THE EFFECTS OF LATE NITROGEN ON THE YIELD AND QUALITY OF MILLING WHEAT

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ABSTRACT

The quality of wheat milled to produce flour for leavened bread is related to its protein content. The presence of specific proteins in milling wheat gives dough its elastic properties and dertermines baking quality. Good quality wheat will produce loaves with high volumes and a fine crumb texture. It is known that wheat cultivars differ in their ability to produce good quality bread through differences in the composition of their protein. In cultivars of good quality, the greater the protein content, the better the quality of bread produced.

The Manawatu Mills Limited, Palmerston North varies the price it pays for milling wheat according to cultivar and protein content. Premiums can be obtained by increasing grain protein content. This presents local wheat growers with the financial incentive to improve the yield and quality of their crops.

To investigate the feasibility of using late applications of nitrogen fertiliser to increase the protein content and yield of milling wheat three trials were carried out at different sites during the spring and summer of 1989/90. These sites were at Kairanga, Almadale and Waituna West in the Manawatu region using the cultivar Rongotea. They were chosen to provide a range of environmental conditions, particularly temperature, over which to test the effect of nitrogen fertiliser on protein content. To achieve different temperature regimes, these sites are situated at low, medium and high altitude. It has been suggested that temperature over the grain-fill period can influence both protein content and composition of wheat, which in turn influences its ability to produce good quality bread. Four different rates of nitrogen fertiliser were applied just prior to the boot stage. These were 0, 20, 40 and 80 kg N/ha.

There were significant differences in grain yield amongst sites with Kairanga achieving 6.4 tonnes/ha, Almadale 5.9 tonnes/ha and Waituna West 6.8 tonnes/ha. These yields were above the long term district average. Grain yield responded to late nitrogen at Kairanga and Waituna West. Yields increased from 6.1 to 6.9 tonnes/ha at Kairanga and from 6.4 to 7.2 tonnes/ha at Waituna West as application rates increased from zero to 80 kg N/ha. Any potential yield response at Almadale was suppressed due to an

infection of the root rot fungus, 'take-all'. The yield response at Kairanga resulted from an increase in grain weights whereas at Waituna West it resulted from an increase in ear numbers at harvest. At both responsive sites late nitrogen delayed conopy senescence.

Protein contents also varied significantly amongst sites and in response to the application of nitrogen fertiliser. Protein content (14% moisture basis) ranged from 8.87 to 10.87% at Kairanga, from 10.35 to 11.28% at Waituna West and from 12.97 to 13.69% at Almadale as application rates increased from zero to 80 kg N/ha. The differences in protein levels obtained from different sites resulted in a considerable variation in baking quality. Samples from eight plots from each site were sent to the Wheat Research Institute, Christchurch, for test baking. Average bake scores were 19 at Kairanga, 21 at Waituna West, and 26 at Almadale. There was a strong, positive relationship between bake score and grain protein content amongst these samples. A convenient measure of baking quality, the sodium dodecyl sulphate test, was used to estimate baking quality of each plot. This allowed the relationship between baking quality and grain protein content to be identified for each site. The relationship between protein and baking quality differed between sites, being much stronger at Kairanga than at Almadale and Waituna West. The relatively poor relationship between protein and baking quality at Waituna West and Almadale can be partly explained by the limited range of protein contents resulting from treatment effects, particularly at Almadale. There was evidence that site had influenced the relationship between protein content and baking quality.

At Kairanga and Waituna West late applications of nitrogen fertiliser significantly increased both grain yield and protein content. The yield increases, combined with the price premiums for increased protein, meant that it would have been profitable to apply late nitrogen. At Almadale there was no yield response and the protein response was limited, making late applications of nitrogen uneconomic. Pest and disease pressure at Almadale reduced yield, contributing to grain protein content being above the point where premiums are available. It was concluded that it can be economically feasible to use late applications of nitrogen on crops which have a high potential yield. Factors limiting yield, such as pests, diseases and moisture stress, will limit any potential benefit.

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ABBREVIATIONS USED

°C	degrees Celsius
cv	coefficient of variation
DM	dry matter
gr	grain
G.S.	growth stage
ha	hectare
HI	harvest index
HMW	high molecular weight
kg	kilograms
LAD	leaf area duration
LAI	leaf area index
LMW	low molecular weight
LSD	least significant difference
m	metre
mm	millimeter
MDD	mechanical dough development
mg	milligrams
MJ	megajoules
N	nitrogen
NAR	net assimilation rate
NHI	nitrogen harvest index
SDS	sodium dodecyl sulphate
W	Watts
WRI	Wheat Research Institute
wt	weight

CHAPTER I

INTRODUCTION

New Zealand has an annual requirement for milling wheat of approximately 300,000 tonnes (Loney, 1989). However there has nearly always been a shortfall in supply, with importation of mainly Australian wheat required in most years (Logan, 1985). The level of imports has risen from approximately 26,000 tonnes in 1979 (Stonyer and Durbin, 1981) to 170,000 tonnes in 1989 (Anon., 1990a). During this period the New Zealand wheat industry was deregulated.

In February 1987 the New Zealand Wheat Board no longer controlled the internal market or importation of milling wheat. Individual mills were responsible for securing their own supplies and determining the quality requirements for the wheat they purchased. Deregulation was implemented to expose the industry to market forces. Under Wheat Board control there was no emphasis placed on quality requirements nor were there any objectives in place to meet future needs (Lindley, 1989).

Deregulation occurred at a time when increasing emphasis was being placed on milling wheat quality as competing exporters have attempted to hold or improve market share (Wilson, 1990). This and the fact that the New Zealand industry had been insulated from market forces meant that deregulation was traumatic for the industry (Ryan, 1989).

Today the New Zealand wheat crop is competing against imported wheat of high quality with both price and quality set by wheat on the world market, particularly Australian wheat (Gray, 1989).

The Manawatu Mills in Palmerston North supplies flour to bakeries in the southern North Island. Their annual requirement for bread wheat is 22,500 tonnes and for biscuit wheat 5,500 tonnes (Mitchell, 1990). Wheat growers supplying the Manawatu Mills are contracted to sell wheat at a price which can vary according to the quality of the wheat they supply. Quality is determined by an index system with lines of wheat achieving

100 index points receiving the base price (Anon., 1989). Lines can achieve more or less than the base price depending on the final index points they achieve. The index is made up of two parts: one is the contribution from the cultivar growers choose and the other from the protein content of the wheat produced. Only cultivars with acceptable baking characteristics are eligible. Protein content is included in the index because protein is the most important constituent of wheat affecting its baking quality (Moss, 1981). The cultivar index has a narrow range with only two points separating the three cultivars specified. However the protein index provides wheat producers with the opportunity to achieve price premiums of up to 16% with index points rising as protein contents go from 10.0% to 12.9% and over (Anon., 1989). There is a positive relationship between protein content and baking quality in milling wheat (Moss, 1981). Even though this relationship is imprecise (Wilson, 1990), protein content is used as a convenient measure of quality in milling wheat. The relationship also varies with cultivar (Cawley, 1981), hence the inclusion of cultivar in the quality index.

