EFFECTS OF NITROGEN FERTILISER ON THE GROWTH, DEVELOPMENT AND YIELD OF MAIZE (*ZEA MAYS* L.).

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SUMMARY

The response of a commercial maize cultivar (PX610) to nitrogen fertiliser (urea) was studied. Four levels of nitrogen viz. 84, 168, 336 and 672 kg/ha were applied over three different growth stages as follows: (i) all at planting; (ii) $\frac{1}{2}$ at planting, $\frac{1}{2}$ at 6 weeks growth; (iii) $\frac{1}{3}$ at planting, $\frac{1}{3}$ at 6 weeks growth, $\frac{1}{3}$ at 50% silking. The plants were grown at a population of 96,900/ha and water was continuously applied to the crop through a trickle irrigation system.

Total and component plant responses were determined on several occasions throughout the experimental period to physiological maturity. Nitrogen levels and distribution within the plant were also measured.

The yields of grain (11,000-14,000 kg/ha) and total plant dry matter (24,000-29,000 kg/ha) recorded at physiological maturity were high. However, no significant plant dry weight responses to different rates and times of nitrogen fertiliser application were detected. Nevertheless, critical analysis of these responses did show that the rate at which plants reached their maximum dry matter production (upper asymptote) was greatest in the treatments receiving intermediate levels (168 and 336 kg/ha) of nitrogen fertiliser.

Significant differences were recorded in terms of the nitrogen content of the plant in the response to the nitrogen applied. Uptake of nitrogen increased with nitrogen rate and the concentration of nitrogen in the grain and most other plant components, increased with higher rates of nitrogen fertiliser. During early growth there was a precocious accumulation of nitrogen in the leaves. Substantial losses of dry weight and nitrogen from non-grain components, especially the stems, occurred over the period of rapid grain filling. These losses were noticeable at an earlier stage in plants showing visual nitrogen deficiency symptoms (those receiving no nitrogen fertiliser and 84 kg N/ha). However, these plants appeared to make more efficient use of available nitrogen in grain production than plants receiving higher rates of nitrogen.

INTRODUCTION

Maize has been grown in New Zealand for over a century. The traditional grain growing district has been Gisborne, where suitable environmental conditions prevail. Over recent years there has been a rapid expansion of maize production for grain, silage and greenfeed. For example, in the 1970/71 season (NZMAF estimates), 12,000 hectares of maize was grown for grain while in 1962/63 only about 3,000 hectares were grown; in the 1971/72 season 18,600 hectares were involved in grain production. Respective estimates for the 1972/73 and 1973/74 seasons were 16,300 and 17,800 hectares. Furthermore maize growing has now extended far beyond Gisborne with the Waikato, Bay of Plenty and Hawkes' Bay districts being regarded as major grain producing areas of New Zealand. Further south in the Manawatu and Canterbury high yielding crops of maize are also being grown for silage and greenfeed under suitable environmental conditions.

Along with the upsurge in maize growing in these districts there has been the need for more agronomic information (Gooding, 1972) on the yield response, in terms of grain and total dry matter production; on the appropriate rate of nitrogen application and on the timing of the application for maximum response under the prevailing environmental conditions. With more maize being utilised in intensive animal production enterprises (Jagusch and Hollard, 1974) the quality of the dry matter produced assumes greater importance.

Research conducted by NZMAF scientists (e.g. Douglas *et al*, 1972), indicates that for maize grown on soils recently out of high producing pasture, no nitrogen fertiliser additions are required to produce grain yields in the region of 12,500 kg/ha (200 bushels/acre). Current farmer practice, however, is to apply high rates of nitrogen fertiliser whenever the crop is grown.

This experiment, conducted in the Manawatu over the 1972/73 summer, was carried out to provide further agronomic information on the question of using nitrogen fertiliser on maize and to examine the way in which nitrogen is partitioned by the plant during its growth and development.

CHAPTER ONE

REVIEW OF LITERATURE

This review emphasises aspects of growth and development of the maize plant in relation to the level of available nitrogen and its efficiency of utilisation in dry matter production. A detailed description of the maize root system and its growth and distribution is also included. The review also provides a summary of published information against which the present results may be discussed.

1.1 INTRODUCTION

Nitrogen is considered the most important of all essential elements in plant growth and reproduction (Viets, 1965; Allison, 1973). Nitrogen is a constituent of plant proteins, enzymes, amino acids, ribonucleic acids which constitute the genetic code, as well as many metabolic intermediates involved in synthesis and energy transfer (Viets, 1965; Hera, 1971; Allison, 1973). Nitrogen is also an essential component of the chlorophyll molecule which is involved in the trapping of light for the production of sugars by photosynthesis (Donald et al, 1963). Allison (1973) notes that nitrogen is also present in prominent amounts in the growing tips of plants and may be mobilised from one part of the plant to another as source-sink patterns change. Hera (1971) cites reports that indicate the important role the plant root system plays in nitrogen nutrition, not only in absorption and transport, but also in the synthesis of nitrogenous substances which are only partially used in root development, the remainder being translocated to the shoot.

Responses of crops to nitrogen are highly variable due to the complex interplay of soil factors affecting its availability and the above-ground environmental conditions (Berger, 1962; Viets, 1965; Allison, 1973). Maize has a high requirement for nitrogen (Kurtz and Smith, 1966) and in all the examples cited by Berger (1962) the nitrogen requirements are substantially greater than the other major nutrients such as phosphorus and potassium. Nitrogen occupies a unique place in soil-plant nutrition and on a worldwide basis, in that more crops are deficient in nitrogen than in any other element (Viets, 1965).

1.2 SOURCES OF NITROGEN FOR CROP PLANTS

Plants grown in cultivated areas depend on three major sources of nitrogen (Allison, 1973): (1) soil nitrogen; (2) nitrogen fixed from the air by symbiotic and free-living microorganisms; (3) nitrogen from commercially produced fertilisers.

Total nitrogen in the plough layer of different soils is usually in the range of 1100 kg/ha to 4500 kg/ha (Kurtz and Smith, 1966) but can be up to 7000 kg/ha for highly productive mineral soils (Donald et al, 1963). A substantial portion of this nitrogen (95% or more) may be in a stable form as soil organic matter, unavailable to plants (Date, 1973). In some cases, when the organic matter content of the soil profile is considered the total nitrogen in the profile may reach 17000 kg/ha (Donald et al, 1963).

During the growing period of a crop, as the result of microbial mineralisation, 1-3% of the total soil nitrogen may become available for crop utilisation (Scarsbrook, 1965; Kurtz and Smith, 1966; Allison, 1973). Allison (1973) reports for a maize crop grown on a fertile loam, that it is likely to remove 1.5-3% of the nitrogen in the ploughed layer in a single season but on very sandy soils, with low organic matter contents, removal of up to 6% of the total nitrogen may be possible. Kurtz and Smith (1966) also consider that up to 5% of the total nitrogen may be mineralised under exceptional circumstances.

Some soils when first cultivated may not require supplemental nitrogen, because of the high organic matter levels, in order to produce high crop yields. With the increased intensity of cropping, and the use of high yielding cultivars resulting in a decline in organic matter levels, a greater proportion of cropped soils now require nitrogen fertiliser additions in order to achieve high levels of production (Allison, 1973; Date, 1973). Soils brought into cultivation from high producing grass-legume pastures, where annual fixation of 168 to 336 kg/ha of nitrogen is not uncommon, as in Australia and New Zealand (Allison, 1973), may not require supplementary fertiliser at least in the first few years of cropping (Douglas et al, 1972). In New Zealand, Melville and Sears (1953) reported levels of 600-700 kg N/ha/yr fixed in a red and white clover-ryegrass pasture under good growing conditions.

1.3 ASPECTS OF MAIZE GROWTH AND DRY MATTER ACCUMULATION

This section includes a discussion of dry matter distribution in the maize plant over the various stages of growth and development to physiological maturity.

1.3.1 Growth and Distribution of Dry Matter in Plant Parts

Sayre (1948) noted that maximum dry weight of leaves and stems occurred about 93 days after planting although maximum leaf area occurred earlier (at 71 days) during tasselling and silking. At silking approximately 50% of the total plant dry weight had been produced (Sayre, 1948; Hanway, 1962b). Millar (1943) reported that from 63-88 days after emergence, the stems accumulated dry matter at a faster rate than leaves; previous to this accumulation took place at a similar rate. Sayre (1948) reported that grain formation began 80 days after planting; little loss in dry weight occurred in other tissues (except the husks) after day 80 and thus it was concluded that most of the dry matter produced in photosynthesis passed into the grain.

There is general agreement that most of the grain dry matter in cereals is produced by photosynthesis after flowering, but no agreement on the amount contributed nor that mobilised from other plant parts during grain filling. The upper two-thirds of the leaves appear to be largely responsible with little dry matter coming from the stem or ear (Sayre, 1948; Hanway, 1962a; Allison and Watson, 1966). However, other workers (Kiesselbach, 1950; Hay et al, 1953; Duncan et al, 1965; Daynard et al, 1969; Center et al, 1970; Adelana and Melbourn, 1972; Edmeades, 1972) have found significant losses from stems during grain filling. These workers suggested that temporary accumulation in the maize stem immediately after silking was probably due to limited ear-capacity, with later depletion resulting from increased ear-capacity (with grain development) or possibly reduced photosynthesis. Some work suggests the greater importance of stem reserves if the leaf area is reduced or shaded during grain filling (Hoyt and Bradfield, 1962; Duncan et al, 1965; Allison and Watson, 1966). Smaller dry weight losses in other plant parts have been reported, the husks being most often mentioned (Miller, 1943; Sayre, 1948; Hay et al, 1953; Allison and Watson, 1966; Daynard et al, 1969). A decline in root growth has also been noted over grain filling (van Eijnatten, 1963; Mengel and Barber, 1974a) but not by Foth (1962).

Population density has a variable effect on translocation of mobile sugars from maize stems to the grain. For example, Sayre (1948) obtained no reduction in stem dry weight with 28,000 plants/ha whereas Kiesselbach (1950) obtained large reductions with 19,000 plants/ha.

1.3.2 Dry Matter Distribution in the Mature Maize Plant

Edmeades (1972) has summarised the highly variable reports in the literature concerning the proportions of the total dry matter above-ground made up by the constituent parts. This summary, presented in Table 1.1, is based on maize plants in which fertilisation and grain growth has been successful.

Table 1.1 Percentage of total shoot dry matter in different plant parts at maturity (after Edmeades, 1972).

Plant Part	Percentage (Medium maturity - after Hanway, 1963)	Range (Reported from the literature)
Stem (+ leaf sheath)	24	18-29
Leaves	13	8-16
Husk + Shank	7	5-9
Cob	9	8-11
Grain	48	38-58
	100	

The proportion of the total plant dry weight contributed by the roots has been assessed by some workers under field conditions. Foth (1962) observed at 8 days prior to tasselling, with an early maturing maize cultivar, that the roots comprised 32% of the total weight of the plant. At 100 days after planting, however, the proportion had dropped to 9% which is similar to the data reported by Kiesselbach (1948) and van Eijnatten (1963), for maize root dry weights at maturity. Weihing (1935) reported that roots formed a greater proportion of the total weight in late maturing (larger) maize cultivars than early maturing (smaller) cultivars.

1.3.3 Photosynthesis and Dry Matter Production

The total dry matter production of the maize crop, which is distributed amongst the tops and roots, is equal to net photosynthesis (Moss and Musgrave, 1971). The relationship between photosynthesis and yield is not simple but it seems well established that enhanced photosynthesis leads to greater yields. This relationship would be more direct if all the dry matter produced by the plant (including roots) was harvested. In more physiological terms, Beevers (1969) reports that the growth of plants well supplied with water and nutrients, depends primarily on (1) the accomplishments of photosynthesis in the green portions of the maize plant and (2) the transport of synthesised organic compounds from the photosynthesising tissues to the metabolic sinks. Reproductive yield depends on the accumulation of photosynthate as osmotically inactive starch in the grain (Beevers, 1969). This is permanent storage of photosynthate, but throughout vegetative growth various tissues, for example, stems, may store photosynthate on a temporary basis.

The chief photosynthetic organs of the maize plant are the leaves; green leaf sheath and husks may also contribute to dry matter production (Watson, 1956). Allison and Watson (1966) noted that at flowering the leaf sheath provided 20% of the maize plant's photosynthetic area while the leaf laminae provided the rest. Mitchell (1970) reports that the maize leaf sheath contributes 6-10% of the total photosynthate of mature maize plants. Because of their small surface area the maize ear makes little contribution to photosynthetic production (Allison and Watson, 1966).

The size and efficiency of the photosynthetic system determines the final crop yield (Watson, 1956). The size of this system can be determined by the sum of the areas of the leaf laminae per unit area of land, or the leaf area index (LAI) (Watson, 1956). This measure does not take account of other photosynthesising tissues such as the leaf sheath and husks and therefore is not a complete measure of the photosynthetic system. Photosynthetic efficiency can be measured by calculating the net assimilation rate (NAR), or the increase in dry matter per unit leaf area (Watson, 1956).

Because NAR (or unit leaf rate, E) is influenced by the environmental light regime and temperature it is a highly variable measure; it also may vary within and between the same species under similar environmental conditions and is, therefore, less open to manipulation under field conditions for increasing crop yield. Leaf area, however, can be manipulated by cultural practices such as nitrogen fertiliser topdressing to increase leaf growth (Watson, 1956).

The total leaf area of the maize plant continues to expand rapidly until just prior to flowering and then may peak one or two weeks later (Sayre, 1948; Kiesselbach, 1950; Adelana and Milbourn, 1972). The potential maize grain yield which is produced late in the season is determined by the leaf area which is produced early in the season (Hanway, 1962a).

For efficient maize production it is necessary to maintain a large leaf area in an active, functional state for as long as possible. Leaf area duration (LAD) is the integral of LAI over a specified time period and accounts for the magnitude and longevity of leaf area, having the dimension of time (Watson, 1947). In maize grown at commercial plantings (40,000-80,000/ha) the LAI increases gradually with time and may be maintained at a relatively high value of 4-7 for up to 8 weeks after flowering (Allison, 1964; 1969; Pendleton et al, 1968).

As the bulk of the grain dry matter is produced after flowering leaf longevity may play an important part in the determination of yield. There are few reports in the literature on factors affecting leaf longevity in maize (Edmeades, 1972). Hanway (1962a) notes that less than the potential yield of grain will actually be produced if (i) the NAR is decreased by any environmental factor such as a moisture deficiency later in the season (ii) the leaf area is prematurely reduced e.g. by a nutrient deficiency or hail damage to leaves. Yield increases could be expected with increasing leaf area, with no other factors limiting, until the point where shading by the upper leaves reduces the light intensity to some of the lower leaves causing their NAR to decline to zero, and the leaves to senesce (Hanway, 1962a; Williams et al, 1965a; Allison, 1969).

The growth rate of the maize crop depends on the leaf area exposed to photosynthetically active radiation (400 nm to 700 nm wavelength) (Monteith, 1969). The percentage absorption of solar radiation and crop growth rate increases with LAI in the region 4-8 in the vegetative growth stages of the crop (Williams et al, 1965b; Allison, 1969). In the grain forming period crop growth rate was maximised at a lower LAI. At higher leaf area indices crop growth rate declined with time due to a fall off in photosynthetic efficiency of the leaves (Allison, 1969).

Plants such as maize, Sorghum, Paspalum and sugarcane, which are of tropical or sub-tropical origin, were found in the late 1960's to possess an adjunct to the normal Calvin or C_3 pathway of photosynthesis occurring in temperate species such as wheat, barley and ryegrass. This pathway is commonly referred to as the Hatch and Slack or C_4 pathway as dicarboxylic acids such as malate and aspartate (4-carbon compounds) are the initial products of photosynthesis. In the C_3 plant two molecules of the 3-carbon compound phosphoglyceric acid are the initial products. Certain physiological and anatomical features of the C_4 plant contribute to a generally higher dry matter production than that of C_3 plants; these are briefly summarised in the following paragraph.

Under optimal conditions of light and temperature the C_4 plant can attain rates of photosynthesis in the region of 60-100 mg carbon dioxide (CO_2) assimilated $.dm^{-2}.hr^{-1}$, compared to rates of 10-35 mg CO_2

assimilated .$dm^{-2}.hr^{-1}$ for the C_3 plant (Downton, 1971). The C_3 plant has a temperature optima for photosynthesis of 15-25C whereas the C_4 plant functions best at 30-35C (Phillips and McWilliam, 1971). C_4 plants continue to increase their photosynthetic rates up to light intensities exceeding that of full sunlight (Bjorkman, 1971); C_3 plants generally light-saturate and show no further increases in their photosynthetic rates at greater than 20-30% of full summer sunlight (Downton, 1971; Gifford, 1971). The C_4 plant possesses a specialised leaf anatomy ("Kranz"-type) and this along with the presence of a highly efficient carboxylating enzyme (phosphoenolpyruvate carboxylase), whose activity is 50-100 times that of ribulose-diphosphate carboxylase found in C_3 plants (Hatch and Slack, 1970), allows it to photosynthesise effectively down to low ambient levels of CO_2 concentration (5 ppm compared to 50 ppm for C_3 plants), and also to retain most of the fixed CO_2. Photorespiration in the C_3 plant may result in the loss of up to 40% of the fixed CO_2 (Downton, 1971).

1.3.4 Shoot-Root Relations in Maize

The shoot and the root systems require a supply of water, nutrients and carbohydrates for growth processes. Water and nutrients absorbed from the soil by the root system are transported to the shoot while carbohydrates manufactured in the green tissues of the shoot are transported to the roots. Carbohydrate supply is likely to limit root growth more than shoot growth and therefore any phenomenon that increases carbohydrate assimilation or decreases its use by the shoot may increase root growth, with a subsequent decline in the ratio of shoot dry weight to root dry weight or the shoot/root ratio. Similarly mineral and water supply may limit shoot growth more often than root growth resulting in an increase in shoot/root ratio (Brouwer, 1962). Thus when other limiting factors are eliminated shoot growth continues at a rate that depends on the minerals and moisture supplied by the roots, and conversely, root growth continues at a rate depending on the carbohydrate supplied by the shoot (Brouwer, 1962).

With growth and development of the maize plant the shoot/root ratio changes with the shoot growing at a faster rate than the roots (Brouwer, 1962; 1966; Foth, 1962). Foth (1962) reported that between 23 and 54 days after planting, both the roots and shoots grow rapidly with the shoot/root ratio increasing from 2 to 5.1. Over the next 13 days shoot weight doubled while root weight increased only slightly with brace root development; the shoot/root ratio, therefore, increased

markedly to 9.3. With rapid brace root development over the next 13 days (post-pollination to early milk stage), and the slowing of top growth, the shoot/root ratio showed a decline from 9.3 to 7.7. The ratio increased again after 80 days from planting due to little further root growth but a 50% increase in shoot weight during grain filling; by the 100th day (physiological maturity) the shoot/root ratio had reached 10.7.

The shoot/root ratio is also affected by various environmental factors such as water supply, temperature, light intensity and nitrogen supply (Brouwer, 1966). For example, maize plants in early stages of growth grow separate from one another and with all their leaves exposed to light. As leaves begin to overlap and mutual shading occurs then the shoot, being nearer the source of carbohydrate supply, has an advantage and root growth is retarded. Thus, in the maize crop exhibiting "complete" cover the shoot/root ratio is higher than when this is not the case, under similar mineral supply and temperature regimes (Brouwer, 1966). Brouwer (1966) points out, however, that the above explanatory approach, although giving a satisfactory interpretation, simplifies the actual situation due primarily to the fact that shoots and roots undergo morphological and anatomical changes as well as weight changes under the influence of various environmental factors.

Increasing N supply to maize plants increases the shoot/root ratio (Brouwer, 1962; 1966; Viets, 1965; Peters and Runkles, 1967). Troughton (1957) reviewed the effects of N supply on the roots of grasses and concluded that those plants grown under conditions where N availability was a limiting growth factor, would have a well developed root system but a poorly developed shoot system; plants grown with excess available N would have the opposite relative development. Shoot growth exceeds root growth when N is supplied to plants previously grown under conditions of less than optimal supply.

1.3.5 Black Layer and Physiological Maturity in Maize

Physiological maturity is defined as the time of maximum grain dry weight (Aldrich, 1943; Shaw and Loomis, 1950). It is of interest to be able to define precisely the time of maturity as it permits an accurate measure of the grain filling period (pollination to physiological maturity) (Eastin *et al*, 1973). Grain yields are essentially a function of both the length of the grain filling period and the synthetic efficiency of the plant during that period; this information could be used in a breeding program with the aim of

lengthening the grain filling period (Daynard and Duncan, 1969; Daynard et al, 1971; Eastin et al, 1973).

Up until recently physiological maturity was determined on a grain moisture content basis which involved continued and tedious sampling and weighing. Plants were considered physiologically mature when the grain moisture content reached 30-35% (Carter and Poneleit, 1973). However, this is a generally unsatisfactory criterion as various workers have shown that the moisture content of the grain at maturity varies widely in maize plants (Dessureaux et al, 1948; Shaw and Thom, 1951b; Daynard and Duncan, 1969; Rench and Shaw, 1971; Carter and Poneleit, 1973).

The growth of maize is closely correlated with temperature and crop maturity is, therefore, more closely related to heat units than to calendar days as in the relative maturity rating. Gilmore and Rogers (1958) and Cross and Zuber (1972) have examined the methods of calculating heat units and the former expressed the measure in terms of effective degree days to maturity.

The early reports of Johann (1935) and Kiesselbach and Walker (1952) described the development of a black layer which is composed of several layers of cells between the basal endosperm of the maize kernel and the vascular area of the pedicel, appearing early in seed development. With shrinkage as physiological maturity approaches, these layers of cells become compressed into a dense layer which appears black to the naked eye. The stimuli and mechanisms involved in its formation are unknown (Daynard and Duncan, 1969). Recent work has shown that the beginning of the development of the black layer at physiological maturity coincides with maximum grain dry matter accumulation (Daynard and Duncan, 1969; Rench and Shaw, 1971). Eastin et al (1973) fed $^{14}CO_2$ to the flag-leaf of Sorghum sp. and showed that the visibility of the dark layer coincided with the cutoff of assimilate to individual grains. Dry weight losses have been noted in maize kernels after black layer formation indicating that maximum dry weight is attained at or near the time of black layer development (Rench and Shaw, 1971; Carter and Poneliet, 1973).

The black layer in the maize kernel develops rapidly over a three day period (Daynard and Duncan, 1969) and its development in the kernels of a particular ear is variable. In the central portion black layer formation occurs at about the same time for individual kernels; it is delayed somewhat in the larger base kernels with the

apical kernels developing earliest (Daynard and Duncan, 1969). Each ear was assumed to have reached maturity when half the kernels in the central portion showed black layer development (Daynard, 1972).

The majority of workers agree that black layer development is a good, easily defined indicator of physiological maturity in maize and could be used as an end-point for purposes of comparing and classifying the relative length of the growing season from planting to maturity, and for determining the length of the grain filling period. Black layer formation has been observed in a number of hybrids with wide ranging maturities and endosperm types (Daynard and Duncan, 1969). Under cooler conditions, however, Daynard (1972) found greater intra-cob variability in black layer development as well as moisture content of the kernels, than did Daynard and Duncan (1969). Daynard (1972), during two growing seasons after a week of cool weather with maximum daily temperatures of 13C or less, observed premature black layer development before the kernels had completely filled and when they had an average moisture content in the region of 40%. This phenomenon could lead to an underestimation of the length of time required for late maturing hybrids to reach a grain moisture content of 30-35% when mechanical harvesting would be possible.

1.4 THE MAIZE ROOT SYSTEM

This section includes a general description of the maize root system, its growth and development in the soil profile in relation to soil moisture and soil fertility and the effect of other environmental factors on root patterns and distribution. A brief discussion of the forms of nitrogen absorbed by maize roots is included. Theories relating to the physiology of nitrogen uptake by maize roots will not be reviewed; these aspects have been generally covered elsewhere (Laties, 1969; Barber, 1972; Pitman, 1972).

Maize has a coarse, fibrous root system (Weaver, 1926; Berger, 1962; Cunard, 1967). Root systems of graminaceous species consist of two components; the original seminal roots and the adventitious or nodal roots (Brouwer, 1966; Aldrich and Leng, 1965). Seminal roots develop from primordia present in the embryo (Brouwer, 1966) and appear soon after the coleoptile has penetrated the seed coat (Danielson, 1967). There are usually three in number in maize (Weaver, 1926), but some variability among cultivars exists (Brouwer, 1966). Seminal roots anchor the developing seedling and play a role in water and nutrient uptake. After the seedling stage these functions are taken over by the permanent or nodal root system (Aldrich and Leng, 1965).

Nodal roots arise adventitiously from the lower nodes of the main axis and the tillers (Brouwer, 1966). These roots form whorls, the first of which occurs at a depth of 2-3 cm in the soil regardless of the depth of planting. The internodes are very short and the entire group of whorls constitutes the root crown (Weaver, 1926). Further adventitious roots originate from the lower above-ground nodes of the stalk and are commonly referred to as "brace" roots (Danielson, 1967).

1.4.1 The Growth and Distribution of Maize Roots

Root growth in maize consists of a series of overlapping stages which can be associated with stages of top growth (Nelson, 1956; Foth, 1962). Root growth depends on the supply of metabolisable substrate received from the shoot (Section 1.3.4) as well as factors in the soil which govern the availabilities of water, nutrients and oxygen; on soil temperature and mechanical properties of the soil which may restrict root elongation (Eavis and Payne, 1969).

During vegetative growth the root system develops rapidly (Mengel and Barber, 1974a). The seminal roots lose their importance as the adventitious roots of the permanent root system develop from the crown (Aldrich and Leng, 1965). Linscott et al (1962) observed that the most rapid elongation (about 5 cm per day over 8 samples) for maize roots occurred in the period 10-30 days after planting and was largely confined to the upper 30 cm of soil (Foth, 1962). Earlier work reported by Weaver (1926) and Millar (1930) supports this finding. However, Nelson (1956) concluded from a review of the literature, that most of the roots at this early growth stage occurred in the 8-15 cm region from the soil surface, running almost parallel to the surface for distances up to 60 cm. Mengel and Barber (1974a) found 66% of the roots to be in the 0-15 cm surface horizon, 34 days after planting. Throughout their length the roots were profusely branched (Weaver, 1926), the branches reaching 3-10 cm in length.

By the 8th week (12 leaf stage) Weaver (1926) found that the roots had extended laterally up to 120 cm from the base of the stalk where most turned downward in an abrupt manner, penetrating vertically to a depth of 60-120 cm. However, Linscott et al (1962) reported lateral extension to be generally limited to 50 cm between rows and 20 cm within the rows with little encroachment from one maize plant root zone to another. In both cases the crop was grown at similar spacings with a similar method of root examination being employed, but soils of different texture were used (see Section 1.4.2d). At this growth stage

a separate group of younger roots had developed and penetrated to a depth of 120-150 cm in the region below the plant, not explored by the main lateral root system (Weaver, 1926). Foth (1962) noted a build up in root density at a depth of 30-40 cm at this growth stage, that is, as the plants neared tasselling, while Linscott et al (1962) observed that 60-70% of the roots by weight were found in the upper 30 cm of soil. Mengel and Barber (1974a) found the greatest density of maize roots in the 0-15 cm layer of soil at about tasselling and that maximum root density from 15 cm to 75 cm depth in the profile occurred over the following 14 days when the plants were changing from vegetative to reproductive growth. However, Foth (1962) reported that root growth over this two week period was confined to that below 40 cm in the soil profile following the completion of growth in the upper 30-40 cm, with the exception of brace root development.

At the 47th day after planting brace roots were about 3 cm in length; by the 54th day 10-13 cm in length and unbranched, but by the 67th day after planting (18 days after beginning of tasselling) they were profusely branched (Foth, 1962). The completion of lateral root growth, 67 days after planting, coincided with the rapid development of brace roots. Over the period from the 67th to 80th day (during ear development) Weaver (1926) and Foth (1962) reported no increase in root growth at a depth of 40-90 cm in the profile while Mengel and Barber (1974a) noted a decline in root growth over successive 15 cm depth intervals from the surface to 75 cm depth in the profile. Brace root development, however, continued over this period and increased root weight by 50% (Foth, 1962).

From day 80 to day 100 (maturity) after planting, Foth (1962) observed no significant change in root weight or distribution when 75% of the roots occurred in the top 23 cm of soil within a lateral spread of 25 cm from the plant. Rows were spaced 102 cm apart and plants within rows 41 cm apart. With narrow spacings, Bloodsworth et al (1958) found 90% of the total dry weight of roots of mature sweet corn in the top 23 cm of soil. With maize grown in rows spaced 71 cm apart and plants within rows 24 cm apart Mengel and Barber (1974a) observed a continued decline in root density over the 5 sampling depths as the plants matured. The maximum depth of rooting at plant maturity can vary considerably according to soil type, namely from 180 cm in a loamy sand (as reported by Linscott et al, 1962) to 240 cm in loess (as reported by Weaver, 1926). Linscott et al (1962) observed only 5-8% of maize roots below 91 cm in nitrogen fertilised or non-fertilised

plants at maturity. Weihing (1935) grouped maize cultivars grown in various parts of U.S.A. into small, medium and large (late maturing) vegetative types. He noted that the deepest penetrating roots at maturity were usually observed in the larger cultivars, with maximum root depths of 170, 185 and 188 cm being reported for small, medium and large types respectively.

Barley (1970) questions the reliability of "root weight" data as used in the above studies because of the presence of contaminants such as foreign organic matter and mineral soil. The larger and thicker roots also contribute more to the total weight of roots but are less important in terms of function (nutrient and water uptake), than the more delicate and lighter branchlets (Weaver, 1926; Barley, 1970). Since many fine rootlets are lost during sampling similar objections apply when assessing root length (Weaver, 1926).

1.4.2 The Effect of Environment on Maize Root Growth.

The genetically controlled characteristics of a plant root system will develop only when the environment is in proper balance (Danielson, 1967). The suitability of a soil as an environment for root growth and function depends on the availability of materials such as water, nutrients and oxygen, on temperature and the degree of mechanical impedence to root extension (Eavis and Payne, 1969). The following factors will be discussed in relation to the growth and development of roots in soils: soil water, drainage and aeration; soil fertility and fertiliser placement; soil temperature; soil structure compaction and mechanical impedence. A discussion of maize root patterns and the effect of population density will also be included.

(a) Soil water, drainage and aeration:- Peters and Runkles (1967) list three general ways in which soil water influences root systems, (1) direction of growth; it is well recognised that roots will "follow" water in the soil when close to or in direct contact with it. Cunard (1967) also reports this fact. (2) lateral extent and depth of penetration; Weaver (1925) grew maize plants, with similar hereditary characteristics, for 5 weeks in a rich, loess soil with different available water contents, one of 19% and the other of 9%. Under the former conditions total root area was 1.2 times greater than the transpiring surfaces of stems and leaves, whereas under the latter conditions the root area was 2.1 times greater than that of the top. Weaver (1926) reports for soils of similar physical and chemical composition (fine sandy loams), where maize was grown under irrigated

and non-irrigated conditions, that for the well watered plots the roots were concentrated in the upper 30 cm of soil with a maximum penetration of 70 cm. Under dry land conditions, however, the roots had a lateral spread of 36 cm greater than irrigated maize with a maximum depth of penetration of 117 cm and they were more branched. At maturity, the roots of the maize plants grown under dry land conditions had shown little further development, due to the inability of water stressed shoots to supply materials for growth, while those under irrigation had penetrated to 180 cm. (3) relative weight of tops and roots; Danielson (1967) notes from reports in the early literature that relative to the weight of the tops, the greatest weight of roots is produced in soils with the smallest amount of water. Recent studies, however, in which only the root systems have been studied, have shown that increased soil suction due to drying reduces the rate of growth of roots (Brouwer, 1966; Danielson, 1967; Kramer, 1969). Decreased water content also impedes root penetration by increasing soil strength, thus reducing the extent of the root system and restricting the volume of the soil explored (Grable, 1966). Increased water stress reduces overall plant growth, but root growth is less influenced than shoot growth (Peters and Runkles, 1967).

Adequate distribution of oxygen in soils is necessary to ensure plant roots can satisfy their respiratory requirements (Trouse, 1971). Water and oxygen enter soils via the large pores (Trouse, 1971) and connect with smaller diameter pores within the aggregates themselves. The extent of anaerobic zones in soils is greatly influenced by the distribution of water in soils as oxygen diffuses 10,000 times faster in the gas phase than in the liquid phase (Greenwood, 1969). Water-logging due to poor drainage or the presence of an impervious or compacted layer in the soil profile, may lead to the development of anaerobic conditions which could severely damage root systems of plants (Letey et al, 1962).

When a crop is irrigated the depth, lateral spread and configuration of the root system is unimportant provided its capacity for nutrient and water uptake is realised and sufficient anchorage is provided for the plant. The activity of a shallow root system may be adequate for high yield under proper environmental conditions (Danielson, 1967). Under field conditions, however, the topsoil is rarely maintained in a condition for optimum production so a plant may need an extensive root system to meet nutrient and transpirational demands, when surface layers become depleted (Danielson, 1967). Frequent light irrigations may promote shallow rooting especially in the vegetative

growth stages (Weaver, 1926; Danielson, 1967) which could result in desiccation of these roots if dry periods subsequently occurred or irrigation could not meet the demands of the plant. An extensive root system that exploits the subsoil allows maximum utilisation of soil and water resources and is a necessary insurance against drought period (Hanway, 1966; Danielson, 1967).

(b) Soil fertility and fertiliser placement:- Most workers have noted a proliferation of roots on entry into a localised zone of high fertility (Weaver, 1926; Nelson, 1956; Duncan and Ohlorogge, 1958; Viets, 1965; Nelson and Hansen, 1968). Some conflicting results concerning the response of roots to individual nutrients, particularly nitrogen, have been reported in the literature. Linscott et al (1962) found that weight and penetration of maize roots in nitrogen fertilised plots was substantially greater than in non-fertilised plots for the period 40–65 days after planting. The differences disappeared, however, as maturity approached. On the other hand, Younts and York (1956) found that root activity as determined by measuring uptake of labelled calcium (^{45}Ca), and water from a 61–66 cm region of the soil profile was depressed by nitrogen fertiliser additions, throughout the season. Danielson (1967) considers the conflicting results may be due to greater variation in the nitrogen supplying potential of soils throughout the growing season; Viets (1965) implicates competition of the root and shoot for carbohydrate and nitrogen. Under conditions of adequate nitrogen sufficient of these materials are available for maximum root growth; when the whole plant is nitrogen deficient, nitrogen applied to an individual root may cause rapid growth because of a sufficiency of carbohydrate.

The effect of phosphorus on root growth has received less attention than nitrogen (Danielson, 1967) with conflicting results again being reported. Duncan and Ohlrogge (1958) reported a rapid development of fine roots due to the greater length of continually branching roots in association with combinations of nitrogen and phosphorus in fertiliser bands. Phosphorus or nitrogen alone produce little or no response. According to Weaver (1926), phosphorus may promote growth in length and number of branches in root systems. Danielson (1967) reports that there is little evidence to suggest that potassium is involved in root growth and development and the importance of micronutrients has yet to be ascertained.

(c) Soil Temperature:- Because soil temperature influences many

plant physiological functions it exerts an effect on the development and activity of plant roots (Danielson, 1967; Trouse, 1971). Many species have a lower temperature optima for root growth than shoot growth (Danielson, 1967). The roots of small grains have a temperature optima for growth about 20C, whereas maize roots grow best about 25C (Hagan in Richards et al, 1952). Trouse (1971) reports that warm zone plants such as maize show "normal" root proliferation and "normal" root activities at soil temperatures of 24-32C. Root elongation is severely reduced at 18C.

Soil temperature is regulated by the physical condition of the soil via the transmission of heat into, within and out of the soil (Trouse, 1971).

(d) Soil structure, texture compaction and mechanical impedence:- Russel (1949) considers that the best approach to evaluate the effect of soil structure on plant growth is to describe water, aeration and temperature effects as well as compaction conditions that greatly influence root activity and plant growth, rather than an elaboration of the physical architecture (structure) of the soil. This approach will be followed here. Water, aeration and temperature effects have been described in previous sections; compaction and mechanical impedence effects are described below.

