the S-88 site.

Table 4.10. Soybean dry matter yield at mid-bloom (R2) and seed-initiation (R5) stages as a function of N fertilizer, population density and cultivar at four sites

Treatment	Stage							
	R2 stage				R5 stage			
	Site				Site			
	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
	kg/ha							
N rates (kg N/ha)								
0	1576	3667	970	2870	4768	12230	2243	7078
45	1732	3743	1012	2906	5552	12030	2414	7186
90	1714	4240	1175	2838	5424	12770	2512	7672
180	1848	3815	1144	2935	5788	12480	2794	7513
Trend	ns	ns	L**	ns	L**	ns	L**	ns
Population (plant/ha)								
430,000	1477b	3372b	983b	2628b	4769b	10570b	2444	6867b
650,000	1958a	4360a	1168a	3147a	5996a	14190a	2538	7860a
Cultivar								
Apache	1708	3759	1100	2708b	5223	12250	2520	7551
Maple-Arrow	1727	3973	1051	3066a	5543	12500	2461	7176
C.V.%	17.0	15.4	15.2	12.2	16.6	22.0	18.7	19.8

Means of cultivar and population at any one site followed by different letters are significantly different at P<0.05 level.
L: linear trend. ns: not significant.

The cultivar by N rate interaction at the S-87 site indicated the dry matter yield response was linear with Apache but cubic for Maple-Arrow. For N rates of 45 kg N/ha, Maple-Arrow dry matter yields were the highest, whereas highest dry matter yields with Apache were found at 180 kg N/ha (Table 4.11).

Table 4.11. Effect of cultivar by N fertilizer rate interaction on soybean dry matter yield at seed-initiation (R5) stage at site S-87

Cultivar	N rate (kg N/ha)				
	0	45	90	180	Trend
	--------- kg/ha -----------				
Apache	4656	4752b	5477	6006	L**
Maple-Arrow	4880	6351a	5370	5569	C*

Means followed by different letters in the same column are significantly different at P<0.05 level.
L, C: N fertilizer effect linear and cubic, respectively.
*, **: significant at P<0.05 and P<0.01 levels respectively.

Soybean dry matter yields were generally increased at the high population rates over the low population rates (Table 4.10). The lack of interaction between population and added N indicated that increased population did not require more N fertilizer.

Cultivars produced similar dry matter yields at both growth stages (Table 4.10) except at the O-88 site, R2 stage, where Maple-Arrow produced 13% more dry matter than Apache, indicating Maple-Arrow may have an earlier growth potential than Apache.

A population by cultivar interaction resulted from the fact that Apache produced more dry matter at high populations than low populations (P<0.01) (Table 4.12), whereas Maple-Arrow yields were not affected by population density. Apache produced less dry matter than Maple-Arrow at low populations (P<0.05). Thus Apache yields tended to respond to the high populations more than Maple-Arrow yields.

Table 4.12. Effect of population by cultivar interaction on soybean dry matter yield at seed-initiation (R5) stage at the site S-87

Cultivar	Population (plant/ha)	
	430,000	650,000
	---------- kg/ha ----------	
Apache	4336b	6110a
Maple-Arrow	5206a	5882a

Means followed by different letters are significantly different at P<0.05 level.

Plant size increased linearly with added N where a dry matter yield response to N rates was found (Table 4.13). Plant size decreased at high populations compared with low populations at all sites and stages except for the R5 stage, C-87 site. Maple-Arrow had larger plants than Apache at the R2 stage, O-88 site only.

Table 4.13. Soybean average shoot dry weight as related to N rate, population density and cultivar at mid-bloom (R2) and seed-initiation (R5) stages at four sites

Treatment	Stage							
	R2 stage				R5 stage			
	Site				Site			
	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
	g/plant							
N fertilizer (kg N/ha)								
0	3.0	6.9	1.8	5.4	9.0	23.1	4.3	13.5
45	3.3	7.1	1.9	5.6	10.6	22.2	4.6	13.6
90	3.2	8.0	2.3	5.4	10.2	23.9	4.8	14.7
180	3.5	7.2	2.2	5.6	10.9	23.6	5.5	14.3
Trend	ns	ns	L*	ns	L**	ns	L**	ns
Population (plant/ha)								
430,000	3.4a	7.8a	2.3a	6.1a	11.1a	24.6	5.7a	16.0a
650,000	3.0b	6.7b	1.8b	4.8b	9.2b	21.8	3.9b	12.1b
Cultivar								
Apache	3.2	7.1	2.1	5.1b	9.7	23.1	4.8	14.4
Maple-Arrow	3.3	7.5	2.0	5.8a	10.6	23.3	4.8	13.7
C.V.%	18.7	15.6	18.1	11.0	15.4	22.1	21.2	19.8

Means of cultivar and population followed by different letters are significantly different at P<0.05 level.
L: linear trend. ns: not significant.
*, **: significant at P<0.05 and P<0.01 levels respectively.

1.3. Grain yield.

A grain yield response to N rate was observed only at the S-88 site (Table 4.14). This may be related to low initial soil N content at the S-88 site (Table 3.1). The yield response followed a linear trend (Table 4.15). The regression equation,

$$Y=1265 + 1.16X, \quad (R^2=0.89, P<0.05)$$

indicated that about 1.2 kg additional grain (Y, kg/ha) was obtained per kg added N (X, kg/ha). The severe drought in July, 1988, may be another reason for the response at this site. Field observations indicated vegetative soybean growth was almost stopped after the R2 stage due to drought, and plant height was only about half the height of other sites. Lyons and Early (1952) pointed out that rainfall and temperature were the main climatic factors affecting soybean response to N fertilizer in that grain responses were likely to occur in hot dry growth seasons compared to wet cool seasons. De Mooy et al. (1973) suggested N shortages in soybeans may occur at a time when either soil N supply or moisture conditions in the surface soil layer become limiting. Reduced soybean N fixation due to dry conditions has been reported previously (Weber, 1966b; Sprent, 1976; Peterson and LaRue, 1983). With water deficit conditions, soybean nodules can not function normally and severe dehydration may lead to loss of nodule N fixation capacity (Sprent, 1976). According to Obaton et al. (1982), soybean nitrate

Table 4.14. Significance of F values from analysis of variance of soybean grain yields at four sites

Source	df	Site			
		S-87	C-87	S-88	O-88
		---- Significance of F values ----			
N fertilizer (N)	3	ns	ns	*	ns
Population (Pop)	1	**	ns	*	**
Cultivar (Cul)	1	ns	ns	ns	**
Pop x Cul	1	ns	*	ns	ns
Pop x N	3	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns

**, *: significant at $P<0.01$ and $P<0.05$ respectively.
ns: not significant.

utilization was less affected than N fixation by water deficits. Thus drought would have less effect on N fertilizer availability than on N fixation, resulting in a greater yield response to added N. The linear response agrees with results obtained by MacKenzie and Kirby (1979) as well as some results in the United States (Sorenson and Penas, 197).