The last nationwide surveys of wheat protein contents occurred in 1982 and 1983. The mean levels in those years were 10.7% and 10.5% respectively (Lindley and Humphrey-Taylor, 1987). Two milling wheat cultivars, Oroua and Rongotea eligible for supply to the Manawatu Mills were included in those surveys. In 1982 Oroua grown in the southern North Island had a protein content of 10.9% and Rongotea 10.2%. In 1983 protein contents rose to 11.2% and 10.8% for Oroua and Rongotea respectively. More recently protein contents have apparently increased (G Georgiou, Manawatu Mills, pers. comm.). In the 1989/90 season for example Rongotea achieved an average protein content of 11.5% for lines received at the Manawatu Mills.

For wheat with a protein content of less than 10.0%, the Manawatu Mills reserves the right to decline purchase. For many lines of southern North Island wheat there is an opportunity to increase returns from price premiums for achieving higher protein levels.

Nitrogen fertiliser can be used to increase grain protein content (Martin *et al.*, 1989). While applications applied early in the crop's development have more effect on yield than protein content, applications made after the main yield determining growth stages

raise grain protein content (Drewitt and Dyson, 1987). Yield increases may be possible with latter use of nitrogen fertiliser through increased grain size (Drewitt, 1985).

Environmental factors can influence the relationship between grain protein and baking quality. In particular, temperatures over the grain-fill period have been shown to influence this relationship (Randall and Moss, 1990; Stevenson, 1987a).

This study was undertaken to examine the use of late applications of nitrogen fertiliser on milling wheat at different sites in the Manawatu. The following objectives were set:

-   Assess the feasibility of using late applications of nitrogenous fertiliser to increase the yield and premiums received for milling wheat.

-   Investigate the use of the SDS sedimentation test as a measure of baking quality.

-   Determine the response of bake score and SDS volume to increased grain protein content.

-   Investigate the influence of environment on the relationship between grain protein content and baking quality.

A review of the literature on yield and baking quality in milling wheat and the effect of nitrogen on these attributes is presented in chapter II. Chapter III describes the proceedures used in the field and laboratory during this study. The results have been presented in four different chapters covering environmental aspects, yield, protein content and baking quality. A preliminary discussion is also presented in each of the results chapters. A final discussion brings all results together. The major conclusions from this study are listed in the final chapter.

CHAPTER II

REVIEW OF LITERATURE

2.1   Yield Development

Early investigative work on grain yield in cereals led to the resolution of yield into components. They were: plants/m^2, ears/plant, grains/ear and grain weight (Engledow and Wadham, 1923). The high degree of flexibility and inter-relationship between these components was recognised at this time also. Later, the relationship between crop growth and yield components was investigated, particularly the important growth characteristics of tillering and tiller survival (Frankel, 1935). A high degree of flexibility of yield components allows adaption to a wide range of environmental conditions (McEwan, 1964). The first three components together determine the potential number of grains/m^2. This occurs by the completion of anthesis, when grain set is determined. Grain weight is determined after anthesis (Brooking, 1979). While study of these yield components is useful for determining the structure of grain yield, it does not explain the underlying physiological processes. It is the assimilation of dry matter (DM) and its distribution within the plant that actually determines yield (Langer, 1967; Biscoe and Willington, 1982).

The assimilation of DM is directly related to the amount of photosynthetically active radiation absorbed by the crop (Jamieson and Wilson, 1989). This relationship is consistent between seasons, sites and cultivars (Gallagher and Biscoe, 1978a). Grain yield is dependent not only on total DM assimilation but also on the proportion of this DM distributed to the grain. The ratio of grain to total DM at harvest is known as the harvest index (Gallagher and Biscoe, 1978b).

The absorption of radiation through photosynthesis is directly related to the area of green leaf of a crop (Puckridge, 1971). Leaf area per unit ground area is known as the leaf area index (LAI) while longevity of leaf area is often expressed as leaf area duration (LAD) (Watson, 1947). Leaf area and LAD in combination with photosynthesis and

respiration rates, are the primary determinants of the source capacity or assimilate supply of a crop (Novoa and Loomis, 1981). The rate of DM accumulation in a crop is the product of leaf area and the rate of net photosynthesis per unit of leaf area, or net assimilation rate (NAR) (Watson, 1947). The destination of assimilates is the sink and the demand for assimilates, the sink size (Langer, 1967). Alternative sinks in a wheat plant include the stems, roots and ears. However the ear has greater priority and capacity for assimilates than the alternative sinks (Spiertz, 1978).

Important environmental factors influencing LAI and LAD include temperature, moisture and disease. Temperature influences the size and appearance rate of leaves with higher temperatures generally decreasing the time to achieve maximum LAI (Friend, 1965b) and increasing leaf size up until about 20°C (Friend, 1966). However, high temperatures also increase the rate of leaf senescence, reducing LAD (Spiertz, 1974). Moisture stress reduces LAI by reducing leaf appearance rates (Gallagher and Biscoe, 1979) and leaf size (Jamieson and Wilson, 1989), while also reducing LAD by increasing senescence rates (Biscoe and Willington, 1982). Control of foliar diseases which destroy green leaf tissue can significantly increase LAI and LAD (Spiertz, 1973).

The above factors all influence the area of green leaf available to intercept solar radiation. The conversion of intercepted radiation to DM proceeds at nearly constant efficiency (Biscoe and Willington, 1982). However the efficiency of radiation use can be reduced. In particular, moisture stress can reduce radiation use efficiency (Jamieson and Wilson, 1979). However, the effect of moisture stress on the conversion of intercepted radiation to DM is only of secondary importance to the effect moisture stress has on the amount of radiation intercepted in the first place (Legg *et al.,* 1979).

The availability of nitrogen (N) can influence yield development in wheat. In this review of the effects of N on wheat, N is defined as N containing compounds, both mineral and organic which are found in soil/plant systems.

The application of fertiliser N can increase the LAI and therefore radiation interception in wheat (Pearman *et al.,* 1977; Gallagher and Biscoe, 1978a; Spiertz and Ellen, 1978)

by increasing the size of individual leaves (Langer and Liew, 1973) and by increasing the number of tillers per plant (Pearman *et al.,* 1977). Leaf number per mainstem is not influenced by N supply (Langer and Liew, 1973).