Soil compaction results in an increase in bulk density of the soil due to a change in pore size distribution from larger to smaller pores (Harris, 1971). Danielson (1967) found compaction, resulting from excess cultivation and passage of machinery on a clay loam soil, greatly inhibited root development and yield of maize especially during early growth stages. As noted in part (a) compaction may result in impeded root growth because of an inadequate distribution of water and oxygen. Thus root development may be slowed or stopped on encountering a compacted layer, and the volume of soil explored may be restricted (Parish, 1971). This fact has especial importance under low fertility and dry conditions when root systems, in order to meet the demands for water and nutrients, are often widely spread and sparse (Russel, 1961). Barley et al (1965) considers that soil strength (resistance to penetration) is a phenomenon not limited to compacted soils, but is a common property of soils influencing root elongation.

Waaners and Eavis (1972) grew pea, maize and grass seedlings in coarse and fine sands at varying moisture contents. Bulk densities ranged from 1.34-1.46 $g.cm^{-3}$. In coarse sands distorted roots were

produced after 48 hours growth, mainly due to mechanical impedence to root entry. With less than 20% air porosity, additional reductions in root growth were due to lack of oxygen. In the fine sands root development was normal but elongation rates were reduced, especially in pea seedlings, due to mechanical impedence effects. Effects due to poor aeration were noted in fine sands with less than 25% air porosity.

According to Danielson (1967), soil texture has its greatest effect on root development in relation to water and nutrient availability; abrupt changes in particle size distribution in different horizons in a soil profile alters water movement in a free draining soil, so that sand layers tend to be drier than clay layers; this along with possible variations in soil fertility influence root responses.

(e) Plant density and root patterns:- Weihing (1935) studied the gross morphology of the root systems of small, medium and large vegetative types of maize, under field conditions. The plants were grown in a silt loam soil. He showed that in the absence of root competition the pattern of secondary (adventitious) root development and distribution was dependent on the cultivar as well as hybrid vigour.

Data from Weihing (1935) also shows that roots extending laterally to about 91 cm from the maize plant (at maturity) arise from nodes 1 and 2 in small varieties, nodes 1, 2 and 3 in medium varieties and nodes 1-5 in large varieties. Roots extending laterally to about 30 cm distance arise from nodes 4-8 in small varieties, 5-9 in medium varieties and 6-10 in large varieties. Cunard (1967) makes the following observations from Weihing's data: (i) most of the maize roots are located in a cylinder of soil around the plant, 61 cm in diameter, extending downward to a depth of about 150 cm for the three different types. (ii) in large cultivars the roots are equally distributed in the central cylinder (described above) as well as in an outer cylindrical section of radius 91 cm and 15-23 cm thick (that is, between the first and fifth developed nodes). (iii) the root distribution of medium sized cultivars is well balanced over the whole cylindrical section of 91 cm radius.

As reported in Section 1.4.1, Linscott et al (1962) observed an entirely different pattern of root development when plants were grown at 102 x 61 cm (within row) spacings, as used for commercial grain

production at this time in U.S.A. Haynes and Sayre (1956) grew maize at different within-row spacings; each treatment plot was represented by a single row of plants with spacings of 260 cm between plots to avoid interplot effects. Within-row spacings of less than 20 cm resulted in the normal root pattern of individual plants as expressed by the perimeter of the farthest extension, changing from circular to oblong as a consequence of severe interplant competition. Under these conditions the individual plants produced roots which extended a greater distance from the parent plant as compared with plants not suffering competition from neighbours.

Nordon (1964) noted the effect of population density on the weight and total yield of root clumps which were obtained by loosening soil around the plant, and removing the soil by hand washing. He reported a more pronounced effect on the dry weight of roots than on the volume of soil occupied by root clumps. Dry weights of individual plant roots decreased with an increase in population density from 12,400 to 61,750 plants/ha although the total yield of dry roots increased up to a population density of 49,400 plants/ha and then declined by 9% at 61,750 plants/ha. Cunard (1967) indicates the need for further studies in relation to the effect of interplant competition on root distribution patterns in commercial stands in determining the optimum position for fertiliser placement.

1.4.3 Forms of Nitrogen Absorbed by Maize Roots

Plant roots can utilise directly ammonium, nitrate and nitrite ions as well as organic compounds such as urea, amino acids and amides (Viets, 1965; Allison, 1973). In soils that are well aerated and are at temperatures suited for plant growth, nitrification of these forms culminates in the formation of nitrate which is the predominant form of nitrogen available for absorption by plant roots (Viets, 1965). Thus, because of the nitrification process, plant response to additions of various forms of nitrogen is commonly similar (Allison, 1973).

Kurtz and Smith (1966) consider that greater than 90% of the nitrogen required by maize plants is absorbed in the nitrate form. This statement is exemplified by the relatively high concentrations of nitrate found in various parts of the maize plant at different growth stages, and rapid tissue tests have been devised to test for the nitrate ion as a rough quantitative indicator of the plants nutritional status and need (Viets, 1965). Maize roots are capable, however, of absorbing significant amounts of ammonium nitrogen under certain

conditions (Nelson, 1956) with no significant effect on maize nutrition (Kurtz and Smith, 1966).

1.5 ASPECTS OF MAIZE GROWTH AND NITROGEN ACCUMULATION

This section traces the accumulation of N with the growth of various plant parts and its redistribution during reproductive development and accumulation in the grain.

1.5.1 Maize Growth and Nitrogen Uptake

The growth cycle of maize can be divided into the following stages on the basis of phenological events: planting to emergence; emergence to tasselling and silking (vegetative growth period); fertilisation, ear development and grain filling; maturation of the grain (Berger, 1962). Shaw and Thom (1951a) report that the interval from emergence to tasselling is the most variable in length between seasons. Warm, moist conditions allow rapid growth and a shortening of the interval, while cooler temperatures increase its length. The nitrogen requirements of the maize plant varies over these periods.

From planting to emergence the developing maize seedling is dependent on the mobilisation of seed-stored nitrogen for its early growth processes (Berger, 1962; Aldrich and Leng, 1965). Nitrogen in the maize seed is primarily stored in the form of protein concentrated mainly in the aleurone layer surrounding the endosperm (Wellington, 1966). The nitrogen content of the seed changes very little during germination as soluble nitrogen mobilised from the reserves is resynthesised into the protein of the developing seedling (Mayer and Poljakoff-Mayber, 1963). After 15-18 days growth (Aldrich and Leng, 1965) the new seedling is normally well established with 5-6 leaves unfolded and a fully developed and functional seminal root system. Nitrogen requirements at this stage are minimal (Berger, 1962; Aldrich and Leng, 1965). The permanent nodal root system soon begins to develop and takes over the function of the seminal roots in anchoring the plant and supplying the developing shoot with water and nutrients, which in turn supplies the root system with materials required for its growth (Section 1.3.4).

Workers are in general agreement that nitrogen uptake, under conditions of sufficiency continues from emergence to maturity in maize, but at varying rates (Whitehead *et al*, 1948; Jordan *et al*, 1950; Nelson, 1956; Berger, 1962; Hanway, 1962b; Barber and Olsen, 1968). Hanway (1962b) suggested its importance in maintaining the functional

leaf area in the face of excessive translocation losses that may occur with plant development; leaf death due to nitrogen deficiency can occur at any growth stage.

Nitrogen uptake is most rapid from about 10 days prior to tasselling and silking until 25-30 days after the event (Sayre, 1948; Hay et al, 1953; Nelson, 1956; Hanway, 1962b; Mengel and Barber, 1974b). Sayre (1955) reported a maximum rate of accumulation of 4.5 kg N/ha/day over tasselling and silking, compared with a rate of 3 kg N/ha either side of this period. This period coincided with the most rapid vegetative growth of the maize plants. By silking approximately 48% of the total season's uptake of N had occurred (Hay et al, 1953; Hanway, 1962b; Walker and Peck, 1972a), when about 45% of the total dry matter had accumulated (Hanway, 1962b). In fact the curve for nitrogen accumulation with time in the whole plant, parallels or slightly precedes that for dry matter accumulation until sometime after silking and tasselling (Sayre, 1948; Hanway, 1962b; Donald et al, 1963; Viets, 1965).

It is generally accepted that the growth of plants (frequently measured in terms of dry weight changes with time) can be described by an asymptotic sigmoidal function. A variety of asymptotic functions have been used as models for growth. These include the logistic ($y = y_o/(1 + e^{-(a + bt)})$), log-logistic ($y = y_o/(1 + e^{-(a + b\ln t)})$), and Gompertz ($y = y_o A^{B^x}$) equations (Nair, 1954; Williams, 1964; Bliss, 1970). Viets (1965) notes that the shape of the nitrogen accumulation curve with time is sigmoidal and may be almost linear as the plant reaches maturity. Often, because sampling begins too late, the concave upward portion of the sigmoid curve is not established. The curve for nitrogen accumulation is less sigmoidal than that for dry matter because of the higher rate of nitrogen uptake relative to dry matter accumulation in the early growth of the plants (Viets, 1965). This luxury consumption of nitrogen is the result of the more succulent nature of the young maize plant, that is, a high protoplasmic content relative to structural components such as cellulose and lignin. As mentioned earlier, this increases the capacity of the maize plant to store for future use quantities of soluble nitrogen such as amino acids and inorganic nitrogen, e.g. nitrates (Loewhing, 1961; Viets, 1965). This conservation of nitrogen may have a significant bearing on the response of maize plants to split applications of fertiliser (Section 1.6.4).

1.5.2 Plant Growth and Distribution of Nitrogen in Plant Parts

With the progressively more rapid accumulation of dry matter relative to nitrogen and the concomitant increases in the plant content of structural and reserve carbohydrates, there is a dilution of the N content (Whitehead et al, 1948; Watson, 1963; Viets, 1965). The decline may also be due in part to depletion of the external N supply (Watson, 1963). Translocation of N from the stover (total plant shoot except the grain) to the grain reduces the nitrogen content of various plant parts (Whitehead et al, 1948; Jordan et al, 1950; Hanway, 1962b; 1963).

The 3-4% nitrogen concentration (expressed as a percentage of plant dry weight) found in the young maize plant is greater than at any other time in the growth cycle (Kurtz and Smith, 1966). As the plant grows, accumulation of nitrogen takes place regardless of soil fertility and there is little translocation from one part to another until the ear begins to form (Hanway, 1962b). Translocation from other plant parts to the grain takes place as the grain enters the "blister" stage of development about 12 days after 75% silking, and continues until physiological maturity (Hay et al, 1953; Hanway, 1963).

Hanway (1962b) indicated that translocation from the cob, husk and stalk occurred before that from the leaves. Over a period ranging from 14 days before silking until 16 days after the event the leaves contained about 30% of the total nitrogen of the maize plant, even though they constituted only 13% of the total dry matter accumulation. At tasselling and silking, therefore, the leaves contained a high concentration of nitrogen. Tyner (1946) reports a level of 2.9% (on a 6.6% moisture basis) while Jordan et al (1950) suggests a level of greater than 2% in the leaves at this growth stage, with a slower rate of decline in concentration with ear initiation, than in other plant parts. Johnson et al (1966) recorded a relatively high N concentration in the stem at tasselling (1-2% N), declining rapidly over the following 2-3 weeks to a level of less than 1% at maturity. In one report, husks and cobs showed a small decline in nitrogen content with the approach of maturity (Jordan et al, 1950).

1.5.3 Nitrogen Accumulation in the Grain at Maturity

Grain of commercial hybrids grown in U.S.A. usually contain 1.45 to 1.6% nitrogen at maturity, although specially bred "high protein" cultivars may have as much as 3% nitrogen (Kurtz and Smith, 1966). The grain can accumulate more nitrogen than the whole plant due to

translocation from other plant parts (Jordan et al, 1950; Hay et al, 1953), with up to 65-75% of the protein of the maize plant being found in the grain at maturity (Flynn et al, 1957; Hay et al, 1953; Hanway, 1962b; Jung et al, 1972).

Bressani and Conde (1961) note that nitrogen accumulates in the mature grain of maize mainly as alcohol-soluble zein which constitutes 40-50% of the grain protein nitrogen and correlates highly with total nitrogen.

1.6 FERTILISER NITROGEN AND MAIZE PRODUCTION

Maize places a high demand on soil nutrients particularly nitrogen. The nitrogen requirement for a 7,500-12,500 kg/ha grain crop is in the region of 168-336 kg/ha (Barber and Olsen, 1968). Most soils in the Corn Belt of U.S.A. are capable of supplying about 45 kg N/ha (Barber and Olsen, 1968), the remainder being met from fertiliser nitrogen. The use of irrigation in increasing yields adds to this requirement (Kurtz and Smith, 1966).

Under field conditions the response of the maize plant to increments of N fertiliser is influenced by many uncontrollable and/or hard-to-measure environmental factors (Harshbarger, et al, 1954; Flynn et al, 1957; Baird and Mason, 1959; Berger, 1962; Englested and Terman, 1966; Voss and Pesek, 1967; Colyer and Kroth, 1968; Voss et al, 1970ab; Bishop et al, 1972). Multiple regression analysis has been used to measure the effect of some of the uncontrollable variables on the nitrogen response (Voss and Pesek, 1967; Voss et al, 1970ab). Soil environmental factors such as its supply of nitrogen in relation to the crop's need and the supply of other essential nutrients; the residual effects of preceding increments of nitrogen fertiliser; drainage conditions and the effects of prior cultivation, as well as the previous history of the area can influence responses to N fertiliser. Seasonal weather conditions markedly influence the response of the maize plant to fertiliser nitrogen (N), as does the effect of different hybrids grown under these conditions. Rossman and Cook (1966) note that maximum maize yields result from the most favourable combination of many factors, including soil productivity, fertiliser, moisture, weed control and weather.

The remainder of this section covers the dry matter responses that have been reported for various environments and under the different N fertiliser practices used in maize production. The influence of N fertilisation on the quality of the dry matter produced

and the relation of N concentration in the leaves to yield as well as the influence of the enzyme nitrate reductase on nitrate metabolism in the maize plant are discussed. Some discussion of the efficiency of utilisation of applied N in maize production and the effects of various types of fertiliser and their method of application on recovery by field grown maize plants is included.

1.6.1 Nitrogen Fertiliser and Dry Matter Accumulation

Many reports in the literature indicate a significant increase in the total dry matter or grain dry matter production of the maize plant in response to N fertiliser additions, under diverse environmental conditions (Jordan et al, 1950; Duncan, 1954; Harshbarger et al, 1954; Viets et al, 1954; Gibbon, 1966; Fayemi, 1966; Colyer and Kroth, 1968; Robertson et al, 1968; Gonske and Keeney, 1969; Nunez and Kamprath, 1969; Stevenson and Baldwin, 1969; Jung et al, 1972; Powell and Webb, 1972; Shukla, 1972; Jones, 1973; McCormick and Mackay, 1973). Some workers have recorded dry matter yield decreases with additions of high rates of nitrogen (Larson, 1966; Powell and Webb, 1972). Still others have recorded little or no response to nitrogen additions (Dickson, 1968; Colyer and Kroth, 1968; Cumberland and Douglas, 1970; Douglas et al, 1972).

Maize plants may accumulate dry matter in response to increments of N fertiliser until some other factor under the prevailing conditions limits any further response. Early work reviewed by Nelson (1956) suggested that on soils extremely deficient in nitrogen, near maximum yields would be obtained with applications of about 180 kg N/ha but under more usual field conditions applications in the range of 45-90 kg N/ha would be sufficient. More recent work summarised by Berger (1962) and that of Bishop et al (1972) and Jones (1973) suggests that maize cultivars with a high yield potential should give a significant response to 100-150 kg N/ha. Some of the latest reports, however, have indicated that rates up to 224 and 280 kg N/ha have produced satisfactory maize yields (Robertson et al, 1968; Nunez and Kamprath, 1969; Jung et al, 1972; Powell and Webb, 1972), but these fertiliser practices have yet to be thoroughly evaluated (Jung et al, 1972).

It appears necessary to grow maize at relatively high plant densities in order to maximise dry matter responses to fertiliser N as shown by Duncan (1954), Robertson et al (1968) and others. However,

additions of very high rates of N fertiliser (above 700 kg N/ha) may cause a decline in yield levels due to a fall in soil pH with increased soluble salt concentrations (Powell and Webb, 1972).

The nitrogen content of soils prior to maize cropping can have a marked influence on the dry matter response of the plant to N fertiliser additions (Brown, 1966; Dickson, 1968; Shukla, 1972; Douglas et al, 1972). Shukla (1972) reported a significant grain response with up to 180 kg N/ha applied and a population density of 47,600 plants/ha, at two out of three locations. The top 15 cm of the clay soils at the three locations had total nitrogen contents of 0.10, 0.25 and 0.32% respectively; at the third location no yield response was recorded. Brown (1966) recorded no economic response in terms of higher grain yields from N fertilised maize plants on sandy clay and sandy clay loam soils with total N contents greater than 0.2% or on sandy loam, loamy sands and sands with total N contents greater than 0.15%. In New Zealand, dry matter responses to N fertiliser have not been reported in maize crops grown in soils recently out of high producing grass-clover pastures (Cumberland and Douglas, 1970; Douglas et al, 1972). McCormick and Mackay (1973), however, in growing maize followed by winter grass on the same site for 5 successive years, found that 150-200 kg N/ha was required for maximum grain yields. However, the area had been cropped with maize in rotation with winter grass for 3 years prior to beginning the experiment. In the first two years out of pasture no yield response to nitrogen was recorded, which agrees with the findings of Douglas et al (1972).

1.6.2 Fertiliser Uptake, Nitrogen Content and Yield

When maize is grown on soils low in available nitrogen, application of fertiliser increases the concentration of nitrogen in the plant or plant parts (Viets and Domingo, 1948; Krantz and Chandler, 1951; Bennett et al, 1953; Sauberlich et al, 1953; Viets et al, 1954; Ellis et al, 1956; Genter et al, 1956; Baird et al, 1962; Watson, 1963; Bishop et al, 1964; Robertson et al, 1965; Larson, 1966; Gonske and Keeney, 1969). However, under very low levels of available soil nitrogen and good growing conditions an increase in crop yield may offset the increase in nitrogen supply, with little change in the percentage composition of the plants (Zuber et al, 1954; Kurtz and Smith, 1966).

Application of N fertiliser to the maize crop may also increase uptake of other essential elements such as phosphorus, sulphur, zinc,

manganese, copper, magnesium and boron (Barber and Olsen, 1968; Baker et al, 1970; Bishop et al, 1972).

Increasing the population density, depending on soil nitrogen availability, may decrease the concentration in maize plants. Center et al (1956) applied 67 kg N/ha to maize grown at 24,700 plants/ha and 39,500 plants/ha; respective average grain crude protein contents for the two plant densities were 10 and 9.1%, but with 202 kg N/ha the respective crude protein contents were 11.3 and 11.1%. Similar trends have been reported by Prince (1954) and Stickler (1964). Nevertheless some workers have noted increased protein concentrations in the grain when high levels of N were applied with a plant population in the region of 59,000 plants/ha (Lang et al, 1956; Zuber et al, 1954).

The accumulation of nitrogen above the level where a dry matter yield response is obtained represents luxury consumption (Barber and Olsen, 1968). This phenomenon has been reported many times in the literature and some examples will be given here. Grain nitrogen concentrations are most often reported, due to its important influence on quality. Hunter and Yungen (1955) showed a yield response to nitrogen fertiliser up to 134 kg/ha and an increase in nitrogen concentration with increments up to 358 kg N/ha. With zero to 179 kg N/ha the crude protein % in the grain increased from 6.92-8.74 but with 179-358 kg N/ha the increase was less marked, that is, from 8.74-9.58%. Similarly Zuber et al (1954) showed no grain yield response with increments of fertiliser up to 280 kg N/ha but increases in grain crude protein content were significant over the fertiliser range from 56 kg N/ha to 280 kg N/ha. The crude protein content in the stover increased with added fertiliser from a minimum of 2.07% to a maximum of 6.52%. With 280 kg N/ha the ratio of N in the grain to that in the stover was less than at the 134 kg N/ha level indicating a greater uptake at the higher rate than could be utilised in grain production.

The quality of maize is frequently related to the protein content although maize protein lacks sufficient amounts of the essential amino acids, lysine, tryptophan and methionine necessary in animal diets (Kurtz and Smith, 1966; Barber and Olsen, 1968). Nevertheless large quantities of the total maize production in the U.S.A. is fed to animals as silage or grain. In this country over recent years, greater quantities of maize are being used in animal production enterprises as greenfeed or silage (Menalda and Kerr, 1973; Jagusch and Hollard, 1974). In countries such as Mexico and India, maize grain is also an important part of the human diet (Berger, 1962). With N fertilisation,

however, the quantity of the essential amino acids is not increased because zein increases disproportionately to the non-zein protein which contains significant amounts of these amino acids (Schneider et al, 1952; Sauberlich et al, 1953). The increased crude protein content with N fertilisation is of value to ruminants who are able to manufacture the required amino acids from simple nitrogenous compounds (Aldrich and Leng, 1965), but is of little value to non-ruminants (Kurtz and Smith, 1966). Research into mutant maize cultivars with a better balance of amino acids has been reported (Mertz et al, 1964; Nelson, 1969; Dumanovic, 1971).

The chemical concentrations of nitrogen, phosphorus and potassium are considered as being dependent variables in determining yield in maize (Tyner, 1946; Dumenil, 1961; Viets et al, 1954) and others have improved the relationship by including the effects of environmental factors (Voss et al, 1970ab) and other essential elements (Peck et al, 1969; Walker and Peck, 1972b). The concentration of a particular element in the maize plant is commonly referred to as the critical percentage in relation to yield response. Macy (1936) defines the critical percentage as the concentration above which there is luxury consumption of the nutrient and below which there is a zone of poverty adjustment, which is almost proportional to a deficiency until the minimum percentage occurs. Tyner (1946) considers that Macy's "zone of poverty adjustment" is better defined as a "zone of proportionality" where yield adjustments for practical purposes are directly related to nutrient content. As the nutrient concentration approaches the critical percentage, the need for the particular nutrient and the intensity of the response diminishes. Tyner (1946) defines the critical concentration as that which is just adequate for growth. Ulrich (1952) regards this quantity as a narrow range of concentrations above which the plant is amply supplied with the nutrient and below which the plant is deficient. It is the point at which growth rate and yield first begins to decline relative to plants with a higher nutrient content. Tyner (1946) reported a critical concentration of 2.9% (on a 6.6% moisture basis) in the ear leaf at tasselling which compares favourably with the critical concentration of 3% found by Bennett et al (1953). Viets et al (1954) indicated a N% of 2.83 associated with maximum dry matter yields and suggested a range of 2.2 to 2.8% where the concentration was too low to produce maximum yields although nitrogen deficiency symptoms were not evident in the leaves. Agboola (1972) under tropical conditions, recorded critical nitrogen

concentrations associated with the highest grain yields in the range of 2.85-3.19%.

Critical N concentrations in the maize plant, however, vary under the influence of many factors, as recently reviewed by Bates (1971). The age of the tissue chosen for analysis, the tissue chosen and the cultivar, as well as interactions of the nutrient under consideration with other nutrients, and their supply, affects the critical concentration. Most workers have based their sampling on the work of Tyner (1946) who selected the ear leaf at tasselling as a suitable indicator of the nutritional status of the maize plant.

Viets (1965) describes the relationship between total N content and grain yield in maize as being "U" shaped, in that both high and very low yields were always associated with greater N absorption per unit of yield than those in the middle of the yield range. Viets (1965) considers that the total N requirements cannot be accurately predicted because:

(i) total yield cannot be accurately predicted and N supply may often be a factor in determining the yield itself.

(ii) the relation between N content and yield may be often represented by a "U" shaped curve. The right hand side of the "U" shaped curve is of greater importance as it is associated with high grain yields and represents the region where the N content required per unit increase in grain yield is rapidly rising. High levels of available N are, therefore, necessary along with complementary higher availability of other nutrients. It also becomes more difficult to determine how much of the extra N absorbed represents luxury consumption; reduced intraplant competition for N at high yield and supply levels results in inefficient utilisation of N.

It has been shown in this section that the N concentration in the leaves at flowering may be positively correlated with grain yield. Work reviewed in Section 1.6.5 shows that differences in N availability can arise from variation in leaf area and leaf area duration, with NAR being of lesser importance. While leaf area is a prime determinant of yield it is also dependent on the chemical composition of the leaves. Leaf analysis at tasselling and silking can indicate whether N will be deficient or is deficient and has, therefore, resulted in reduced leaf area and consequently reduced grain yield (Hanway, 1962a).

1.6.3 The Utilisation of Nitrogen in Protein Production in the Maize Plant

A summary of the initial reduction of nitrate by the enzyme nitrate reductase will be given along with some of the factors affecting its functioning and its relation to protein production. The biochemical pathways involved in the metabolism of N will not be discussed. These aspects have been covered in detail elsewhere (Steward and Durzan, 1965).

In order for N to be used in the synthesis of amino acids and proteins it must be in the reduced form. Ammonium nitrogen, urea nitrogen and that in amino acids, if absorbed by the maize plant can be readily used because in these forms the nitrogen is in a reduced state. Nitrate-N, the usual form of nitrogen absorbed by maize plants, must be reduced before it can be utilised in protein production (Donald et al, 1963). Nitrate reduction can take place in the roots or shoots of the maize plant (Donald et al, 1963; Hera, 1971; Pate, 1973). The enzyme nitrate reductase has been implicated in the reduction of nitrate to nitrite, the first step in the N metabolism of the plant (Rossman and Cook, 1966). Its formation is substrate induced (Evans and Nason, 1953) and the enzyme is most active in young leaves, shoot and root tips (Beevers and Hageman, 1969). The reduction reaction requires energy and light appears to be involved in the conversion of nitrates to protein (Hageman and Flesher, 1960; Hageman et al, 1961; Zieserl et al, 1963). These workers concluded that the level of reserve proteins and precursers, and the potential of the plant to synthesise protein during the tasselling period determined maize yields, but the relationship between nitrate reductase activity and yields of grain maize has not been conclusively established (Deckard et al, 1973). Many workers have noted a decrease in protein content of the maize grain with increased population density (Genter et al, 1956; Prince, 1954; Knipmeyer et al, 1962). This has been associated with a decreased nitrate reductase activity in the leaves under shaded conditions.

Deckard et al (1973) investigated further the relationship between nitrate reductase activity and grain yield. These workers applied 337 kg N/ha to six maize genotypes grown at 59,300 and 79,000 plants/ha in separate plots, at 14 days after tassel initiation, tassel emergence and silk emergence. None of the genotypes studied were able to maintain a nitrate concentration in the leaf laminae that would support or maintain a high level of nitrate reductase activity (substrate induced) during the later stages of ear development, even though late

applications of N were made. Enhanced nitrate reductase activity during ear development could have increased the grain protein content. This failure of the treatments to increase leaf laminae concentrations of nitrate to mid or early season levels was suggested to be due to the maize plant having more than one mechanism that regulates uptake and transport to the leaf blade (Deckard et al, 1973). Levels of available nitrate were non-limiting. Jung et al (1972) also observed a decline in nitrate reductase activity in maize leaves with applications of up to 224 kg N/ha, made at a similar growth stage. These workers, however, suggested that with late applications of N insufficient time was available for protein to accumulate in the vegetative tissue before grain formation begins. Works cited in Section 1.5.3 indicate that a large proportion of the grain nitrogen comes from that previously stored in the vegetative tissue. A late application of N may not allow sufficient time for assimilation, especially if nitrate reductase activity remains low, as found by these workers.

1.6.4 The Timing of Nitrogen Fertiliser Application

The standard practice in maize production is to supply N fertiliser at two growth stages, namely at planting as a "starter" fertiliser and as a sidedressing at the loosely defined "knee-high" stage, 30-50 days later when the maize plant is about 60 cm in height. This practice has evolved with the recognition of the growth stages when high nitrogen availability is necessary to meet the requirements for the maize plant to maximise production. Commonly the rate to be applied is split in the ratio of 1/5 : 4/5 or 1/4 : 3/4 or 1/3 : 2/3 or 1/2 : 1/2 at planting and sidedressing respectively (Gibbon, 1966; Dickson, 1968; Robertson et al, 1965; Robertson et al, 1968; Nunez and Kamprath, 1969; Shukla, 1972; McCormick and Mackay, 1973). Starter fertiliser ensures that the young seedling, with limited root development, has ready access to N during the formative growth processes when, for example, the number of leaves to be developed by the plant is determined (Aldrich and Leng, 1965; Allison, 1973). Cold, damp weather prior to planting may limit mineralisation of soil N by microorganisms and thus reduce N availability at planting time (Kurtz and Smith, 1966). The sidedressing at the "knee-high" stage provides the largest portion of the rate to be applied and is necessary to meet the peak demands of the maize plants during rapid vegetative growth just prior to tasselling (Hanway, 1962b; Aldrich and Leng, 1965; Englested and Terman, 1966). Sufficient development of the permanent adventitious roots of the maize plant at this stage, aids the rapid uptake of applied N and reduces

losses in soils subject to leaching (Englested and Terman, 1966; Allison, 1973). Application of fertiliser at this time is also governed to some extent by the ability to move machinery through the maize crop without excessive damage being inflicted on the plants (Kurtz and Smith, 1966).

Nelson (1956) in reviewing early work concluded that the side-dressing application generally proved more effective than at earlier or later stages, except for sandy soils where leaching losses may be high from a single sidedressing.

Some winter applications of N fertiliser are made in parts of the U.S.A. and Canada (Stevenson and Baldwin, 1969). This may be followed by spring pre-plant applications and either planting or sidedressing applications or both. Generally winter applications have resulted in lower maize yields especially with lower rates of fertiliser N (less than 134 kg N/ha, Welch et al, 1971). Denitrification losses of fertiliser N resulted in lower yields when ammonium nitrate, urea and anhydrous ammonia were applied to fine and medium textured soils (Baldwin and Stevenson, 1969; Welch et al, 1971).

In order to measure differences due to time of application of N fertiliser considerable yield increases due to the fertiliser additions are necessary (Welch et al, 1971). A number of workers have recently investigated the response of maize to N fertiliser applications at times other than at the traditional planting and "knee-high" stages (Brown, 1966; Fayemi, 1966; Srivastava et al, 1971; Jung et al, 1972; Jones, 1973). Conflicting results have been reported. Brown (1966) summarised a number of trials in Malawi where rates of N ranging from 18-70 kg/ha, as sulphate of ammonia, were applied in seven different regions in the following manner: (a) all at planting (b) all 3-4 weeks after planting (c) all 6 weeks after planting (d) all at tasselling (e) half at planting, half at 3-4 weeks after planting (f) half at planting, half at 6 weeks after planting and (g) half at planting and half at tasselling. No significant differences were found between split and non-split applications in terms of grain yield. Timing was not important as long as the bulk of the nitrogen was applied during the first month of growth (Brown, 1966). Fayemi (1966) working in Nigeria used similar splits for 90 kg N/ha rate of sulphate of ammonia or urea as (a), (b) and (c) above with other divisions as follows: (i) half at 1 month, half at 2 months; (ii) quarter at planting, quarter at 1 month, quarter at 2 months, quarter at 3 months. The

trials were conducted over 4 years on a sandy loam soil. In 3 out of 4 years the highest yields were obtained from the treatment (i) plots. Delaying N applications for 1 month, under heavy rainfall conditions, reduced leaching losses; delaying the application for 2 months showed no beneficial effects. Maize plants receiving all the N in a single dose at one month after planting had significantly higher grain N percentages (1.83% as compared to 1.78%) for plants from other treatments. Jones (1973) conducted a three year trial in Nigeria with 56, 112 and 224 kg N/ha as calcium ammonium nitrate applied all or in part at planting, sidedressed $3\frac{1}{2}$ weeks after planting or sidedressed 7 weeks after planting (2 weeks before silking). Different sites were used each year to avoid possible residual N effects from previous applications. Over the three years no statistically significant advantage was found from split applications of N. Grain yield responses were significant up to 112 kg N/ha with further slight increases up to 224 kg N/ha. There were significant differences in N concentration in the leaf immediately below that subtending the ear due to N fertiliser level, but there were no significant differences between treatments (time of application) or any significant interaction between N level and treatments. Leaching was not a factor in causing inefficient use of N fertiliser over the three year period.

Jung et al (1972) in Wisconsin U.S.A. examined the effect of time of application to maize of 56-224 kg N/ha as urea, ammonium nitrate and potassium nitrate for six consecutive weeks, beginning 7 weeks after planting in 1969 and 5 weeks after planting in 1970. The soil type was a loamy sand and the plots received irrigation water. Significant declines were recorded for grain and tissue yield (based on oven-dry weight of the aerial portion at the early dent stage) when N was applied later than 8 weeks (late vegetative growth) after planting. This indicates a morphological stage of development when N was used inefficiently in growth processes. Significant increases in grain and tissue yields were reported for N fertiliser rates up to 112 kg/ha for one cultivar and 224 kg/ha for another. Both were short maturing cultivars. Percent N in the grain and tissue generally increased as time of N application was delayed supporting the contention that N was being used inefficiently in grain production. N uptake by the plants decreased for the later N applications and showed a similar response pattern to yields of grain and tissue.

The ability of plants to store large amounts of N for future use during early growth, and thus largely protecting it from possible

denitrification and leaching losses, may account for the lack of advantage of split applications of fertiliser, in some situations, when the opposite result was expected (Gerdel, 1931; Viets, 1965).

1.6.5 Nitrogen Fertiliser, Leaf Area and Dry Matter Yield

As outlined in Section 1.3.3 the size and efficiency of the photosynthetic system, primarily that of the leaves, determines the final crop yield. A change in nutrient supply affects yield mainly by influencing the net amount of photosynthesis of the crop (Watson, 1963).

The work of Watson (1956; 1963) suggests that nitrogen fertilisation may affect maize yield predominantly by increasing leaf area or LAI and that the effect on NAR up to a certain LAI is of secondary importance. It has been shown by various workers (Dungan, 1928; 1930; Hanway, 1969) that maize grain yield reductions are proportional to the leaf area removed from the plant, the greatest reduction in grain yield occurring if loss of leaf area, due possibly to hail, wind or insect damage, is sustained near tasselling (Hume and Kranzke, 1929; Dungan, 1934; Hanway, 1969). The early work of Gerdel (1931) and lately that of Nunez and Kamprath (1969) suggests that with high rates of N fertiliser, increasing grain yields are the result of the greater efficiency of a given leaf area in producing grain, rather than an increase in the leaf area of the maize plant. Early (1965) calculated from Gerdel's (1931) data the relative maximum yield (grain/dm^2 of leaf area) of the low fertility treatment maize plants to be 53% of its relative maximum yields of grain as compared to 100% for the high fertility highest yielding plots.

Work of Eik and Hanway (1965) indicates that starter fertilisers are likely to increase the leaf area of the maize plant and the rate of leaf emergence. Maintenance of N supply throughout the growing season increases leaf longevity and thus enhances dry matter production (Hanway, 1962a; 1962b; Eik and Hanway, 1965). Early et al (1967), however, reports that extensive vegetative growth is not a prerequisite for high grain yields. These workers found that shading of the maize plants for 21 days during the reproductive phase reduced grain production more than shading for 54 days during vegetative growth. Enhanced vegetative growth from starter fertiliser may not increase grain yield due to the hastening of "complete" cover in the maize crop and shading of leaves during the reproductive phase. Eik and Hanway (1965) noted that leaf death during the grain filling period was occasionally increased by the use of starter fertilisers but the effect was nullified by side-

dressing with nitrogen.

At a given N rate the relative dry matter yields of maize plants increased linearly up to a LAI of 3.5; with an LAI greater than 3.5 yields declined with 112 kg N/ha but remained constant with the 168 kg N/ha and 280 kg N/ha fertiliser rates (Nunez and Kamprath, 1969). Hoyt and Bradfield (1962) noted yields began to decline when the LAI of maize plants reached 3.3 and related this to a lower NAR with reduced photosynthesis in the shaded lower leaves. With the plants amply supplied with water and nutrients, the dry matter yield and LAI were linearly related up to a LAI of 2.7 and an actual decline in yield occurred at an LAI of 4 due to the shading effect (Hoyt and Bradfield, 1962). The relative contribution in terms of dry matter produced per dm^2 by the top six leaves, the middle three leaves and the bottom 5-7 leaves, for maize stands of LAI 3.3, was 4 : 2.2 : 1 (Hoyt and Bradfield, 1962).

Increasing population density up to 74,000 plants/ha was found to decrease leaf area per plant (Eik and Hanway, 1965) by about 33% (Allison, 1969) at the final harvest.