Table 4.15. Soybean grain yields as a function of N rate, population density and cultivar at four sites

Treatment	Site			
	S-87	C-87	S-88	O-88
	kg/ha			
N rates (kg N/ha)				
0	2573	3357	1258	3477
45	2552	3611	1297	3534
90	2626	3467	1415	3427
180	2655	3459	1457	3589
Trend	ns	ns	L**	ns
Population (plant/ha)				
430,000	2498b	3437	1273b	3228b
650,000	2705a	3510	1440a	3785a
Cultivar				
Apache	2635	3510	1348	3879a
Maple-Arrow	2568	3436	1365	3134b
C.V.%	8.6	19.6	12.7	11.6

Means of cultivar and population followed by different letters are significantly different at $P \leq 0.05$ level.
L: linear trend.
**: significant at $P \leq 0.01$ level. ns: not significant.

High population rates increased soybean grain yield by 306, 167 and 555 kg/ha over the normal rate at the S-87, S-88 and O-88 sites, respectively (Table 4.15), demonstrating generally a greater yield potential of high populations under these conditions. Lack of interaction between population and N fertilizer indicated that increased populations did not require more N fertilizer for grain production. In fact, increased population resulted in increased nodule mass, and presumably, increased N fixation (Weber, 1966b). Further, field observations showed soybeans grown at high populations grew taller, and this effect could reduce grain loss during harvest.

Grain yield response to cultivar was observed only at the O-88 site (Table 4.15), where Apache yielded 745 kg/ha more than Maple-Arrow. This difference could, in part, be due to better nodule initiation per plant with Apache than Maple-Arrow, resulting in more potential N fixation. In addition, some lodging occurred with Maple-Arrow after the R4 stage in the field while little lodging occurred with Apache, indicating that Apache may be better suited for this area.

At the C-87 site, Apache yields increased with increasing populations, whereas Maple-Arrow yields decreased as population increased (P=0.0648) (Table 4.16). This indicated a greater yield advantage of Apache in high populations, apparently due to a greater yield potential at most growth stages at high populations compared to Maple-Arrow. Consequently, the use of high populations to increase grain yield requires selection of a responsive cultivar.

Table 4.16. Effect of population by cultivar interaction on soybean grain yield at the C-87 site

Cultivar	Population (plant/ha)	
	430,000	650,000
	---------- kg/ha	----------
Apache	3242	3778
Maple-Arrow	3631	3242

contrast "Cultivar effect for population 650,000", P=0.0647.
contrast "Population effect for Apache", P=0.0648.

Grain yields were correlated with dry matter in both stages on the Ste-Rosalie soil (S-87 and the S-88 sites). The relationship was closer at the R2 stage than at the R5 stage (Table 4.17). These correlations occurred where dry matter or grain yield responses to added N were noted. Thus it should be possible to detect grain yield differences at an early stage on N dificient sites.

Table 4.17. Correlation coefficents of soybean grain yield versus dry matter yield at mid-bloom (R2) and seed-initiation (R5) stages at four sites

Stage	Site			
	S-87	C-87	S-88	O-88
R2	0.87**	0.20	0.95**	0.07
R5	0.72*	0.17	0.85**	0.68

*, **: significant at P<0.05 and P<0.01 levels, respectively.

The soybean dry matter and grain yields varied markedly among the four sites. They were generally proportional to the initial soil N contents and soil test P values but not to soil test K levels (Table 3.1). All plots received 120 kg P_2O_5/ha. Consequently, the relationship of yields to soil test P may be fortuitous. It was more likely that a combination of factors such as initial soil N, soil pH and moisture stress were related to final yield differences among sites. Further, it is interesting to note that dry matter or grain yield increases occurred at sites with moderate to high nodule weights. Thus N fertilizer responses can occur even in the presence of well-nodulated plants. Responses of nodule values to N fertilizer were most evident in this experiment compared to dry matter and grain yields. Lack of grain yield response to N fertilizer at the S-87 site indicated that early N stress at the R5 stage, which caused a dry matter response at that site, was not translated into grain yield reduction. Thus N fertilizer was more effective in promoting soybean vegetative growth (sites S-87 and S-88) than grain yields. According to Zapta et al. (1987), symbiotically fixed N is the most effective N source for soybean grain production while fertilizer N is relatively inefficient. The stimulation effect of N fertilizer on soybean growth without affecting grain yields was also reported by Uziakowa (1959) and Deibert et al. (1979). Thus a temporary N stress in the field may not lead to grain yield reduction.

1.4. Summary

N fertilizer consistently depressed soybean nodulation, but improved soybean growth when initial soil N contents were low. Grain yield responses to added N were obtained only when plants were stressed due to low initial soil N levels and severe drought. N fertilizer was effective in promoting soybean vegetative growth while inefficient in promoting grain production. High populations increased nodule mass per unit area, plant biomass and grain yields. Cultivar differences were most evident in nodulation, with Apache generally having better nodulation ability. In addition, at one site (O-88), Apache produced higher grain yield and at another site (C-87) was more responsive to high populations than Maple-Arrow. Thus a combination of high population, Apache and low N fertilizer input, may lead to high production with low cost agronomic practices.