LAD is also influenced by N supply (Pearman *et al.,* 1977; Spiertz and Ellen, 1978; Spiertz and De Vos, 1983). LAD is especially important during the grain-fill period. Most of the assimilates used for grain growth originate from photosynthesis in the top few leaves after anthesis (Langer, 1967). However, after ear emergence (immediately prior to anthesis) no new leaves are produced so maintaining photosynthetic capacity is dependent on maintaining the existing leaf area (Gallagher and Biscoe, 1978a). The demand for N by developing grain is very high, consequently N is often translocated from vegetative tissue to satisfy this demand, increasing the rate of leaf senescence and decreasing LAD and the grain-fill period (Sinclair and de Wit, 1975). The proportion of grain N derived from reserves present by anthesis can be almost 100% in situations where soil mineral N is not available (Puckridge and Donald, 1967) to less than 50% where large quantities of N are taken up after anthesis (Spiertz and Ellen, 1978).

Improved N supply can increase (Spiertz and van de Haar, 1978) or decrease (Pearman *et al.,* 1977; Gregory *et al.,* 1981) NAR. Gregory *et al.,* (1981) found that it was the fractional loss of N from leaves which determined NAR. Pearman *et al.,* (1977) found that N decreased NAR but that the associated increase in leaf area resulted in significantly increased DM production. Spiertz and van de Haar (1977) also found that increased DM accumulation resulting from increased N was mainly due to increased leaf area rather than NAR. The decrease in NAR associated with an increase in N supply may be due to an increase in dark respiration rates (Pearman *et al.,* 1977; Spiertz and van de Haar, 1978) or simply due to an imbalance between source and sink (Evans, 1975). If the source capacity is greater than the available sink size, then increasing N supply, resulting in increased leaf area or LAD, may cause a compensating fall in NAR (Evans and Rawson, 1970).

2.2 Effect of Nitrogen Fertilisation on Yield

Nitrogen fertilisation experiments have been carried out in New Zealand since the early part of this century (Wright, 1967). The benefits of N fertiliser for wheat yields in some situations have long been recognised. Lynch, (1959) after reviewing 35 years of experiments with N on wheat, concluded that the only recommendation that could be given was that N fertiliser should only be applied to wheat sown into stubble, rather than ground previuosly in pasture or forage crops. Little N fertiliser was used on wheat crops in New Zealand up until the late 1960's (Wright, 1967) because of the practice of growing wheat crops in paddocks out of pasture (Claridge, 1972).

The demand for N in a growing crop is dependent on the growth rate and N content of new tissue, which in turn varies with N availability, moisture availability, temperature and plant competition (Novoa and Loomis, 1981). The response of wheat to N fertiliser is dependent on the availability of N in the soil, with soils having large reserves of N being very unlikely to produce yield responses to N fertiliser (Wright, 1969; Montgomery, Inch and Baird, 1986; Withers, 1986). In New Zealand, crop history is a strong indicator of soil N reserves, particularly the length of period since the ground was in permanent clover based pasture (Wright, 1967), due to the large reserves of organic N present under these pastures (Keeney and Gregg, 1982).

Methods used to measure the N status of soil as an indicator of fertiliser N requirements include measuring soil nitrate levels (inorganic N) (Ludecke, 1974) and also the amount of potentially mineralisable N (organic N) present in the soil (Quin, Drewitt and Stephen, 1982). Paddock history has been used to form the basis of an index of the N status of paddocks in Britain (Needham, 1982) and New Zealand (Montgomery, Inch and Baird, 1986), with N fertiliser recommendations based on the index and assessment of potential yield for the site when N is not limiting. The measurement of the N status of the crop itself is another approach used to make fertiliser N recommendations. This has been achieved by measuring the sap nitrate concentration by use of indicator test strips (Withers and Palenski, 1984; Withers, 1986). A guide to the use of this sap nitrate test and a full set of recommendations for applying N fertiliser to wheat and barley crops has been published by Petrochem NZ Ltd (Anon., 1988a).

2.2.1 Effect of Early Nitrogen on Wheat Yields

For the purposes of this review 'early' applications of N refer to applications made from sowing through until early stem elongation. 'Late' applications are defined as those occurring from late stem elongation until immediately after anthesis.

The initial response of wheat grain yields to early applications of N fertiliser on responsive sites tends to be linear, but, as N application rates increase the response levels off to a plateau, before finally declining (Benzian and Lane, 1981; Daly and Dyson, 1987). Applications of N fertiliser prior to tillering increase the number of tillers formed per unit area (Dougherty and Langer, 1974; Spiertz and De Vos, 1983; Strong, 1986) resulting in an increase in the number of ears/m^2 present at harvest (McNeal *et al.*, 1971; Daly and Dyson, 1987). Applications of N made after tillering may increase ear/m^2 at harvest (Dougherty, Love and Mountier, 1978; Stephen, Saville and Kemp, 1985) through an increase in the survival rate of tillers already formed (Hansen, Wilson and Ovenden, 1983). Ear number per unit area has been identified as the most important yield component influencing yield in wheat (Hampton, 1981; Withers and Pringle, 1981). Although yield components are flexible, with compensation occurring if one component is low (Nourafza and Langer, 1979), there are limits to this compensation so that if ear numbers are too low, yields are reduced (Hampton, McCloy and McMillan, 1981).

Early applications of N also influence the number of spikelets/ear and the number of grains/spikelet which together determine grains/ear. Many workers have found that early N increases grains/ear and ear/m^2 (McNeal *et al.*, 1971; Stephen, Saville and Kemp, 1985). Dougherty, Love and Mountier (1978) found that early N increased spikelets/ear and grains/spikelet at low plant populations but at high plant populations, higher ear numbers resulted in a decline in grains/spikelet. Langer and Liew (1973) found that enhanced N availability between the double ridges and floret initiation stages increased both spikelets/ear and grains/spikelet. N applied after floret initiation increased grains/spikelet only, but was not as effective as applications made prior to floret initiation.

Many workers have found that early N reduces grain weight in situations where N has resulted in yield increases (McNeal *et al.*, 1971; Guy, 1985; McCloy, 1985a) and when yields have declined or remained unchanged (Dougherty, Love and Mountier, 1978; Stephen, Saville and Kemp, 1985; Martin, 1987). The reduction in grain weight associated with the use of N fertiliser is caused by a greater increase in the sink capacity of the crop compared to the source capacity (Pearman *et al.*, 1977) resulting in increased competition for assimilates (Scott, 1981). However early N may increase grain weight when optimum growing conditions result in an increase in the source capacity of the crop (Spiertz and van de Haar, 1978).