1.6.6 Effect of Nitrogen Fertiliser on the Components of Yield

Total grain yield in the maize plant is made up of the following major components (Leng, 1954): (1) the number of ears per plant
(2) the weight of grain per ear
(a) grain weight
(b) number of grains per ear
(i) number of rows per ear
(ii) number of grains per row.

There are few reports in the literature concerned with the effect of N fertiliser on the components of grain yield in maize. Alexander (1952) noted a non-significant increase in row number per ear with 448 kg P_2O_5/ha and 358 kg N/ha applied separately then in combination, as compared to maize grown on soil low in available N and P. Schreiber et al (1962), however, applied 84 kg N/ha and 336 kg N/ha to sweetcorn as single or split applications at three growth stages (planting, higher internode elongation and tasselling) and found highly significant increases in row number per ear with nitrogen and when applied at planting only. Apparently no effect was noted on ears per plant, grains per row or weights of individual grains. Although row number per ear increased with increments of N fertiliser, no significant yield response was recorded as ears with lower row numbers compensated by increasing

individual grain number and size. Jordan et al (1950) noted a significant increase in ear weight (cob and grain) with increments of N fertiliser up to 134 kg N/ha at two plant densities of 9,900 plants/ha and 29,500 plants/ha.

1.6.7 Recovery of Fertiliser Nitrogen by Maize Plants

Apparently many plants including maize, make inefficient use of available nitrogen during a growing season. Recovery of fertiliser N is usually less than 60% and may be less than 40% depending on the rate applied (Bartholomew, 1971). For example, Robertson et al (1965) harvested maize plants at the early dent stage and calculated recoveries of 53%, 38% and 23% from 168, 336 and 672 kg N/ha of fertiliser applied in the traditional manner. Hunter and Yungen (1955) recorded mean recoveries of N in the maize grain at maturity of 42%, 37%, 27% and 22% respectively, from fertiliser applications of 56, 112, 168 and 224 kg N/ha at planting. Jones (1973) applied 56, 112 and 224 kg N/ha to a maize crop in 1969 and 1971 and calculated recoveries in the total plant of 72%, 75% and 46% in 1969 and 51%, 47% and 41% in 1971, for the respective fertiliser rates. The apparent recovery of fertiliser was not significantly affected by when the fertiliser was applied or whether it was split over several times of application.

Many factors affect N recovery by crop plants and thus few general unqualified statements can be made regarding the efficiency of N fertiliser usage. Extensive reviews of these factors have been published and the reader is referred to the works of Allison (1966), Bartholomew and Clark (1965), Nelson and Hauck (1965) for detailed discussions.

Leaching of nitrate nitrogen (NO_3-N) in soil water is considered the most important means by which N is lost from soils (Allison, 1965; Bartholomew, 1971). Other mechanisms affecting N recovery such as denitrification and volatilisation losses will be briefly discussed in relation to water availability and the method and form of fertiliser applied.

Bartholomew (1971) considers that the majority of NO_3-N losses by leaching occur after the crop has ceased to absorb N and water from the soil profile. Leaching implies removal of nitrate in water from the soil profile but under the prevailing cropping conditions the movement of nitrate may be upward (with moisture withdrawal by plants), or downward with water additions although there is usually a net downward movement. Nitrate may remain in the root zone for considerable periods

without being absorbed by the plant (Bartholomew, 1971). Soil water content is considered the most important single factor influencing and/or controlling N uptake and use by maize plants grown in the field (Viets, 1967; Bartholomew, 1971). Low soil water suction (high soil water content) is generally most favourable for rapid uptake of N by maize plants. Viets (1967) summarises the specific factors favourably affected under these conditions: (i) the size of the soluble and exchangeable nutrient pool (ii) the diffusion rate of ions (iii) the extension of root systems (iv) and the mass flow of water. Soils should not, however, reach a saturated state as the development of anaerobic conditions inhibits root activities and may cause denitrification losses. Facultatively anaerobic microorganisms (e.g. Pseudomonas sp.) may use nitrate in place of oxygen as an electron acceptor in their respiratory metabolism, resulting in its reduction to gaseous forms of nitrogen (Whitehead, 1970). Soils with a low water holding capacity (e.g. sands) may lose greater amounts of NO_3-N by leaching as rainfall or irrigation water moves rapidly through these soils (Harmsen and Kolenbrander, 1965). Bartholomew (1971) observed that N recovery (as ^{15}N) by maize plants was greater in seasons of greater moisture availability than in dry seasons. Data of Jones (1973) supports this contention as recovery was higher in 1969, a year of above average rainfall for the district, than in 1971 when rainfall was below the average.

1.6.8 Method of Application of Fertiliser, Source of Nitrogen and Effect on Recovery

Only ammonium, ammonium forming and nitrate fertilisers will be referred to in this section; a general summary of methods of N fertiliser application in relation to the efficiency of utilisation of N by maize plants will be given.

Starter fertilisers containing a small amount of N are usually banded 4-5 cm to the side and a short distance below the maize seed (Donald et al, 1963; Barber and Olsen, 1968). This avoids possible damage to the germinating seedling by the fertiliser or its hydrolysis products and usually provides an adequate source of N for the plant during early growth. The bulk of the N fertiliser, as discussed in Section 1.6.4, may be applied as a pre-plant dressing or as a sidedressing during the vegetative growth of the plant. Solid forms of fertiliser are seldom banded as broadcast applications followed by ploughing and discing (pre-plant) have generally been found to be as efficient in supplying the crop with N (Donald et al, 1963; Kurtz and Smith, 1966). This may not be so

on sandy soils where leaching of NO_3-N may reduce the recovery by maize in the early growth stages, before the plants are large enough to utilise water and N at a rate sufficient to limit downward movement of NO_3-N (Barber and Olsen, 1968). Nelson (1953) compared the movement from banded fertiliser of nitrate and ammonium ions with irrigation on a virgin fine sandy loam soil with a low infiltration rate and a profile depth of 61 cm overlying gravel. After ploughing and harrowing, 672 kg N/ha as ammonium nitrate was banded at a depth of 9 cm and a distance of 7.6 cm from the side of an irrigation furrow, these being 86 cm apart in the plots. Previously, maize grown under these conditions with 134 kg N/ha as ammonium nitrate (broadcast or split applications) and 61 cm of irrigation water, produced no significantly different grain yield responses. Banding of fertiliser resulted in NO_3-N being most concentrated above and on both sides of the band with lateral movement limited to 15 cm. A moderate concentration reached 27 cm in depth and some nitrate reached a depth of 57 cm, where it accumulated just above the gravel layer. With a total of 17 cm of irrigation water (3 separate applications) applied ammonium nitrogen moved no more than 7 to 10 cm over 24 hours (Nelson, 1953). The mobility of the nitrate ion to greater soil depths implies that it may be absorbed by the more mature part of the maize root system whereas the ammonium ion is more available to the laterally extending roots than to those penetrating to lower level (Cunard, 1967).

The use of highly concentrated forms of N in maize production in the U.S.A. has increased with the introduction of anhydrous ammonia (82% N) and aqua ammonia (21%) (Aldrich and Leng, 1965). However, urea is still used extensively in many countries (Allison, 1966). Differences in terms of the efficiency of usage have been reported under field conditions. For example, Viets et al (1954) and Jung et al (1972) recorded lower maize grain yields with calcium nitrate and potassium nitrate than with the ammonia, ammonium sulphate, ammonium nitrate and urea. Laboratory and glasshouse work also indicates marked differences in behaviour of solid and liquid N fertilisers in the soil-fertiliser-crop system. Generally, however, with proper use under field conditions little difference exists in the efficiency of solid or liquid forms in increasing crop yield (Hauck and Russel, 1969).

The hydrolysis of urea in soils via the enzyme urease, may result in N fertiliser losses due to the volatilisation of ammonia. Because of the restricted sorption and lack of mixing with the soil, volatilisation is greatest when urea fertiliser is applied to the

surfaces of dry soils. This is especially apparent when heavy applications are made to soils with a low cation exchange capacity (e.g. sands) or a low capacity to sorb the applied N (Gasser, 1964). In maize producing areas over recent years, with the increased usage of highly concentrated sources of N, injection into the soil between the rows to a depth of about 15 cm minimises volatilisation losses. More rapid soil adsorption of the ammonia formed during urea hydrolysis is likely using this application technique. Specially constructed tractor drawn machinery are being used (Jackson and Chang, 1947; Barber and Olsen, 1968; Hauck and Russel, 1969).

Ammonium fertilisers or ammonium forming fertilisers when applied under conditions suitable for maize growth, may be converted to the anionic and therefore mobile nitrate ion by nitrifying bacteria. This process can, therefore, affect the recovery of fertiliser N by maize plants by increasing the possibility of leaching losses or under anaerobic conditions, contribute to reduced recovery due to denitrification losses (Aldrich and Leng, 1965; Hauck and Russel, 1969). Wetselaar et al (1972) suggests that banding of N fertilisers at high concentrations (greater than 400 ppm, the ceiling rate for nitrification of urea and aqua ammonia) would drastically reduce nitrification and may help regulate nitrate formation in relation to the crop's requirement over the growth cycle. Initial high concentrations in the band would result in minimal nitrification at a time when the plant requirements are low; with time the local concentration in the band becomes reduced as outward diffusion into a greater volume of soil takes place. Nitrification would increase and more nitrate would become available to match the increased requirement of the maize plant. Consequently, recovery of N fertiliser may be increased.

1.7 NITROGEN DEFICIENCY SYMPTOMS IN MAIZE

The maize plant is dependent solely on the soil for its supply of N and thus a deficiency can occur at any growth stage depending on the adequacy of this supply, which can be supplemented by fertiliser additions. The visual symptoms of N deficiency in maize often appear during the period of most rapid growth of the maize plant when Sayre (1955) reported requirements for N to be in the region of 3 kg/ha/day (Section 1.5.1).

Nitrogen starvation in the early growth stages, before the rapid growth period, is manifested by leaves becoming greenish-yellow to orange-yellow in colour, with the tips gradually dying under severe

stress (Hoffer, 1941). Stunted, spindly plants result (Hoffer, 1941; Aldrich and Leng, 1965). The leaf symptoms are more definite if the deficiency occurs at later growth stages due to the translocation of N from older to younger and more rapidly growing tissues (Krantz and Melsted, 1964). There is a marked yellowing of the leaves since the yellow pigments such as carotins and xanthophylls predominate with the loss of the green chlorophyll pigment. This occurs first at the tips of the lower leaves and if the N deficiency persists, the yellowing follows up the midrib in a typical "V" shaped pattern, while the leaf margins remain green (Krantz and Melsted, 1964). The tip of the leaf dies and the whole leaf may turn yellow before dying and withering up, a condition frequently referred to as "firing" (Hoffer, 1941; Krantz and Melsted, 1964). Progressively, leaves higher up the stalk show these symptoms with the decline in leaf N content being paralleled by a similar decline in the leaf sheaths and internodes of the stalk (Viets, 1965).

Qualitative, rapid chemical tests for NO_3-N have been used to confirm N deficiency symptoms in maize plants. A normal healthy maize plant contains an abundance of NO_3-N in its sap during active growth and the presence of these reserves is indicated by a positive test (blue colour when a few drops of concentrated sulphuric acid containing diphenylamine, is added to a small portion of the test tissue). An adequate supply of N is therefore assumed, this reaction being typical of all dark green maize plants (Hoffer, 1941). A negative reaction (absence of a blue colouration) indicates that no reserve nitrate is present and this evidence confirms the yellowish-green symptoms indicating N deficiency. Tests are normally made on internodal tissue of the maize stalk (Hoffer, 1941). Other tests such as Bray's nitrate test have also been used (Bray, 1945).

CHAPTER TWO

METHODS AND MATERIALS

The aims of the experiment were to determine the response, in terms of grain and total dry matter, to nitrogen fertiliser applied at increasing rates and at different times during the growth cycle; to obtain information on the fate of applied nitrogen and its relation to growth and development and dry matter accumulation in the maize crop; to ascertain the effects of applied nitrogen on nitrogen levels in the whole plant and its component parts. The initial parts of this section describe the experimental layout of the trial used to examine these effects.

This section also outlines sampling procedures and methods used in measuring the growth of component parts of the plant and those used in determining the nitrogen content of plant parts and the chlorophyll content of the leaves. A method of sampling roots in the field is also described and finally an account is given of the statistical methods used to examine the data.

2.1 INTRODUCTION

2.1.1 Experimental Site

The experiment was conducted on part of paddock No. 30 of the Massey University No. I Dairy Farm. The soil at the site is derived from river alluvium of recent origin and is classified as Manawatu sandy loam. The 0.13 ha experimental site is almost flat with a gentle slope of 0-3° from West to East. The latitude of the site is 40° 23'S, and the altitude is 30m above sea level.

Profile studies of the soil indicated a slightly compacted layer 7-11 cm from the surface caused by over-cultivation, but no evidence of drainage impedence was found, except for a little darkening in soil colour due to greater retention of moisture in this region. The profile was generally free draining in nature. Various textural classes of sand and silt occur below the surface horizon (26 cm) to 60 cm on the western side of the plot area and 96 cm on the eastern side. Below these depths coarse sand and gravel predominate.

Temperature and rainfall data was obtained from Grassland Division, D.S.I.R., Palmerston North, 0.8 km east of the site. Solar radiation data was recorded at Ohakea R.N.Z.A.F. Station, 16 km west of the site. This data is presented in Appendix 1. Monthly rainfall data recorded at the site for the period from December 1972 to April 1973 is given in Table 2.2.

2.1.2 Experimental Layout

A split-plot experimental design was used. It consisted of 4 randomised complete-blocks with 12 treatment plots plus a control per block. The treatments consisted of four levels of nitrogen fertiliser (main factor), each of which was equally divided into three subplots reflecting the times of application of the fertiliser (subfactor). A table of random numbers was used in assigning treatments to main and subplots within each block (Table 2.1).

Each subplot consisted of 6 rows each of 41 maize plants spaced at about 20 cm intervals within the row and rows about 51 cm apart. Sampling was restricted to previously selected points consisting of 4 plants within the centre two rows of each subplot, these being adequately guarded by the remaining two rows on either side and the two plants between sample points within the row. The above plant spacings corresponded to a within plot population of 96,900 plants per hectare (approximately 39,200 plants per acre).

The layout is illustrated in Fig. 1. Tractor access routes are indicated; the whole plot area was guarded by 4 rows of machine sown maize plants.

Table 2.1 Summary of Nitrogen Fertiliser Treatments.

Rate Applied kg/ha (lb/ac)	Time+ of Application	Splitting of Application I	II	III
84 (75)	1	84	-	-
	2	42	42	-
	3	28	28	28
168 (150)	1	168	-	-
	2	84	84	-
	3	56	56	56
336 (300)	1	336	-	-
	2	168	168	-
	3	112	112	112
672 (600)	1	672	-	-
	2	336	336	-
	3	224	224	224

+Time 1 : all applied at planting.

Time 2 : ½ applied at planting ("starter"), the remainder at 6 weeks after planting ("sidedressing").

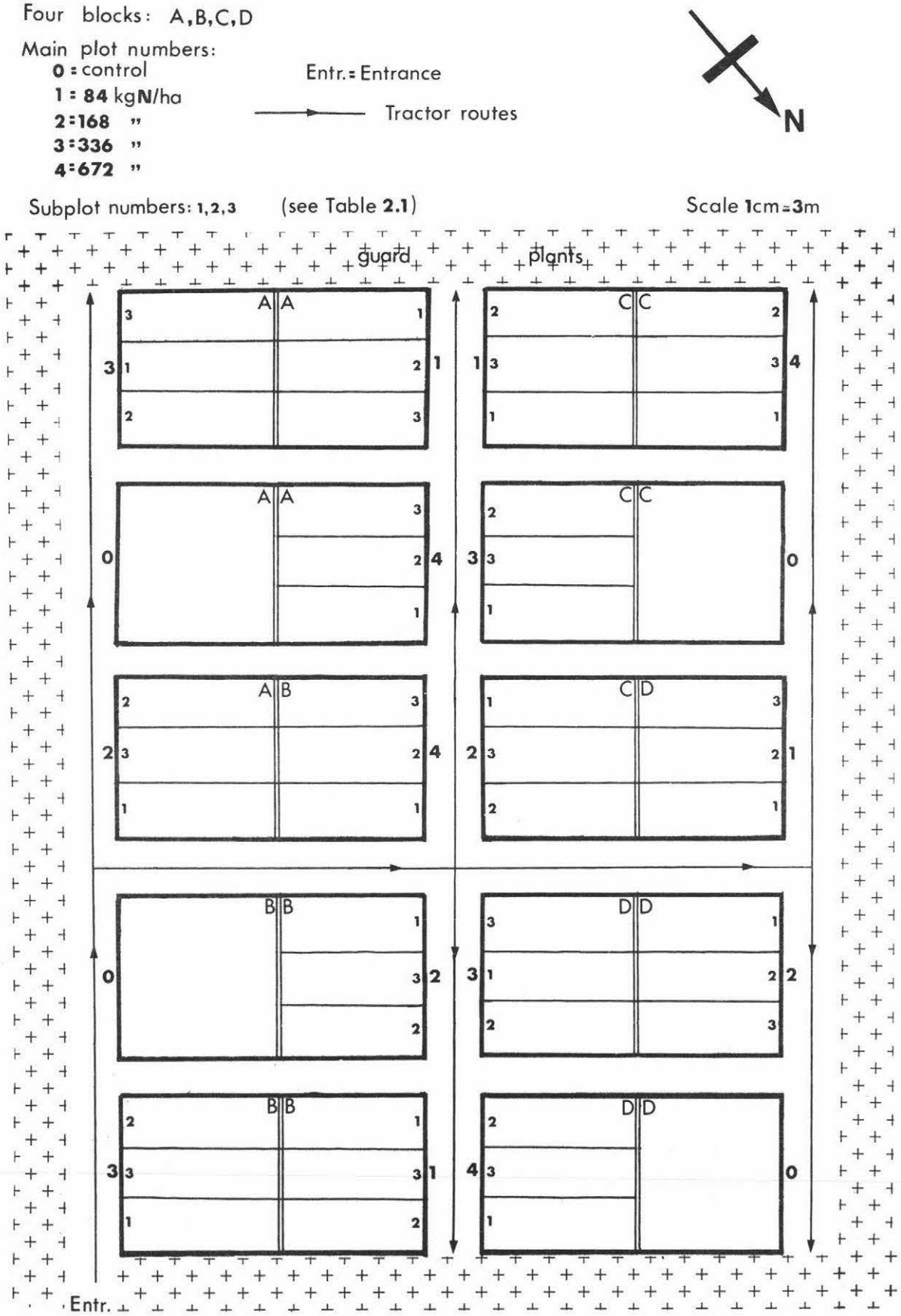
Time 3 : ⅓ applied at planting, ⅓ at 6 weeks and ⅓ at 50% silking, approximately 13 weeks after planting.

2.1.3 History of Plot Area and Cultural Operations

Prior to the present experiment the plot area supported a ryegrass-clover pasture, however, during dry, warm summers pasture species become reduced in numbers allowing ingress of weeds. Hay and/or silage was taken from the area in 1962-66, 1968 and 1970; a choumollier crop was grown in 1967. Superphosphate was applied annually at the rate of 251-627 kg/ha to the 1.05 ha paddock containing the plot area, from 1960 to 1970.

On 9.8.72 soil samples were taken for total nitrogen determination (Appendix 2). Results showed a low to moderate level (Ball, pers. comm.) of 0.175% and a carbon to nitrogen ratio of 12:1. Soil tests on samples taken 49 days after ploughing indicated an adequate level of phosphorus but a slight deficiency of potassium in the plot area (Appendix 2). Appendix 2 also summarises the cultural

FIG. 1 Experimental Layout



operations. Soil pH (1:2.5 soil/water ratio) was 5.4. On 11.9.72 1,000 kg/ha of lime and 153 kg/ha of superphosphate were broadcast over the paddock. Edmeades (1972) showed a visual magnesium deficiency while growing maize on this soil type so Kieserite (hydrated magnesium sulphate) was applied to the plot area as a precautionary measure prior to planting (Appendix 2).

A single full season hybrid, Northrup King PX610, was chosen for this study. Seed was provided by Thomas Corson and Son Ltd., Gisborne. PX610 is a three way hybrid which is classified as a 115 day relative maturity cultivar. This cultivar does not produce tillers readily and is currently being grown commercially in the Manawatu. Prior to sowing, this seed line had a germination test of 96%.

The seed was sown to a depth of 6 cm using hand planters; two seeds plus chemical insecticide for control of wireworm (Melanotus cribulosis) and cutworm (Persectania aversa) were placed at each planting site as determined by marks on a string grid drawn over each plot. One block per day was sown over 4 days; harvesting and nitrogen fertiliser applications followed the same pattern.

Sowing of the first block (replicate) took place on the 6.11.72 and the seedlings in the fourth block had emerged by 15.11.72, 6 days after sowing. The major part of the thinning and transplanting, from surrounding machine sown rows, took place 7-9 days after emergence, transplanted plants being noted and avoided at subsequent harvests. Environmental conditions were good for transplanting with few transplanted plants failing to survive. Approximately 4% of the stand were transplanted; those dying were replaced and the stand was complete and growing vigorously by 30.11.72.

Weed control using pre-emergent and post-emergent herbicides (Appendix 2) was excellent, being maintained throughout the growth of the crop.

Invasion by Argentine stem weevil (Hyperodes griseus) was prevented by insecticide application at the time of atrazine application (Appendix 2). Minor infestations of corn ear worm (Helicoverpa armigera conferta) and army worm (Pseudoletia separata) were controlled by aerial application of insecticide on 8.3.73. No fungal or viral infections were noted throughout the life of the crop.

Irrigation was applied, depending on rainfall, almost continuously from early December 1972 to late April 1973. Soil moisture levels were maintained near field capacity with tensiometer readings being taken every day and gravimetric measurements at approximately 14 day intervals, to assist in assessing the moisture status of the soil over the growth period of the crop. A trickle irrigation system was used to apply approximately 1,100 litres of water per hour over the 0.13 ha area. The arrangement of the lateral and attached whiskers (microtubes) in relation to plant rows is shown in Plate 1. Each 1.3 cm diameter lateral with its alternately attached whiskers (0.05 cm diameter) irrigated effectively two adjacent rows of maize plants, the point of application of water from each whisker being the centre of the 51 cm space between rows. No attempt was made to adjust the length of the whiskers to allow for the slight slope along the rows or the friction opposing water movement, due to the length of the laterals. Whiskers were cut to a standard length and inserted in an alternate pattern along the laterals at a standard distance apart. The position of the whisker outlet was experimented with until a sufficient spread of moisture from the point outlets along the length of the lateral resulted in the complete wetting of the soil between the rows, as movement of water took place from the point of application with continued irrigation. The whiskers were then fixed in position (as were the laterals) using wire clips, to counter movement due to temperature changes over a daily cycle. A constant pressure of 68.95 KPa (10 p.s.i.) was maintained in the irrigation system by the insertion of a pressure reducing valve at the trough water source. A filter was inserted in the 3.8 cm diameter main pipe from which the laterals were run. This irrigation system allowed the maize crop to remain virtually free of visual water stress during the season.

The 1972/73 summer in the Manawatu was drier and warmer than usual except for an unseasonably cool December (Table 2.2, and Section 3.1).

Plate 1 Showing the arrangement of irrigation laterals and whiskers between rows of maize plants.

Plate 2 Showing the soil injector and its operation.

Table 2.2 Summary of Monthly Rainfall Data (mm)

Period	Month						Total
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	
1972-73[+]	-	46	56	17	110	69	298[*]
1972-73[++]	29	43	50	16	102	59	299
1928-69[+++]	79	99	85	74	67	81	485

[+]Recorded at the site.

[++]Recorded at Grasslands Division, D.S.I.R., Palmerston North, 0.8 km from the site.

[+++]Recorded at Grasslands Division, D.S.I.R., Palmerston North, 0.8 km from the site; mean monthly rainfall over 41 years.

[*]Total for 5 months only.

2.2 EXPERIMENTAL PROCEDURES AND TECHNIQUES

2.2.1 Introduction

Nitrogen was applied at three different stages of crop growth. The first, concomitant with planting ("starter" application) and the second when the plants had reached the 5-6 expanded leaf stage 6 weeks after planting ("sidedressing" application) followed practices commonly found in farming. The third application, seven weeks after the second corresponded to the time when 50% of the plants had silks protruding from the primary ear prophyll, a distance of 1 cm or greater. Hand injection of fertiliser on a per plant basis facilitated application at this time. Six harvests were taken over the life of the crop. The first harvest took place at 5 weeks from planting; consecutive harvests followed at 5, 5, 3, 3 and 5 weekly intervals, with harvest six being coincident with physiological maturity and the termination of the experiment.

Root samples were taken by hand at harvest one. At harvests two, four and six these samples were obtained by lifting wire-netting containers with the front-end loader of a Ford 5000 tractor. Root sampling was restricted to the Time 2 subplot application (Table 2.1) of the 168 kg/ha and 672 kg/ha nitrogen treatments and the control plots, over the four blocks.

2.2.2 Form of Nitrogen Applied

Granular urea (Olins, 46% N, less than 1% biuret) was dissolved

in water at the rate of 25 g per 100 ml of solvent. Various quantities of this solution equivalent to the rates listed in Table 2.1 were applied to the maize crop.

2.2.3 Method of Fertiliser Application

A hand operated soil injector was used to apply nitrogen to individual plants within a plot. A steel plate welded 18 cm from the injection points allowed the fertiliser to be applied consistently at the same depth in the soil. The quantities applied were highly repeatable as was shown by random checks made in the field using a measuring cylinder. The pattern of fertiliser distribution, from six small holes spaced evenly around the circumference, 1.5-2 cm from the tip of the injector, was similar to that of a tractor-drawn banding machine. The injecting machine is illustrated in Plate 2.

The injector was inserted 10 cm to the side of each plant in the plot to a depth of 18 cm, the point of application being approximately the same at each time of application. After each application the hole left by the injector was closed over by soil to reduce volatilisation losses of nitrogen from the liquid applied.

2.2.4 Root Sampling Technique

The method devised for studying the maize root system was considered the most suited to the conditions likely to be encountered. The approach devised was only considered as a means of sampling a representative portion of the root system subject to a particular nitrogen treatment. The roots were not restricted to a given volume of soil by the container which was deliberately constructed of wire-netting to allow unrestricted root growth and movement of water, nutrients and oxygen.

Forty-eight root containers were constructed from "chicken" netting which was easily bent to the shape required. Wire clips were used to hold the sides and bottom together. The container shape was rectangular (20 cm x 51 cm) projected to a depth of 91 cm. The containers were buried prior to planting in positions determined by the random allocation of the treatments involved and the proximity of the tractor access routes (that is, they were positioned at the end of the two centre sample rows that were nearest the access routes; there were three or more guard plants at the ends of the sample rows before the first container grown plant was encountered). It was necessary to leave approximately 10 cm of the wire container

protruding above the surface of the soil, so that it could be attached to the frame at the time of lifting and to allow for possible slip during lifting. Thus the actual container dimensions were extended to approximately 100 cm in depth. The sandy nature of the soil at the experimental site allowed for relatively easy digging to a depth of 91 cm for the insertion of the containers and easy lifting at the appropriate times by the hydraulics of a Ford 5000 tractor. Troughton (1957) and others have criticised this sampling technique in that the soil profile is disturbed prior to growing the plant, however, on refilling the containers an effort was made to reconstruct the undisturbed profile. One plant was grown in each container.

At the appropriate harvests a steel frame was attached to the top of the root container, the shoot having been previously removed. The bucket of a front-end loader, attached to a Ford 5000 tractor, was then connected to the frame and the tractor's hydraulics used to lift the container plus its soil and root sample to the surface (Plate 3). While attached to the frame the container could be carried to the edge of the plot area and placed on a trailer for transport to the laboratory. It was convenient to reattach the front-end loader to the frame and container during the initial low pressure washing of the soil from the roots outside the laboratory. The final washing in the laboratory to remove soil particles closely adhered to the roots involved considerable tedium. It was also difficult to distinguish between living and dead parts of the root system. Brace roots were included in the sample at later growth stages.

2.2.5 Field Observations

The third application of nitrogen to 16 plots was made when approximately 50% of the plants in the centre two sampling rows showed silks emerging from the primary ear prophyll to a distance of 1 cm or greater. Counts of plants showing tassels and silks were made from 5.2.73 to 13.2.73. Application of fertiliser began on 7.2.73 and finished on 13.2.73 and thus extended over two more days than at the previous two application times, when the fertiliser was applied on the basis of one replicate per day. The percentage silking over this period ranged from 45-50% for eight plots and 50-59% for the remainder. The percentage of plants showing emerged tassels (tassels visible in the whorl without manipulation of the leaves) over the same period for the 16 plots ranged from 45-85%.

Plate 3 Showing root sampling operation; steel frame, container and sample.

Harvest six was conducted when the maize plants were physiologically mature. According to Daynard and Duncan (1969), Rench and Shaw (1971) and Daynard (1972) this occurs when a fully developed black layer is visible to the naked eye, after removal of the pedicel from the base of the kernel. Daily observations were made from 19.4.73 to 5.5.73. A portion of the husks were removed from the central region of the primary ears of four plants per plot, allowing examination of the kernels while the ears remained attached to the plant. Four kernels from each ear were removed daily for examination; when 75% of the kernels sampled per plot showed complete black layer development, along with three out of four replications of the plot treatment, then harvesting of plants from the sixth sampling point in these plots took place. Except for one treatment that was harvested on 26.4.73, the remainder were harvested between 1.5.73 and 5.5.73.

Counts were made on the 4.1.73 and 31.3.73 to ascertain the extent of tillering. It was found that less than 1% of the plant stand possessed tillers so further counts were dispensed with. None of the randomly selected harvest plants, over the six harvests, possessed tillers.

On 11.4.73, 22 weeks after sowing, field sampling of the penultimate expanded leaf of two plants per treatment was carried out for chlorophyll content determination. Five discs (15.45 cm^2, total area) were taken per leaf laminae, from the base to the tip. The ten discs per treatment were bulked and held in a moist, dark environment until analysis. Just prior to analysis five discs per treatment were chosen at random and these were boiled in 95% ethanol for 10 minutes at 83C. The method used for the chlorophyll extractions is summarised in Appendix 3.

2.2.6 Measurements on Harvested Plants

Harvesting was sequential and destructive in nature. A maximum of 9 sampling points was allowed for along the 8.2 m length rows. The first 3 points (nearest to the tractor access routes) were concerned with root sampling, the remaining 6 were consistent in position throughout all plots, and the shoots at these points were utilised at harvests 1 to 6. In the treatments where root samples were taken, the corresponding shoots were also sampled providing they appeared normal when compared with surrounding plants. Plants for the first root sampling were taken from guard rows so reducing the

numbers of plants required in the sample rows.

After being cut off at ground level and labelled, the plant shoots were transported to the laboratory for dissection and weighing. Two out of four plants available at each sampling point were selected at random, prior to entering the plots. Thirty to thirty-three plants from one replicate were harvested per day, the variation in number depending on the number of root samples taken. Plants were harvested between 7 a.m. and 8.30 a.m. on all occasions.

Root samples were taken from the plots at the completion of four days of harvesting, dissecting and weighing of shoots. This was necessary because of time limitations. The containers of soil and root material were labelled and transported to the laboratory where the soil was carefully washed away from the roots using an outside hose. Removal of roots from the container sides and the remaining soil, foreign organic matter and dead root material was done in the laboratory by hand with the aid of tweezers and root washing apparatus. Total root samples were then superficially dried by wrapping them in paper after which they were weighed and placed in a forced draught oven at 85C for dry matter determination. Table 2.3 lists the variables measured at each harvest.

(a) Photosynthetic area: this was determined by passing the leaf laminae through an automatic area meter (Model AAM-5). Leaves that were not fully expanded were passed through the machine as such, so that only the exposed photosynthetic area was measured. Leaves were detached at the junction of the leaf laminae and the sheath. The sheath area enclosing the stem was measured by wrapping paper around the stem, simulating this area, then passing the paper through the automatic area meter. This was done for each portion of the green stem, the sum being the total sheath area for the particular plant. The photosynthetic area of the husks was ignored. From harvests 4-6 when portions of the leaves and sheaths became senescent, these portions were excluded from the area measurements. Leaf and sheath areas were not measured at all if 50% or greater of the area was senescent.

(b) Huskless ear lengths: during harvests 4-6 the lengths of the huskless ear was measured from the base of the cob to the apex. The effective huskless length represented the portion of the total actually supporting grain.

(c) Weights: on arrival at the laboratory plant shoots were

dissected into the following components: (i) leaves - all expanded leaf laminae; in earlier harvests this included unexpanded leaves and leaf sheaths above the stem apex, or above the point of attachment of the tassel peduncle prior to tassel emergence.

(ii) stem - including leaf sheaths below the point of attachment of the tassel peduncle.

(iii) dead leaves - greater than 50% non-green area.

(iv) husks - including silks, tassel, tassel peduncle, cob shank and aborted secondary cobs (if present).

(v) ear - removed from the point of attachment to the ear shank.

Fresh weights of the above portions were determined immediately, and after measuring of leaf and sheath areas these portions were dried in a forced draught oven for 48-96 hours at 85C, when they were removed and dry weights recorded. Ears were shelled by hand after drying and total kernel dry weights for individual ears determined at this stage as well as the dry weights of 100 kernels selected at random from each ear. Dry weights of individual plant parts were determined, but the dried material from comparable parts of the two plants sampled per plot at each harvest were bulked, prior to grinding and subsequent nitrogen content determinations.

Table 2.3 Plant Variables Measured at Each Harvest

Variable Measured	Harvest Number
Laminae area	1–6
Sheath area	2–6
FW, DW and % DM of leaves	1–6
FW, DW and % DM of stems	1–6
FW, DW and % DM of husk	3–6
FW, DW and % DM of dead leaves	5–6
FW of ear (cob + grain), DW and % DM of ear	4–6
FW, DW and % DM of roots	1 and 2, 4 and 6
DW of cob	3–6
DW of grain[+]	4–6
DW of 100 kernels	4–6
Length of huskless ear	4–6
Effective length of huskless ear	4–6
Number of rows of grain per huskless ear	4–6
Measurement of nitrogen content[++] (on a dry weight basis)	
% N of leaves[+++] stem and roots	1 and 2, 4 and 6
% N of husk, cob and grain	4–6

FW = fresh weight; DW = dry weight

% DM = dry matter content on a fresh weight basis

[+]grain from primary ear; secondary ears of no consequence in grain production. Dry weight of grain was adjusted to 15.5% moisture content.

[++]see Appendix 4 for description of method.

[+++]only functional leaves included; N content of dead leaves ignored.

2.2.7 Percentage Nitrogen Determination

Micro-Kjeldahl digestion units were used in the determination of nitrogen content of plant parts.

In the case of leaf laminae, husks, grain and root samples, the total bulked dried material from the two sampled plants per treatment was used during grinding. A representative portion of stem and cob materials were utilised.

A Wiley mill was used to grind the plant material to pass a sieve of 1 mm diameter openings (see "Official Methods of Analysis", A.O.A.C., 10th ed., 1965, p.202). After the grinding of each sample the machine was completely dismantled and thoroughly cleaned. A representative subsample of the finely-ground well-mixed plant

material was then placed in labelled, screw-top glass containers, until chemical analysis. See Appendix 4 for a description of the method used.

2.3 STATISTICAL METHODS

Bulked data for two plants per subplot were used in the statistical analysis. The analysis was carried out with the aid of the Massey University B6700 computer. All programs written for this analysis are available on request.

2.3.1 Preliminary Analysis of Data

Prior to conducting the analysis of variance a computer program was written and used to determine the frequency distribution of the raw data for each variable to be considered in the analysis. This showed that the distribution of the data approximated that of the normal distribution. However, for completeness the distributions of log and square root transformed data were also obtained. These transformations did not generally result in a closer approximation to the normal distribution so the raw data were used in the analysis of variance.

An arcsine transformation of percentage dry matter data was not considered necessary as Edmeades (1972) found that the variance ratios for the two sets of analyses (i.e. of raw and arcsine transformed data) showed only slight differences. This indicated that significance tests (F-tests) were not biased by the scale of the data.

2.3.2 The Analysis of Variance

Data was analysed within harvests using a standard analysis of variance for a fixed effects model (Steel and Torrie, 1960 pp.245-247). A computer program was written for the split-plot analysis of variance. The formulae of Steel and Torrie (1960) were used to calculate standard errors for treatment comparisons between various means. Least significant differences at 5% and 1% levels of significance were calculated for comparisons of paired means when F was significant in the analysis of variance for the main factor, subfactor and interaction effects (Steel and Torrie, 1960). A summarised form of various analyses of variance for selected variables are presented in the Appendices.