2. Soybean nutrient uptake and residual soil inorganic N as affected by N fertilizer, plant population density and cultivar

2.1. Nutrient uptake

2.1.1. N uptake

Soybean N uptake was largely affected by added N and population (Table 4.18). The effect of cultivar was limited to one site with N uptake in grain (R8 stage), and there was a population by cultivar interaction at two sites at the R8 stage.

N uptake tended to parallel dry matter or grain yields in that N uptake increased linearly with added N at two of four sites at the R2 stage and three of four sites at R5 stage (Tables 4.18 and 4.19). N uptake in grain increased linearly with added N at the S-88 site. The relationship between soybean N uptake (kg N/ha) at the R2, R5 and R8 stages and N rates was as follows,

Site S-87: $Y2=51.6 + 0.11X$, ($R^2=0.95$, $P<0.05$),

$Y5=117.4 + 0.20X$, ($R^2=0.96$, $P<0.05$);

Site S-88: $Y2=22.8 + 0.10X$, ($R^2=0.92$, $P<0.05$),

$Y5=44.6 + 0.16X$, ($R^2=0.98$, $P<0.01$),

$Yg=65.0 + 0.09X$; ($R^2=0.88$, $P<0.05$);

Site O-88: $Y5=200.0 + 0.26X$, ($R^2=0.94$, $P<0.05$);

where, Y2 is N uptake (kg/ha) at the stage R2,

Y5 is N uptake (kg/ha) at the stage R5,

Yg is N uptake in grain, (the R8 stage, kg N/ha),

and X is the rate of added N (kg/ha).

These results indicated greater N uptake per unit added N at the R5

Table 4.18. Significance of F values from analysis of variance of soybean N uptake at mid-bloom (R2) and seed-initiation (R5) stages, and in grain (R8 stage.

		Stage											
		R2 stage				R5 stage				R8 stage			
		Site				Site				Site			
Source	df	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
		Significance of F value											
N fertilizer (N)	3	**	ns	**	ns	*	ns	**	*	ns	ns	**	ns
Population (Pop)	1	**	**	*	**	**	**	ns	*	*	ns	**	**
Cultivar (Cul)	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**
Pop x Cul	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*	ns
Pop x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant at P<0.05 level.

Table 4.19. Soybean nitrogen uptake at mid-bloom (R2) and seed-initiation (R5) stages and in grain (R8 stage) as related to N rate, population density and cultivar

Treatment	Stage											
	R2 stage				R5 stage				R8 stage			
	Site				Site				Site			
	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
	kg N/ha											
N rate (kg N/ha)												
0	50	139	23	102	115	360	44	201	137	194	66	204
45	59	143	25	107	131	358	51	206	140	210	66	199
90	61	164	35	107	134	400	62	230	143	204	76	199
180	71	154	40	113	154	394	73	245	144	207	81	202
Trend	L**	ns	L**	ns	L**	ns	L**	L**	ns	ns	L**	ns
Population (plant/ha)												
430,000	52b	129b	28b	96b	120b	324b	57	208b	136b	201	68b	184b
650,000	68a	171a	33a	119a	147a	423a	58	233a	146a	207	77a	218a
Cultivar												
Apache	58	145	31	104	129	387	58	229	144	208	71	223a
Maple-Arrow	63	155	31	111	138	369	57	212	138	200	73	178b
C.V. %	19	17	22	14	24	23	22	19	5	7	6	6

L: linear trend. **: significant at $P<0.01$ level. ns: not significant at $P<0.05$ level. Means of cultivar or population at any one site followed by different letters are significantly different at $P<0.05$ level.

stage than the R2 or R8 stages, and such increases were generally found where dry matter or grain yield increases occurred as well. Soybean grain N contents were linearly increased with added N at the S-88 site (Appendix 1), which correspondingly raised the grain crude protein levels linearly from 32.6% to 34.7% at this site (Appendix 2). Small and Ohlrogge (1973) pointed out soil N is usually depleted during the R2 to R5 stages and soybeans may experience N stress. For Site S-88, increased N uptake was accompanied by increased soybean growth and grain yield. For Site S-87 and O-88, increased N uptake was not translated into grain yield responses, indicating N fertilizer effects did not carry through to grain production. According to Zapta et al. (1987), mineral N fertilizer was ineffective in the redistribution processes from vegetative organs to growing seeds. This may explain the reduced influence of added N to N uptake in grain relative to N uptake in early growth stages.

Compared with low populations high populations increased N uptake (kg/ha) at the R2 and R5 stages for the S-87, C-87 and O-88 sites. Population responses at the S-88 site occurred only at stage R2. Field water deficits may have restricted N uptake at the R5 stage at this site. High populations resulted in greater N uptake in grain at three of the four sites (Table 4.19). These responses could be related to greater potential N fixation, as greater nodule mass per unit area was produced at high populations compared to the low populations (Table 4.5). Further, Hardy et al. (1973) and Bello et al. (1980) reported increased N fixation as population densities increased.

No difference in N uptake occurred with cultivars at any site, except for O-88 site where Apache removed 25% more N in grain than Maple-Arrow (Table 4.19). This response was associated with increased grain yield.

No interactions were found at the R2 or R5 stage at any site. However, there was a plant population by cultivar interaction in grain N uptake at two sites (Table 4.20). At the S-88 site, grain from Maple-

Table 4.20. Effect of population by cultivar interaction on soybean N uptake in grain at the S-88 and C-87 sites

Site	Cultivar	Population (plant/ha)	
		430,000	650,000
		------ kg N/ha ------	
S-88	Apache	70b	73b
	Maple-Arrow	66b	81a
C-87	Apache	190ab	226a
	Maple-Arrow	212ab	188b

Means followed by different letters at same the site are significantly different at $P \leq 0.05$ level by contrast test.

Arrow at high populations contained more N than grain from any other population by cultivar combination. At the C-87 site, however, Maple-Arrow at the high population density had lower N uptake in grain than Apache, and at low populations, there were no cultivar differences. Again, these interactions were associated with the grain yield responses.

2.1.2. P uptake

There was no effect of added N on crop P uptake (kg/ha) at the R2, R5 and R8 stages (Table 4.21).