Whether or not an early application of N results in an increase, zero response, or decrease in wheat yields on sites which are potentially responsive to N fertiliser depends on the presence of factors which restrict yield (Martin *et al.*, 1989).

Soil moisture availability has a significant influence on the yield response to N. Early applications of N fertiliser increase vegetative growth, depleting soil moisture reserves, which may result in plant water stress (Dougherty, Scott and Langer, 1974; Scott, 1978a). On soils with a low water-holding capacity, there is often an interaction between response to N fertiliser and moisture availability (Drewitt, 1979; Drewitt, 1985; Drewitt and Dyson, 1987). These workers found that without irrigation yield responses to N were zero or negative but were positive when irrigation was applied. Soil moisture deficits can restrict responses to early N application through a suppression of tillering, and consequently, ear numbers/m^2 (Drewitt and Rickard, 1972). When soil moisture levels are sufficient to allow increased tillering in response to N but subsequently becomes limiting, yield depressions result from a depression in grain weight (Drewitt, 1985). Irrigation can also have a negative influence on yield responses to N. Dougherty and Langer (1974) found that irrigation reduced yield in wheat at high levels of N, primarily through a reduction in the number of grains/spikelet resulting from increased competition for assimilates between vegetative and reproductive growth.

Yield response of wheat to fertiliser N may be dependent on the control of pests and diseases, which can reduce photosynthetic capacity, restricting the supply of assimilates

and reducing yields (Risk, 1974; Daly and Dyson, 1987). The application of N itself can increase the severity of foliar diseases (Smith and Wright, 1974; Cromey and Beresford, 1989) by producing micro-environments favourable to fungal disease (Cromey and Beresford, 1989).

Yield responses to N can be limited by the increased requirement for other nutrients when N is applied, particularly phosphate (McLeod, 1974; Douglas and Slay, 1983).

2.2.2 Effect of Late Nitrogen on Wheat Yields

Late applications of N are less effective in increasing wheat yields compared to early applications because late N results in increased N supply in the wheat plant after most of the important components determining yield have been established (Spiertz and van de Haar, 1978; Stephen, Saville and Kemp, 1985; Martin *et al.*, 1989). Stephen, Saville and Kemp (1984) found that the poorer the yield response to early N, the better the response to late N relative to early N. The best yield responses to late N compared to 'the control' still occurred at sites which had the best response to early N. For example, at sites exposed to moisture stress, late N may be more effective than early N through not depressing yields (Stephen, Saville and Kemp, 1984). A similar effect was observed by Withers (1986) where late N was considerably more effective than early N in a situation where early N had depressed yields, through an increase in mildew infection. However, late N still increased yields over 'the control'.

Late N increases grain yield primarily through an increase in grain weight (Spiertz and van de Haar, 1978; Stephen, Saville and Kemp, 1985; Guy, 1986; Strong, 1986; Martin, 1987). Some workers have also found that late N also increases grain numbers/ear (Spiertz and Ellen, 1978; Martin, 1987). Grain weight is increased in those crops which are source limited and where late N increases the LAD of the canopy (Spiertz and van de Haar, 1978; Spiertz and De Vos 1983). Yield responses to late N through an increase in grain weight are reduced when the crop is sink limited (Martin, 1987) or when soil moisture is not adequate (McCloy, 1985b) or when pest and disease pressure reduces LAD (Spiertz and De Vos, 1983). The reduced response to late N in crops which are sink limited can result in yield responses to late N interacting with early

N, ie responses to late N are higher when early N is applied (Strong, 1982).

Late applications of N made prior to anthesis have generally been much more effective in increasing grain yields than applications made at or post anthesis (Finney *et al.*, 1957; Strong, 1982). Presumably, this is because N applied at or after anthesis is less likely to be available in the canopy in time to significantly benefit LAD. At those sites where irrigation is not available, there is a greater likelihood of low soil moisture levels restricting N uptake, as soils dry out post anthesis compared to pre anthesis (Drewitt and Rickard, 1972).

2.3   Determination of Grain Protein

Developing wheat grains are strong sinks for N compounds used to manufacture protein (Sinclair and de Wit, 1975). This N can originate from mobilisation of plant reserves (Spiertz and Ellen, 1978) or from uptake during the grain-fill period (Quin and Drewitt, 1979). The efficiency of translocation of the total N absorbed by the crop to the grain is an important measure of N use efficiency (Novoa and Loomis, 1981) and is described by the nitrogen harvest index (NHI). As with grain yield, the supply of N to wheat crops has a major influence on the protein content of grain at harvest, with increasing N supply generally increasing grain protein (Wright, 1967; Drewitt and Rickard, 1972; Langer and Liew, 1973; Spiertz and Ellen, 1978; Withers, 1986). N supply depends on soil factors such as humus content and the balance between immobilisation and mineralisation (Novoa and Loomis, 1981) soil physical properties including moisture content (Withers and Pringle, 1981) and N fertiliser (Martin *et al.*, 1989).

At a given level of N supply there is an inverse relationship between grain yield and grain protein content (Drewitt, 1979; Martin, 1987; Pushman and Bingham, 1976). This effect is known as the 'dilution effect' and is caused by the dilution of grain protein by increased quantities of starch as yield increases (Martin *et al.*, 1979).

The addition of small amounts of N in a low fertility situation may result in a decrease in grain protein content (Dougherty, Love and Mountier, 1978; Benzian and Lane, 1979). This is because small additions of N may increase the size of the sink

proportionately more than it increases the availability of N from the soil or from remobilisation during grain-filling.

Most workers have found that as N supply increases there is a near linear increase in grain protein content (Benzian and Lane, 1981; Guy 1985; Strong, 1986; Daly and Dyson, 1987) even though grain yields may level off or decline. This linear response occurs even at very high rates of applied N. The highest rates of N used in the above studies ranged from 175 kg N/ha to 400 kg N/ha.

It has consistently been found that late applications of N are more effective at raising grain protein content than early applications (Drewitt, 1975; Spiertz and van de Haar, 1978; McCloy, 1985b; Strong, 1986; Drewitt and Dyson, 1987). However the efficacy of late N in increasing grain protein declines rapidly if application is delayed until after anthesis (Finney *et al.*, 1957; Strong, 1982). It is probable that late N is more effective at increasing grain protein because it is less effective at increasing grain yields, consequently protein dilution does not occur to the same degree.