2.3.3 Curve Fitting

First degree ($y = a + bx$), second degree ($y = a + b_1x + b_2x^2$)

and third degree ($y = a + b_1x + b_2x^2 + b_3x^3$) polynomial equations were fitted to the total dry weight and grain dry weight data collected at physiological maturity, for each of the five main factor treatments. The main factor was nitrogen (N) level per unit area, the levels being N = 0, 84, 168, 336 and 672 kg/ha. There were four replications of the main effects. A standard multiple regression program on a B6700 computer ("BASIS") was used to estimate "best fit" values, the coefficients of determination (R^2) and the standard error of the estimate for the fitted curves. The cubic polynomial was found to be the "best fit" to both sets of data based on the lowest sum of deviations from the estimated curves, consistent with the highest R^2 and the lowest standard error of the estimate. The predicted response curves to increasing increments of fertiliser N for total dry weight and grain yield are presented in Fig. 3 (Chapter 3).

Logistic, log-logistic and Gompertz curves were also fitted separately to total dry weight data for each of the main factor treatments. A second factor (time of application of N) at three levels (Table 2.1) was superimposed on the main effects, in a split-plot design. Dry weight data were obtained at six stages during growth, there being twelve (4 x 3) observations at each time. These data were regressed against time to estimate the growth curves for each main effect.

The asymptotic regressions were transformed into linear equations as follows:

(i) logistic

$\text{logit } y = a + bt$, where $\text{logit } y = \ln\left(\frac{y}{y_o - y}\right)$

(ii) log-logistic

$\text{logit } y = a + b.\log t$

(iii) Gompertz

$\log y = \log y_o + (\log A)\, B^x$

(Bliss, 1970).

Estimates of the upper asymptote (y_o) were made using maximum likelihood iterative procedures (see below), until the "best fit" curve was obtained (Bliss, 1970).

After the first iteration the R^2 values for the log-logistic were well below those for the Gompertz and logistic curves, so further iterations using this curve were dispensed with. After a further 2-4 iterations over all treatments, the corrections to the transformed

independent variate were negligible (b_2 not significant) for the Gompertz curves, but for the logistic curves the adjustments to the estimated value of the upper asymptote were still significant, even though the R^2 values over all treatments were only slightly less than those for the Gompertz. Thus the Gompertz curve was considered to be more appropriate and the best fit to the data. The iterative procedure used in relation to the Gompertz curve will now be briefly summarised.

The linear form of the Gompertz curve has been noted to be:

$$\log y = \log y_o + \log A\ (B^x)$$

This form is identical to an equation of the form $Y = a_1 + b(r^x)$ where log A represents the regression coefficient to be estimated by the "least squares" method. A plot of the dependent variate $Y = \log y$, (y = total plant dry weight), against the independent variate (x = time in days) transformed to r^x, shows a linear relationship. The slopes of these lines for the various treatments is estimated by the regression coefficients (Section 3.3.1). An initial estimate of r^x was made from an eye-fit of a smooth curve to the data. Starting with this first estimate (r_o) each x was transformed to $Z_1 = r_o^x$ and a linear regression was computed, relating the log response to Z_1. Its intercept a_1 is an estimate of the upper asymptote. An auxillary maximum likelihood x-variable (xr_o^{x-1}) was included in the equation in order to adjust r_o^x in subsequent iterations. Thus the multiple regression fit becomes:

$$\log y = a_1 + b_1 r_o^x + b_2\ (xr_o^{x-1})$$

A standard multiple regression program on a B6700 computer ("BASIS") was used to estimate a_1, b_1 and b_2. Adjustments to r were made using the relation:

$$r = r_o + \frac{b_2}{b_1}$$

for successive iterations, until b_2 became non significant according to the t-test for the null hypothesis, Ho : $b_2 = 0$. A final least squares solution was estimated without the auxillary variate and the best fit values for the Gompertz curve were obtained along with the estimated values for the upper asymptote (y_o), A and B. Similar procedures were used for the other two models using the variate $\frac{1}{Q} = (1/(1 - \frac{Y}{y_o}))$ for the auxillary in iterating y_o in the logistic (Bliss 1970). In order to compare differences among the regression coefficients for the various treatments the homogeneity of their variances was tested by Bartlett's Chi-square (X^2) (Steel and Torrie,

1960). A non significant test indicated that these variances were homogeneous and consequently a pooled estimate of the regression coefficients was obtained. This was used to construct least significant differences (L.S.D.) to test the significances of differences among the regression coefficients for each treatment.

CHAPTER THREE

RESULTS

In an endeavour to aid presentation and interpretation the initial section of this chapter presents a general description of the growth and development of the crop from sowing to final harvest. This is followed by data on grain yields and plant dry matter production of the final harvest - the ultimate assessment of the treatments imposed. Having presented the overall picture subsequent results then refer to the chronological growth, development and nitrogen uptake of the crop which lead up to these ultimate yields.

Throughout this chapter reference is made to Appendices containing supporting information and selected analyses. These can be found at the back of the thesis.

3.1 GENERAL DESCRIPTION OF THE GROWTH AND DEVELOPMENT OF THE MAIZE CROP

Following successful sowing and plant establishment the time taken in days and effective degree days (Appendix 1b) for the maize plants to reach 50% tasselling, 50% silking and physiological maturity are presented in Table 3.1 as means over all plots.

Table 3.1 Days to 50% tasselling, silking and physiological maturity.

Stage of Development	Days	Effective Degree Days
50% tasselling	86	579
50% silking	93	620
Physiological maturity	180	1175

Table 3.2 shows that for three separate periods of 5, 4 and 4 days duration in December 1972, the daily maximum air temperatures were all below the 42 year average (Table 3.3). On 9 out of these 13 days the daily minimum air temperatures were also below the average.

Table 3.2 Daily air temperatures* for December 1972.

DAY	5	6	7	8	9	13	14	15	16	19	20	21	22
Daily max.(C)	18.6	17.0	19.0	18.5	19.0	18.0	18.1	19.3	18.5	17.8	18.8	19.8	18.1
Daily min.(C)	10.5	11.9	9.6	6.8	12.2	12.7	4.9	5.5	14.2	9.6	10.6	8.6	5.0

*Recorded at Grasslands Division, D.S.I.R., Palmerston North, 0.8 km from the experimental site.

November 1972 experienced daily temperatures above the average which were also (in this year) higher than the mean December temperatures. For the remainder of the growing season, however, temperatures followed the usual trend (Table 3.3).

Table 3.3 Mean daily air temperatures.

Period	Month					
1972/73*	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Mean daily max.(C)	20.5	19.5	22.9	23.6	21.4	17.9
Mean daily min.(C)	11.7	10.7	13.0	13.2	12.7	10.8
1928-1970*						
Mean daily max.(C)	18.5	20.6	21.8	22.2	20.9	18.1
Mean daily min.(C)	9.7	11.5	12.6	12.6	11.5	9.4

*Recorded at Grasslands Division, D.S.I.R., Palmerston North, 0.8 km from the experimental site.

Over the period from 6.12.72 to 20.12.72 the plant leaves were visibly wind-damaged throughout the plots. The tips of newly expanded leaves were often split and small dead areas appeared on some leaves. The conditions described above may have delayed the occurrence of tasselling and silking. Rainfall during December was well below average (Table 2.2).

The most rapid vegetative growth occurred over a period from 55 days (1.1.73) until 85 days (30.1.73) after planting. After tasselling most plants possessed 14-15 expanded leaves and all reached 2.5 to 2.7 m in height approximately two weeks after 50% silking (Fig. 2). Maximum leaf area index (LAI) occurred near the beginning of rapid grain filling approximately four weeks after pollination or about 130 days after planting. Leaf area declined rapidly thereafter.

The senescence of the lower leaves as the plants matured was particularly noticeable in plants under N stress, namely those receiving only 84 kg N/ha or no N fertiliser (Plates 4, 6 and 9). Visible N deficiency symptoms became evident in these plots about mid-January 1973 during vegetative growth and with time became progressively marked.

By 130 days after planting the grain had reached the "milk" or "blister" stage of development. At 146 days the "dent" stage had been reached. Grain development and filling (pollination to physiological maturity) occupied approximately 74 days.

Only a single ear was produced per plant, commonly at the 7th or 8th node, on this cultivar (PX610). Any secondary ears appearing

FIG. 2 General Plant Growth and Development at each Harvest

Scale : 3cm = 1m

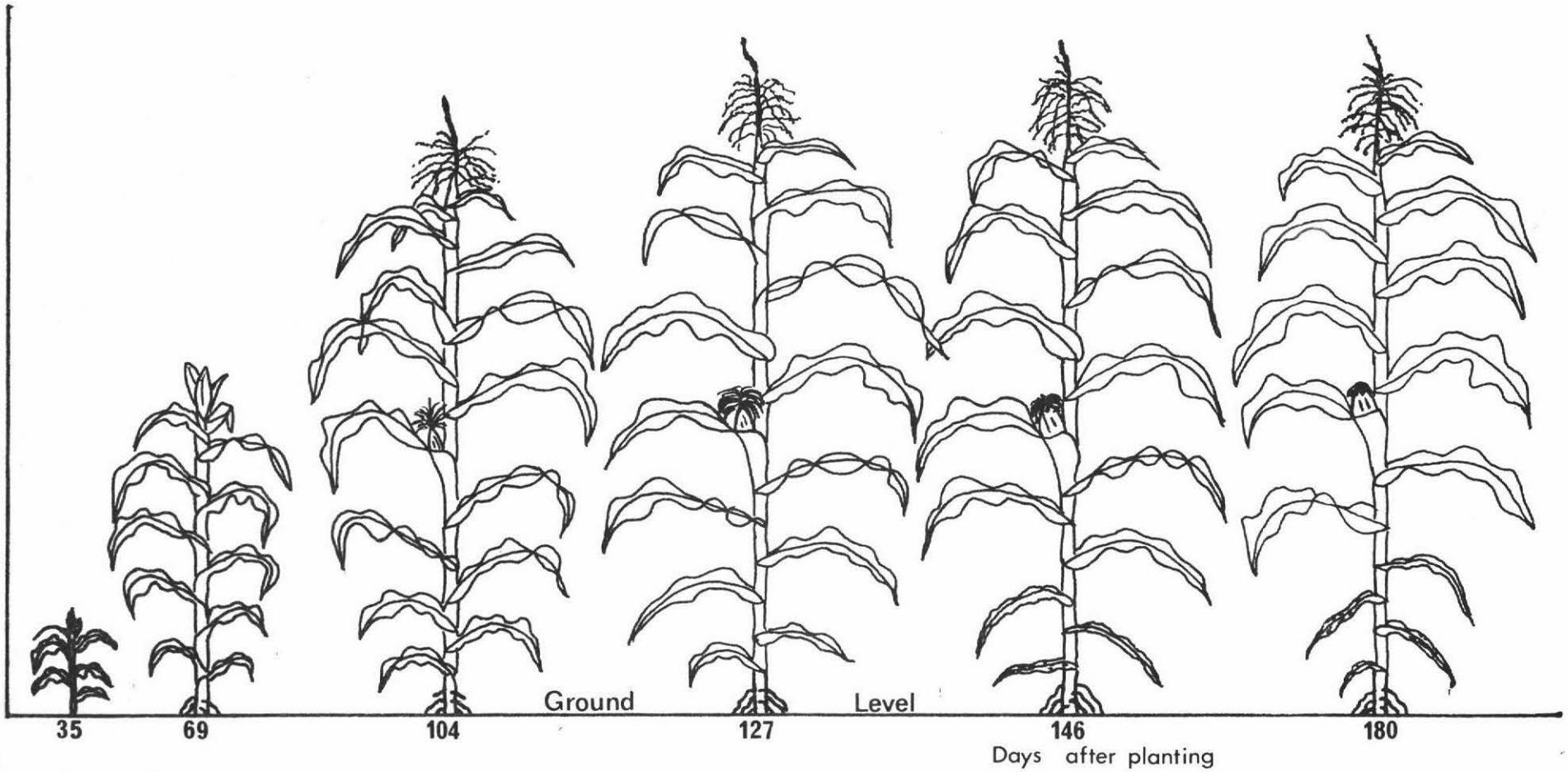


Plate 4 Showing N deficiency symptoms in the lower portions of plants from a plot receiving no N fertiliser.

Plate 5 Showing normal colouration in the lower portions of plants from a plot receiving 672 kg N/ha.

Plate 6 Showing lower leaf and stem portions of individual plants receiving 672 kg N/ha (LHS) and no N fertiliser (RHS).

Plate 7 Showing individual plants receiving 672 kg N/ha (LHS) and no N fertiliser (RHS).

Plate 8 Showing individual plants receiving 168 kg N/ha (LHS) and no N fertiliser (RHS).

Plate 9 Showing individual plants receiving 84 kg N/ha (LHS) and no N fertiliser (RHS).

aborted early and made no contribution to grain yield.

Root growth and development was rapid in the maize plants. For example, 69 days after planting (harvest 2) roots had penetrated to a depth of 91 cm or greater. Root dry weight continued to increase until about 130 days after planting.

Lodging did not occur in any of the plots, nor was tillering of any consequence; all plants survived from the completion of transplanting to maturity.

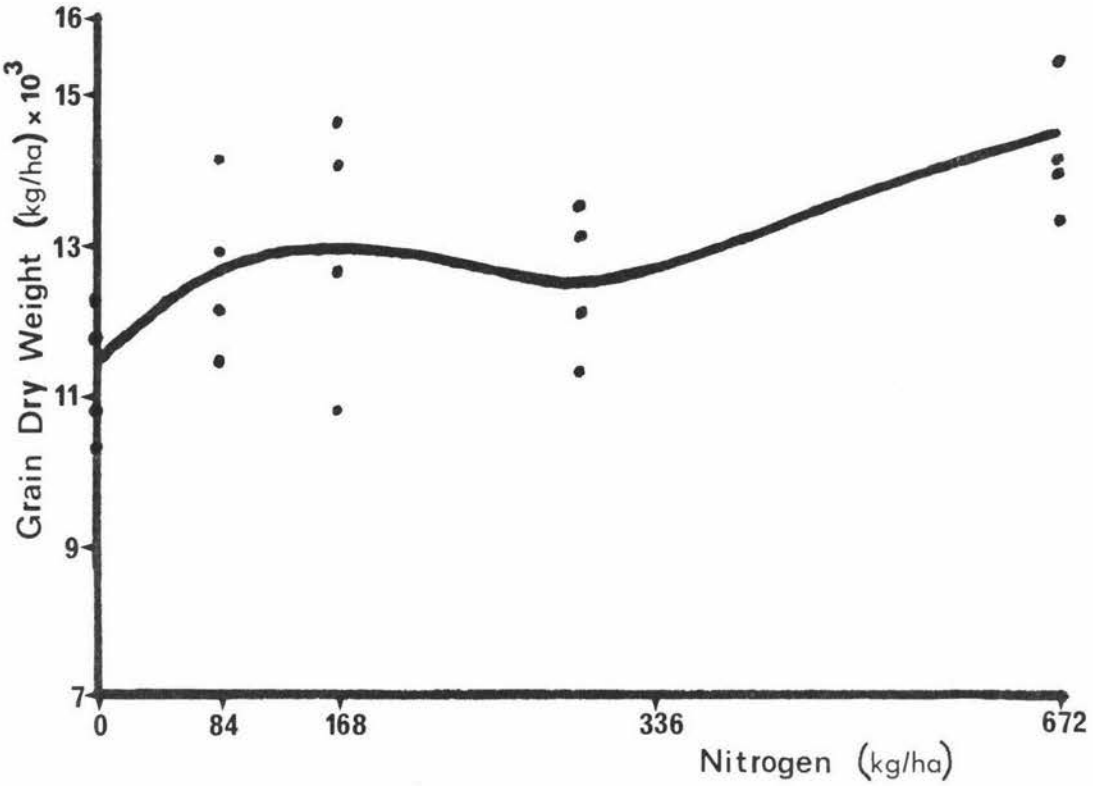
3.2 GRAIN YIELD AND PLANT DRY MATTER PRODUCTION (FINAL HARVEST)

Grain yields and plant dry matter production (excluding roots) per unit area recorded at physiological maturity were high and attained as much as 14,486 kg/ha (231 bushels/ac) and 31,000 kg/ha respectively (Fig. 3).

In spite of an apparent response to fertiliser nitrogen, the differences obtained failed to reach statistical significance. As shown in Table 3.4 this was largely due to the rather different response trend recorded by the treatments receiving a split dressing of nitrogen at planting and six weeks later, particularly at 336 kg N/ha.

Applying fertiliser nitrogen as split dressings at different stages of growth had no significant effect on grain yields or plant dry matter production. Similarly there was no significant interaction recorded between rate and time of nitrogen application. Appendix 5 contains the appropriate analyses of variance (ANOVA).

FIG. 3 Total Plant Production (excluding Roots) and Grain Yield



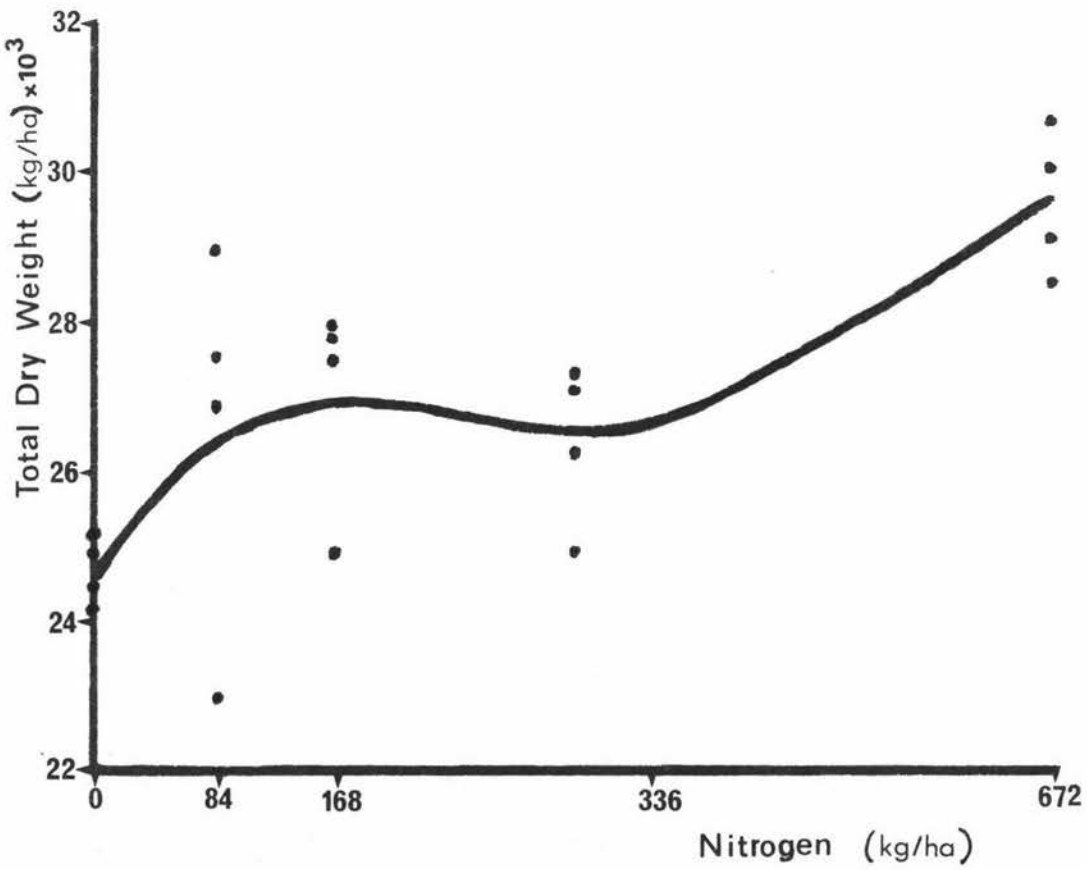


Table 3.4 Summary of total dry matter yields for grain and the whole shoot.

Grain dry matter (kg/ha)						
Time* of application	N rate (kg/ha)					Subplot means
	0**	84	168	336	672	
1	10605	12434	12108	13207	14486	12568
2	10591	13652	13322	11868	13192	12525
3	12093	11948	12969	13001	13488	12700
Main plot means	11096	12678	12800	12692	13722	

Total dry matter (kg/ha)						
Time* of application	N rate (kg/ha)					Subplot means
	0**	84	168	336	672	
1	23227	25513	25450	27380	31062	26526
2	23028	27955	27316	24103	27124	25905
3	26079	26440	26875	25709	28096	26639
Main plot means	24111	26636	26547	25731	28761	

*1 = all applied at planting; 2 = $\frac{1}{2}$ applied at planting, $\frac{1}{2}$ at 6 weeks after planting; 3 = $\frac{1}{3}$ applied at planting, $\frac{1}{3}$ at 6 weeks and $\frac{1}{3}$ at 50% silking, approximately 13 weeks after planting.

**Control plots subdivided and sampled the same way as those receiving N fertiliser.

3.3 GROWTH IN TOTAL DRY WEIGHT AND COMPONENT PARTS

The first part of this section presents data relating to the accumulation of the total shoot dry weight as recorded at six harvest times over the growth cycle, for the various nitrogen treatments.

Latter parts of this section are concerned with dry weight changes in plant components over the growth of the maize crop.

3.3.1 Total Shoot Dry Weight

The non-significant response in terms of total shoot dry matter was consistent over all harvests and for harvests 4 to 6 when grain dry weight data was obtained. Therefore, a more direct analysis was made of the growth curves by fitting asymptotics (Chapter 2) and testing the treatments for significant differences. A comparison of the growth curves obtained for the various N treatments is presented in Fig. 4. Appendix 6 shows these curves with their actual data, R^2 values and equations. The linear regression lines obtained for the various treatments when log y is plotted against r^x are presented in Appendix 7. The associated ranked regression coefficients are presented in Table 3.5 with their corresponding nitrogen treatments.

Table 3.5 Regression coefficients for total shoot dry weight over time.

Regression coefficients	N rate (kg/ha)				
	0	84	672	336	168
b	-6.6536	-6.7127	-6.9280	-7.2603	-7.4598
Standard error of b values	0.1314	0.1230	0.1129	0.0978	0.1118

σ_b^2 pool = 0.067204

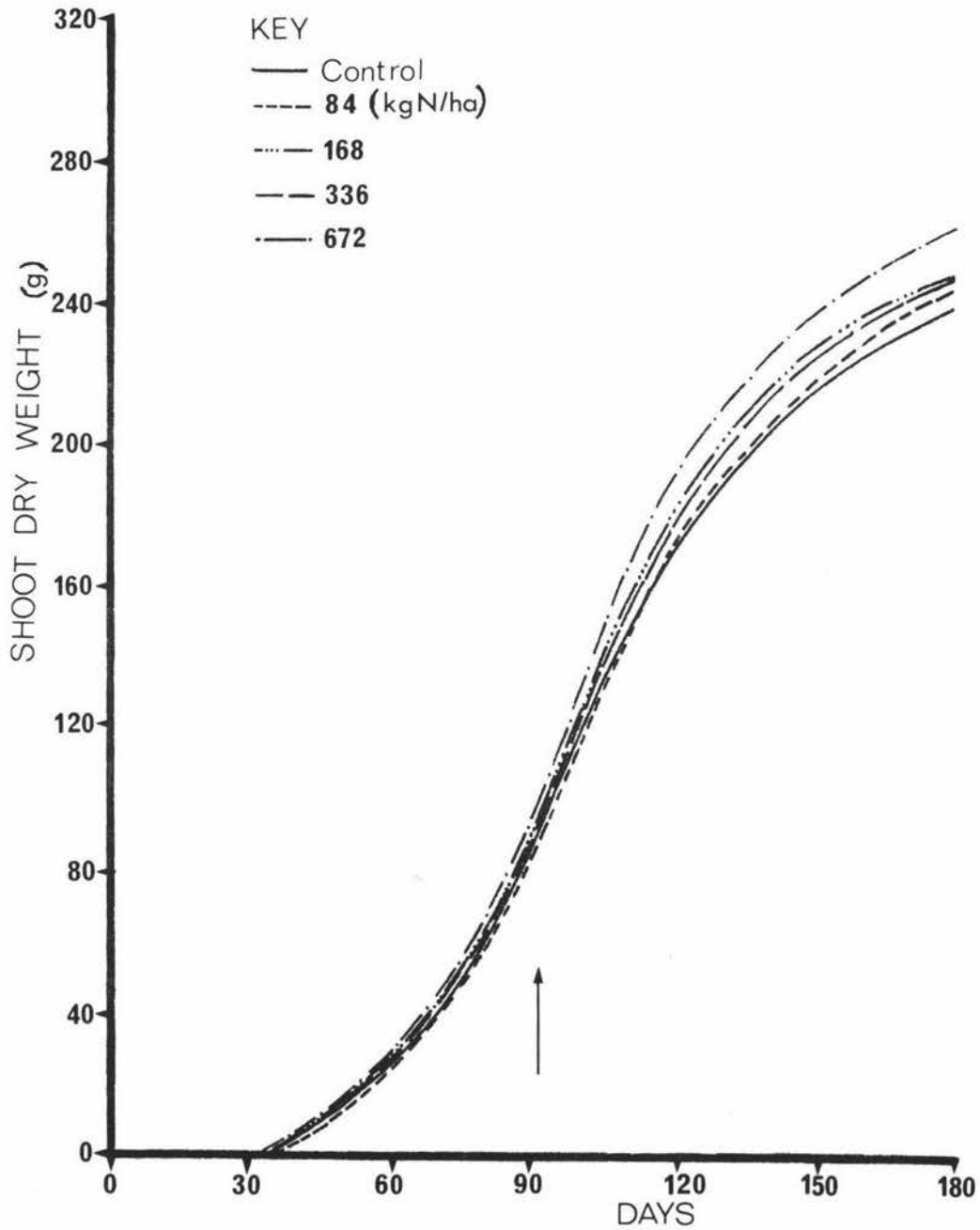
$L.S.D_b(.05) = 0.3270$; $L.S.D_b(.01) = 0.4343$.

At the 5% level of significance the L.S.D. showed that the regression coefficients could be divided into two groups. That is, the rate of approach to the upper asymptote (potential limit of dry matter production) for maize plants receiving 168 kg N/ha and 336 kg N/ha were significantly greater than those from the remaining treatments (Fig. 4). At the 1% level of significance the grouping was not so distinct as it showed progressive overlapping. However, the rate of approach to the upper asymptote for plants receiving 168 kg N/ha was consistently greater than that of all treatments, apart from those receiving 336 kg N/ha.

FIG.4 Comparison of Growth in Total Shoot Dry Weight Per Plant

Fitted Curves with Observations and Equations Presented in Appendix **6**

↓ indicates time of **50%** silking



3.3.2 Dry Weight Changes in Vegetative Components

(a) Leaves: Leaf dry weight (Table 3.6) was the only component of total yield that showed a significant response to increasing N application. This occurred over the period from mid vegetative growth to physiological maturity (Harvests 3 to 6). A comparison of the various times of application of N fertiliser, however, showed no significant differences, but there was a significant interaction between rate and time of application of N at harvest 4. (ANOVA for leaf dry weight at harvests 3, 4 5 and 6 are presented in Appendix 8).

Table 3.6 Summary of leaf dry weight per plant (g).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
2 (69)	24.8	19.8	23.9	23.4	25.0	2.78	n.s.
3 (104)	31.1	32.8	36.2	36.3	39.3	1.44	**
4 (127)	32.9	30.4	37.3	34.6	35.8	1.30	**
5 (146)	29.2	27.6	33.7	33.8	34.4	1.49	**
6 (180)	17.8	18.2	21.6	18.8	24.2	2.08	*

+Standard error (S.E.) for comparison of means between N rates.

++n.s. not significant; * .05 > P > .01, ** P < .01 (from ANOVA).
() days from planting.

At harvests 3, 4 and 5 the leaf dry weight for the three highest rates of N is significantly greater than that for plants receiving 84 kg N/ha and no N. At harvest 6 (physiological maturity) plants receiving 672 kg N/ha produced a significantly greater leaf dry weight than all other plants except those receiving 168 kg N/ha. Table 3.7 indicates that the significant interaction at harvest 4 was contributed to by those plants receiving 84 kg N/ha over three different growth stages having a significantly greater effect on leaf dry weight than those receiving the nitrogen fertiliser over two growth stages.

Table 3.7 Interaction effects between N rate and time of application for leaf dry weight (g).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	28.6	34.8	37.1	39.2	3.57
2	26.7	38.4	34.9	34.1	
3	36.1	38.7	31.7	34.0	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

There was little change in leaf dry weight over all treatments, having reached a maximum at harvest 3 (11 days after 50% silking) or harvest 4 (33 days after 50% silking) until the last 5 weeks of grain filling when a substantial decline (average of 36%) was recorded (Fig. 5). The decline was due to the senescence of the lower leaves caused in part by shading and in part by mobilisation of nutrients (particularly N) from the leaves to the rapidly growing portions of the plant. As might be expected leaf death tended to be greater in the control plots and those receiving 84 kg N/ha where plants showed visual N deficiency symptoms over the late vegetative and reproductive period. It is considered, however, that the arbitrary method used to assess dead leaf (viz. any leaf with greater than 50% non-green area) failed to reflect the "yellowing" seen in the control and lowest nitrogen plots (Plates 4-9).

The relative growth rate of the leaves, presented in Fig. 6, reached a maximum between 35 and 69 days after planting in all treatments. It slowed to about half this growth rate over the next 35 days and continued to decline through to the final harvest.

As expected, leaf area measurements at harvests 2-6 for the various treatments reflected leaf dry weight (Table 3.6), that is, a larger leaf area was associated with a larger dry weight. Leaf area and leaf area index (LAI) data are presented in Fig. 7 and tables of these data are included in Appendix 9(a). At harvest 3 plants receiving 336 and 672 kg N/ha had a significantly greater leaf area than plants receiving no fertiliser. At harvest 4, however, those receiving 168 kg N/ha had a significantly greater leaf area than plants from all other treatments. Nineteen days later, at harvest 5, those plants

FIG. 5 Total Shoot Dry Weight and Percentage Distribution in Plant Parts

G, C, H, S, L, DL are grain, cob, "husk", stem, leaf, dead leaf, dry weight fractions respectively.

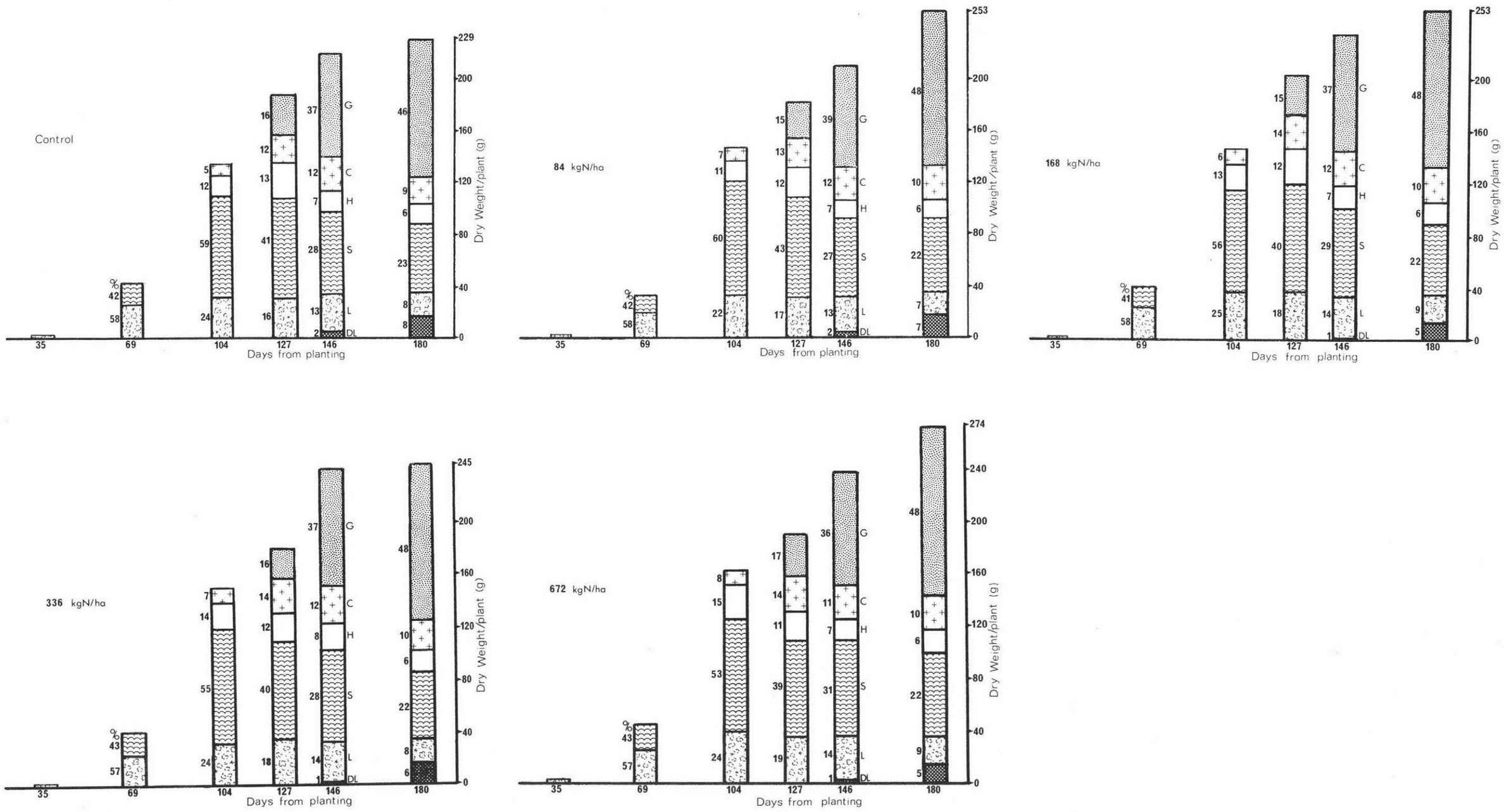
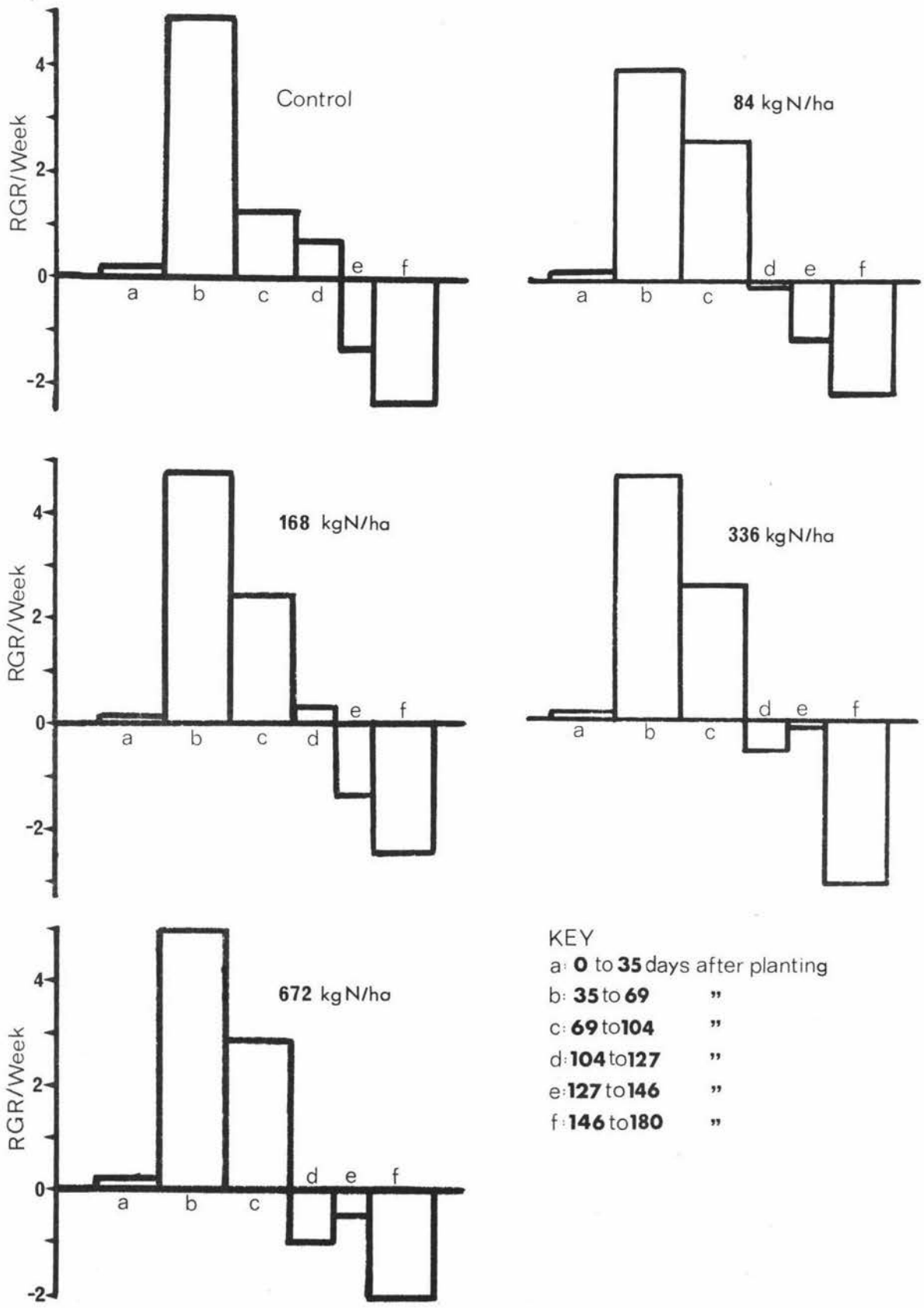