Crop P uptake was greater at high population rates compared to low

Table 4.21. Significance of F values from analysis of variance of soybean phosphorus uptake at mid-bloom (R2) and seed-initiation (R5) stages, and in grain (R8 stage).

Source	df	R2				R5				R8			
		Site				Site				Site			
		S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
		Significance of F value											
N fertilizer (N)	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Population (Pop)	1	**	**	ns	**	*	**	ns	*	ns	ns	**	**
Cultivar (Cul)	1	ns	*	ns	**	ns	ns	ns	ns	ns	ns	*	**
Pop x Cul	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*	ns
Pop x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

**, *: significant at $P<0.01$ and $P<0.05$ levels, respectively.
ns: not significant at $P<0.05$ level.

population rates at the R2 and R5 stages for the S-87, C-87 and O-88 sites, respectively (Table 4.22). Low yields and low soil P contents at the S-88 site (Table 3.1) may have restricted soybean P uptake and limited differences due to population. It is clear that availability of the added P at planting time was restricted at this site (Appendix 3). Surprisingly, P uptake in grain was increased with high populations at the S-88 site, as well as the O-88 site (Table 4.22). Generally, differences were related to increased grain yields. Hanway and Weber (1971b) and Loberg (1979) showed soybean N, P and K accumulation generally increased with increasing yield. The low precipitation in July at the S-88 site may have been the limiting factor in growth and only when precipitation increased was the higher population able to exploit more soil and fertilizer P.

Cultivar differences in P uptake occurred at two sites (C-87 and O-88) at the R2 stage where Maple-Arrow contained more P than Apache (Tables 4.21 and 4.22). This difference was associated with difference in plant dry matter yield. By the time the plant had reached the R8 stage, Maple-Arrow still removed more P in grain than Apache at the S-88 site, but the latter removed more P in grain at the O-88 site (Table 4.22). Maple-Arrow generally had higher P contents in grain compared with Apache (Appendix 3). Thus responses in S-88 and O-88 sites were likely due to genetic differences and increased grain yields, respectively.

Inconsistent population by cultivar interactions on P uptake in grain occurred at two sites (Tables 4.21 and 4.23). At the S-88 site, Maple-Arrow removed more P than Apache at high populations, whereas at low

Table 4.22. Soybean phosphorus uptake at mid-bloom (R2) and seed-initiation (R5) stages, and in grain (R8 stage) as related to N rate, population density and cultivar

Treatment	Stage											
	R2 stage				R5 stage				R8 stage			
	Site				Site				Site			
	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
	kg P/ha											
N rate (kg N/ha)												
0	4.4	10.5	1.8	9.5	11.7	34.4	3.2	20.8	19.9	22.4	5.7	24.2
45	5.0	10.9	2.1	9.4	14.0	33.4	3.7	20.6	20.0	24.4	5.8	24.4
90	5.0	11.8	2.2	9.4	12.9	35.5	3.7	22.4	20.5	22.9	6.4	23.4
180	5.4	10.5	2.1	9.7	13.6	33.6	4.1	20.9	20.7	22.1	6.3	23.9
Population (plant/ha)												
430,000	4.4b	9.4b	2.0	8.7b	12.0b	29.4b	3.6	19.6b	19.5	22.8	5.7b	22.1b
650,000	5.5a	12.5a	2.2	10.3a	14.1a	39.0a	3.7	22.3a	21.1	23.1	6.4a	25.7a
Cultivar												
Apache	4.9	10.3b	2.1	8.9b	12.4	34.0	3.7	21.6	20.0	23.1	5.8b	26.1a
Maple-Arrow	5.0	11.6a	2.1	10.1a	13.7	34.4	3.6	20.4	20.6	22.9	6.3a	21.8b
C.V. %	20	17	17	14	23	23	23	18	14	21	13	11

Means of cultivar or population at any one site followed by different letters are significantly different at P≤0.05 level.

populations, there was no difference between cultivars. At the C-87 site, Apache at high populations removed more P than Maple-Arrow, but at low populations the reverse occurred. Again, these differences were related to genetic differences in grain P contents and grain yields for the S-88 and C-87 sites respectively.

Table 4.23. Effect of population by cultivar interaction on soybean P uptake in grain at the S-88 and C-87 sites.

Site	Cultivar	Population (plant/ha)	
		430,000	650,000
		------- kg P/ha -------	
S-88	Apache	5.7b	5.8b
	Maple-Arrow	5.8b	6.9a
C-87	Apache	21.2	24.9
	Maple-Arrow	24.5	21.3

Contrast "Apache vs Maple-Arrow for 650000 at C-87 site" P=0.0760.
Contrast "430000 vs 650000 for Apache at C-87 site" P=0.0688.
Means followed by different letters are significantly different at P<0.05 level for population and cultivar combinations at site S-88.

2.1.3. K uptake

Increased fertilizer N increased soybean K uptake linearly at the S-87 and O-88 sites, R2 stage, but only at the S-88 site at the R8 stage (Tables 4.24 and 4.25). This may be caused by a complementary effect of N and K (Dibb and Thompson, 1985), which has been found with many plant species (Russell et al., 1954; Barber and Olsen, 1968; MacLeod, 1969; Ajay et al., 1970; Hanway and Weber, 1971b; Mengel et al., 1976). According to Ajay et al. (1970), plants needed greater K uptake for active N metabolism when N fertilizer was applied. Increase of K uptake in grain with added N at the S-88 site was associated with increased

Table 4.24. Significance of F values from analysis of variance of soybean potassium uptake at mid-bloom (R2) and seed-initiation (R5) stages, and in grain (R8 stage)

Sources	df	R2 stage				R5 stage				R8 stage			
		S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
		Significance of F value											
N fertilizer (N)	3	*	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns
Population (Pop)	1	**	**	**	*	**	**	ns	**	ns	ns	**	**
Cultivar (Cul)	1	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	*	**
Pop x Cul	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant at P<0.05 level.

Table 4.25. Soybean potassium uptake at mid-bloom (R2) and seed-initiation (R5) stages, and in grain (R8 stage) as related to N rate, population density and cultivar.