Apart from the supply of N to a wheat crop, other factors also influence the protein content of grain. Important management factors include irrigation (Drewitt and Rickard, 1971) and disease control (Spiertz and De Vos, 1983). In soils with a low water holding capacity, irrigation reduces grain protein content (Drewitt and Rickard, 1972; Drewitt, 1975; Scott, 1981; Drewitt and Dyson, 1987). This decline in protein content is usually associated with an increase in yield, although it can be due to leaching of N from the rooting zone as a result of irrigating (Cameron, 1983). The effect of moisture on grain protein occurs mainly through its influence on grain yield (Campbell, Davidson and Winkleman, 1981). Important environmental influences on grain protein include radiation and temperature. Low radiation intensities increase grain protein content, mainly through a reduction in yield (Kolderup, 1975; Spiertz, 1977). Increasing temperature also increases grain protein content (Sosulski, Lin and Paul, 1966; Sofield *et al.*, 1977a; Randall and Moss, 1990). The synthesis of protein in developing grain is favoured more by increasing temperature than is starch synthesis (Spiertz, 1977; Bhullar and Jenner, 1985). However, the influence of temperature on grain protein is

mainly a result of the indirect effect of temperature on grain yield, rather than directly on protein synthesis (Partridge and Shaykewich, 1972).

When comparing the direct effects of N supply, temperature and moisture on grain protein content, Campbell, Davidson and Winkleman (1981) found that the effect of N was twice as great as the temperature effect and 15 times the moisture effect.

2.4   Harvest Index

Harvest index (HI) is defined as the ratio of grain dry weight to total dry weight (Biscoe and Willington, 1982).   Different wheat cultivars can vary widely in HI (Gent and Kiyomoto, 1989).

Over 80% of the overall yield increases achieved with modern wheat cultivars is due to the increase in HI in these cultivars compared to old cultivars (Perry and D'Antuono, 1989).   Harvest index is inversely related to stem height (Gent and Kiyomoto, 1989) with short strawed cultivars distributing proportionately more assimilate to the ear than standard height cultivars (Spiertz and van de Haar, 1978).

Many workers have reported that early applications of N decrease HI (Dougherty and Langer, 1974; Dougherty, Scott and Langer, 1975) by increasing total DM proportionately more than grain yield. However early N applications may increase HI when these applications result in an increase in leaf area duration during the grain fill period, allowing greater production of assimilates (Spiertz and Ellen, 1978).

Late applications of N (just prior to or at ear emergence) tend to have minimal effect on yield components influencing grain number/m^2 and total DM but may increase yields through an increase in grain weights, thus increasing the HI (Spiertz and van de Haar, 1978; Spiertz and De Vos, 1983).

Any factor negatively influencing grain weight will reduce HI. These include increased temperature and low light intensity (Spiertz, 1977), disease and pests (Spiertz and De Vos, 1983), moisture stress (Gallagher and Biscoe, 1978a) and lodging (Stapper and

Fischer, 1990b).

2.5 Nitrogen Harvest Index

Nitrogen Harvest Index (NHI) measures the efficiency of translocation of N to the grain and is defined as the ratio of N present in the grain to the total N present in grain and straw (Anderson, 1985). Nitrogen harvest index varies according to cultivar (Quin and Drewitt, 1979). Nitrogen fertiliser may decrease NHI (McNeal *et al.,* 1971) particularly if lodging results (Eilrich and Hageman, 1973). This occurs mainly through a marked decrease in assimilation with reduced translocation of N to the grain. However N applied just prior to ear emergence, may have no effect on NHI (Spratt and Gasser, 1970) or can increase NHI (Spiertz and van de Haar, 1978; Spiertz and Ellen, 1978).

2.6 Recovery of Nitrogen Fertiliser

From an economic viewpoint it is important to recover as much nitrogen fertiliser as possible from the crop to which it was applied. However it is also important to maximise recovery because of the potential polluting effects residual N may have. Leaching of nitrate to groundwater and subsequent enriching of streams and lakes and the contamination of water used for domestic consumption are well recognised environmental problems (Keeney and Gregg, 1982; Briggs and Courtney, 1985; Croll and Hayes, 1988).

In soils where oxygen concentration is low, through water logging for example, nitrate is metabolised by anaerobic bacteria as an electron sink (Allison, 1966). Products of this metabolism include nitrous oxide (N_2O) (Cady and Bartholomew, 1960). Nitrous oxide is a greenhouse gas which is increasing in concentration in the atmosphere (Lowe *et al.,* 1988). It is also one of the gases which controls stratospheric ozone (Anon., 1988b).

Recovering fertiliser N applied to a crop can be achieved by increasing the yield or the N content (or both) of the crop. A commonly used measure of the efficiency of N fertiliser is the % N recovered by the crop. Two methods are used, one method using N fertiliser tagged with ^{15}N and the other, a nontracer method. The tracer method is

more accurate but also expensive and involved compared to the nontracer method which is adequate where the chief interest is in the practical evaluation of N fertiliser response (Allison, 1965). Calculation of N recovery using the nontracer method is as follows:

$$\% \text{ N recovery} = \frac{\substack{\text{N harvested in crop - N harvested in crop} \\ \text{with N fertiliser} \qquad \text{without N fertiliser}}}{\text{Fertiliser N added}} \times 100$$

(Anon., 1983)

This method of calculating recovery of N fertiliser does not account for all N taken up by the crop. With any crop harvested and removed from the paddock there are crop residues, for example cereal straw or stubble. Most field work has found that average recoveries are only 50-60% of applied N (Allison, 1966; Lathwell, Bouldin and Reid; 1970; Anon., 1983).

What are the causes of variation in the amount of N recovered in the crop? Craswell and Strong (1976) found that N recovery varied from 38% to 65% of applied N on a clay soil in Queensland. Rainfall and fertiliser placement had the largest influence of N recovery in a wheat crop. High rainfall (444 mm) over the growing period of the crop produced better plant growth and subsequently a greater quantity of N in above-ground parts than was the case with low rainfall (255 mm). Under low rainfall, 15 cm depth fertiliser placement restricted uptake compared to 45 cm depth because of less favourable soil moisture regimes at the shallow placement. Water applied in excess of plant requirements is unlikely to adversely influence N recoveries if the N fertiliser is applied to a growing crop in quantities able to be utilised by the crop (Allison, 1965).