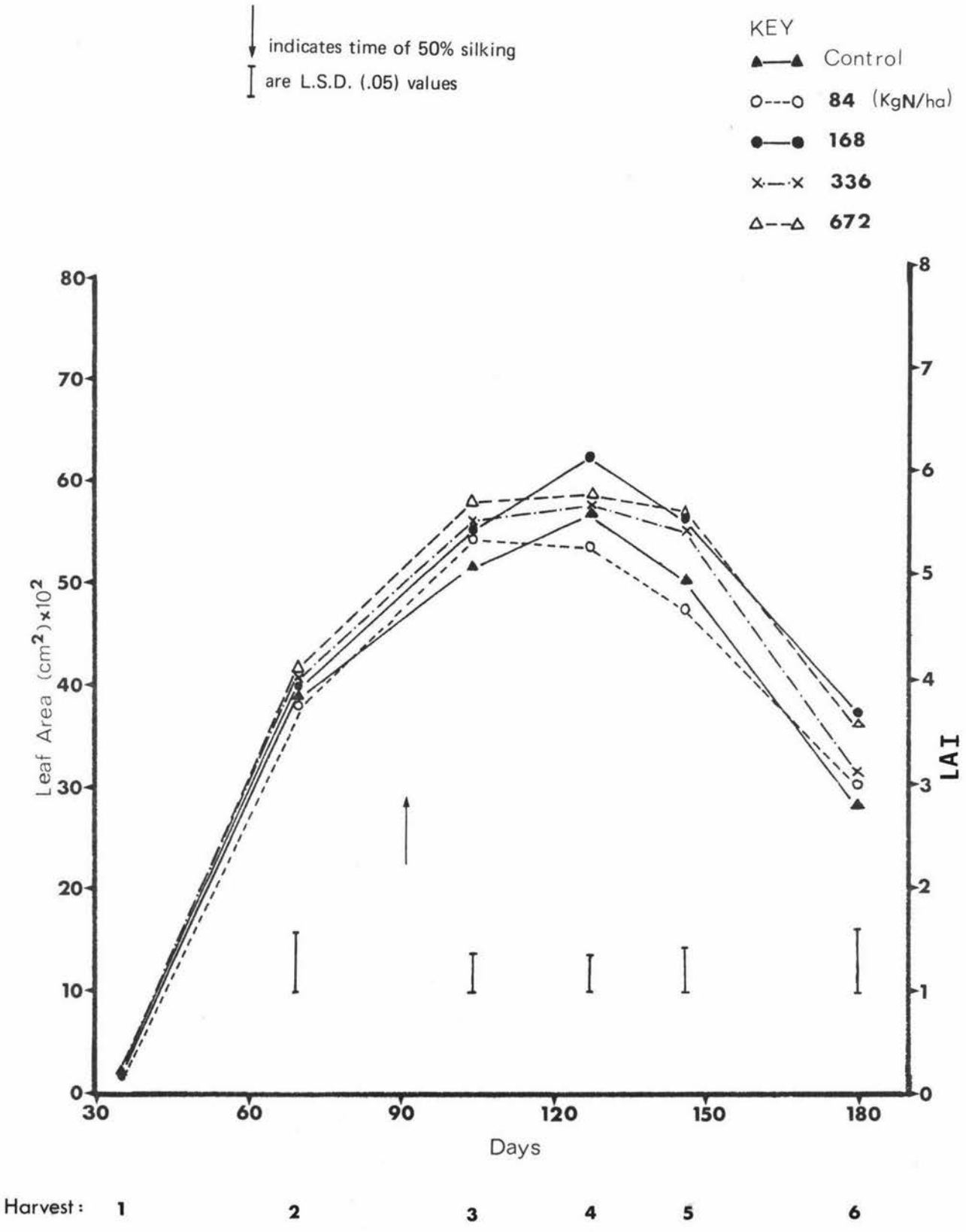
FIG. 6 Relative Growth Rate of Leaves



KEY

a: **0** to **35** days after planting
b: **35** to **69** "
c: **69** to **104** "
d: **104** to **127** "
e: **127** to **146** "
f: **146** to **180** "

FIG. 7 Leaf Area Per Plant and L A I



receiving 168 kg N/ha or more were significantly greater in leaf area than plants from the treatments receiving less nitrogen. At harvest 6, however, only those receiving 168 and 672 kg N/ha had a significantly greater leaf area than plants from the control plots. Leaf area was not significantly affected by time of application of fertiliser at any stage of the analysis nor were any significant interactions between rate and time of application recorded.

Fig. 7 also shows the development and maintenance of LAI. LAI increases rapidly between harvest 1 and 2. By 76 days after planting (about 2 weeks before 50% silking) all plants had a LAI greater than 4 which was maintained for the shortest period (82 days) by plants in the control plots. Plants receiving increasing rates of N maintained a LAI greater than 4 for 86, 105, 97 and 104 days respectively, according to N levels. Thus a high LAI was maintained for a period well into grain filling in all treatments. By physiological maturity the LAI of plants receiving 0, 84, 168, 336 and 672 kg N/ha had declined by 44%, 37%, 33%, 42% and 35% of their respective maxima.

Sheath area was first measured at harvest 2. Data for this and the following harvests are presented in Table 3.8. The analyses of variance for sheath area at harvests 2, 3, 4 and 5 showed no significant response to increasing levels of N fertiliser. At the final harvest plants receiving 168 and 672 kg N/ha had a significantly greater sheath area than plants from other treatments.

Table 3.8 Summary of sheath area per plant (cm^2).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
2	479	422	470	490	488	49	n.s.
3	1416	1460	1470	1453	1530	60	n.s.
4	1578	1495	1598	1511	1501	64	n.s.
5	1504	1432	1527	1567	1509	45	n.s.
6	485	541	664	550	692	55	*

+S.E. for comparison of means between N rates.

++ * .05 > P > .01

n.s. not significant (from ANOVA)

A comparison of the various times of application showed a significantly greater sheath area for plants receiving N at 3 different growth stages than those receiving the N at 2 different stages. This was evident only at physiological maturity when a significant interaction of N rate and time of application was also recorded. Table 3.9 presents the interaction effects recorded at physiological maturity (Harvest 6).

Table 3.9 Interaction effects between N rate and time of application for sheath area (cm^2).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	561	737	615	602	86.7
2	436	590	580	624	
3	626	666	454	850	

[+]See Table 3.4

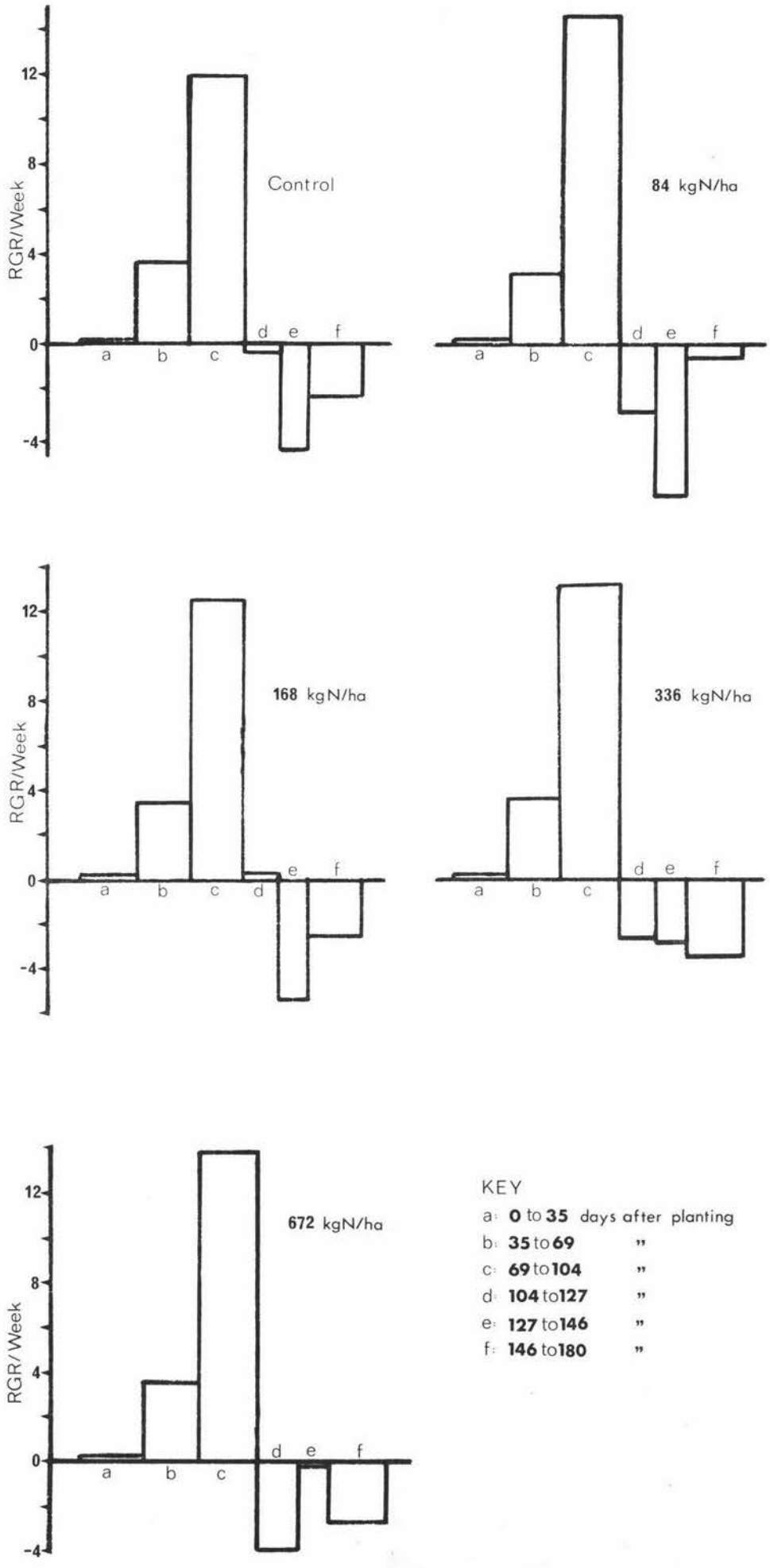
[++]S.E. for comparisons between interaction means.

For both the lowest and highest rates of N (Table 3.9) plants receiving N over 3 different growth stages had a significantly greater sheath area than those receiving N over 2 growth stages. The sheath area of plants receiving 672 kg N/ha over 3 growth stages was also significantly greater than those receiving the whole rate at planting. Appendix 9(b) presents the ANOVA for harvest 6 data.

Sheath area, as expected, increased most rapidly from 69 to 104 days after planting, when stem growth was maximal (Fig. 8). Functional sheath area was generally greatest at harvest 4 (Table 3.8). All plants showed a massive decline in functional sheath area over the last 35 days of grain filling, the declines being greatest for plants under N stress. Sheath portions were arbitrarily excluded from measurement if they had less than 50% green area.

(b) Stems: from day 35 to day 69, the period of most rapid leaf growth, the stems (Fig. 8) were growing at about 25% of their maximum growth rate per week. The most rapid increase in stem dry weight and stem length took place in the period from day 69 to day 104 after planting. By comparison the relative growth rate of the leaf was about 50% of its maximum over this period (Fig. 6).

FIG. **8** Relative Growth Rate of Stem



KEY

a: **0** to **35** days after planting
b: **35** to **69** "
c: **69** to **104** "
d: **104** to **127** "
e: **127** to **146** "
f: **146** to **180** "

As shown in Table 3.10 the application of N fertiliser had no significant effect on the dry weight of the stem. No significant effect of time of application was recorded nor were there any significant interactions of rate and time of application shown by the ANOVA at any growth stage.

Table 3.10 Summary of stem dry weight per plant (g).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
2	17.9	14.6	16.9	17.4	19.2	2.97	n.s.
3	77.8	87.4	81.2	83.5	86.7	5.66	n.s.
4	76.4	77.6	81.9	75.3	74.0	3.84	n.s.
5	62.5	59.3	67.3	67.7	73.4	4.97	n.s.
6	51.7	56.5	55.2	51.3	60.9	3.88	n.s.

+S.E. for comparison of means between N rates.

++n.s. not significant (from ANOVA).

It is of interest to note that stem dry weight of plants receiving nil and 168 kg N/ha appeared to maintain a maximum dry weight for a longer period than those in the other treatments.

(c) Roots: Root dry weight data were obtained at harvests 1, 2, 4 and 6 for three of the main treatments (0, 168 and 672 kg N/ha). As shown in Table 3.11 no significant differences in root dry weights between treatments were obtained. Root dry weight reached a maximum or near maximum at harvest 4 just prior to rapid grain filling. Over the grain filling period root dry weights appeared to decline under the nitrogen treatments.

Table 3.11 Root dry weight per plant (g).

Harvest number	N rate (kg/ha)	Mean dry weight per plant+ (g)	S.E.++	Significance level+++
1	0	0.90	0.434	n.s.
	168	0.76	0.371	n.s.
	672	0.71	0.461	n.s.
2	0	13.6	3.53	n.s.
	168	8.3	2.19	n.s.
	672	12.2	4.76	n.s.
4	0	25.3	8.27	n.s.
	168	29.3	11.26	n.s.
	672	29.1	8.75	n.s.
6	0	25.9	10.11	n.s.
	168	20.9	7.56	n.s.
	672	20.5	5.05	n.s.

+mean of 4 replications per treatment.

++S.E. associated with each treatment mean.

+++n.s. not significant (from ANOVA).

Shoot to root ratios presented in Table 3.12 show that the ratio increases steadily throughout the growth and development of the maize plant and was frequently at a higher level in the presence, than in the absence of fertiliser N. The notable exception was at harvest 4, reflecting the considerable increase in root dry weights of the N treatments recorded at this time.

Table 3.12 Shoot to root ratios.

Harvest number	N rate (kg/ha)	Shoot dry weight per plant (g)	Root dry weight per plant (g)	Shoot/Root
1	0	1.1	0.9	1.2
	168	1.3	0.76	1.7
	672	1.6	0.71	2.3
2	0	47.9	13.6	3.5
	168	41.4	8.3	5.0
	672	43.5	12.2	3.6
4	0	198.8	25.3	7.9
	168	209.4	29.3	7.2
	672	183.3	29.1	6.3
6	0	219.1	25.9	8.5
	168	259.9	20.9	12.4
	672	258.1	20.5	12.6

3.3.3 Dry Weight Changes in Reproductive Components

(a) "Husk": "husk" dry weights were first recorded at harvest 3 (104 days after planting), and are presented in Table 3.13.

Table 3.13 Summary of "husk" dry weight per plant (g).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
3	15.8	16.6	19.4	21.1	24.2	2.06	**
4	23.4	21.7	25.2	21.8	22.2	1.99	n.s.
5	16.4	15.5	16.9	19.1	16.7	1.37	n.s.
6	14.8	15.2	15.4	15.0	17.4	0.87	n.s.

+S.E. for comparison of means between N rates

++n.s. not significant; ** $P < .01$ (from ANOVA).

At harvest 3 "husk" dry weights for plants receiving 672 kg N/ha were significantly greater than those receiving 168 kg N/ha or less. This difference, however, had disappeared by the next harvest. The timing of N fertiliser application had no significant effect on the "husk" component nor were any significant interactions between N level and time of application recorded at any harvest. "Husk" dry weight reached a maximum at harvest 4 (beginning of rapid grain filling) except for plants receiving 672 kg N/ha when the greatest dry weight was recorded 3 weeks earlier. During the early grain filling period "husk" dry weight declined rapidly to a similar level over all treatments and showed only small changes thereafter. Part of the decline in dry weight of this portion would have been due to losses of parts of tassels and silks between harvests.

(b) Cob: cob dry weights are presented in Table 3.14. No significant differences in dry weight with increasing N application or due to time of application were shown by the ANOVA at any harvest. No significant interactions between N level and time of application were recorded at any growth stage.

Table 3.14 Summary of cob dry weight per plant (g).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
3	7.5	9.5	9.4	10.9	12.9	1.74	n.s.
4	25.4	24.1	28.2	26.0	26.1	1.82	n.s.
5	26.5	25.4	27.8	29.2	26.5	1.80	n.s.
6	21.7	25.4	25.7	23.9	26.9	1.53	n.s.

+S.E. for comparison of means between N rates.

++n.s. not significant (from ANOVA).

Rapid accumulation of dry weight in the cob was evident up to the "milk" stage of grain development (Harvest 4). Subsequently only slight increases were evident with a tendency for a small decline in cob dry weight as the plants neared physiological maturity.

No significant differences were shown by the ANOVA for huskless ear length and effective huskless ear length (portion supporting grain) at 127 and 146 days after planting, but at physiological maturity all N

treated plots had a significantly greater cob length than that of plants from the control plots. However, only plants receiving 672, 336 and 168 kg N/ha had an effective cob length significantly greater than that of plants receiving no fertiliser. Another cob component of interest viz. the percentage of grain filled, showed no significant differences over the last three harvests.

(c) Grain Components: The response to increasing rates of N in terms of total grain yield per plant was not significant as discussed in Section 3.2 (Appendix 5). No component of grain yield (grains/ear, row number/ear, grains per row) showed a signficant response to N fertiliser. Table 3.15 shows data for these components of grain yield at physiological maturity.

Table 3.15 Summary of components of grain yield at physiological maturity.

Component	N rate (kg/ha)					Significance level+
	0	84	168	336	672	
Grains/ear	474	503	493	487	504	n.s.
Grains/row	34	36	35	30	36	n.s.
Grain rows/ear	14	14	14	16	14	n.s.

+n.s. not significant (from ANOVA).

3.4 DRY MATTER CONTENTS OF PLANT COMPONENTS

The changes in dry matter content with time for leaves, stems, ears and "husks" are presented in Fig. 9. At physiological maturity, plants receiving no fertiliser N had a significantly greater leaf dry matter content than plants receiving 336 and 168 kg N/ha (ANOVA, Appendix 10). Plants receiving no N fertiliser and 84 kg/ha had higher dry matter contents at physiological maturity than plants from other treatments.

Stem dry matter contents showed similar trends, with those plants from the control and 84 kg N/ha treatments having as high or higher dry matter contents as those plants receiving greater rates of N fertiliser. This was apparent from 69 to 127 days after planting and again at physiological maturity. At 104 days after planting, those plants receiving 84 kg N/ha had a significantly greater stem dry matter content (ANOVA, Appendix 10) than plants from other treatments. At 127 days after planting these plants continued to have a significantly greater

dry matter content than plants from all other treatments except the controls (Fig. 9) (ANOVA, Appendix 10) but thereafter differences were no longer significant.

Ear and "husk" dry matter contents increased in a near linear fashion with time. No significant differences in response to increments of N fertiliser were recorded so only the two extreme treatments are presented for these components in Fig. 9. The dry matter contents of the ear at physiological maturity ranged from 55 to 57%.

3.5 TOTAL PLANT NITROGEN

As shown in Table 3.16, the total N accumulated in the shoots of the maize plants increased with time reaching a maximum for all plants at physiological maturity (Harvest 6).

Table 3.16 Yield of N in the whole shoot (kg/ha).

Harvest number	N rate (kg/ha)					S.E.+	Significance level++
	0	84	168	336	672		
1	4.8	4.9	4.4	4.8	5.7	0.71	n.s.
2	106.5	95.4	121.2	127.8	139.7	13.47	*
4	185.9	205.9	273.6	277.7	289.8	17.18	**
6	227.2	256.4	281.2	300.8	355.4	16.81	**

+S.E. for comparison of means between N rates.

++n.s. not significant, * .05> P>.01, ** P<.01 (from ANOVA).

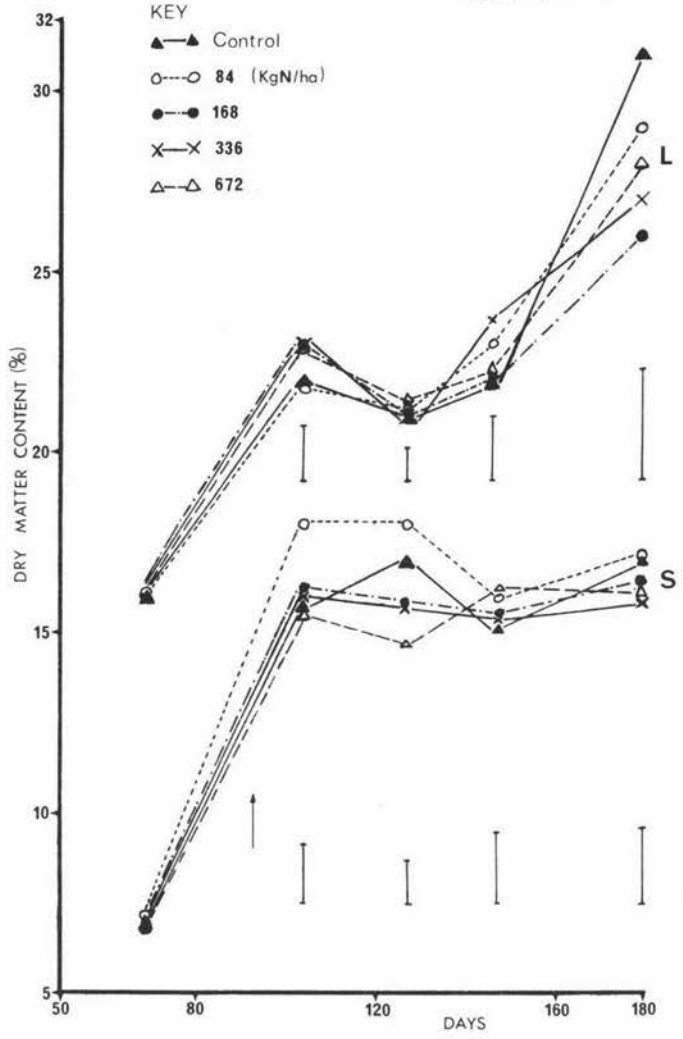
At harvests 2, 4 and 6 (69, 127 and 180 days after planting), increases in total N were generally detected in the maize shoots (Appendix 11) with increasing rates of N fertiliser. The timing of the nitrogen application, however, had few significant effects on total and component yields of nitrogen in the plants (Appendix 11 and 12 for examples). A significant interaction between N rate and time of application was recorded at harvest 4 (Table 3.17).

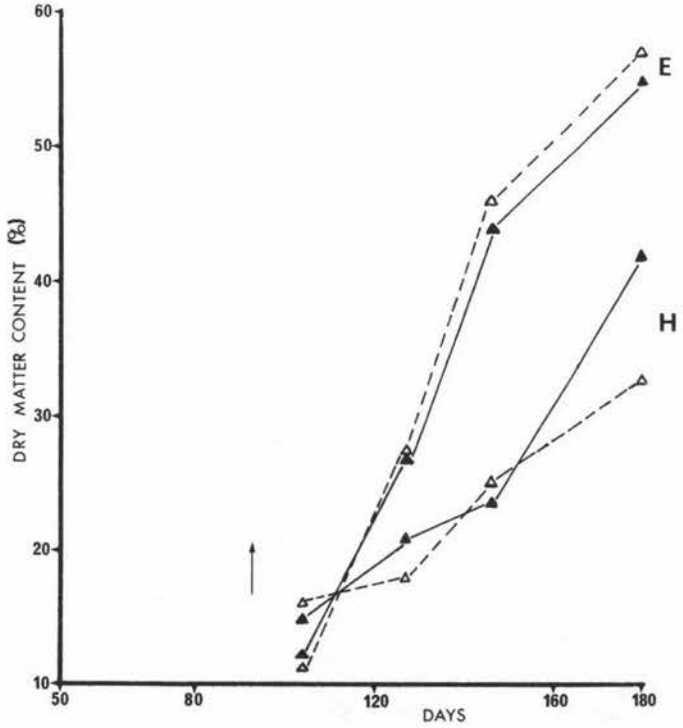
At harvest 2 only those plants receiving 672 kg N/ha had accumulated a significantly greater amount of N than the control plants. However, by harvest 4 plants receiving 168, 336 and 672 kg N/ha had all accumulated significantly greater amounts of N than plants in the control treatment and those receiving 84 kg N/ha. At physiological

FIG. 9 **Dry Matter Content (Fresh Weight Basis) of Shoot Components**

↓ indicates time of 50% silking

I are L.S.D. (.05) values. **L, S, E, H** are leaf, stem, ear (cob + grain), "husk", respectively.





maturity plants receiving 168 kg N/ha or greater had accumulated significantly greater amounts of N than found in plants receiving no N fertiliser.

Data presented in Table 3.17 indicates that at harvest 4 plants receiving 84 kg N/ha split over 3 times of application had a significantly higher total N content than plants receiving the rate as one dressing at planting, or split equally between applications at planting and after six weeks growth.

Table 3.17 Interaction effects between N rate and time of application for total N content (g).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	190.5	273.6	300.8	331.6	26.42
2	171.0	291.4	301.7	277.3	
3	256.2	255.7	230.7	260.4	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

Fig. 10 indicates that the uptake of N is relatively rapid in the early vegetative period and shows a decline in rate with time. By comparison dry matter accumulation is initially relatively slower but increases at a faster rate during the mid-growth period, then declines in rate approaching the final harvest. For example, at harvest 2 the shoot had accumulated 39% and 47% of its total nitrogen but only 16% and 19% of its total dry matter in treatments receiving no nitrogen and 672 kg N/ha, respectively. However, by harvest 4, while nitrogen yields had doubled, dry matter yields had increased almost 5-fold. Fig. 11 shows that the trends are similar for the intermediate N treatments. This early uptake of N is stored mainly in the leaves which are growing rapidly at this time, whereas at later stages the grain component becomes the increasingly dominant storehouse of nitrogenous compounds. Fig. 11 presents the actual amounts of N in various plant components and the total nitrogen yield at harvests 1, 2, 4 and 6.

The data for all treatments presented in Table 3.18, indicates that the rate of uptake of N is most rapid during the period of intensive vegetative growth prior to tasselling.

FIG. 10 Accumulation of Dry Matter and Nitrogen with Time Relative to the Final Harvest

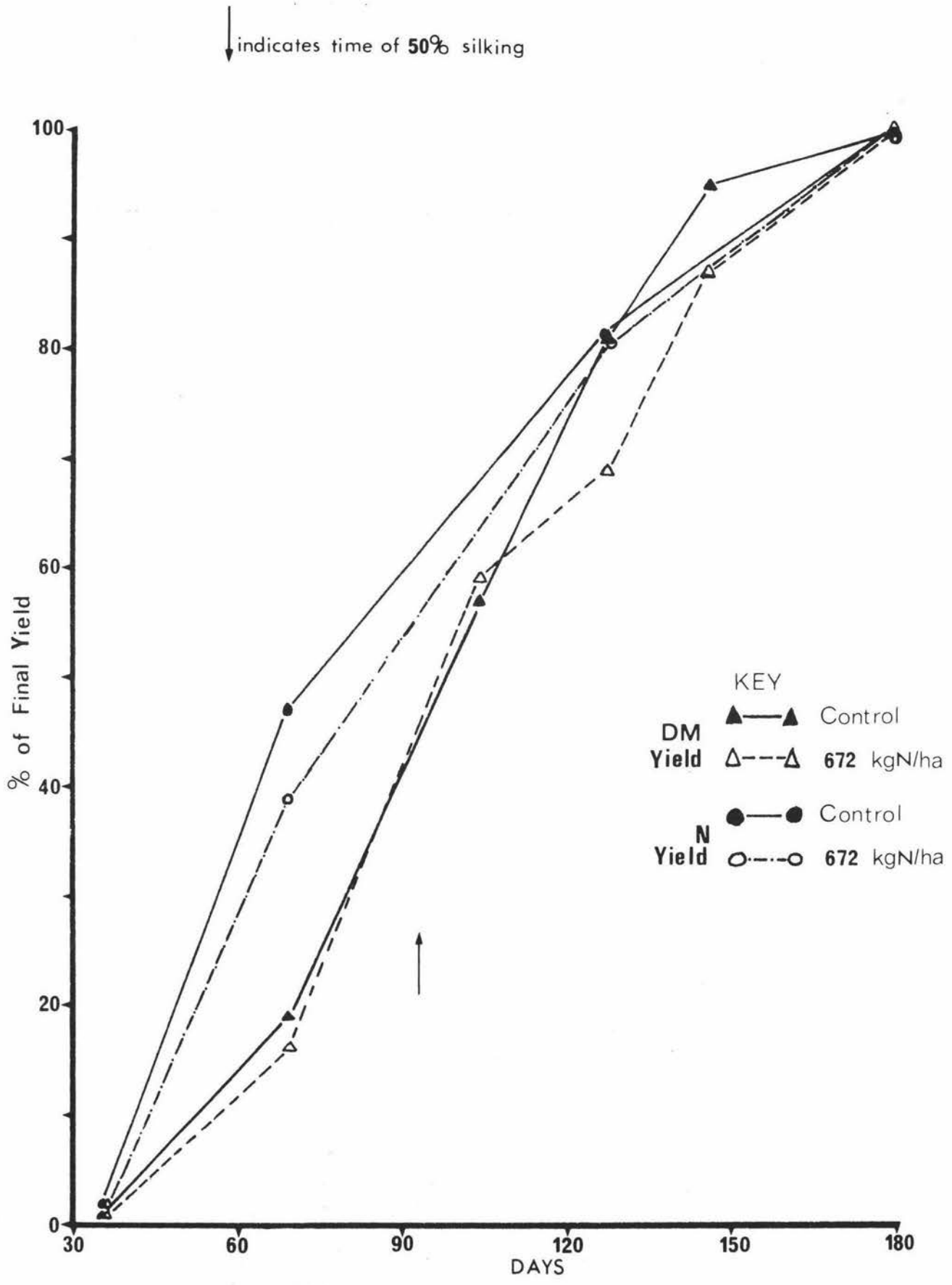


FIG. 11 Total Shoot Nitrogen Yield and Percentage Distribution in Plant Parts

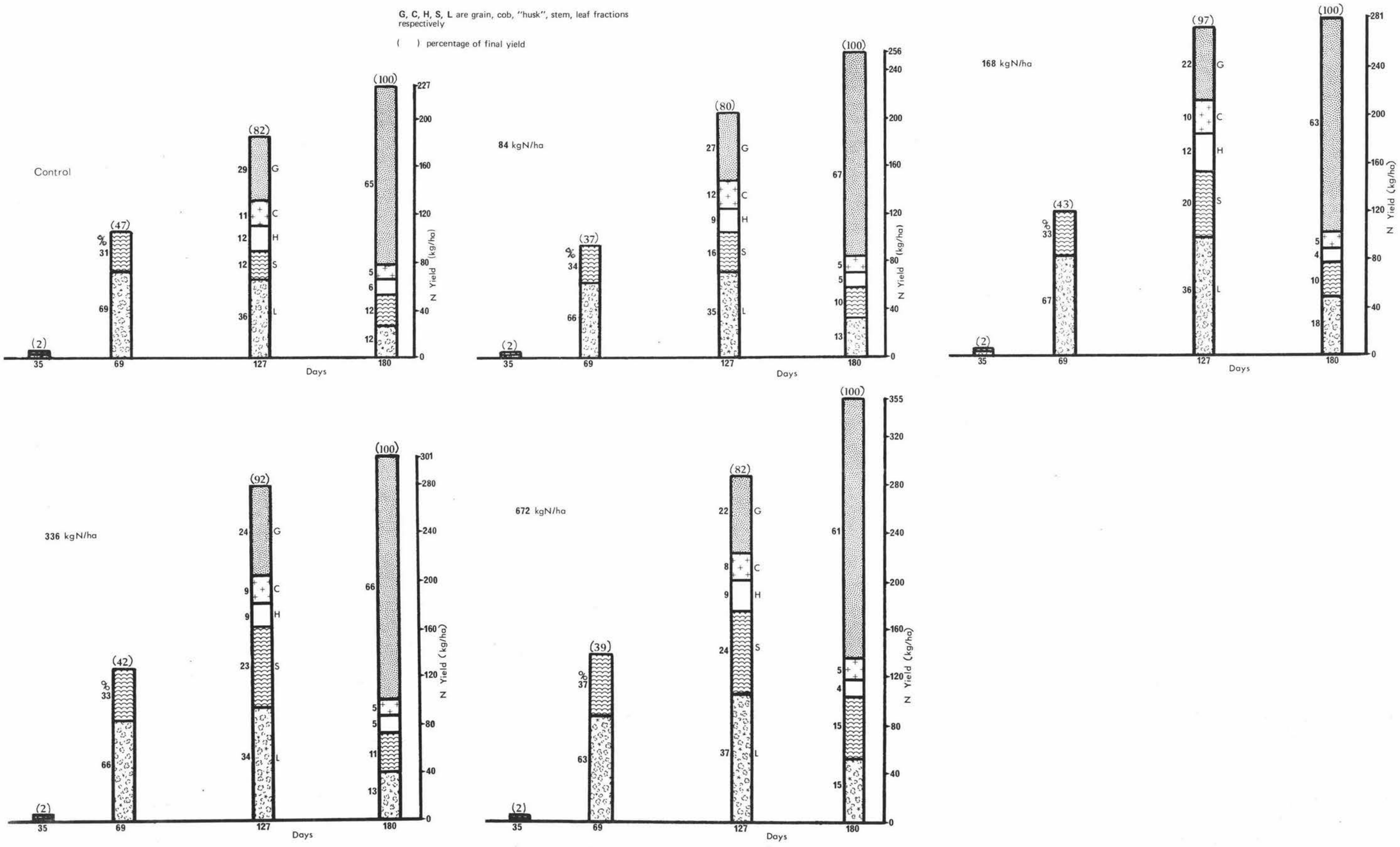


Table 3.18 Nitrogen uptake per day (kg/ha).

Period	N rate (kg/ha)				
	0	84	168	336	672
Planting to Harvest 1 (35 days)	0.14	0.14	0.13	0.14	0.16
Harvest 1 - 2 (34 days)	2.97	2.65	3.43	3.63	3.95
Harvest 2 - 4 (58 days)	1.38	1.91	2.63	2.59	2.59
Harvest 4 - 6 (53 days)	0.77	0.94	0.13	0.43	1.23

It is of interest to note the very substantial drop over the period of rapid grain filling to physiological maturity (Harvest 4 - 6), particularly in those treatments receiving intermediate levels of nitrogen application, 168 and 336 kg N/ha.

Over the major grain filling period (127 - 180 days after planting), leaf N content declined rapidly in all treatments to about 40-60% of their values at 127 days after planting. Some of the N loss would be due to that included in the "dead-leaf" fraction (not measured) but most of the loss would be due to translocation of stored leaf N to the rapidly growing grain. No significant differences in leaf N content was shown by the ANOVA at harvests 1 and 2. By harvest 4, however, plants receiving levels of 168 kg N/ha or greater possessed significantly greater leaf N contents than those receiving 84 kg N/ha and no fertiliser N (Appendix 12). This relationship also applied to plants receiving 168 and 672 kg N/ha at harvest 6. There was also a significant interaction between N rate and time of application at harvest 4. Table 3.19 indicates that this interaction was contributed to by those plants receiving 84 kg N/ha over 3 times of application having a significantly greater leaf N content than those receiving this rate split equally between a planting application and one 6 weeks later. Also, plants receiving 168 kg N/ha over 2 times of application had a leaf N content that was just significantly greater than those receiving the rate over 3 times of application.