Treatment	Stage											
	R2 stage				R5 stage				R8 stage			
	Site				Site				Site			
	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88	S-87	C-87	S-88	O-88
	kg K/ha											
N rate (kg N/ha)												
0	37	76	24	53	89	169	46	113	45	59	23	67
45	42	84	25	57	105	178	50	118	47	65	24	68
90	41	91	28	59	102	117	52	130	48	62	26	67
180	47	87	27	66	107	195	56	134	46	61	27	69
Trend	L**	ns	ns	L**	ns	ns	ns	ns	ns	ns	L**	ns
Population (plant/ha)												
430,000	37b	74b	24b	56b	91b	159b	51	112b	45	61	23b	62b
650,000	46a	95a	28a	62a	110a	201a	52	132a	48	63	27a	73a
Cultivar												
Apache	41	81	26	56	95	172	50	122	49a	64	26a	76a
Maple-Arrow	43	88	27	61	107	188	53	125	44b	59	24b	59b
C.V. %	20	19	18	18	21	25	8	17	11	21	13	13

L: linear trend. **: significant at P<0.01 level. ns: not significant at P<0.05 level. Means of cultivar or population at any one site followed by different letters are significantly different at P<0.05 level.

grain yields. The following equations described the relationships between the K uptake at the R2 stage and K uptake in grain as a function of N rates,

Site S-87: $Y2=37.8 + 0.05X$, ($R^2=0.87$);

Site 0-88: $Y2=53.2 + 0.07X$, ($R^2=0.99$, $P<0.01$);

Site S-88: $Yg=23.6 + 0.02X$, ($R^2=0.88$, $P<0.06$);

where, Y2 is the K uptake (kg K/ha) in the R2 stage,

Yg is the K uptake in grain (kg K/ha),

X is N rate (kg N/ha).

Increased .population density increased K uptake at the R2 and R5 stages for the S-87, C-87 and 0-88 sites (Table 4.25). At the S-88 site, high populations produced more K uptake at the R2 stage but this effect was not found at the R5 stage. K uptake in grain with high populations compared to low populations was increased at the S-88 and 0-88 sites (Table 4.25). All these responses were associated with increased dry matter or grain yields in high populations, probably due to greater exploitation of soil and fertilizer k at high plant populations.

There was no effect of cultivar on K uptake for the two cultivars at the R2 and R5 stages (Table 4.24). However, K uptake in grain was affected by cultivar at three of four sites. Apache removed more K in grain than Maple-Arrow at the S-87, S-88 and 0-88 sites (Table 4.25). These responses were due to genetic difference at these sites as Apache grain consistently showed higher K contentrations than Maple-Arrow (Appendix 4). Response at the 0-88 site was associated with greater grain yield with Apache relative to Maple-Arrow as well.

Interactions among experimental factors did not affect plant K uptake at any site.

2.1.4. Correlation of nutrient uptake dry matter and grain yields

Soybean N, P and K uptake at each stage of growth was correlated with dry matter yields at the same stage of growth, but correlations of the R2 stage uptake values with later stage dry matter yields were reduced on the higher-yielding O-88 site (Table 4.26). Correlations between grain yield and N, P and K uptake at R2 and R5 stages were significant on the Ste-Rosalie soil sites (S-87 and S-88), where plant growth was stressed and grain yields were low. This indicated low early nutrient supply in this soil could have affected subsequent soybean growth and grain production. For Ormstown (O-88) and Chicot (C-87) soils, grain yield and nutrient uptake at R2 and R5 stage were not correlated.

N, P and K uptake in grain were all related to grain yield except for K at the S-87 site. Thus for the high populations and productive cultivars, greater nutrient removal may enhance depletion of soil nutrients. Greater P and K nutrient input should be considered to maintain soil fertility.

Table 4.26. Simple correlation coefficients of soybean R2 and R5 stage dry matter yields (Y2 and Y5, respectively), and grain yield (Yg) versus N, P, K uptake at R2 and R5 stages and uptake in grain (R8 stage) at four sites

		Stages								
		R2			R5			Grain		
Site	Yield	N	P	K	N	P	K	N	P	K
S-87	Y2	0.90 **	0.97 **	0.95 **						
	Y5	0.94 **	0.98 **	0.97 **	0.93 **	0.93 *	0.97 **			
	Yg	0.73 *	0.81 *	0.77 *	0.71 *	0.44 ns	0.55 ns	0.93 **	0.82 *	0.60 ns
C-87	Y2	0.98 **	0.96 **	0.94 **						
	Y5	0.92 **	0.90 **	0.86 **	0.94 **	0.98 **	0.83 *			
	Yg	0.19 ns	0.22 ns	0.36 ns	0.22 ns	0.14 ns	0.24 ns	0.90 **	0.84 **	0.90 **
S-88	Y2	0.85 **	0.93 **	0.93 **						
	Y5	0.93 **	0.71 *	0.61 ns	0.97 **	0.96 **	0.91 **			
	Yg	0.92 **	0.87 **	0.93 **	0.81 *	0.74 *	0.79 *	0.97 **	0.91 **	0.92 **
D-88	Y2	0.90 **	0.99 **	0.58 ns						
	Y5	0.74 *	0.46 ns	0.53 ns	0.81 *	0.96 **	0.85 **			
	Yg	0.35 ns	0.02 ns	0.07 ns	0.53 ns	0.60 ns	0.33 ns	0.98 **	0.98 **	0.99 **

*, **: significant at $P<0.05$ and $P<0.01$ levels, respectively.
ns: not significant at $P<0.05$ level.

2.2. Residual soil inorganic N

As the soil ammonium levels were low (generally in the range of 0.7 to 2.6 kg N/ha) and of little agronomic significance, only results of soil nitrate will be discussed.

Fall soil nitrate levels in the 0-50 cm depth were generally not affected by plant populations and cultivars but were consistently affected by N rates (Table 4.27).