The type of fertiliser N used can influence N recovery through losses occurring before the crop has a chance to utilise it. Fertilisers which are susceptible to volatilisation of ammonia, for example, ammonia solutions and urea, may suffer significant losses (Allison, 1966). Urea is readily hydrolysed by the enzyme urease into ammonia (Steele, 1982). Theobald and Ball (1984) comparing urea and ammonium sulphate found volatilisation losses of 8% for ammonium sulphate and 42% for urea at an application rate of 50 kg N/ha. At an application rate of 200 kg N/ha, 86% of N applied as urea

was lost but only 10% from ammonium sulphate. Subsequent N recoveries were higher from ammonium sulphate than urea applications, particularly at the higher N rate. Carter, Bennett and Pearson (1967) found that N recovery by forage sorghum was the same when comparing sodium nitrate and ammonium sulphate. Although soil analysis showed N from plots receiving sodium nitrate tended to be present lower in the soil profile significant quantities had not leached below the rooting zone and so recovery was not affected. However, on free-draining soils, fertiliser N applied as nitrate is more susceptible to leaching than N applied as ammonium or urea, particularly when applied at sowing when the crops root development will be limited (Van Burg, Dilz and Prins, 1982). Pumphrey and Harris (1956) found that the timing of fertiliser N application had an influence on the recovery of N in grain maize. N fertiliser applied at pre-plough was poorly utilised compared to N applied to the growing crop, except in a year of poor crop production when there were no differences. In years which produced responses to fertiliser N, a pre-ploughing application resulted in an average of 51% recovery compared to 66% recovery of side-dressed N, over all rates. Similar results were obtained with autumn versus spring applications of N in winter wheat (Welch *et al.*, 1966).

The influence of rate of fertiliser N application on recovery has been inconsistent. While some researchers have found that recoveries declined with increasing rates of N fertiliser (Pumphrey and Harris, 1956; Carter, Bennett and Pearson, 1967), others have measured an increase in N recovery with increasing rates of N fertiliser (Bartholomew and Hiltbold, 1952; Viets, 1960). Dotzenko (1961) found that different plant species differed in the response of N recovery to increasing rates of N fertiliser. While some species showed declining N recoveries in response to increasing rates of fertiliser, others recovered more. In a review of N availability to plants, Scarsbrook (1965) concluded that there was no simple relationship between application rate and N recovery with factors such as soil moisture and plant species influencing N recovery.

2.7   The relationship between Protein Content and Baking Quality

2.7.1 Introduction

Protein present in grains of wheat (or any seed) can be classified into two groups. One group are the metabolic and structural proteins and the other the storage proteins which provide a reserve of predominantly N and sulphur for germination (Miflin and Shewry, 1983). Storage proteins can be further categorised into those soluble in water, the albumins/globulins; those soluble in alcohol, the gliadins and the remainder as glutenins (Sutton, 1989). The gliadins and glutenins (both insoluble in water) are collectively known as gluten. Glutenins are split into high and low molecular weight fractions. Gliadins and glutenins have unique properties of flow and elasticity and it is these physical properties which are responsible for the variation in the quality of bread baked from milled wheat (Meredith and Dewdney, 1979). It is the disulphide bonds between cystine amino acids in the gliadins and glutenins which are of great importance in providing the cohesion and elasticity necessary for making good leavened bread (Bushuk and Wrigley, 1974). Hydrogen bonding between glutamine amino acids in these proteins also contributes to this property (Beckwith, Wall and Dimler, 1963). During baking, carbon dioxide gas expands these proteins to give bread its aerated and spongey texture (Aykroyd and Doughty, 1970).

2.7.2 Baking Quality

In New Zealand, most bread is baked using a mechanical dough development method (MDD), described by Cawley (1964). This method replaces several hours of fermentation of dough prior to baking with a short period of intensive mixing to develop the dough. In order to effectively evaluate the quality of flour used in this baking process, an MDD bake test was introduced in 1973 (Cawley, 1979). This uses a scoring system which is based on the volume of a loaf achieved after baking a 125 g sample of the flour under test, in conjunction with an assessment of crumb texture. Most scores achieved are between 15 and 25 (Lindley, 1985). The scales used in this system are designed to give loaf volume and crumb texture about equal weighting (Mitchell, 1983a).

Two other characteristics measured and reported with the MDD bake test are optimum work input and water absorption. Optimum work input measures the amount of work dough requires to reach maximum viscosity during mixing (Lindley and Moore, 1989). It is the most important factor influencing the compatability of flour with the MDD baking process in New Zealand bakeries (Gould, 1989). Dough which has had either insufficient or too much work input, will have less than maximum potential viscosity. It is considered desirable to have work inputs in the medium range of 7-12 Watt hours/kg (Wh/kg) (Lindley and Humphrey-Taylor, 1987). This means that achieving optimum quality bread is not too dependent on being very accurate when mixing doughs of low optimum work requirement, yet alleviates the need to spend more time and power mixing dough with a high optimum work input (Lindley and Moore, 1988). Water absorption is a measure of the quantity of water a dough requires to reach a convenient consistency for bread production. High water absorption is beneficial because it conveys softness and better keeping ability to bread (Lindley and Moore, 1989). Water absorptions of around 60% are typical for New Zealand wheats in most years (Lindley and Humphrey-Taylor, 1987; Lindley and Moore, 1988). An important exception to this is in flour milled for biscuit rather than bread making, where absorptions of between 50-54% are considered desirable (Parkyn, 1985). When baking biscuits, moisture needs to be removed, so the minimum quantity needed to produce acceptable dough is regarded as desirable.

Causes of variation in optimum work input include season, district of production, cultivar (Mitchell, 1985; Lindley and Humphrey-Taylor, 1987) and protein (Lindley and Moore, 1989). Water absorption is related to the protein content of the flour used in the dough (Finney et al., 1957) and also to the cultivar (Lindley and Moore, 1989).

Because of the expense and relatively large sample sizes required for assessing wheat quality from commercial bake tests, many small scale tests have been developed to facilitate testing of large numbers of small samples, for wheat breeding programmes for example (Blackman and Gill, 1980). Many of these small scale tests are listed by Griffin (1983a). One of these tests, the sodium dodecyl sulphate (SDS) sedimentation test, was used in this study as a measure of baking quality. It is a small, simple,

repeatable test used for measuring protein quality (Griffin, 1983b). Prior to the SDS sedimentation test the most widely known of the small scale tests listed by Griffin (1983a) were the Pelshenke and Zeleny tests (Axford, McDermott and Redman, 1979). The Pelshenke test measures the stability of yeasted dough balls in water (Pushman and Bingham, 1975) while the Zeleny test measures the sedimentation volume of flours in dilute lactic acid (Pinckney *et al.*, 1957). Acid insoluble proteins (sediment) have high molecular weights and are a major determinant of baking quality (Orth and Bushuk, 1972). The SDS sedimentation test overcame the Zeleny tests requirement for flour through the ability of sodium dodecyl sulphate to disperse proteins from wholemeals, thus alleviating the need to use flours (Axford, McDermott and Redman, 1979). The test is described in the materials and methods chapter, section 3.7. Compared to the Pelshenke and Zeleny tests, the SDS sedimentation test has been found to be more convenient and more closely correlated to baking quality (Axford, McDermott and Redman, 1979). Blackman and Gill (1980) found the SDS sedimentation test to be the best small scale test of inherent protein quality, being strongly correlated with loaf volume but independent of site and degree of sprout damage. Similarly Griffin (1983a) found the SDS sedimentation test to be strongly correlated with bake score and independent of alpha-amalyse content. He also found a strong correlation with grain protein which was in contrast to Blackman and Gill (1980). Preston, March and Tipples (1982) found that the SDS sedimentation test was a good means of predicting baking quality of Canadian wheat, but that in samples containing wheat from different environments, protein levels influenced this predictability. At lower protein contents ($< 13.0\%$) the relationship was strong, while for wheat with a protein content of over 14%, it was not significant. With samples from the same environment, the SDS sedimentation test was strongly correlated to baking ability, independent of protein content.