Table 3.19 Interaction effects between N rate and time of application for leaf N content (g).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	0.64	0.93	0.80	1.07	0.101
2	0.58	1.05	1.00	1.00	
3	0.82	0.83	0.92	0.95	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

Analysis of variance of stem N content data at harvest 1 showed no significant differences but at harvest 2 those plants receiving 672 kg N/ha had a significantly greater N content than those receiving 84 kg N/ha and no fertiliser N. At harvest 4 the analysis of variance showed the same significance groupings as described for leaf N content at this time. A significant interaction between N rate and time of application was also shown by the ANOVA. By harvest 6, however, only plants receiving the highest rate of N (672 kg N/ha) had significantly greater stem N contents than plants receiving 84 kg N/ha and no fertiliser N. Data presented in Table 3.20 indicates that the significant interaction recorded at harvest 4 was contributed to by those plants receiving 84 kg N/ha split over 3 times of application having a significantly greater stem N content than those plants receiving all the rate at planting. Also, plants receiving 336 kg N/ha at planting and over 2 times of application had a significantly greater stem N content than those plants receiving the N over 3 times of application. Plants receiving 672 kg N/ha at planting, as well, had a significantly greater stem N content than those plants receiving N over 2 or 3 times of application.

Table 3.20 Interaction effects between N rate and time of application for stem N content (g).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	0.24	0.59	0.73	0.87	0.091
2	0.29	0.46	0.71	0.53	
3	0.44	0.50	0.43	0.59	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

At harvest 4 there was a tendency (Fig. 11) for plants receiving no N fertiliser and 84 kg N/ha to have a higher proportion of their total N content in the grain, than in plants from other treatments. This is reflected to some extent in the lower proportion present in the stems of plants receiving no fertiliser N and 84 kg N/ha (Fig. 11). These differences in grain N content, however, did not reach significance. At harvest 6, however, plants receiving 336 and 672 kg N/ha had a significantly higher grain N content than plants receiving 84 kg N/ha and no fertiliser N. At this harvest (physiological maturity) from 60 to 67% of the total shoot N, over all treatments, had accumulated in the grain. No significant interactions between N rate and time of application were recorded at any growth stage.

The N content of the roots was calculated from root dry weight data (Table 3.11) and root N concentration date (Table c, Appendix 13). These data are presented in Table 3.21 along with the estimated yield of N per hectare, contained in the roots.

Table 3.21 Root N content and yield.

Harvest number	N rate (kg/ha)	N content (g/plant)	N yield+ (kg/ha)
1	0	0.02	1.53
	168	0.01	1.53
	672	0.01	1.33
2	0	0.17	17.9
	168	0.12	12.1
	672	0.23	23.9
4	0	0.20	21.2
	168	0.21	22.5
	672	0.38	39.8
6	0	0.18	18.5
	168	0.17	18.1
	672	0.23	24.1

+Estimated yield of N per hectare contained in roots to a depth of 91 cm

These results indicate that the highest N fertiliser application tended to increase the N yield of the roots.

At physiological maturity (harvest 6) the N yield in the roots, as a mean over the three treatments, represents 7% of the total plant (shoot + root) N yield.

Over the major grain filling period (Harvests 4 - 6) cob and "husk" N contents declined by about 50% (Fig. 11). At harvest 4 the "husk" N content of plants receiving 168 kg N/ha were significantly greater than those from all other treatments, except receiving 672 kg N/ha. There was also a significant interaction between N rate and time of application recorded for "husk" N content at this harvest. At later harvests these differences disappeared. This significant interaction was contributed to by those plants receiving 168 kg N/ha split between an application at planting and at 6 weeks growth, having a significantly greater "husk" N content than those receiving all the rate at planting. Also plants receiving 336 and 672 kg N/ha at planting had a significantly greater "husk" N content than those receiving these rates over 3 times of application. Plants receiving 672 kg N/ha split between a planting

application and one at 6 weeks, also had a significantly greater "husk" N content than those receiving this rate over 3 applications. The relevant data are presented in Table 3.22.

Table 3.22 Interaction effects between N rate and time of application for "husk" N content (g).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	0.21	0.23	0.31	0.29	0.044
2	0.16	0.35	0.23	0.29	
3	0.21	0.32	0.18	0.17	

[+]See Table 3.4

[++]S.E. for comparisons of interaction means.

No significant differences were recorded for cob N content, but over the major part of grain filling the N content declined at different rates over the various N treatments. Consequently at harvest 5 only plants receiving 336 kg N/ha had a significantly higher N content than those receiving 84 kg N/ha and no fertiliser, while at harvest 6 only plants receiving 672 kg N/ha showed this relationship.

3.6 CONCENTRATION OF NITROGEN IN PLANT COMPONENTS

(a) Vegetative Components:

(i) Leaves and Stems:- During the first month of growth the concentration of N (N%) in the leaves and stems reached a high level of 3.5 to 4.0%. Thereafter N concentration declined steadily as the plants continued to grow and develop through to grain maturity, as shown in Fig. 12 (data in Appendix 13 Tables (a) and (b)). Apart from only one occasion the N% in the leaves was also consistently higher than that in the stems, throughout the experiment. The rate of decline, however, was noticeably greater in the stems than the leaves. By harvest 4 the concentration of N in the stems had plateaued at a level less than 1% while that of the leaves was still close to 2% or greater.

The effect of nitrogen fertiliser application on leaf N concentration, was first in evidence at the second harvest (69 days after planting) when all nitrogen treatments showed a significant increase in N% compared with the control. By the 4th harvest the

significant superiority of 84 kg N/ha over no nitrogen had disappeared. The remaining nitrogen treatments maintained their higher nitrogen concentration in the plant, compared with the control treatment, through to the final harvest and in some instances were significantly superior to the 84 kg N/ha treatment. No effect of time of application of N was evident at harvests 1, 2 and 6, but at harvest 4 plants receiving nitrogen at planting and at six weeks showed a significantly greater leaf N% than those receiving N on three occasions. Appendix 14 contains the appropriate ANOVA. No significant interactions between nitrogen rate and time of application were recorded at any harvest for leaf N%.

A very similar trend in N% with time was also evident in the stem component except that at the final harvest only the highest nitrogen fertiliser treatment (672 kg N/ha) was significantly higher in N concentration than the control and lower nitrogen treatments. No effect of time of N application was recorded at any harvest but at harvest 4 a significant interaction between N rate and time of application was recorded. The significant interaction at this harvest was due in part to the plants receiving 168 and 672 kg N/ha at planting having a significantly greater stem N% than those receiving the rate over 2 or 3 split dressings. Also plants receiving 336 kg N/ha at planting or split between a planting application and one after 6 weeks growth had a significantly greater stem N concentration than those receiving the rate over 3 times of application. The relevant data are presented in Table 3.23.

Table 3.23 Interaction effects between N rate and time of application for stem N concentration (%).

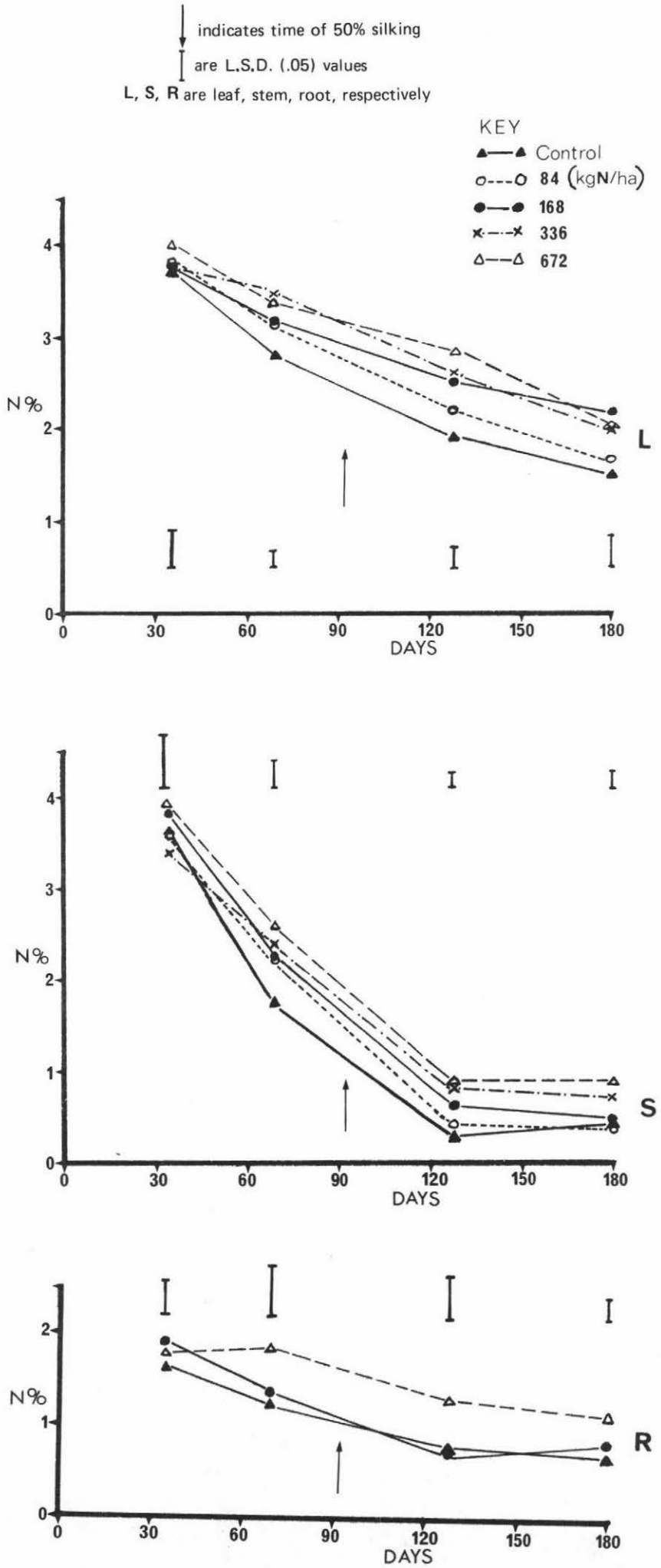
Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	0.35	0.79	0.90	1.05	0.098
2	0.41	0.56	0.89	0.79	
3	0.52	0.55	0.66	0.82	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

(ii) Roots:- The nitrogen concentration in the roots, also generally declined with time (Fig. 12) (data in Appendix 13, Table c)

FIG. 12 Nitrogen Concentration in Leaf, Stem and Root



from the first harvest. Only at the highest rate of application of nitrogen fertiliser (672 kg N/ha) was there a significant and consistent increase in the N% of the roots. Time of application of N was not considered for this component.

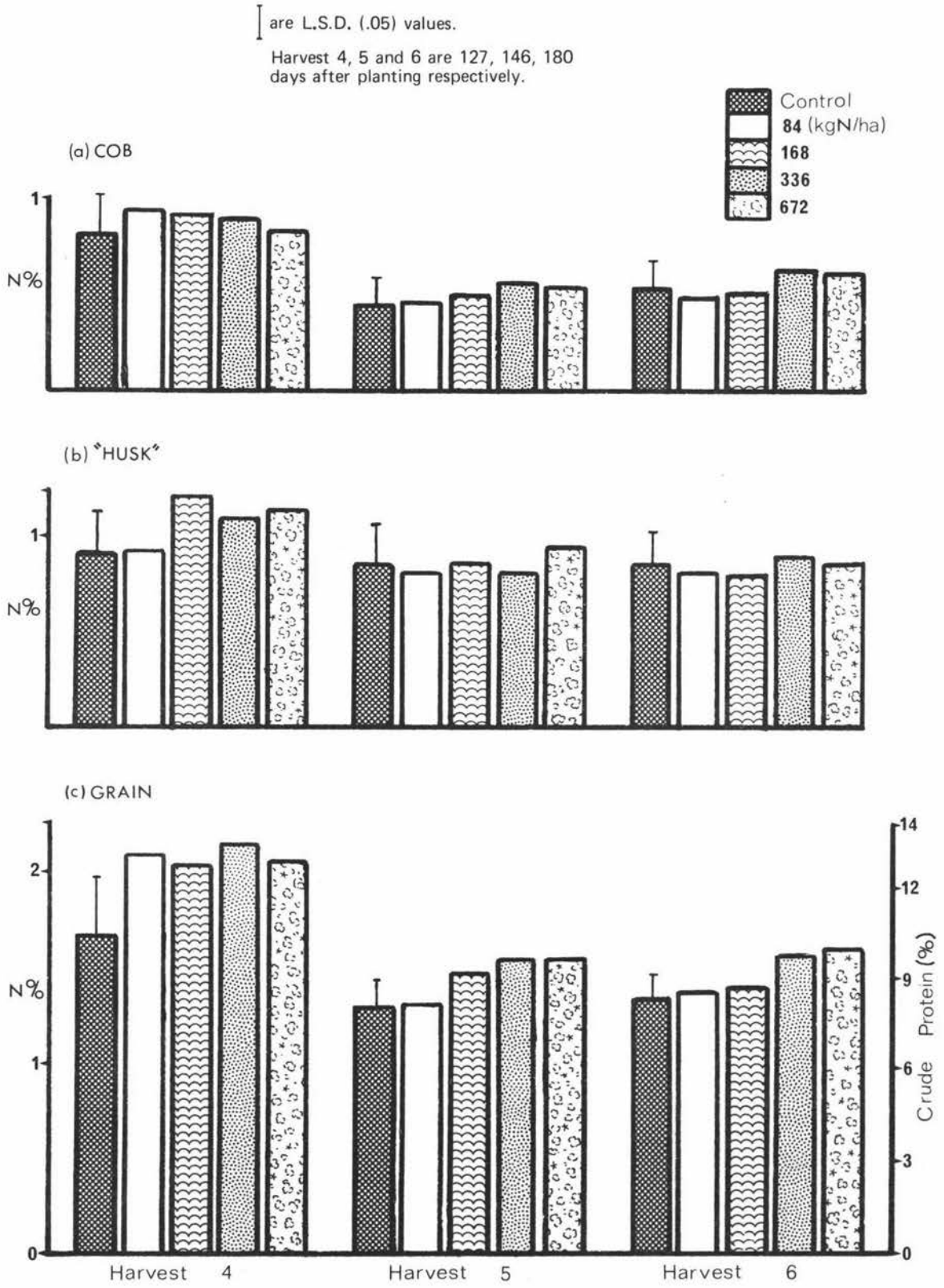
(b) Reproductive Components:

(i) Cob:- As presented in Fig. 13 the N concentration of the cob was less than 1% in all treatments. There appeared to be a similar decline in N% during the period of rapid grain filling (Harvest 4 to 5) whether in the presence or absence of nitrogen fertiliser, but thereafter there was little change. There was no significant increase in N% to even the highest rate of nitrogen application. At harvests 5 and 6 there were no significant effects of time of application on cob N% but as harvest 4 plants receiving all their N at planting had a significantly greater concentration than those receiving it as a split dressing at planting and 6 weeks later. No significant interactions were recorded.

(ii) "Husk":- There was a negligible change in the N% of the "husk" with time in the control treatment, remaining at a level a little below 1%N. However, the application of 168 and 672 kg N/ha caused a significant increase in N% of the husk in its very early stage of development, compared to plants receiving 84 kg N/ha and no fertiliser N, but this difference declined and had disappeared by the final harvest (Fig. 13). No significant effect of time of application of N was recorded for this component, nor were the interactions of N rate and time of application significant at any stage of the analysis.

(iii) Grain:- As in the cob component, N% of the grain showed a marked decline during the period of rapid grain filling (Harvests 4 to 5). Thereafter the N% levelled off and showed little change over the period of maturation to final harvest. The application of nitrogen fertiliser caused a significant increase in the nitrogen concentration of the grain as compared with the control, at harvests 4, 5 and 6 but at harvest 5 the effect was limited to rates of application of 168 kg N/ha or greater and at harvest 6 (physiological maturity) to the two highest rates of application (336 and 672 kg N/ha) (Fig. 13) (data in Appendix 15). No significant effect of time of application of N was recorded at harvest 4 and 6. At harvest 5, however, plants receiving N split over 3 times of application had significantly greater grain N concentration than those receiving all the rate at planting or split equally between planting and after 6 weeks of growth. A

FIG. 13 Nitrogen Concentration in Cob, "Husk" and Grain



significant interaction between nitrogen rate and time of application was recorded at harvest 6. This interaction was contributed to by those plants receiving 84 kg N/ha over 3 application times having a significantly greater grain N concentration than those receiving all the rate at planting. Also, plants receiving 168 kg N/ha at planting had a significantly greater grain N concentration than those plants receiving this rate over 3 times of application. Table 3.24 contains the relevant data.

Table 3.24 Interaction effects between N rate and time of application for grain N concentration (%).

Time[+] of application	N rate (kg/ha)				S.E.[++]
	84	168	336	672	
1	1.22	1.49	1.56	1.67	0.074
2	1.37	1.40	1.50	1.52	
3	1.50	1.29	1.61	1.54	

[+]See Table 3.4

[++]S.E. for comparisons between interaction means.

3.7 RECOVERY OF FERTILISER NITROGEN

The percentage of the nitrogen fertiliser recovered by the maize plant relative to the control plots at harvests 4 and 6 is presented in Table 3.25.

Table 3.25 Recovery of fertiliser N (%).

Harvest number	N rate (kg/ha)				
	0	84	168	336	672
4	-	24	52	27	15
6	-	34	32	22	19

Recovery of fertiliser N would be expected to increase with time since the uptake of N was continuous over the growth cycle (Table 3.18). However, this was only true for the lowest and the highest rate of N as the intermediate rates (168 and 336 kg N/ha) showed a decline in %

recovery over the grain filling and maturation period. With increasing rates of fertiliser N, depending on the plant's capacity to absorb increasing quantities of available N, it is likely that % recovery would decline. This is not the case at harvest 4 (grain at "milk" stage of development) due to the unusually high recovery by plants receiving 168 kg N/ha. At harvest 6 the expected pattern is followed.

3.8 CHLOROPHYLL CONTENT

An attempt was made to estimate, by chlorophyll extraction (Appendix 3) the visual N deficiency symptoms evident in plants receiving 84 kg N/ha and no fertiliser N. Plates 4-9 show evidence of these colour differences at tasselling and silking, some 9 weeks prior to analysis. Photographs in the field and of selected plants show the striking "V" shaped leaf-tip death (Plates 4 and 6) and the lighter colouration of the leaf and stem portions of N deficient plants (Plates 4 and 6-9). Table 3.26 summarises the results of the chlorophyll extractions.

The data presented show that the application of fertiliser nitrogen increased the chlorophyll content of the leaf.

Table 3.26 Colour density after extraction in ethanol.

	N rate (kg/ha)				
	0	84	168	336	672
Colour density	2.05	3.05	3.41	3.51	3.81
L.S.D. (.05) = .592					

While there appeared to be a further increase with further additions of N fertiliser, this trend only reached statistical significance when comparing the highest with the lowest rate of application.

CHAPTER FOUR

DISCUSSION

4.1 EXPERIMENTAL RESULTS

4.1.1 Grain and Total Dry Matter Yields

The range of total shoot dry matter yields at maturity (24,000-29,000 kg/ha) and grain dry matter yields (11,000-14,000 kg/ha) (Table 3.4) is similar to that previously reported for the Manawatu by Edmeades (1972). Menalda and Kerr (1973) obtained silage yields of 20,900 kg/ha after 156 days growth of the cultivar PX610 in the same locality and season as the present experiment, but with minimal irrigation. In the warmer, more northern areas of New Zealand total grain yields in the region of 9,400-15,700 kg/ha have been reported (Cumberland et al, 1971; Douglas et al, 1971; 1972) and in the South Island (Canterbury) Jagusch and Hollard (1974) have reported a dry matter yield over 150 days of 29,000 kg/ha. These dry matter yields are considered high by world standards (Cumberland et al, 1971; Edmeades, 1972). In areas such as the Manawatu, where dry summers may occur, varying amounts of irrigation water may be required depending on soil characteristics, in order to produce yields of this magnitude. Commercial maize growers using mechanical harvesting techniques have obtained grain yields in excess of 12,500 kg/ha in some maize growing areas of New Zealand, for example, in the Gisborne and Waikato districts.

4.1.2 Dry Matter Accumulation and the Nitrogen Response Curve

Fig. 4 indicates that with time dry matter tends to accumulate in an exponential fashion, from about 70 days after planting (23 days before 50% silking) until about 130 days after planting (37 days after 50% silking) when the rate of increase begins to noticeably decline as the upper asymptote or maximum accumulation is approached. Over this 60-70 day period, which includes the change from vegetative to reproductive growth, the stem contains the highest proportion of the total dry matter accumulated, the leaves representing the next highest portion at about half that of the stems, over the various N treatments (Fig. 5). From day 130 to day 180 after planting (physiological maturity) dry matter is accumulated in the grain at a rapid rate, there being only a small proportion (14-16%) of the total accumulation at each harvest present in the grain prior to this time.

ANOVA over the growth cycle of the maize plant, at six different growth stages, showed no significant differences in the response to increasing rates of N fertiliser as measured by the accumulation of dry matter (Appendix 5 contains ANOVA of data collected at physiological maturity). This result was unexpected in view of the efforts made to

select a site with a low soil N level. It was also possibly due to an inadequate discriminatory power in the analysis of the response. Coefficients of variation were 28%, 33%, 16%, 13%, 14% and 13% for the main factor (N rate) from harvest 1 to 6. It was hoped that a more direct analysis of the growth curves by fitting asymptotics and testing the treatments for significant differences might further resolve any trends in the data. This procedure did enable the various treatment responses to be differentiated with reference to their rate of approach to the potential limit of dry matter production (upper asymptote). It showed that the rate of approach for plants receiving 168 and 336 kg N/ha was significantly greater than those in other treatments. These differences can be seen by examining closely the upper portions of the curves presented in Fig. 4.

No exact reason can be given for these differences. However, data tends to support the groupings described above. As illustrated in Fig. 11, plants receiving 168 and 336 kg N/ha had by harvest 4 (127 days after planting, just prior to rapid grain filling) accumulated near their maximum N yield (97 and 92% respectively) whereas plants from other treatments had accumulated only about 80% of their respective maxima. This is also reflected in a greater percentage recovery of the N applied, at harvest 4, by plants receiving 168 and 336 kg N/ha (Table 3.25). Fig. 4 shows that harvest 4 occurs near the stage when the curviture towards the upper asymptote for each treatment can be distinguished. Because of the marked influence of N on the growth processes, the earlier and greater accumulation of N in plants receiving 168 and 336 kg N/ha, may have resulted in these plants reaching a total shoot dry matter production closer to their potential than was the case for plants from other treatments, before the onset of physiological maturity. Root dry weight analyses up to harvest 4 showed no differences between plants receiving 0, 168 and 672 kg N/ha (Section 3.3.2c), but it is possible that the plants receiving 168 and 336 kg N/ha were able to absorb and transport N to the shoot at a relatively faster rate than plants from other treatments. Even though plants receiving 672 kg N/ha absorbed greater overall quantities of N, their production potential of course was higher. However, the amount of N required to reach this higher potential was accumulated at a slower rate than in plants receiving 168 and 336 kg N/ha, therefore, these plants were further from reaching their potential at physiological maturity than those plants receiving 168 and 336 kg N/ha. In plants under N stress (those receiving no N fertiliser and 84 kg N/ha) the

lack of available N later in the season would have contributed to a lower potential dry matter production (Fig. 4) and may have also affected the rate of approach to this lower potential. The significantly greater leaf area recorded at harvest 4 for plants receiving 168 kg N/ha may have contributed to the ability of these plants to approach their maximum dry matter production at a relatively faster rate than plants from other treatments, because of greater assimilate production and its utilisation in growth processes. It is also possible that a better "balance" between the various nutrients required to produce near the plants' potential under varying N regimes, was attained by plants receiving the intermediate rates of N.

Hanway (1962a) has reported differences in the growth rates of maize plants grown in areas of varying fertility, relating to all major nutrients. However, it is recognised that N is most important of all essential elements in growth and development (Viets, 1965; Allison, 1973) and that a suitable balance of essential nutrients is necessary (Aldrich and Leng, 1965; Barber and Olsen, 1968; Powell and Webb, 1972). No visual symptoms of nutrient deficiencies, except those for N, were detected in the present experiment. The proportions of total shoot dry weight in the various plant components at each harvest showed little variation between treatments (Fig. 5). Hanway (1962b) reported a similar finding. The distribution of shoot dry weight at maturity amongst the various plant parts were in the range reported in the literature (Table 1.1), over all treatments.

Fig. 3 shows the predicted response curve for grain dry weight and total dry weight at physiological maturity. Dry weight tended to increase slightly, but not significantly, with up to 168 kg N/ha. Indications from the literature suggest that dry matter responses normally occur with relatively low rates of N fertiliser within the range of 100-150 kg/ha, although significant responses from higher rates of 200-250 kg N/ha have recently been reported by Jung et al (1972) and Robertson et al (1968). With increasing rates of fertiliser dry matter responses plateau or may decline when extremely high rates of fertiliser are applied. Usually, however, the N content of the plant continues to increase with higher rates of N as evident in this experiment (Table 3.16).

Data from this study suggest that soil N was an important factor in determining the responses observed. Table 3.16 indicates that physiologically mature maize plants in the control plots had a total

shoot accumulation of 227 kg N/ha. Soil tests for total N on 9.8.72 (Appendix 2) indicated a level of 0.175% N in the top 15 cm of soil. Assuming that a furrow slice (to 15 cm depth) of topsoil weighs 2,240,000 kg/ha (Buckman and Brady, 1969), then the total N content of the plot area prior to planting was about 3,920 kg/ha. The accumulation of 227 kg N/ha in the shoot plus an allowance of approximately 20 kg N/ha (Table 3.21) for the N accumulated in the roots represents a total uptake in the control plants of 6.3% of that present in the top 15 cm of the soil. Ball (pers. comm.) recorded a recovery of 5.7% of the total soil N in grass grown in a legume-free sward for one year. This result was obtained in the same locality and season and on the same soil type. Allison (1973) has reported the likelihood of the removal of up to 6% of the total N in the ploughed layer (15 cm depth) in maize grown on sandy soils low in organic matter, but suggests a figure of 1.5-3% for the more fertile loam soils. These results imply that a high mineralisation rate, at least twice as great as the 1-3% frequently reported (Scarsbrook, 1965; Kurtz and Smith, 1966) occurred under these experimental conditions and season and hence tended to mask the effects of the N fertiliser applied. The C:N ratio of the organic residues in the present experiment was 12:1 which indicates (Scarsbrook, 1965) that the mineralisation of N exceeded the immobilisation rate (in microbial protein) which would allow a net release of N.

The main criterion used in choosing the site for the present experiment was that the soil had a low N content. As expected on this sandy site the soil test prior to planting was relatively low, viz. 0.175% N. The soil was also free-draining in nature and, therefore, well aerated allowing greater oxidation, with warm summer temperatures (Appendix 1a), of the relatively low organic matter level present in the soil. The low water-holding capacity of this soil necessitated the installation of an irrigation system over the whole plot area. This allowed the effects of the N fertiliser on the growth and development of the maize crop to be studied without the complicating effects of water stress at any growth stage. High availability of water to the maize plants throughout the growing season must have contributed substantially to the high dry matter yields recorded (Table 3.4). One might also expect that such an environment would have led to an ideal condition for achieving a substantial nitrogen response. However, in terms of dry matter yield, this did not occur.

It is recognised that no reliable soil test has or possibly can be developed to predict accurately prior to planting the degree of

mineralisation likely to occur as the season progresses. Various microbial and chemical tests have been tried (Scarsbrook, 1965; Kurtz and Smith, 1966; Allison, 1973) but generally the laboratory conditions under which these tests are performed have little applicability to the field situation. In the field, highly variable climatic factors (e.g. temperature and rainfall) and the nature of the residues from the previous crop may increase or decrease the actual amount of N that may be released by soil microorganisms over the growth cycle of the maize plant.

Often no dry matter yield responses to N fertiliser have been recorded when maize crops are grown on soils of high organic matter levels and therefore high N reserves (Brown, 1966; Dickson, 1966; Douglas et al, 1972; Shukla, 1972). This includes parts of Australia and New Zealand where the intensity of cropping has not reached the high levels found, for example, in the Corn Belt of U.S.A. In these latter areas, soil organic matter levels have declined to low or moderate levels of around 4% or less (Buckman and Brady, 1969; Allison, 1973; Mengel and Barber, 1974a). In the less intensely cropped soils, therefore, organic reserves in general are still relatively high (in the region of 8% organic matter) allowing for greater mineralisation during the growing season.

4.1.3 Time of Fertiliser Application and Plant Response.

As pointed out by Welch et al (1971) it is necessary to obtain considerable increases in yield due to N fertiliser, to be able to measure differences due to time of application. This premise is borne out to a large extent by the results of the present experiment. No substantial evidence was obtained to justify the practice of splitting the N over several stages of growth. In terms of dry weight response there were no significant effects of time of application. Sheath area measurements at harvest 6, however, did show a significant advantage for applications of N made at three different stages (Time 3 split, Table 2.1) over that applied in equal proportions at planting and 6 weeks later. This may have been an artifact, however, as measurement was influenced by an arbitrary decision depending on the proportion of green material in the sample. No interactions between N rate and time of application of N for dry weight components were considered important.

In terms of N concentration in plant parts three components were significantly affected at two different harvests, by the timing of the

fertiliser application. At harvest 4 (beginning of rapid grain filling) plants receiving N in equal portions at planting and 6 weeks later had a significantly higher leaf N concentration than those receiving $\frac{1}{3}$ of the rate at each of these times plus $\frac{1}{3}$ at 50% silking. This response may be related to the plants' ability to take up large amounts of N (if available) in the early vegetative growth stages (Fig. 10 and Table 3.18) from about 30-70 days after planting. With the latter method of application smaller amounts of N were available to the plant (per N level) over this growth period, the final $\frac{1}{3}$ being applied when the uptake rate and leaf growth were declining from their respective maxima. Cob N concentration at harvest 4 showed a significant increase for plants receiving all their N at planting as opposed to those receiving N in equal portions at planting and at 6 weeks growth. At this stage the cob had reached almost maximal dry weight, but the reason for this particular response is not clear.

At harvest 5 (53 days after 50% silking) plants receiving the last portion of the N rate at 50% silking possessed a significantly higher grain N concentration than plants subjected to all the rate at planting or split equally between planting and 6 weeks later. It is of interest that this occurred after the period of rapid grain development (Harvest 4 to 5), but the pattern was not manifested at physiological maturity. One reason for applying N at 50% silking was to try and ascertain the effect on grain quality. The interaction between rate and time of N application reached significance at the final harvest (physiological maturity) due in part to plants receiving 84 kg N/ha over 3 different growth stages having a significantly greater effect than those receiving the whole rate at planting (Table 3.24). There is, therefore, a suggestion that the late application of N did have some effect on the grain N concentration when the application rate was low and presumably the need for N high.

Some further interaction terms are considered important. At harvest 4 (34 days after the last N application at 50% silking) stem, leaf and the total shoot N content all showed that the plants receiving 84 kg N/ha split over 3 times of application had a significantly higher N content than plants receiving the rate as one dressing at planting, or split equally between a planting and 6 weekly application (Tables 3.20, 3.19 and 3.17). It appears that when low rates of N are applied (e.g. 84 kg N/ha) and N deficiency symptoms develop, then a significant response to a late application of N is possible as the plant has insufficient stored N to meet the demands of the developing grain.

However, for plants treated with higher rates of N such as 336 kg N/ha, the opposite trend seemed evident. In each of these cases plants receiving N earlier in the growth (all the rate at planting or ½ at planting and ½ at 6 weeks of age) had significantly greater N contents than plants receiving N over 3 split dressings. This could be explained by the greater uptake of available N during early growth (Fig. 10) and the significantly greater amounts taken up (Table 3.16) with increased availability. Those plants receiving 336 kg N/ha over 3 times of application would have received only 224 kg N/ha during early growth compared with the full rate which was available to plants from the other treatments during this period. This reduced availability may have contributed to the lower N content recorded for plants from this treatment. The application of the final portion (112 kg N/ha) of the 336 kg N/ha rate near the end of the vegetative growth of the plant (50% silking) may have had little effect of the N content because of the reduced ability of the plants to accumulate N at this stage, with increased reliance being placed on previously stored N to meet the needs of reproductive development (Loewhing, 1961; Viets, 1965). Under these experimental conditions plants receiving 336 kg N/ha had accumulated the major part of their N (92%) by harvest 4 (Fig. 11).

Data referring to N uptake (Table 3.18) and previously published reports indicate that it is important for the maize plant to have access to adequate available N at planting and during the period of rapid vegetative growth, usually about 6 weeks later, the requirements of course being much greater at the latter growth stage. Because of the apparently exceptional conditions for mineralisation of soil N (Section 4.1.2) under the present experimental conditions all plants had access to an adequate supply of available N during the seedling and early vegetative growth stages. This is of importance as during the seedling stage N availability may affect (a) the number of leaves developed by the maize plant during later growth (Aldrich and Leng, 1965; Allison, 1973) and (b) the size of the leaf area produced. Along with the high mineralisation rate of soil N and the constant supply of irrigation water, plants from the control plots were able to produce a dry matter yield similar to those receiving N fertiliser and, therefore, largely negated the effect of time of application of N in terms of dry matter production and N content. Sufficient N was available from the soil source early in the season to enable the plants to produce a high dry matter yield. The extra available N provided by increasing rates of fertiliser affected N content only in that it allowed varying rates of

luxury consumption depending on availability.

Most published reports, however, indicate that N applied later than the "knee-high" stage (about 6 weeks after planting) is of little benefit in increasing maize yields except possibly under high rainfall and leaching conditions (e.g. Sravastava et al, 1971, in India). The rapid growth and development of the maize root system (Section 4.1.5(ii)) during shoot growth and its penetration to depths of about 180 cm (Linscott et al, 1962) depending on soil profile characteristics, would mitigate to some extent against substantial losses of N via the leaching mechanism. Nelson (1956), from a review of the literature, indicated that N applied at the "knee-high" stage was more effective in increasing yields than when it was applied at earlier or later growth stages. Later reports of Jung et al (1972) and Deckard et al (1973) suggest that applications made later in the growth of the maize plant may also be made less effective by a lower concentration of the enzyme nitrate reductase that is likely to be present in the leaves at this stage. This enzyme is thought to be involved in the reduction of nitrate (the form of N most often accumulated by maize plants, Section 1.4.3) to nitrite which is necessary in the preliminary steps prior to the incorporation of N into amino acids and proteins which are utilised in growth processes (Rossman and Cook, 1966). Nitrate reductase activity, therefore, may be a determinant of maize yields, but cause-and-effect has yet to be conclusively established. Some of these findings may be applicable to the present experiment. Also, field applications of N to maize plants at stages later than "knee-high" would possibly negate the benefit from applied fertiliser due to plant damage by the machinery involved.

Further to the above arguments it has been shown (Table 3.18) that the uptake of N slowed considerably over grain filling so N applied after vegetative growth would probably have less or little effect on dry matter production or grain quality. It is suggested, therefore, that in this experiment a high proportion of the 61-67% of the total N accumulated that was present in the grain at physiological maturity (Fig. 11) was derived from that previously stored in the vegetative tissues. Reports in the literature indicate that from 50-70% of the nitrogen in the grain at physiological maturity is derived from vegetative storage (Hanway, 1962b; Jung et al, 1972) and that at this growth stage from 65-75% of the total plant accumulation may be found in the grain (Flynn et al, 1957; Hay et al, 1953; Hanway, 1962b), which agrees with the present findings.

The rapid accumulation of N during the period from 35-69 days after planting (Table 3.18) did not seem to be affected by an unseasonably cool December in 1972 (Section 3.1) although the time to tasselling and silking was probably delayed by 1-2 weeks. Shaw and Thom (1951a) note the possibility of cool temperatures causing a delay in the occurrence of this growth stage. This ability to store N during early growth, even during a period of cooler temperatures, may have contributed to the general lack of advantage found for splitting of the N application (Gerdel, 1931; Viets, 1965). In this experiment, approximately 42% of the total N over all treatments had accumulated by 69 days after planting but only 16% of the total dry matter (Fig. 10). The work of Hanway (1962b) in Iowa U.S.A. supports the contention of a delay in dry matter accumulation. This worker found that over a number of fertility treatments, at about 65 days after planting, 46% of the total N had accumulated in the maize plants along with 24% of the total dry matter. Edmeades (1972) recorded a time of 70 days for a late maturing cultivar to reach 50% tasselling when planted in mid-November in the same locality. This was equivalent to 520 effective degree days in the 1969/70 season as compared with 579 (Table 3.1) in this study.