Table 4.27. Significance of F values of soil nitrate levels at 0-50 cm depth in fall and spring samples at four sites

Source	df	Site--sampling season					
		S-87	C-87	S-88		O-88	
		Fall	Fall	Fall	Spring	Fall	Spring
		----- Significance level of F-values-----					
N fertilizer	3	**	**	**	**	**	**
Population (Pop)	1	ns	ns	ns	ns	ns	*
Cultivar (Cul)	1	ns	ns	ns	ns	ns	ns
Pop x Cul	1	ns	ns	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns	ns	*

**, *: significant at $P<0.01$ and $P<0.05$ levels, respectively
ns: not significant at $P<0.05$ level.

For the fall 0-50 cm depth soil samples, increased N rates consistently increased residual soil nitrate levels linearly at each site (Table 4.28). The effect carried over to the spring of 1989 at two sites (S-88 and O-88), indicating residual effects of N fertilizer could occur in the second crop year. At these two sites, nitrate levels at the low N rates in the spring were greater than in the fall, indicating mineralization and nitrification had occurred.

Table 4.28. Soil nitrate levels at 0-50 cm depth as related to N rates and plant population density

Treatment	Site					
	S-87	C-87	S-88		O-88	
	Year	Year	Year		Year	
	87	87	88	89	88	89
	Fall	Fall	Fall	Spring	Fall	Spring
	kg N/ha					
N fertilizer (kg N/ha)						
0	36.3	55.9	19.4	25.4	33.6	53.8
45	30.4	66.8	28.0	37.2	38.2	53.6
90	45.8	85.9	42.9	43.1	38.8	67.7
180	56.5	135.8	53.3	56.7	64.1	71.8
Trend	L**	L**	L**	L**	L**	L**
Population (plant/ha)						
430,000	39.1	90.3	36.1	39.5	40.8	65.2b
650,000	45.4	81.9	35.7	41.7	46.5	58.3a
C.V.%	38.4	48.9	46.7	32.2	41.7	17.9

Means followed by different letters for population at any site are significantly different at P<0.05 level.
L: linear trend. **: significanc at P<0.01 level.

When soil depths were compared for fall samples, two different patterns of nitrate accumulation were observed. For sites S-87 and S-88, on the Ste-Rosalie clay soil, nitrate accumulation increased with added N at both depths and more nitrate was found in the top 0-25 cm than the 25-50 cm depth, indicating leaching was slow (Table 4.29). For site C-87, the Chicot sandy clay loam, nitrate levels in the top 0-25 cm depth were not related to N rates. However, a linear increase in nitrate accumulation with added N was found at the 25-50 cm depth. For site O-88, the Ormstown silty clay loam, linear N accumulation with added N

Table 4.29. N fertilizer effect on residual soil nitrate levels in fall and spring at two depths and four sites

	Season											
	Fall								Spring			
	Site								Site			
	S-87		C-87		S-88		O-88		S-88		O-88	
	Depth		Depth		Depth		Depth		Depth		Depth	
N rate	A	B	A	B	A	B	A	B	A	B	A	B
(kg N/ha)	kg N/ha											
0	28.6	7.7	25.5	30.4	11.6	7.8	11.0	22.6	17.8	7.7	30.8	22.9
45	22.2	8.3	26.3	40.5	18.9	9.1	11.9	26.2	25.6	11.6	29.3	24.4
90	31.9	13.6	27.3	58.6	26.6	16.3	13.2	25.6	28.8	14.3	36.5	31.2
180	41.1	15.4	35.3	100.5	32.5	20.8	15.4	48.7	31.0	25.7	32.2	39.7
Trend	L**	L**	ns	L**	L**	L**	L**	L**	L**	L**	ns	L**
C.V.%	46	54	52	60	62	43	22	55	29	57	24	26

L: linear trend. ns: not significant. **: significant at P<0.01 level.
A, B: 0-25 and 25-50 cm depth, respectively.

was found in the 0-25 and 25-50 cm depths but greater accumulation with added N was found in the 25-50 cm depths. These results indicated more added N was leached from the 0-25 cm to the 25-50 cm depth for the Chicot and Ormstown soils with coarser texture, compared to the Ste-Rosalie soil with finer texture. Other researchers have noted the influence of soil texture on nitrate leaching and it is generally accepted that nitrate-N is more readily leached in coarser than in finer textured soils (Morgan and Street, 1939; Harmsen and Kolenbrander, 1965).

With spring samples, nitrate levels of the 0-25 cm depth increased markedly compared to values from the previous fall but little change occurred in the 25-50 cm depth. Thus mineralization and nitrification occurred in the 0-25 cm depth. Greater increases occurred in the 0 and 45 N/ha treatment plots. For the 180 kg N/ha rate, a slight decrease in 0-25 cm and slight increase in 25-50 cm nitrate levels indicated reduced mineralization and nitrification or limited leaching of nitrate over winter. In comparison, soil nitrate levels at the O-88 site increased more than those of the S-88 site over winter (Table 4.29). This was probably related to poor drainage of the Ste-Rosalie soil at the S-88 site (Lajoie, 1960).

Spring 1989 soil nitrate levels in the 0-50 cm depth were positively related to nitrate levels in the fall, 1988, at the S-88 site, possibly due to limited mineralization and nitrification and leaching over winter. The change of soil nitrate levels over winter was inversely related to fall 1988 nitrate level at the O-88 site, probably due to a greater mineralization and nitrification at lower N rates than at high N rates (Table 4.30). A net gain of soil nitrate-N over winter in the 0-50 cm depth implied mineralization and nitrification of soil organic N at site S-88 and 0-88 were the major processes. This may be due to the low residual soil nitrate-N contents in the fall, which were generally in the range of 30 to 65 kg N/ha. These values were lower than a critical fall nitrate-N value of 120 kg N/ha developed by Liang (1989) in a corn intensive management experiment on Chicot soil. Below this value, Liang found a gain of soil nitrate over winter in the 0-60 cm soil depth. Thus results from these two soybean sites were consistent with his work.

Table 4.30. Simple correlation coefficients between fall and spring soil nitrate levels and over-winter change of soil nitrate levels at the 0-50 cm depth at the S-88 and 0-88 sites

Site	Spring vs Fall	Change vs Fall	Change vs Spring
S-88	0.94**	-0.57	-0.27
0-88	0.68	-0.71*	0.08

*, **: signicant at P<0.05 and P<0.01 levels, respectively.