2.7.3 Relationship between Protein Content and Quality

The relationship between grain protein content and subsequent ability to produce bread of acceptable quality has been found to be significant by many overseas researchers (Finney *et al.*, 1957; Doekes and Wennekes, 1982; Preston, March and Tipples, 1982). All of these studies found strong positive relationships between protein and loaf volume.

However, very high protein contents may decrease loaf volume, probably because of a change in protein composition (Bushuk, Rodriguez-Bores and Dubetz, 1978) and also because of the presence of non-protein N in the grain (Finney *et al.*, 1957).

In New Zealand, the relationship between protein content and bake score, although positive, was found to be inadequate as a means of predicting bake score in harvest samples of wheat (Wilson, 1983). Even when samples were segregated into cultivars and protein content, protein content was found not to be a reliable enough predictor of baking score to be of use to commerce (Mitchell and Casutt, 1983). Stevenson (1987a) examined the relationship between bake score and flour protein, over different seasons for the cultivars Rongotea and Oroua. He found a positive but flattening response, of MDD bake score to increasing protein content, up to 12% protein. Douglas (1987) also found a flattening response of MDD bake score to protein. Both studies found protein to be an inadequate means of predicting bake score because of the variation produced by different districts of production.

This apparent difference between overseas and New Zealand wheat can be partly explained by the fact that in overseas countries only cultivars of known bread-making ability are acceptable (Wilson, 1990) whereas in New Zealand most of the milling wheat cultivars released prior to 1984 were not high grade milling cultivars but rather were utility and general purpose wheats (Griffin, 1985). For example, comparing the quality of the cultivars used in Stevenson's (1987a) study with overseas wheat it, is evident that they were well below world standards (Mitchell, 1983b).

The fact that cultivars vary widely in their ability to produce good quality bread at the same protein content is very well documented (Bushuk, Briggs and Shebeski, 1969; Hall and Lancaster, 1979; Blackman and Gill, 1980; Cawley, 1981; Drewitt, 1985; Drewitt and Dyson, 1987; Martin, 1987). Differences in wheat quality have been explained in terms of the composition of the protein component, particularly the proportions of gliadin and glutenin (Campbell and Cressey, 1983). Later the investigation of high molecular weight (HMW) glutenin subunits found that the presence of certain subunits was strongly associated with good baking quality in New Zealand and Australian grown

wheat (Griffin, 1983a) and a range of northern hemisphere wheats grown in Canada (Ng and Bushuk, 1988). The volume of sediment from the SDS sedimentation test has been positively correlated with these subunits (Griffin, 1983a).

Sutton, Hay and Griffin (1989) found that the presence of specific HMW glutenin subunits could be used as a good predictor of loaf volume and bake score in a wide range of New Zealand wheat lines. A model based on quantifying specific HMW glutenins was able to account for 72% and 77% of variation in loaf volume and bake score respectively. Models for predicting baking quality which are based on identifying specific glutenin fractions have shown better predictive power than models based on protein content (Sutton *et al.*, 1990).

Similar models using HMW glutenin subunits as a means of predicting baking quality and with high coefficients of determination have been found for Canadian wheat (Lukow, Payne and Tkachuk, 1989) and British wheat (Payne *et al.*, 1987a).

The major component of wheat glutenin protein is the low molecular weight (LMW) fraction (Weiser, Seilmeier and Belitz, 1990). It has been found that LMW glutenins also influence quality. Payne *et al.*, (1987b) found that the LMW subunits were responsible for most of the variation in quality while working with biscuit wheat. Recent studies of the influence of LMW glutenin subunits on baking quality in Australian bread wheats found good correlations between them (Metakovsky *et al.*, 1990). In a comparison of Australian and world wheats, Gupta *et al.*, (1990) found a lower correlation between HMW glutenin subunits and quality in Australian compared with world wheats. However, the reverse was true for the LMW fraction where associations with quality were higher for Australian wheats.

The gliadin fraction of wheat storage proteins has also been found to influence baking quality. In particular, it has been suggested that gliadins control loaf volume (Finney, Jones and Shogren, 1982). An increasing ratio of gliadin to glutenin in wheat protein has a positive influence on loaf volume (Orth and Bushuk, 1972; Doekes and Wennekes, 1982). Huebner (1989) found a negative relationship in wheat between "anti-baking

quality fraction gliadins", and a general score of wheat quality. Subsequent studies discovered that different gliadin fractions originating from different chromosome blocks have positive or negative association with dough quality (Metakovsky *et al.*, 1990).

It is increasingly evident that any relationship between the composition of wheat storage proteins and quality are likely to depend on both gliadins and glutenins (Graybosch and Morris, 1989; Metakovsky *et al.*, 1990).

2.8 Factors influencing the Relationship Between Grain Protein Content and Baking Quality

2.8.1 Fertiliser

Finney *et al.*, (1957), using foliar applications of urea solution, found that as grain protein content increased there was an increase in variation of loaf volume at a given protein content. An association was found between reduced loaf volumes from those expected and water soluble protein, indicating incomplete gluten synthesis. The use of N fertiliser to increase wheat protein content can change the amino acid composition of that protein (Abrol *et al.*, 1971). In particular, increasing grain protein content can increase the glutamic acid and proline content of wheat (Sosulski, Lin and Paul, 1966). Glutamic acid and proline constitute over 50% of the amino acid composition of gluten (Woychik, Boundy and Dimler, 1961). Glutamic acid is probably the major form in which N is mobilised during grain-filling (Blumenthal *et al.*, 1990a). Incomplete protein synthesis may therefore still result in increased glutamic acid levels in wheat.