4.1.4 Nitrogen Fertiliser, Leaf Area Index and Longevity of the Photosynthetic Area.

The data presented in Fig. 7 shows that the leaf area index (LAI) of the maize plants from all plots reached a relatively high value of 4 during rapid vegetative growth about 70 days after planting. By 104 days after planting (11 days after 50% silking) the plants from all treatments had a LAI greater than 5. This was near the end of vegetative growth. Percentage absorption of solar radiation and crop growth rate have been shown by Williams et al (1965b) and Allison (1969) to increase with LAI in the region of 4 to 8 over the vegetative growth stages. A LAI of 4 or greater was maintained by all the maize plants for a relatively long period extending well into grain filling. However, this period was longer for the plants receiving higher nitrogen applications than for those in the control and lowest nitrogen treatments where visual N deficiency symptoms were recorded. For example, plants exhibiting these symptoms maintained a LAI of 4 or greater for 12 weeks including 9.5 weeks over the grain filling period. Plants receiving 168 kg N/ha maintained a LAI of 4 or greater for 15 weeks, 12 of which covered grain filling.

The leaf area duration (LAD) of 9.5 weeks after flowering found

in this study for plants grown at a population of 96,900/ha and receiving low rates of N or no N fertiliser, is longer than has been reported by most other workers. For example, it is about 1 week longer than that reported by Allison (1969) working in Rhodesia and 2-3 weeks longer than that reported by Eik and Hanway (1965) in Iowa U.S.A. Adelana and Milbourn (1972) working in a cooler climate in Southern England reported a similar figure. These plants were grown at densities ranging from 40,000 to 80,000/ha. Edmeades (1972) also found an increased leaf longevity (10 weeks in total) for two cultivars grown at 75,000/ha in the Manawatu. Under New Zealand conditions where no rapid temperature decline or shortening of the photoperiod is experienced with the approach of the autumn, leaf life appears to be maintained with continued grain filling well into the autumn (Edmeades, 1972). Such conditions are in contrast to rapid climatic changes experienced in the autumn of continental climates. Comparatively disease free conditions in this country also helps sustain leaf life (Edmeades, 1972).

It is suggested that the maintenance of a high LAI over the major part of grain filling was an important determinant in the high grain dry matter yields recorded (Table 3.4). Others have noted its importance in the production of a high grain yield (Sayre, 1948; Allison and Watson, 1966; Hanway, 1962b). In this study, from 18.2.73 (11 days after 50% silking) until 13.4.73 and up to 1.5.73, when the major part of grain filling had taken place, a LAI of between 4 and 6.14 was maintained over all treatments (Fig. 7).

As well as the actual size and duration of the leaf area, the efficiency (net assimilation rate, NAR) of the leaf area in producing grain dry matter should be considered. Data presented in Appendix 9(a) indicates that a maximum leaf area comparable to those receiving higher rates of N was possible for plants receiving 84 kg N/ha or no N fertiliser (although the soil supply was high, Section 4.1.2). Grain yields, however, obtained at harvest 4 to 6 (Table 3.4) showed no significant differences which probably indicates that the NAR of the leaves was not affected by increasing N rate. Reports of Watson (1963) and Hanway (1962a) suggest that NAR is little affected by plant nutrition and that N fertiliser usually has the most profound effect on dry matter production by increasing leaf area. Contrary to this argument, Gerdel (1931) and Nunez and Kamprath (1969) suggest that relatively low rates of N fertiliser (about 100 kg N/ha) is usually sufficient to produce maximum leaf area, equivalent to that attained by plants receiving higher rates of fertiliser. The plants receiving the

high rates of N, however, usually produced a higher grain yield due to a higher NAR. The present results support in part both of these arguments. Although significant differences in leaf area were evident in this experiment this did not result in significant differences in grain and total dry matter accumulation with increasing N levels. However, the rate of approach to the upper limit of dry matter production was certainly affected (Section 4.1.2).

The appearance of visual N deficiency symptoms in plants receiving no fertiliser and 84 kg N/ha had only a slight effect on the dry matter production of these plants. This could be related to the fact that the deficiency manifested itself after the period of most rapid leaf growth and, therefore, probably had a reduced effect on leaf area production and LAD (Hanway, 1962a). The absence of water stress at any growth stage may also have lessened the usual impact of this condition.

The shading of leaves lower in the canopy may have reduced the potential grain production of the plants with high N contents (those receiving 168 kg N/ha or greater) to nearer the level of those receiving the lower rate or no N fertiliser. This could be the result of reduced leaf nitrate reductase activity, since its function is probably light dependent (Hageman and Flesher, 1960; Hageman et al, 1961; Zieserl et al, 1963). The work of Nunez and Kamprath (1969) indicates that above a LAI of 3.5 grain yields tend to decline due to shading of the important leaves feeding the ear. The relatively high plant density (96,900/ha) that was used in this study might well have accentuated this effect. Even though plants from all treatments reached a LAI greater than 3.5, plants receiving adequate N produced higher LAI's than those deficient in N. This, along with the possibly less efficient use of a higher N content, may have resulted in a reduction in the yield potential realised for plants receiving 168 kg N/ha or higher rates (Section 4.1.7). The contribution of the lower 5-7 leaves to dry matter production is considerably less than the upper 9 or so leaves (Hoyt and Bradfield, 1962) under shaded conditions. These were also the leaves most severely affected by the development of the N deficiency late in the vegetative growth of the maize plants. The higher leaf dry matter content at physiological maturity (Fig. 9) of plants under N stress (control and 84 kg N/ha treatment), as compared to plants from other treatments, indicates that the leaves as a whole from these plants were nearer a non-functional condition. The absence of a similar pattern of response to N in leaf area measurements, as those for leaf dry weight (Section 3.3.2a) may be explained by the

observations of Pendleton et al (1967) and Early et al (1967) that leaf area is much less responsive to changes in light intensity than is leaf dry weight.

4.1.5 Total Dry Weight Changes in Other Components.

Stems, roots, "husk", and cobs all lost dry weight during the grain filling period. The application of nitrogen fertiliser also failed to influence this significantly.

(i) Shoot Components

After reaching a maximum dry weight shortly after 50% silking (Table 3.10) the stems began to lose dry weight slowly at first then rapidly over the period of greatest accumulation of grain dry matter. Several workers have reported losses from stems beginning 14 to 35 days after pollination reaching a maximum over the period of rapid grain filling (from harvest 4 to 5) (Kiessebach, 1950; Allison, 1969; Adelana and Milbourn, 1972; Edmeades, 1972). In this study, such losses were considerably higher in the low and no nitrogen treatments than in the higher nitrogen fertiliser treatments, viz. a loss of 22% and 32% of the respective maximum dry weights in the 0 and 84 kg N/ha treatments versus 18% and 15% in the 336 and 672 kg N/ha treatments. Approximately 70% of the total grain dry matter accumulation in plants from all treatments had taken place by harvest 5 (146 days after planting) when the grain had reached the "dent" stage of development. From harvest 5 to physiological maturity the decline in stem dry weight occurred at an even faster rate in all treatments. Plants showing N deficiency symptoms generally had a higher stem fibre content (significantly so for plants receiving 84 kg N/ha at harvest 3 and 4) than plants receiving higher rates of N (Fig. 9). This occurrence may be the result of earlier mobilisation of N from the stems of these plants reducing the protoplasmic content of the tissue, with consequent laying down of greater amounts of fibrous supporting constituents.

The "husk" portion which included the cob shank, ear husks, silks, tassels and tassel peduncles reached a maximum dry weight near the beginning of rapid grain fill and then declined rapidly over this period in all treatments. From harvest 5 to physiological maturity there was little change in "husk" dry weight (Table 3.13). It was not possible to distinguish which portion of the "husk" component actually was most affected over this period but Millar (1943), Sayre (1948), Hay et al (1953), Allison and Watson (1966) and Edmeades (1972) have all reported losses from actual ear husk and/or shank portions and suggested that

such losses represented movement of assimilates to the grain. There have been few reports of declines in cob dry weight over grain filling. Edmeades (1972) cites Manson (1967) as the only report, indicating a 15% decline over this period. This is approximately the magnitude of the declines in this study which ranged from 7 to 15% over the treatments imposed.

The above discussion indicates that a substantial mobilisation of reserves of soluble sugars takes place from the stems and husk during rapid grain filling in all plants. This mobilisation, however, appears to be greater for plants showing visual N deficiency symptoms (except for the losses from the "husk" of plants receiving 168 kg N/ha) than in normal healthy plants. Greater mobilisation of these reserves accumulated during the earlier growth of the N deficient plants, is probably necessary to meet the peak demand of the grain sink when photosynthate production by the N deficient leaves is likely to be less due to (i) a significantly smaller leaf area over grain filling than plants receiving 168, 336 and 672 kg N/ha (Appendix 9(a) and Fig. 7) and (ii) a lower chlorophyll content (Table 3.26). Over the remainder of grain filling stem reserves continued to be utilised but at a greater rate in plants receiving 168, 336 and 672 kg N/ha, than in N deficient plants. By comparison the "husk" component appeared to contribute little to the grain, as its dry weight showed negligible change. It is of interest to note that as the functional leaf area declined with leaf senescence, along with the slowing of assimilate production with the approach of maturity, stem reserves were utilised to a greater extent by plants receiving adequate N, in order to meet the demands of a larger grain sink. It is suggested that the small amount of dry matter that accumulated in the cob over the rapid grain filling period in most treatments (Table 3.14) indicated the presence of a small excess of dry matter arriving at the grain, resulting in some temporary storage in the cob. Although no consistent pattern was evident it is possible that some of these cob reserves were subsequently used in grain filling in some treatments.

(ii) Roots

Many studies concerned with the growth and development of the maize plant have ignored the roots. The roots have an important role in the uptake of water and nutrients and anchorage of the plant; they are also intimately involved in the metabolism of N in the plant (Hera, 1971).

Unfortunately, the use of root sampling and washing techniques to measure root production unavoidably introduces considerable errors. The three main problems to overcome are as follows (Newbould, 1968):

(i) rapid turnover of small roots and root material (e.g. root hairs) between sampling times.

(ii) the effect of disturbing the soil environment. Some attempt in this case was made to return the soil to the level in the profile from whence it came. The rather structureless nature of the profile may have lessened this effect somewhat. Only 2 plants out of the 48 grown in containers failed to grow in an apparently normal manner.

(iii) the high variability between samples that is usually obtained, due to the crudity of the estimation technique and, more often, due to soil heterogeneity. This may have been a critical factor affecting the results of the present experiment.

As the 50 cm width of the buried container extended from mid-row to mid-row, it is suggested that the technique employed allowed an effective sampling of the lateral root extension to be made, remembering that the container was made of open-mesh wire permitting free exit and entrance of roots. The containers sampled the maize root systems to a depth of 91 cm. Linscott et al (1962) found only 5-8% of the roots of mature maize plants to be below this depth in the soil profile. From an eye assessment at the appropriate harvests the majority of roots were located in the upper 20 cm of the profile. This agrees with the findings of Bloodsworth et al (1958), Foth (1962) and Mengel and Barber (1972a) who reported that at any growth stage more than 60% of the roots of maize plants are located in the top 30 cm of soil. A high proportion of the maize root system, therefore, was sampled using this technique (see below). Sayre (1955) reports that the mature maize plant contains approximately 30g of roots while Foth (1962) gives a figure of 25g for a quick maturing cultivar grown on a loam soil type. As shown in Table 3.11 such root weights are similar to those obtained in this study. However, Barley (1970) levels criticisms at root weight data because of the difficulty in separating completely soil particles from the root sample. Nevertheless, most studies have used this type of technique but, as in the present study, comprehensive and detailed analyses have not been attempted as it was felt the technique did not justify it.

Although the N fertiliser was applied consistently at the same

side and approximately the same position opposite each plant, no particular concentration of roots was observed in this region. It would suggest that the technique employed in the presence of trickle irrigation did not lead to any high "spots" of fertility. Other workers have noted root proliferation on entry into localised zones of high fertility (Duncan and Chlorogge, 1958; Viets, 1965; Nelson and Hansen, 1968).

Under the present experimental conditions root elongation in all the treatment plots examined was rapid; some roots had penetrated to at least 30 cm below the depth of sampling (91 cm) by 69 days after planting. Linscott et al (1962) noted the greatest root elongation between 10 and 30 days after planting. Root dry weight increased most rapidly over the period 35 to 69 days after planting which supports the finding of Linscott et al (1962) who found the greatest increase in the period 40 to 65 days after planting. Maximum root dry weight (25-29g), including brace roots, was recorded for samples taken at harvest 4, just prior to rapid grain fill. During grain filling, however, the mean root dry weight for plants receiving 168 and 672 kg N/ha declined by 29% of their maximum with little change for plants receiving no fertiliser (Table 3.11). This supports the finding of Mengel and Barber (1974a) but is contrary to that of Foth (1962) who showed no change in root weight during the latter part of grain filling. The suggested decline in root dry weight for plants receiving fertiliser N may be the result of greater intraplant competition for photosynthate between the shoot and roots (Brouwer, 1966). Grain dry matter production tended to be greater in plants receiving N fertiliser, than for those from the control plots. It is possible that in addition to shoot components some dry matter was also mobilised from the roots to satisfy the grain sink. The shoot to root ratios over the major part of grain filling (Harvest 4 to 6) increased by 72% and 100% for plants receiving 168 and 672 kg N/ha but only by 8% in plants from the control plots (Table 3.12). These increases are primarily due to a build up in grain dry matter (Foth, 1962).

Assuming that all plants in each treatment underwent similar root growth and development with time, then it is possible to estimate the root yield per hectare to a depth of the sampling container (Table 4.1). Assuming also that approximately 80% (allowing 10% for losses during washing and 10% of the root system outside the container) then root yield per hectare was approximately 3,400, 2,750 and 2,680 kg/ha for plants receiving 0, 168 and 672 kg N/ha respectively. In other words,

approximately 15%, 10% and 10% of the total plant dry weight of these respective treatments was contained in the roots. These results are similar to those previously indicated by the data of Weihing (1935), Foth (1962) and van Eijnatten (1963).

Table 4.1 Estimated root dry weight data (kg/ha).

Harvest number	N rate (kg/ha)	Estimated root yield+
1	0	95
	168	80
	672	75
2	0	1,432
	168	871
	672	1,281
4	0	2,653
	168	3,081
	672	3,059
6	0	2,727
	168	2,204
	672	2,148

+calculated from mean dry weight data per plant (Table 3.11)

Root growth did not seem adversely affected by the slightly compacted layer at 7-11 cm in the profile, nor by the variations in texture with depth in the profile. Root growth continued into the gravel which was at approximately 60 cm depth in the profile.

4.1.6 Nitrogen Uptake and Distribution

Nitrogenous fertiliser had its most striking and positive effect on the rate of N uptake by the plants during the period of maximum leaf growth (Fig. 6) when stem growth (Fig. 8) was only 25% of its maximum from 35 to 69 days after planting. This implies rapid movement of nitrogenous compounds from the roots to the shoot. Root growth was also rapid over this period (Table 3.11) and the N not utilised in this process would have been exported to the shoot to meet the greater needs of its rapidly developing tissues (Hera, 1971). Pate (1971) also noted

the precocious accumulation of reserves of proteins and other solutes associated with the rapid expansion of young leaves. The rate of uptake by plants in the various nitrogen treatments (Table 3.18) reflected the level of N available to their root systems. As might be expected the uptake rate of those plants showing visual N deficiency symptoms, from about 70 days after planting, was distinctly lower than those for plants receiving higher rates of N (Table 3.18). However, there were no significant differences in root growth (Section 3.3.2c) for plants receiving nil or even the highest rate of N application over this period. Sayre (1955) reported an average daily uptake rate of 3 kg N/ha and a maximum uptake near tasselling and silking of 4.5 kg/ha/day. These figures are similar to those recorded in this study (Table 3.18) for plants receiving 168, 336 and 672 kg N/ha.

The N accumulation curve (Fig.10) follows the pattern suggested by Viets (1965), being less sigmoidal than that for dry matter accumulation due to the more rapid accumulation of N relative to dry matter early in the growth of the plants. In this experiment the differences are possibly more marked than usual due to a cool December (Section 3.1) which delayed tasselling by 1-2 weeks. Luxury consumption of N in the early growth stages is indicated by the steeper gradient of the N accumulation curve relative to that for dry matter (Fig. 10). It allows the plant to store large quantities of soluble N for future growth (Loewhing, 1961; Viets, 1965). This is illustrated by a high concentration (3-4% N) in the leaves and stems (Fig. 12) at harvest 1, 35 days after planting. With time the concentration in all plant components declined reflecting dilution of the N level as dry matter accumulated and nitrogen was translocated to the grain as source-sink patterns changed (Figs. 12 and 13).

The concentration of N in the stems, over all treatments, declined at a faster rate than that of the leaves and reached a much lower level prior to rapid grain filling (Harvest 4, 127 days after planting) (Fig. 12). At harvest 2 (69 days after planting) the N concentration in the stems and leaves had reached a significantly lower level in plants receiving no N fertiliser than that in the plants receiving increasing increments of N. At harvest 4, however, the plants receiving 84 kg N/ha could be grouped with the controls for both stems and leaves (Fig. 12). The greater decline in N concentrations in the leaves and stems of plants receiving these treatments would reflect to some extent the lower availability of N to the root systems of these plants. This hypothesis is supported by a significantly lower N

concentration found in the roots of the plants receiving no N fertiliser, at harvest 2 and 4 (Fig. 12). By harvest 4 the N concentration in the stems (Fig. 12) had reached a level of less than 0.9% N over all treatments. This agrees with the reports of Jordan et al (1950) and Johnson et al (1966) for stem N% at a similar growth stage. Leaf N%, however, except in plants receiving no N fertiliser, was greater than 2% over all treatments (Fig. 12). A level of 2-3% (Tyner, 1946; Jordan et al, 1950; Johnson et al, 1966) is considered usual at tasselling and silking which occurred some 40 days earlier than harvest 4.

The more rapid decline in N% in the stems relative to that of the leaves would be mainly due to dilution effects as by harvest 4 the stem contained a much higher proportion of the dry matter accumulated (Fig. 5) than did the leaves, over all treatments. Also, as noted earlier, the leaves tend to accumulate large quantities of nitrogenous compounds during rapid growth. Consequently, the leaves (Fig. 11) at 69 days after planting contained about two-thirds of the total shoot N content and at harvest 4 about one-third, but they still contained the highest proportion of any plant part at this growth stage.

It seems likely that in the N deficient plants some N was translocated from stem reserves and to a lesser extent from leaf reserves prior to the rapid grain filling between harvests 4 and 5. This, therefore, also contributed to the significantly lower N concentrations found in the stems and leaves of these plants at harvest 4. At harvest 2 only the stem N contents of plants receiving 672 kg N/ha were significantly greater than plants showing N deficiency symptoms (those receiving nil and 84 kg N/ha) but at harvest 4 those receiving 168 kg N/ha or higher levels had significantly greater N contents than N deficient plants. Fig. 11 illustrates these changes. All plants showed similar changes in stem dry weight over the period from harvest 2 to 4 (Table 3.10), but as noted earlier N concentrations in the stems at harvest 4 for N deficient plants was significantly less than those in other treatments. This suggests earlier translocation of N from the stems of the N deficient plants in order to meet the demands of the developing grain. Similar trends could have occurred to some extent in the leaf component as suggested by the decline in N content of this component in the control plots (Fig. 11) from harvest 2 to 4.

Stem dry weight and nitrogen concentration generally declined over grain filling (Table 3.10, Fig. 12) therefore stem N content

declined (Fig. 11). The small declines in stem N% over this time in all but the N deficient plants indicates that some translocation to the grain was occurring in these plants. Plants receiving no N fertiliser showed an increase in N concentration from 0.29% to 0.47% possibly because of the continued mobilisation of N from rapidly senescing leaves, but restricted entry into the grain as maturity approached and black layer formation began.

Leaf N concentration continued to decline over grain filling in plants from all treatments (Fig. 12). At physiological maturity plants receiving 168, 336 and 672 kg N/ha still had a leaf N concentration greater than 2%, whereas those receiving 84 kg N/ha and no N fertiliser had significantly lower concentrations of 1.69 and 1.59% respectively, reflecting again the less favourable supply situation and possible earlier translocation of N to the grain in these treatments. Hanway (1962b) reported that translocation of N to the grain from other plant components does not usually occur until the "blister" stage of grain development, except under N deficient conditions. Harvest 4 is coincident with this stage of grain development and therefore the results of the present study support his findings. At physiological maturity leaf N content was about half its value at harvest 4, over all treatments (Fig. 11). This decline is influenced somewhat by an arbitrary decision to exclude from measurement leaves with less than 50% green area. No data are presented (Fig. 11) for the N content of the dead leaf component as the N concentration measurements refer only to that of the functional leaves; the data for leaf N content, therefore, underestimates slightly the actual leaf N content. Some of the leaves included in the dead leaf component were devoid of any green areas, their chlorophyll having been completely degraded. This was more often the case for plants showing N deficiency symptoms, whereas plants receiving higher rates of N removed less of the N contained in their lower leaves.

At harvest one (35 days after planting) the N% in the roots (Fig. 12) was the highest recorded for all treatments. This relates to the luxury uptake of N by the young maize plant (Viets, 1965). Mengel and Barber (1972b) noted the greatest uptake of N into maize roots during the first month of growth at about 20 days after planting. By 30 days after planting this rate had declined by 85% and had reached a stable low rate of entry when the plants were 70 days old. Root dry weight in the present experiment reached a maximum between harvest 2 and 4 so some dilution of the N concentration in the roots may have

occurred contributing to the decline in concentration, the rate of which was greatest over this period (Fig. 12). Over grain filling only small changes in root N concentration are evident (Fig. 12). This is consistent with a relatively low uptake of N over this period (Table 3.18) and a greater mobilisation of N reserves from other shoot organs (especially the leaves, Fig. 12). Only one report was found concerning the concentration of N likely in maize roots at any particular growth stage. Viets (1965) notes the paucity of such information. Robertson (1973) reported a figure of 1.32% N for the concentration in maize roots in the pre-bloom stage about 60-70 days after planting. The maize crop was grown on a fertile silt loam with 75 kg N/ha. Fig. 12 indicates similar concentrations for plants sampled about the same period (69 days after planting). A considerably higher concentration, however, of 1.87% was found in the roots of plants receiving a higher rate of N (672 kg/ha).

Cob N% declined from approximately 0.9% to approximately 0.5% over the treatments during rapid grain filling from harvests 4 to 5 and remained almost constant from harvests 5 to 6 (Fig. 13a). This resulted in a decline in the N content of the cob. Its value at harvest 6 (physiological maturity) was about half its value at harvest 4 (beginning of rapid grain filling) (Fig. 11). Cob dry weight changed only slightly over this period (Table 3.14). This suggests the likelihood of some translocation of N from the cob to the grain during rapid grain filling. The N concentration in the "husks" also declined over rapid grain filling and like that of the cob remained essentially the same over the remainder of grain filling (Fig. 13b). The N content of the "husk" also declined over the major grain filling period (Harvest 4 to 6) (Fig. 11) but the "husk" also lost some dry weight over this period (Table 3.13). Again there is a suggestion of some loss of "husk" N to the grain over the rapid grain filling period, but because of the various inclusions in this component it is not possible to indicate precisely which portion(s) actually lost N during this period. Hanway (1962b) reported that translocation of N from the cob, husk and stem usually preceded that from the leaves in normal maize plants.

The N% of the grain was first recorded at the "blister" or "milk" stage of development at harvest 4. At this time the N concentration, except for plants from the control plots was relatively high being greater than 2% N (or 12.5% crude protein) (Fig. 13c). A greater proportion of the total N accumulated, compared with dry matter, was present in the grain at this stage (Figs. 5 and 11). From harvests 4

to 5 (grain in dent stage of development) dry matter accumulated at a relatively faster rate than N, which resulted in a dilution of the N concentration in the grain (Fig. 13c). Over the final period of grain filling (Harvests 5 to 6) the accumulation of dry matter in the grain represented approximately half the amount accumulated over the 19 days between harvests 4 and 5 (Fig. 5). The N% in the grain over all treatments, however, showed little change, suggesting that the accumulation of N was sufficient, up until black layer formation, to largely negate the effect of dilution of the concentration in the grain by the increase in dry matter accumulation. Since the uptake of N is slow over the grain filling period (Table 3.18) this reflects the continued mobilisation of N reserves from other plant organs up until physiological maturity was reached (Hay et al, 1953; Hanway, 1963).

Data presented in Appendix 15 indicates that only plants receiving 336 and 672 kg N/ha attained a grain N concentration in the region of 1.45 to 1.6% N commonly reported for the mature grain of commercial hybrids grown in the U.S.A. (Kurtz and Smith, 1966). Although these data suggest that a high level of N availability, combined with a relatively high population density (96,900 plants/ha), will result in a high N concentration in the mature grain, the response seems to plateau with higher rates of N (Fig. 13c). Hunter and Yungen (1955) have also reported this phenomenon.

4.1.7 Nitrogen Deficiency Symptoms and Maize Production

The data discussed in the previous section indicates that the appearance of visual N deficiency symptoms in some of the maize plants was consistent with a significantly reduced concentration of N, at some growth stage, in all plant parts studied, with the exception of the cob. These differences, however, were not associated with a significant reduction in growth as measured by grain and total dry matter accumulation (Table 3.4).

Plates 4 and 6 show the development of the classical N deficiency symptoms in the lower leaf portions and stem internodes of plants receiving no fertiliser N. These deficiency symptoms (also evident in plants receiving 84 kg N/ha) however, did not visually manifest themselves until about 70 days after planting and consequently growth in terms of height was not affected (Hoffer, 1941; Aldrich and Leng, 1965). Chlorophyll extractions at 25 days before physiological maturity showed an increase with increasing N rate (Table 3.26). A reduction in leaf chlorophyll content occurs with the development of a N deficiency

with the degradation of the chlorophyll molecule, supplying more nitrogen to the growing tissues (Krantz and Nelsted, 1964). The penultimate expanded leaf was sampled in order to obtain some consistency in age of the tissue sampled and to avoid any possibility of leaf senescence influencing the sample. Although statistically no significant difference between the chlorophyll content of plants receiving 84 kg N/ha and 168 kg N/ha existed and a significant difference existed between plants receiving 84 kg N/ha and no fertiliser N, these results were influenced to some extent by the fact that N deficiency influences initially the lower and older portions of the plant. N is preferentially mobilised from older tissues to supply the needs of the rapidly growing younger tissues. If the deficiency persists then the leaves and other vegetative parts higher up the plant become affected, as was the case in the present experiment. Plates 8 and 9 show that similar N deficiency symptoms are evident in the lower portions of the shoots of plants receiving 84 kg N/ha (compared to the plants receiving no N fertiliser), but not in those receiving 168 kg N/ha.

Table 4.2 indicates that the ratio of N in the grain to that in the stover (all parts of the shoot except the grain) for plants receiving 168, 336 and 672 kg N/ha was considerably less than those for plants that showed N deficiency symptoms.

Table 4.2 Ratio of grain nitrogen to stover nitrogen at physiological maturity.

N treatment (kg/ha)	0	84	168	336	672
Ratio	1.91	2.05	1.69	0.97	1.56

This indicates that there was a greater uptake in plants receiving higher rates of N than could be used in grain production. This suggests, therefore, luxury consumption of N in terms of grain production for plants receiving the three highest rates of N, since only small increases in yield were produced by the extra N accumulated. Plants that showed the N deficiency symptoms were more efficient in the production of dry matter because of a greater internal "reuse" of nitrogen. In other words, the plants under N stress exhibited a greater plasticity in internal "reuse" and redistribution of N than those receiving adequate levels of N. This was manifested in a greater withdrawal of leaf and stem N reserves during grain filling in order to

counter lower overall uptake of N by plants receiving no fertiliser and 84 kg N/ha (Table 3.18). Sufficient N was still available, however, for the production of a grain and total dry matter yield in the region of that attained by plants not showing these symptoms. It is possible that the greater plasticity in N usage exhibited by N deficient plants, was enhanced by the absence of water stress. For example, under dry-land conditions, N uptake would probably have been more limited (Viets, 1967) due to either a smaller amount of soil N becoming available or restricted root development (Weaver, 1926). Maximisation of internal efficiency of N usage may result in a lower crop yield and a product lower in N content (Viets, 1965). In this study only the lower N content reached statistical significance.

4.1.8 Fertiliser Nitrogen and Its Efficiency of Utilisation.

The "difference" method (Section 3.7) was used to calculate the percentage recovery of fertiliser at the "milk" stage of grain development (Harvest 4) and physiological maturity (Harvest 6). Hauck (1971) contends that this method of calculating the percentage recovery in plants, over-estimates the actual recovery. Apparently the assumption that mineralisation and other transformations during the course of the experiment is the same for fertilised and unfertilised soils, is often invalid.

The recoveries of N fertiliser (Table 3.25) could, therefore, generally be described as being low but comparable recoveries reported in the literature rarely exceed 60% for low rates of N (Robertson et al, 1965; Bartholomew, 1971). At harvest 4 the recovery of fertiliser N in plants receiving 168 and 336 kg N/ha is higher, especially for the former treatment, than in plants receiving the low rate of nitrogen (84 kg N/ha). The reason for this occurrence is uncertain but it may relate to the more rapid uptake and attainment of near yield potential as discussed in Section 4.1.2. Over the grain filling period the data (Table 3.25) indicates that the recovery declined for plants receiving 168 and 336 kg N/ha, whereas it continued to increase (as expected) for plants receiving 84 and 672 kg N/ha. Although it is recognised that as plants mature, especially if they have access to a high level of available N, significant amounts of N may be leached from the tops and roots (Allison, 1973; Terman and Allen, 1974). But this did not seem to occur to a marked extent in the case of plants receiving the highest rate of nitrogen (672 kg/ha) and having the highest nitrogen content at harvests 4 and 6 (Table 3.16). These declines in percentage recovery,

however, may be an anomalous result caused by the method of calculation and the fact that plants receiving 168 and 336 kg N/ha had accumulated 97 and 92% of their total uptake by harvest 4 (Fig. 11). Plants from other treatments, including those in the control plots had only 80% of their total uptake by harvest 4 and continued to accumulate considerable quantities of N over grain filling. The relative increase in N content over grain filling, therefore, was much greater than for plants receiving 168 and 336 kg N/ha.

A contributing factor to the generally low recovery of fertiliser N would undoubtedly be the high degree of mineralisation of soil N (Section 4.1.2) evident under the conditions of this experiment. This is emphasised by the method of calculating the percentage recovery of fertiliser N. Some leaching of nitrate-N may also have contributed to the low recovery of fertiliser N, especially with the very high rates of N applied under sandy conditions. No significant differences were shown, however, between the effects of time of application on total dry matter yields and only on a few occasions for components of N yield, which may indicate that the leaching factor was less important; a greater loss of N would be expected from the application of high rates of N to the maize plants at planting. The extensive nature of the maize root system (apart from the first month of growth), combined with the maintenance of the soil near field capacity promoting rapid uptake of N (Viets, 1967) would have mitigated against heavy leaching losses. However, the maize root system was of greatest density in the top 20 cm of soil (Section 4.1.5(ii)) and at the beginning and near the end of the growth cycle of the maize plant, when uptake of N was relatively slow, some considerable losses could have occurred with water moving at a faster rate through the profile.

It is unlikely that losses of N due to volatilisation of ammonia from the hydrolysis of applied urea, had a significant effect on the recovery of fertiliser N by maize plants. These losses would have been minimised by the application of urea to a depth of 18 cm in the soil and the filling in of the hole left by the injector immediately after applying the fertiliser.

4.3 CONCLUSIONS

1. Total dry matter yields and yields of individual plant parts, including the grain, over the growth cycle of the maize plant were not significantly affected by increments of N fertiliser up to 672 kg/ha. These results suggest that in terms of dry matter production there is

no justification for the application of N fertiliser to maize when the crop is grown on a soil recently out of pasture and when adequate water is provided. The total N yield and yields of individual plant parts, however, showed significant responses after the first month of growth.

2. No substantial favourable evidence was obtained for the splitting of the N rate over several growth stages. The results show, however, that the plants' greatest requirement for nitrogen is during the first 6 to 8 weeks of growth.

3. Nitrogen uptake by the maize plant increased with increasing levels of fertiliser N. The nitrogen taken up during the early growth of the plant was stored mainly in the leaves and also in the stems, "husks" and cobs, from where it was later mobilised to support grain development. The grain, therefore, eventually became the major storage organ for nitrogen. The nitrogen contained in the stems of nitrogen deficient plants was mobilised at an earlier growth stage than from other plant parts.

4. Dry matter was also mobilised from various plant parts especially the stems in order to meet the requirements of the grain sink. This occurred to a greater extent in N deficient plants.

5. Despite the development of classical visual N deficiency symptoms during late vegetative growth in plants from the control plots and those receiving 84 kg N/ha, a high total dry matter and grain yield was attained by these plants. This was attributed in part to the more efficient utilisation of available nitrogen in grain production by these plants.

6. The maintenance of a large leaf area over the major part of grain filling by plants from all treatments probably made a significant contribution to the high grain yields recorded.

7. High availability of water at all growth stages would certainly have made a substantial contribution to the high yields that were recorded.

8. The level of available soil nitrogen had a marked effect on the dry matter responses to fertiliser N. Some assessment of this source of nitrogen should be attempted prior to planting the crop in order to increase the efficiency of utilisation of N in maize production. This assessment is hampered by the lack of a sufficiently reliable field test for nitrogen availability.

9. The concentration of N in the mature grain increased with increasing rates of N fertiliser, but seemed to plateau with rates greater than 336 kg N/ha.

10. The roots contain a significant proportion (approximately 12%) of the total dry matter of the maize plant and thus have an important influence on source-sink relationships. This relationship warrants further detailed study.

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APPENDICES

* .05 > P > .01

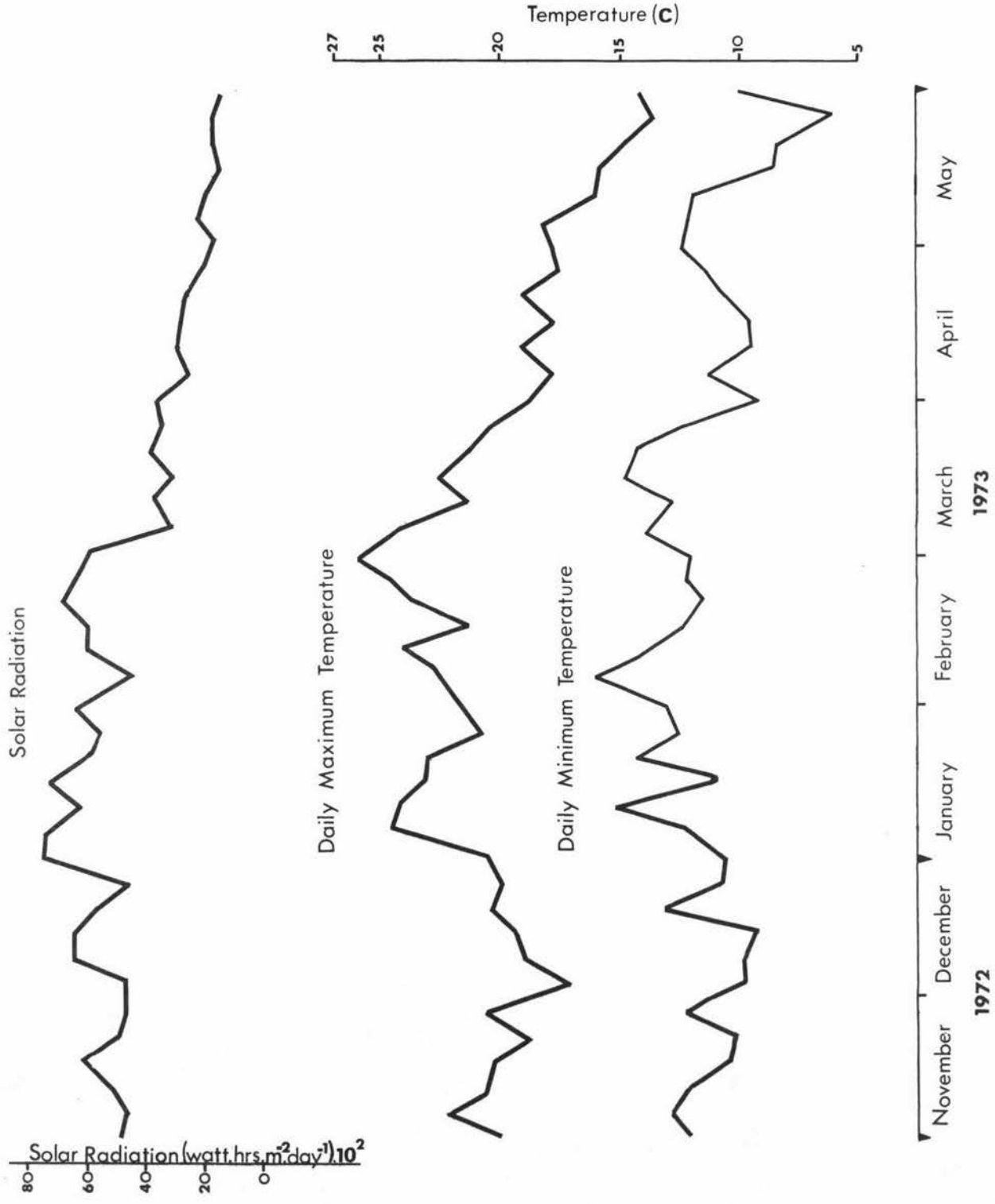
** P < .01

n.s. not significant at the 5% level

Appendix **1 (a)** Weather Data for the Experimental Period

Solar radiation data measured with an Eppley pyranometer at Ohakea R.N.Z.A.F Station.
Maximum and minimum temperatures, measured with standard meteorological instruments at Grasslands Division, D.S.I.R., Palmerston North.