Regression equations were developed to describe the relationship of 0-50 cm soil nitrate levels in fall and spring and N rates (Table 4.31). In the fall of 1987, there was a marked variation between sites. At the C-87 site, soil nitrate increases were greater per unit added N than those at the S-87 site. Increase of residual soil nitrate per unit added N seemed to be constant at the S-88 and 0-88 sites for both fall and spring samples. In the spring of 1989, soil nitrate levels in the 0 N plots at the 0-88 site were about two times those of the S-88 site. About 23 kg nitrate-N/ha was released in the 0-50 cm depth at the 0-88

Table 4.31. Regression equations of 0-50 cm soil nitrate levels versus N rates at four sites

Site	Season	Year	Regression equation	R^2
S-87	fall	1987	Y=37.38 + 0.13X	0.29
C-87	fall	1987	Y=50.28 + 0.45X	0.76**
S-88	fall	1988	Y=20.76 + 0.19X	0.85**
	spring	1989	Y=27.46 + 0.17X	0.67**
O-88	fall	1988	Y=30.34 + 0.17X	0.58**
	spring	1989	Y=52.86 + 0.11X	0.67**

Y is soil nitrate level (kg N/ha). X is N rate (kg N/ha).
**: significant at $P \leq 0.01$ level.

site, which was in the range of 11-31 kg N/ha found in north-central Alberta (Malhi et al., 1985). About 7 kg N/ha nitrate-N was released at the S-88 site, indicating reduced mineralization and nitrification, probably due to poor drainage as a result of high clay content in the soil (Lajoie, 1960). The low pH at the S-88 site compared with the O-88 site was also not favorable for microbiological activities involved in mineralization and nitrification processes.

Population effects on soil nitrate were seen only at the O-88 site in the spring of 1989 (Table 4.28). Higher soil nitrate levels were observed with the low population rates, probably due to reduced C additions from plant residues, and consequently increased N mineralization and nitrification.

A cultivar by N rate interaction was found at the O-88 site with spring samples (Table 4.32). With Apache, the nitrate levels showed a linear trend with added N, whereas with Maple-Arrow, the trend was cubic.

Table 4.32. Effect of cultivar by N rate interaction on spring soil nitrate levels at 0-50 cm depth in spring, 1989 at O-88 site

Cultivar	N fertilizer rate (kg N/ha)				
	0	45	90	180	Trend
	---------- kg N/ha ----------				
Apache	48.3	55.6	69.9	81.9	L**
Maple-Arrow	59.1	51.6	65.4	61.7	C*

L, C: linear and cubic trend, respectively.
*, **: significant at P=0.05 and P<0.01 levels, respectively.

2.3. Summary

N fertilizer generally increased soybean N and K uptake but had no effect on P uptake during early growth stages. As for nutrient uptake in grain, effects of added N on N and K uptake were associated with increased grain yields as well as increased N concentrations in grain. Increased nutrient uptake with increased populations were associated with increased dry matter or grain yields. The cultivar effects on nutrient uptake were not consistent and were related to both genetic differences and yield differences. In addition to increases in plant N uptake, added N not taken up by the crop increased soil nitrate accumulation linearly and the effect lasted through to the next spring. The accumulation was affected by soil texture. With coarser textured soils, nitrate accumulation extended to deeper depths compared to the finer textured soils. Mineralization and nitrification of soil organic N in the 0-50 cm depth resulted in a net gain of soil nitrate over winter. Where mineralization and nitrification occurred to a larger extent, increases in spring nitrate levels were inversely correlated with nitrate levels of the previous fall and mineralization of soil organic N was restricted to the 0-25 cm depths.

CHAPTER V. SUMMARY AND CONCLUSIONS

Soybean responses to N fertilizer rates, population densities, and cultivar differences were investigated on three Quebec soils at four sites. Two sites were used in each of 1987 and 1988. N fertilizer rates 0, 45, 90 and 180 kg N/ha, population densities 430,000 and 650,000 plant/ha, and cultivars Apache and Maple-Arrow were used. The soils were Ste-Rosalie clay, Chicot sandy clay loam and Ormstown silt clay loam.

N fertilizer consistently depressed soybean nodulation. Soybean growth was improved with added N where soil initial N contents were low but grain yields were generally not affected. Added N fertilizer generally increased soybean N and K uptake in the early growth stages but did not affect grain N or K uptake unless yield responses were obtained. Soybean P uptake was not affected by added N. Fertilizer N increased soil nitrate accumulation. These residual nitrate values were not high after the first year of N fertilizer application and some net gain over winter through mineralization and nitrification occurred in the 0-25 cm depths.

Increased plant populations resulted in increased nodulation, dry matter yields and grain yields. Consequently, plant nutrient uptake was larger and greater nutrient input may be required to avoid depletion of soil nutrients.

Cultivar effects were most pronounced in nodulation characteristics. Apache generally had better nodulation capacity and tended to be more adapted in high population growth patterns. Greater cultivar differences were evident in grain nutrient uptake. Apache tended to remove more K in grain than Maple-Arrow, while the reverse occurred in grain P uptake.

Contributions from interactions between these experimental factors to grain yield were minimal.

Based on these results, the following conclusions were drawn:

1. The major grain yield increases were achieved with increased plant populations. High plant populations resulted in greater nodulation advantage and increased soybean dry matter yields compared to the low populations. Consequently increased N, P and K nutrient uptake also occurred with high populations.

2. The two cultivars tested, Apache and Maple-Arrow, generally produced similar dry matter and grain yields on the Ste-Rosalie soil, where yields were low due to moisture stress or low initial soil N values. On the relatively fertile Ormstown soil Apache produced higher grain yields than Maple-Arrow, probably due to better nodulation capacity of Apache than Maple-Arrow at this site.

3. Soybean grain yields were increased with added N when soil nitrate levels were below 17 kg N/ha at the 0-20 cm depth.

4. Added N increased grain crude protein contents when yield responses to added N were obtained. Thus there is a potential for increased protein production in N deficient soil.

5. Soil nitrate accumulation increased with added N, but the levels were not high and mineralization and nitrification in the upper soil depths led to some net gain of nitrate over winter. Movement of nitrate occurred in the loam soils but was very limited in the clay soil.

6. A program for high grain yield with reduced cost should employ high population densities, Apache cultivar and N rates from 0 to 45 kg

N/ha in southern Quebec. The higher nutrient removal with high populations and productive cultivars should be taken into account in developing a fertilizer program for continuous soybean production.

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APPENDIX

Appendix 1. Soybean grain N content analysis

Appendix 1.a. Analysis of variance of soybean grain N content (%) at four sites

Source	df	Site			
		S-87	C-87	S-88	O-88
		------ Significance of F value ------			
Population (Pop)	1	ns	ns	ns	ns
Cultivar (Cul)	1	ns	ns	ns	ns
N fertilizer (N)	3	ns	ns	*	ns
Pop x Cul	1	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns

*: significant at $P<0.05$ level.
ns: not significant at $P\leq0.05$ level.

Appendix 1.b. Soybean grain N content as related to population density, cultivar and N fertilizer at four sites

Treatment	Site			
	S-87	C-87	S-88	O-88
	---------- N % ----------			
Population (plant/ha)				
430,000	5.43	5.81	5.33	5.69
650,000	5.41	5.91	5.32	5.76
Cultivar				
Apache	5.47	5.92	5.27	5.76
Maple-Arrow	5.37	5.80	5.38	5.69
N fertilizer (kg N/ha)				
0	5.33	5.76	5.22	5.85
45	5.48	5.79	5.14	5.63
90	5.43	5.89	5.38	5.77
180	5.43	6.00	5.56	5.64
Trend	ns	ns	L**	ns
C.V.%	5.4	6.7	6.1	6.2

L: linear trend. ns: not significant at $P\leq0.05$ level.
**: significant at $P\leq0.01$ level.

Appendix 2. Soybean grain protein content analysis

Appendix 2.a. Analysis of variance of soybean grain protein content (%) at four sites

Source	df	Site			
		S-87	C-87	S-88	O-88
		----- Significance of F value -----			
Population (Pop)	1	ns	ns	ns	ns
Cultivar (Cul)	1	ns	ns	ns	ns
N fertilizer (N)	3	ns	ns	*	ns
Pop x Cul	1	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns

*: significant at P<0.05 level.
ns: not significant at P<0.05 level.

Appendix 2.b. Soybean grain protein content as related to population density, cultivar and N fertilizer at four sites

Treatment	Site			
	S-87	C-87	S-88	O-88
	------------- protein % ------------			
Population (plant/ha)				
430,000	33.9	36.3	33.3	35.5
650,000	33.8	36.9	33.2	36.0
Cultivar				
Apache	34.2	37.0	32.9	36.0
Maple-Arrow	33.6	36.3	33.6	35.5
N fertilizer (kg N/ha)				
0	33.3	36.0	32.6	36.6
45	34.3	36.2	32.1	35.2
90	34.0	36.8	33.6	36.1
180	33.9	37.5	34.7	35.3
Trend	ns	ns	L**	ns
C.V.%	5.4	6.7	6.1	6.2

L: linear trend. ns: not significant at P<0.05 level.
**: significant at P<0.01 level.

Appendix 3. Soybean grain P content analysis

Appendix 3.a. Analysis of variance of soybean grain P content at four sites

Source	df	Site S-87	C-87	S-88	O-88
		------ Significance of F value -------			
Population (Pop)	1	ns	ns	ns	ns
Cultivar (Cul)	1	*	ns	**	**
N fertilizer (N)	3	ns	ns	**	**
Pop x Cul	1	ns	ns	ns	ns
Pop x N	3	ns	ns	ns	ns
Cul x N	3	ns	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant at P<0.05 level.

Appendix 3.b. Soybean grain P content as related to population density, cultivar and N fertilizer rate at four sites

Treatment	Site S-87	C-87	S-88	O-88
	-------------- P % ----------------			
Population (plant/ha)				
430,000	0.777	0.664	0.452	0.687
650,000	0.775	0.662	0.443	0.682
Cultivar				
Apache	0.756b	0.659	0.428b	0.673b
Maple-Arrow	0.797a	0.666	0.466a	0.696a
N fertilizer (kg N/ha)				
0	0.771	0.666	0.453	0.697
45	0.778	0.676	0.451	0.687
90	0.776	0.664	0.455	0.684
180	0.779	0.645	0.429	0.670
Trend	ns	ns	L**	L**
C.V.%	7.9	5.3	4.0	2.7

L: linear trend. ns: not significant.
**: significant at P<0.01 level.
Means of cultivar and population followed by different letters are significantly different at P<0.05 level.

Appendix 4. Soybean grain K content analysis.

Appendix 4.a. Analysis of variance of soybean grain k content at four sites

Source	df	Site			
		S-87	C-87	S-88	O-88
		------ Significance of F value ------			
Population (Pop)	1	ns	ns	ns	ns
Cultivar (Cul)	1	**	**	**	**
N fertilizer (N)	3	ns	ns	ns	ns
Pop x Cul	1	ns	ns	ns	ns
Pop x N	3	ns	ns	*	ns
Cul x N	3	ns	ns	ns	ns

**, *: significant at P<0.01 and P<0.05 levels, respectively.
ns: not significant at P<0.05 level.

Appendix 4.b. Soybean grain K content as related to population density, cultivar and N fertilizer rate at four sites

Treatment	Site			
	S-87	C-87	S-88	O-88
	------------ K % --------------			
Population (plant/ha)				
430,000	1.82	1.78	1.85	1.91
650,000	1.76	1.78	1.89	1.92
Cultivar				
Apache	1.86a	1.84a	1.96a	1.96a
Maple-Arrow	1.72b	1.72b	1.78b	1.88b
N fertilizer (kg N/ha)				
0	1.75	1.76	1.87	1.91
45	1.83	1.80	1.86	1.91
90	1.81	1.78	1.87	1.95
180	1.75	1.78	1.87	1.91
Trend	ns	ns	ns	ns
C.V.%	7.0	6.6	4.6	4.7

Means of cultivar and population followed by different letters are significantly different at P<0.05 level.
ns: not significant. **: significant at P<0.01 level.