All data is reported as five day averages.



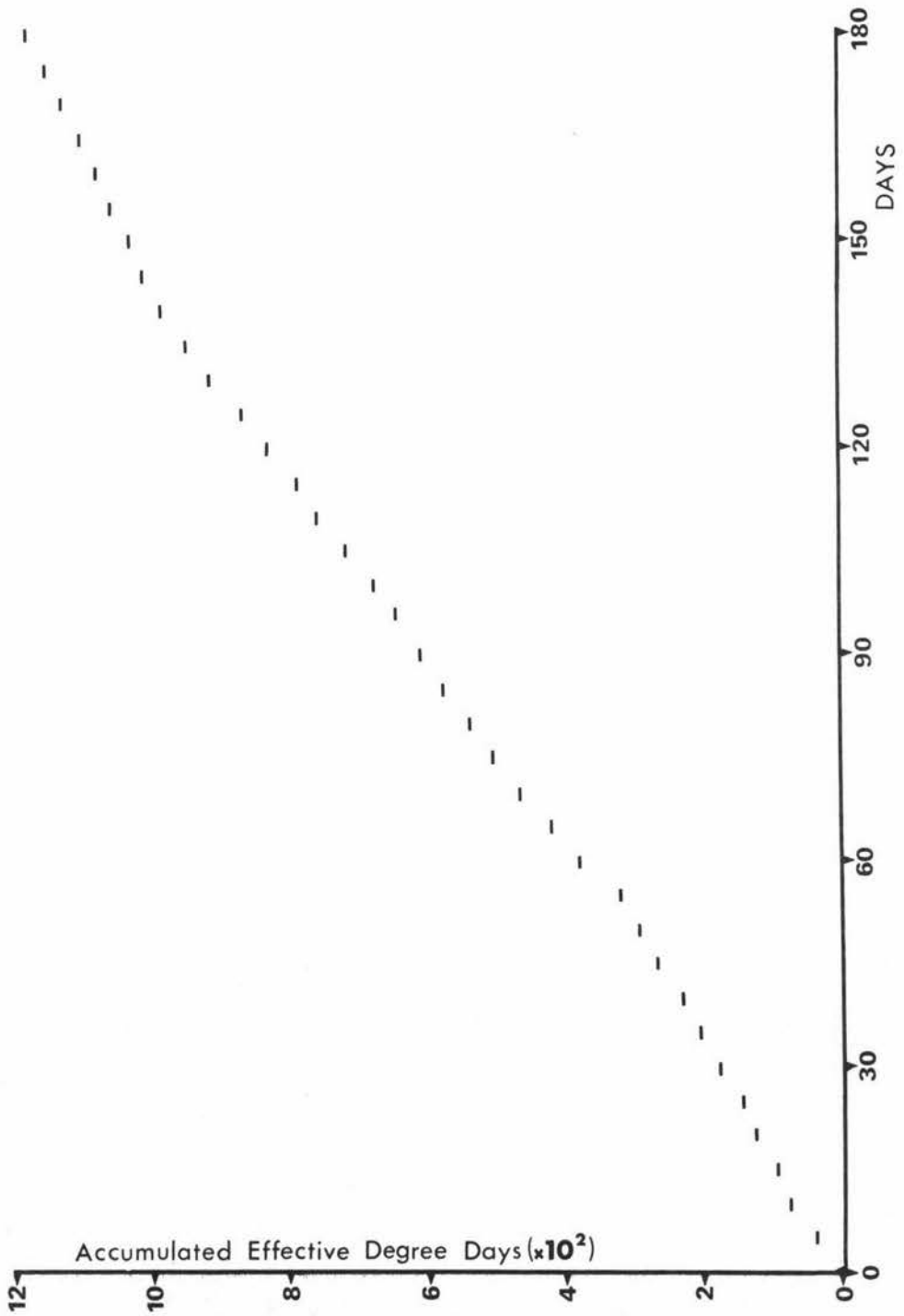
Appendix 1(b) Accumulated Effective Degree Days

Recording began November 6th, 1972, the date of sowing of the first replicate.

Effective degree days =

$$\left[\frac{\text{Daily max.(C)} + (\text{Daily min.(C) or 10C whichever greater})}{2}\right] - 10$$

(after Gilmore and Rogers, 1958)



Appendix 2 Schedule of Operations

Day from sowing	Date	Operation
	9.8.72	16 soil core samples, 2.5 cm diameter, taken to 15 cm depth on grid system over 0.13 ha plot area, for total nitrogen determination.
	17.8.72	Plot area ploughed.
	25.8.72	Discing, rolling and levelling.
	11.9.72	Fertiliser applied to plot area: 49 kg O.S.P., 336 kg lime.
	5.10.72	30 soil core samples, 2.5 cm diameter, taken to 18 cm depth on grid system over plot area for standard P and K availability tests.
	6.10.72	Cultivation with spring tyne cultivator.
	21.10.72	Cultivation with Dutch harrows.
	26.10.72	Applied 152 kg KCl, 152 kg O.S.P., 42.5 kg Kieserite (7.3 kg Mg; 10 kg S) to plot area using conventional combination drill.
	30.10.72	Applied propachlor weedicide at 4.5 kg/ha with 13.6 kg KCl and 31.7 kg O.S.P. using a Gravelly spreader.
	30.10-5.11.72	Placed 48 root containers in position.
0	6-9.11.72	Sowed crop. Gesapon 10 G insecticide applied with seed at 22 kg/ha. Four rows of guard plants sown around entire plot area.
6	12-15.11.72	Emergence. Planting time application of nitrogen (N).
13	19-21.11.72	Bulk of thinning and transplanting.

12–15	21.11.72	2.8 kg a.i/ha atrazine weedicide applied with 0.56 kg/ha Lannate insecticide. Beginning setting up of trickle irrigation system.
	27.11.72	8 tensiometers installed to 46 cm depth in soil over plot area.
21–24	30.11.72	Stand now complete.
23–26	2.12.72	Trickle irrigation system installed and working.
35	11–14.12.72	Harvest 1.
	15.12.72	Detailed study of soil profile in plot area.
42	18–20.12.72	Second N application.
59–62	4.1.73	First count to assess tiller production.
62–65	10.1.73	8 soil core samples, 2.5 cm diameter, taken at 15 cm and 30 cm depths at tensiometer sites for % moisture determinations.
	13.1.73	10 tensiometers installed to 15 cm depth, 8 at similar sites to those installed on 27.11.72.
69	14–18.1.73	Harvest 2. Soil core samples taken for % moisture determinations on 14.1.73. 16 root containers lifted.
	31.1.73	Second count for tiller production. Counts for tassel emergence.
85–88	2.2.73	Soil core samples taken for % moisture determinations.
93	7–13.2.73	Third N application at 50% silking.
99–102	16.2.73	Soil core samples taken for % moisture determinations.
104	18–21.2.73	Harvest 3.
118–121	7.3.73	Soil core samples taken for % moisture determinations.
119–122	8.3.73	Aerial application of Lannate insecticide.

127	11-14.3.73	Harvest 4.
131	15-16.3.73	16 root containers lifted.
141-144	30.3.73	Soil core samples taken for % moisture determinations.
146	1-4.4.73	Harvest 5.
149-153	7.4.73	Began checking in sample rows for black layer development.
153-156	11.4.73	Took leaf discs from all plots for chlorophyll determinations.
160-163	18.4.73	Soil core samples taken for % moisture determinations.
180	26.4.-5.5.73	Harvest 6 at physiological maturity.
184	6-7.5.73	16 root containers lifted. Experiment terminated.

O.S.P. = ordinary superphosphate. Mg = magnesium.

KCl = potassium chloride. S = sulphur.

Leaves

Appendix 3 Method for Determining Chlorophyll Content of Maize Leave

Materials:-

Extracting agent: 95% ethanol.

Method:-

10 ml of ethanol was pipetted into test tubes, arranged in labelled positions in racks, and each containing 5 leaf discs (total area, 15.45 cm^2), representing one plot treatment. The leaf discs were previously held in a refrigerator in labelled screw top glass jars lined with moist filter paper. The test tubes were capped with aluminium foil and the levels of liquid marked before being placed in a water bath for 10 minutes at 83C.. Not all the chlorophyll was extracted from the leaf discs in this time.

After extraction, the racks of test tubes were immersed in cold water and then placed in a refrigerator prior to the colour density being read on an E.E.L. Portable Colorimeter, previously zeroed using an ethanol blank. Levels in the test tubes were made up to the 10 ml mark with ethanol before the samples were transferred to matched colorimeter tubes and the colour density read using the Ilford filter 608. All readings were taken within half an hour of extraction.

Appendix 4 Micro-Kjeldahl Method for Determining Nitrogen Content of Plant Material (basically as described by Clements, 1970)

Materials:-

Digestion mixture: 100 g K_2SO_4 with 1 g selenium powder and 1 litre of concentrated, nitrogen free, H_2SO_4. Mixture heated in fume cupboard until clear.

Indicator mixture: 5 volumes of 0.1% ethanolic solution of bromocresol green to 1 volume of 0.1% ethanolic solution of methyl red.

Boric acid indicator mixture: 2% W/V H_3BO_3 with distilled water, containing 2% V/V indicator mixture.

Hydrochloric Acid: 0.01 N HCl (diluted from standard IN HCl).

Sodium hydroxide: 500 g NaOH per 2 litres of distilled water.

Method:-

Before analysis the finely ground plant material was dried for approximately 8 hours at 95C. 280 mg of each sample was accurately weighed and digested with 5 ml of digestion mixture in 50 ml Kjeldahl flasks, placed in labelled positions on the heating units. Some glass anti-bumping granules were added to each flask before carefully boiling for 2-2½ hours in a fume cupboard, until the solution cleared. During the first half hour of digestion the flasks were frequently turned to ensure complete digestion of the sample. A blank (no plant material added) was included in each run of 22 samples.

After digestion the flasks were allowed to cool for half an hour in the fume cupboard; less than 0.5 ml of distilled water was then added after which the samples were diluted to a 70 ml mark etched on the neck of the flasks. The flasks were stoppered and inverted 3 times following which the digestate was poured into labelled, air-tight containers, being ready for distillation. Samples were kept for no longer than 18 hours before distilling; Clements (1970) suggests that they may be kept in sealed containers for several days without loss of nitrogen.

The Markham still was utilised for the distillations. The outlet from the still was submerged under 5 ml of boric acid indicator mixture in a 100 ml conical flask. 5 ml of diluted digestate was added to the inlet cup of the still plus about 10 ml of NaOH; the stopper was then removed to allow entry into the inner chamber, on replacing the stopper a little NaOH was again added to the cup to prevent nitrogen losses at

this junction during distillation. About 30 ml of distillate was collected in the boric acid indicator mixture, which was then titrated against 0.01 N HCl, the colour change being from blue to mauvy-grey. Before distilling the next sample of digestate, the inner chamber of the still was emptied and flushed with distilled water.

Standardisation of still:-

The method described produced highly repeatable percentage nitrogen estimations and recovery of nitrogen from $(NH_4)_2 SO_4$ standards was greater than 95%, when checks were run periodically during the analysis. Recovery figures in this region are considered acceptable by other workers (Chu, pers. comm.). Clements (1970) obtained figures of 97% or greater for recovery of nitrogen from $(NH_4)_2 SO_4$ standards.

Calculation:-

N% = (titre (sample)-titre (blank)) x 7/10, for a 280 mg sample and where titres are expressed in ml 0.01 N HCl. For sample weights other than 280 mg appropriate adjustments were made.

Appendix 5 Analysis of Variance of Grain Dry Weight Per Plant and Total Dry Weight Per Hectare at Harvest 6 (Physiological Maturity).

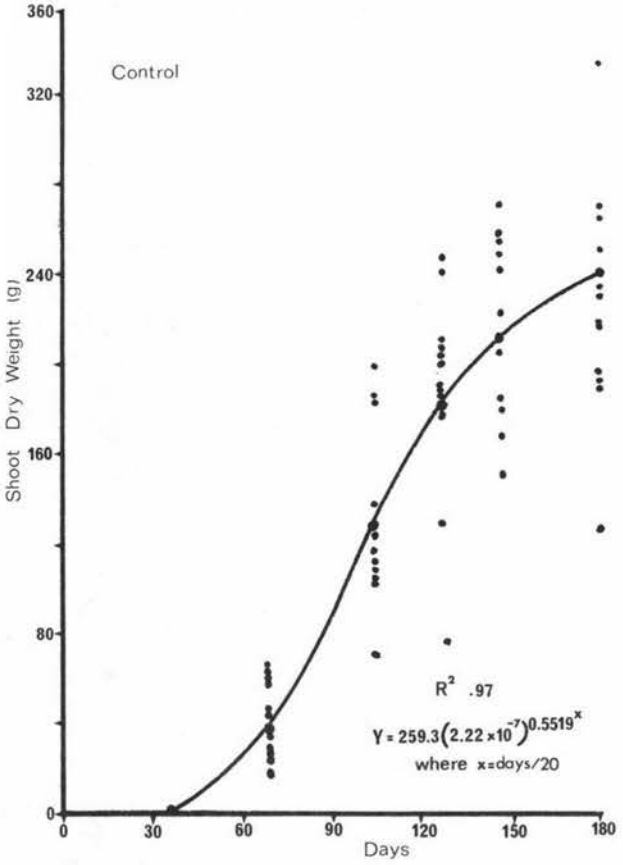
(a) Grain dry weight per plant. (g)

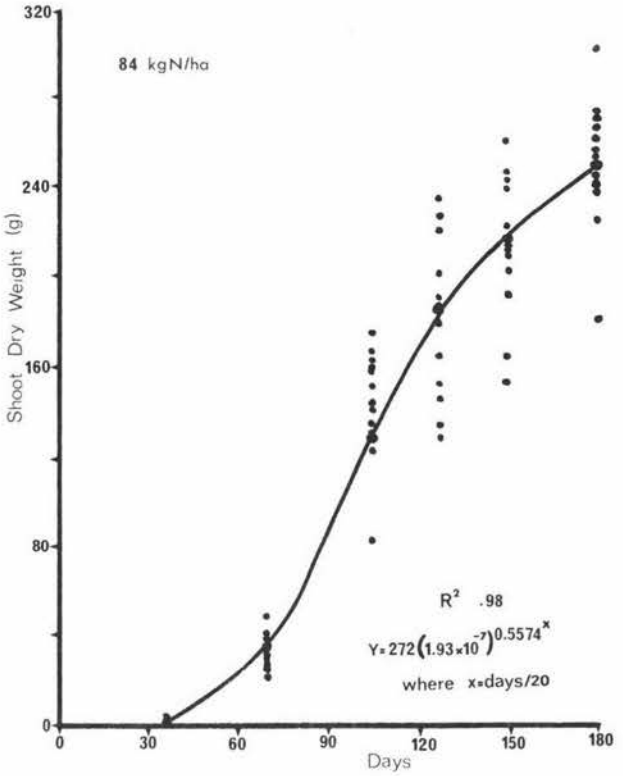
Source	df	Mean Squares	
Block	3	341.34	n.s.
Main Factor	4	971.11	n.s.
Error 1	12	436.13	
Subfactor	2	15.04	n.s.
Interaction	8	257.42	n.s.
Error 2	30	443.20	
Total	59		

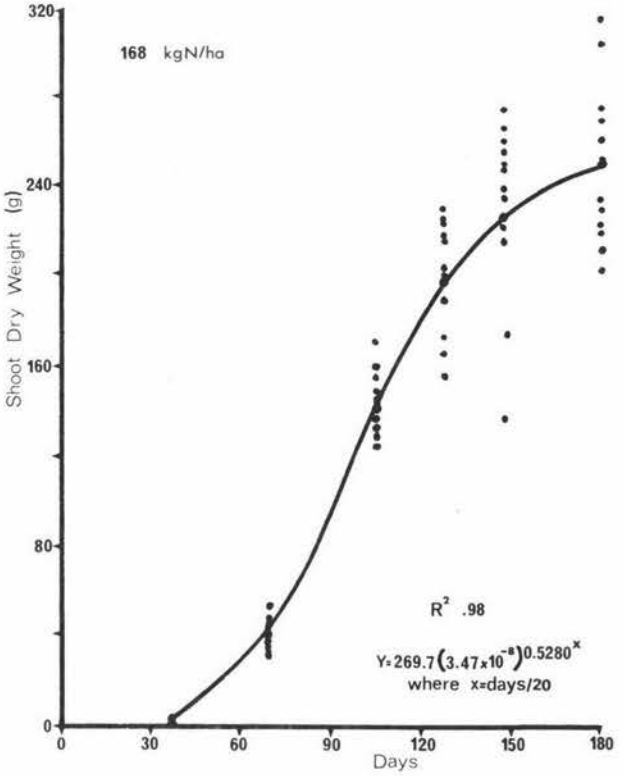
(b) Total dry weight per hectare. (kg/ha)

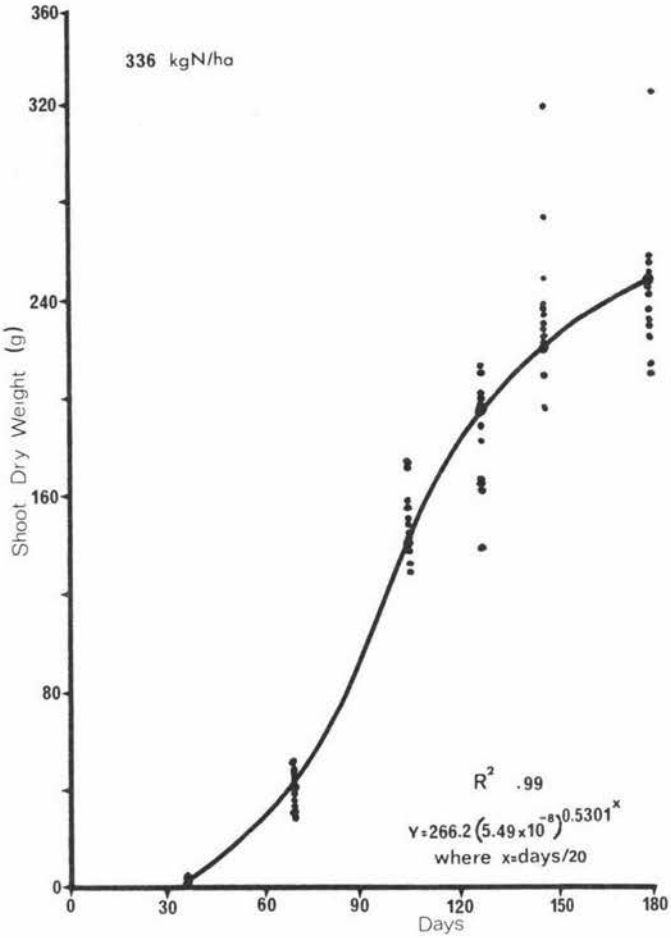
Source	df	Mean Squares	
Block	3	14556142.75	n.s.
Main Factor	4	33985139.28	n.s.
Error 1	12	11725127.01	
Subfactor	2	3129115.25	n.s.
Interaction	8	1149955.89	n.s.
Error 2	30	21452251.77	
Total	59		

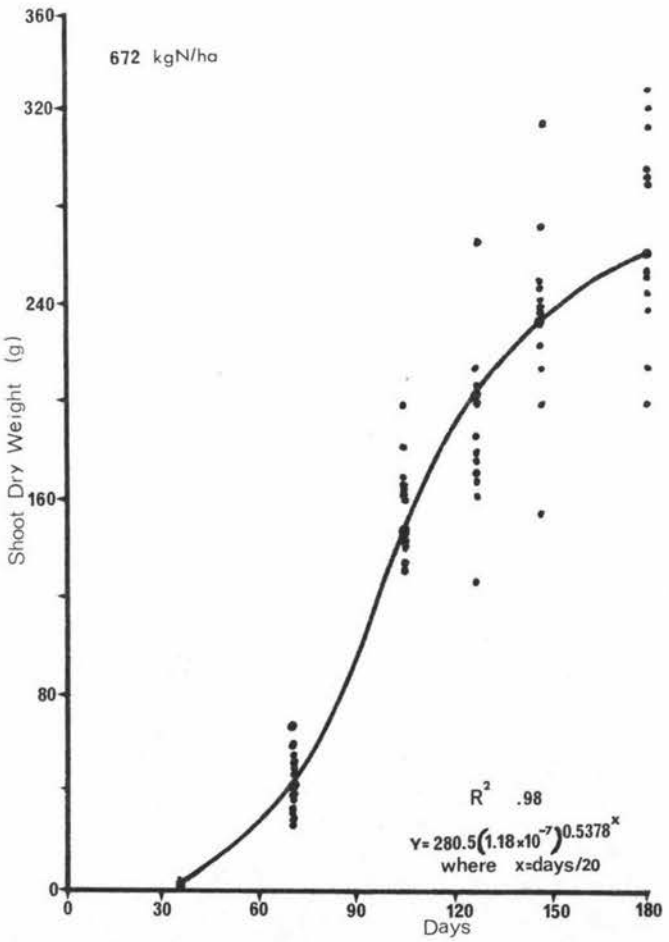
Appendix 6 Growth in Total Dry Weight Per Plant



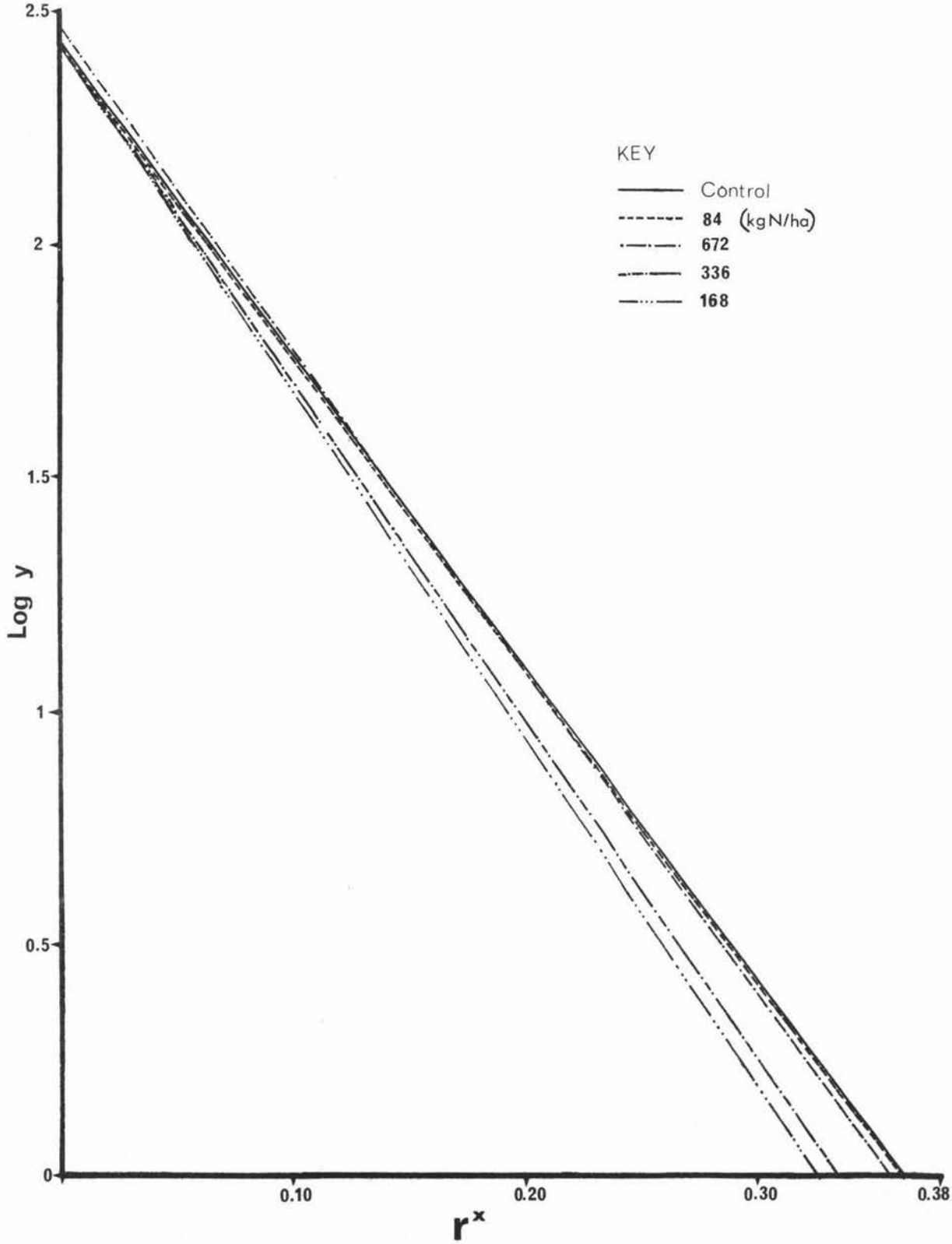





336 kgN/ha
Shoot Dry Weight (g)
360
320
240
160
80
0
0
30
60
90
120
150
180
Days
R² .99
Y=266.2 (5.49x10⁻⁸)^0.5301^x
where x=days/20


672 kgN/ha
Shoot Dry Weight (g)
360
320
240
160
80
0
0
30
60
90
120
150
180
Days
R² .98
Y= 280.5(1.18x10⁻⁷)^0.5378^x
where x=days/20

Appendix 7 Comparison of Dry Matter Increment (y) with Time (x, days).
(Linear form of Gompertz Curves)



Appendix 8 Analysis of Variance of Leaf Dry Weight Per Plant at Harvests 3, 4, 5 and 6.

(a) Leaf dry weight per plant at harvest 3. (g)

Source	df	Mean Squares	
Block	3	38.15	n.s.
Main Factor	4	123.91	**
Error 1	12	12.38	
Subfactor	2	21.73	n.s.
Interaction	8	21.88	n.s.
Error 2	30	23.35	
Total	59		

(b) Leaf dry weight per plant at harvest 4. (g)

Source	df	Mean Squares	
Block	3	26.03	n.s.
Main Factor	4	84.09	**
Error 1	12	10.13	
Subfactor	2	30.51	n.s.
Interaction	8	62.88	*
Error 2	30	25.47	
Total	59		

Appendix 8 (continued)

(c) Leaf dry weight per plant at harvest 5. (g)

Source	df	Mean Squares	
Block	3	82.82	**
Main Factor	4	116.27	**
Error 1	12	13.31	
Subfactor	2	37.98	n.s.
Interaction	8	29.78	n.s.
Error 2	30	22.89	
Total	59		

(d) Leaf dry weight per plant at harvest 6. (g)

Source	df	Mean Squares	
Block	3	91.36	*
Main Factor	4	89.43	*
Error 1	12	25.94	
Subfactor	2	29.10	n.s.
Interaction	8	28.56	n.s.
Error 2	30	19.75	
Total	59		

Appendix 9(a) Summary of Leaf Area and LAI per Plant for the Main Factor Treatments (N rate).

Table (a) Summary of leaf area per plant. (cm^2)

Harvest Number	N rate (kg/ha)					S.E.+	Significance level
	0	84	168	336	672		
2	3900	3887	3996	4083	4146	361.6	n.s.
3	5171	5424	5530	5588	5810	178.3	*
4	5709	5385	6271	5734	5837	169.8	**
5	5036	4788	5631	5508	5634	191.2	**
6	2843	3024	3758	3192	3651	290.0	*

+S.E. for comparison of means between N rates.

Table (b) Summary of LAI per plant.

Harvest Number	N rate (kg/ha)				
	0	84	168	336	672
1	0.15	0.19	0.18	0.16	0.19
2	3.82	3.81	3.91	4.00	4.06
3	5.07	5.32	5.42	5.48	5.70
4	5.60	5.28	6.14	5.62	5.72
5	4.93	4.69	5.52	5.39	5.52
6	2.78	2.96	3.68	3.13	3.58

Appendix 9(b) Analysis of Variance of Sheath Area per Plant at Harvest 6 (Physiological Maturity).

Sheath area per plant. (cm^2)

Source	df	Mean Squares	
Block	3	19413.96	n.s.
Main Factor	4	92526.41	*
Error 1	12	18063.46	
Subfactor	2	55377.43	*
Interaction	8	36956.80	*
Error 2	30	15018.72	
Total	59		

Appendix 10 Analysis of Variance of Leaf Dry Matter Content and Stem Dry Matter Content at Harvest 6 and Harvest 3 and 4 Respectively.

(a) Leaf dry matter content (on a fresh weight basis) at harvest 6. (%)

Source	df	Mean Squares	
Block	3	12.02	n.s.
Main Factor	4	54.89	*
Error 1	12	12.04	
Subfactor	2	17.88	n.s.
Interaction	8	11.59	n.s.
Error 2	30	10.17	
Total	59		

(b) Stem dry matter content (on a fresh weight basis) at harvest 3. (%)

Source	df	Mean Squares	
Block	3	1.86	n.s.
Main Factor	4	14.55	*
Error 1	12	3.18	
Subfactor	2	0.69	n.s.
Interaction	8	4.66	n.s.
Error 2	30	2.09	
Total	59		

Appendix 10 (continued)

(c) Stem dry matter content (on a fresh weight basis) at harvest 4. (%)

Source	df	Mean Squares	
Block	3	2.82	n.s.
Main Factor	4	16.43	**
Error 1	12	1.68	
Subfactor	2	1.74	n.s.
Interaction	8	0.73	n.s.
Error 2	30	1.35	
Total	59		

Appendix 11 Analysis of Variance of Total Shoot Nitrogen Yield per Hectare at Harvests 2, 4 and 6.

(a) Total shoot nitrogen yield at harvest 2. (kg/ha)

Source	df	Mean Squares	
Block	3	1032.19	n.s.
Main Factor	4	3670.16	*
Error 1	12	1088.21	
Subfactor	2	2855.38	*
Interaction	8	980.72	n.s.
Error 2	30	659.99	
Total	59		

(b) Total shoot nitrogen yield at harvest 4. (kg/ha)

Source	df	Mean Squares	
Block	3	3231.29	n.s.
Main Factor	4	26667.01	**
Error 1	12	1770.21	
Subfactor	2	173.86	n.s.
Interaction	8	6824.55	**
Error 2	30	1396.86	
Total	59		

Appendix 11 (continued)

(c) Total shoot nitrogen yield at harvest 6. (kg/ha)

Source	df	Mean Squares	
Block	3	6302.20	*
Main Factor	4	28109.12	**
Error 1	12	1696.39	
Subfactor	2	1006.10	n.s.
Interaction	8	2722.12	n.s.
Error 2	30	2947.23	
Total	59		

Appendix 12 Analysis of Variance of Leaf Nitrogen Content per Plant at Harvests 2, 4 and 6.

(a) Leaf nitrogen content per plant at harvest 2. (g)

Source	df	Mean Squares	
Block	3	0.0512	n.s.
Main Factor	4	0.1096	n.s.
Error 1	12	0.0433	
Subfactor	2	0.0890	n.s.
Interaction	8	0.0379	n.s.
Error 2	30	0.0321	
Total	59		

(b) Leaf nitrogen content per plant at harvest 4. (g)

Source	df	Mean Squares	
Block	3	0.1116	**
Main Factor	4	0.3329	**
Error 1	12	0.0117	
Subfactor	2	0.0091	n.s.
Interaction	8	0.0520	*
Error 2	30	0.0206	
Total	59		

Appendix 12 (continued)

(c) Leaf nitrogen content per plant at harvest 6. (g)

Source	df	Mean Squares	
Block	3	0.0731	*
Main Factor	4	0.1260	**
Error 1	12	0.0204	
Subfactor	2	0.0155	n.s.
Interaction	8	0.0108	n.s.
Error 2	30	0.0131	
Total	59		

Appendix 13 Summary of Leaf, Stem and Root N Concentration per Plant for the Main Factor Treatment (N rate).

Table (a) Nitrogen concentration in the leaves. (%)

Harvest Number	N rate (kg/ha)					S.E.+	Significance level
	0	84	168	336	672		
1 (35)	3.74	3.83	3.78	3.76	3.95	0.189	n.s.
2 (69)	2.84	3.11	3.16	3.47	3.35	0.091	**
4 (127)	1.91	2.21	2.52	2.62	2.82	0.106	**
6 (180)	1.50	1.69	2.20	2.01	2.06	0.157	**

+S.E. for comparison of means between N rates.

() days after planting.

Table (b) Nitrogen concentration in the stems. (%)

Harvest Number	N rate (kg/ha)					S.E.+	Significance level
	0	84	168	336	672		
1	3.61	3.59	3.86	3.39	3.80	0.263	n.s.
2	1.78	2.21	2.24	2.37	2.58	0.139	**
4	0.29	0.42	0.63	0.81	0.89	0.078	**
6	0.47	0.43	0.48	0.63	0.79	0.089	**

+S.E. for comparison of means between N rates.

Appendix 13 (continued)

Table (c) Nitrogen concentration in the roots. (%)

Harvest Number	N rate (kg/ha)	N%	S.E.+	Significance level
1	0	1.62	0.224	n.s.
	168	1.91	0.200	
	672	1.78	0.153	
2	0	1.25	0.436	*
	168	1.39	0.238	
	672	1.87	0.149	
4	0	0.80	0.348	*
	168	0.73	0.031	
	672	1.30	0.196	
6	0	0.68	0.090	**
	168	0.82	0.138	
	672	1.12	0.119	

+S.E. associated with each mean

Appendix 14 Analysis of Variance of Leaf Nitrogen Concentration per Plant at Harvest 4.

Leaf nitrogen concentration per plant at harvest 4. (%)

Source	df	Mean Squares	
Block	3	0.4312	**
Main Factor	4	1.5293	**
Error 1	12	0.0676	
Subfactor	2	0.2246	*
Interaction	8	0.1326	n.s.
Error 2	30	0.0654	
Total	59		

Appendix 15 Summary of Grain Nitrogen Concentration per Plant at Harvests 4, 5 and 6 for the Main Factor Treatment (N rate).

Grain nitrogen concentration per plant. (% and % crude protein)

Harvest Number	Unit	N rate (kg/ha)					S.E.++	Significance level
		0	84	168	336	672		
4	N%	1.67	2.09	2.02	2.13	2.04	0.133	*
	%cr.pr.+	10.44	13.06	12.63	13.31	12.75		
5	N%	1.29	1.30	1.46	1.53	1.54	0.065	**
	%cr.pr.	8.06	8.13	9.13	9.56	9.63		
6	N%	1.33	1.36	1.39	1.56	1.58	0.056	**
	%cr.pr.	8.31	8.50	8.69	9.75	9.88		

+% cr.pr. (percentage crude protein) = N% x 6.25

++S.E. for comparison of means between N rates.