Changes in amino acid composition at high protein contents can increase the ratio of soluble to insoluble glutenins in some wheats, reducing loaf volume (Bushuk *et al.*, 1978). These workers found a flattening response of loaf volume to protein content above 15.5% protein. Doekes and Wennekes (1982) found that N fertiliser, resulting in increased protein, increased the gliadin fraction but had no effect on glutenins, thus increasing the gliadin : glutenin ratio. An increasing gliadin : glutenin ratio was associated with increasing loaf volume. This contrasts with the results of Bushuk *et al.*, (1978), who found that N fertiliser increasing grain protein had no effect on the gliadin fraction, and with Tanaka and Bushuk (1972), who found no variation in the relative

quantities of any of the major protein fractions as protein content varied from 10.5% up to 15.6%. Explanations for these differences include different protein extraction methods and different protein contents (Doekes and Wennekes, 1982). For example, the flour protein contents used in the Bushuk *et al.*, (1978) study were much higher than those in Doekes and Wennekes (1982) study (16.4% vs 12.2% maximum) where baking quality did not vary until about 15.5% protein. Tipples, Dubetz and Irvine, (1977) found that high protein contents (> 17.0%), achieved with N fertiliser, were associated with a deterioration in baking quality at some locations only, indicating a protein x environment interaction.

2.8.2 Environment

The influence of different sites (Sandstedt and Fortmann, 1944) and different seasons (Bushuk, Briggs and Shebeski, 1969) on the relationship between protein and quality in milling wheat has long been recognised. Wheat grown on sulphur-deficient sites may have depressed protein quality due to changes in the accumulation of different gliadin fractions, for example (Huebner and Bietz, 1988). Douglas and Dyson (1985) found a significant depression of bakescore at any given grain N%, as grain potassium levels increased. However Douglas (1987) concluded that large location variations in baking quality could not simply be explained by the concentration of nutrients in wheat.

Temperatures during the flowering/grain-fill period can influence the relationship between protein content and baking quality. Finney and Fryer (1958) found that the accumulated temperatures over 90°F (32°C) during the last 15 days of the grain-fill period were strongly related to decreasing loaf volume at a given protein content. More recently Blumenthal *et al.*, (1991a) found a strong negative correlation between 'heat stress' (hours above 35°C during grain-filling) and baking quality.

The effect of site and season on the relationship between protein and baking quality has been found to be correlated with average temperatures over the heading/grain maturation period (Stevenson, 1987a). This study found protein quality increased as average temperatures increased over the 12°C to 18°C range. Other studies have found that increasing mean temperatures increase baking quality, having a greater influence on

baking quality than grain protein (Martin, 1987).

Randall and Moss (1990) found that as average temperature increased toward a threshold value, baking quality is increased, independently of protein content. The greater the proportion of grain-fill duration exposed to higher temperature, the greater the increase in baking quality. However, above the threshold temperature (approximately 30°C average) even short periods of exposure (3 days) decreased baking quality. This effect was greatest when applied at the middle or late stage of grain-fill (80-95% final grain weight).

Temperature can alter the amino acid composition in wheat (Kolderup, 1975). This study found increasing temperatures (12°C-21°C) increased the gluten fraction in the grain. At temperatures high enough to cause stress, wheat plants will reduce the synthesis of normal proteins and produce a group of proteins known as the heat shock proteins (Blumenthal et al., 1990b) which have been associated with the acquisition of thermotolerance. Similarly, temperature stress (>35°C) during the grain-filling period results in the production of heat shock elements associated with the gliadin genes, increasing the gliadin : glutenin ratio and decreasing baking quality (Blumenthal et al., 1991b). This and other studies have found strong cultivar differences in susceptibility to the influence of heat stress (Finney and Fryer, 1958).

2.9   The Influence of Temperature on Wheat Yields

Temperature has a strong influence on the rate of growth of temperate cereals, including wheat (Friend, 1965a; Gallagher, 1979). The rate of appearance of wheat leaves increases linearly above a base temperature of 0°C (Baker et al., 1986). This response to increasing temperature results in a decrease in the duration of the developmental phases in wheat (Marcellos and Single, 1971). Consequently, wheat development is enhanced in warm compared with cool regions and similarly with late sowing (warm temperatures) compared with early sowing (cool temperatures) when spring sown (Jamieson and Wilson, 1989).

Temperature influences the potential yield of wheat with cool temperatures increasing

potential yield through an increase in grain number/m^2 (Thorn, Ford and Watson, 1968). This is a result of increased tiller production and survival at lower (10°C) compared to higher (30°C) temperatures (Friend, 1965b). Rawson (1971) found that tiller numbers were higher at 12°C than 18°C. The other yield components increased by low temperatures are spikelet numbers/ear (Friend, 1965a) and florets/spikelet (Warrington, Dunstone and Green, 1977). Both of these studies found that the number of tillers surviving to reach maturity was increased by high rather than low temperatures. This was attributed to higher temperatures producing larger plants and hence more sites for tiller buds. The plants used in this study were grown in individual spaced pots and it was concluded that many of the tillers initiated in this situation would never reach maturity in the field or would not even be initiated due to competition. In those studies which have compared the effects of temperature at different stages in the development of wheat, it has been the ear development phase (double ridge/floret initiation to anthesis) which has shown the greatest sensitivity to temperature and the greatest control over final yield (Owen, 1971; Warrington, Dunstone and Green, 1977).

In order to help compensate for the decrease in yield potential in wheat crops where delayed sowing means development occurs at higher temperatures, it has been recommended that sowing rates be increased. For example recommended sowing rates are higher for spring sown compared to autumn sown wheat (Anon., 1978; Montgomery, Inch and Baird, 1986).

The increased plant populations achieved from recommended spring sowing rates are necessary if the ear numbers/m^2 required for maximum yield are to be obtained (McCloy, 1985a).

Apart from the effect of temperature on the potential yield of wheat, there is also a considerable influence on the determination of yield through the effect temperature has on anthesis (Owen, 1971) and grain size (Spiertz, 1977). Temperature can have a direct influence on fertility with grain set being greater at low (12.5°C average) compared to high (up to 24.5°C average) temperatures (Wardlaw, 1970). Warrington, Dunstone and Green, (1977) also found that high (22.5°C average) temperatures reduced grain set

compared to low (12.5°C average), especially in the more distal florets. Very high temperatures at anthesis (35°C) can cause complete failure of grain set (Owen, 1971) as a result of poor pollen development and viability at higher temperatures (Asana and Williams, 1965; Dawson and Wardlaw, 1989). The incidence of low grain set and grain abortion at high temperatures is enhanced at high humidities (Tashiro and Wardlaw, 1990).

Increasing temperatures over the grain-fill period have been shown to depress yields through a reduction in grain weight (Spiertz, 1977; Wardlaw, Sofield and Cartwright 1980; Wiegand and Cuellar, 1981; Wardlaw et al., 1989b). Although increasing temperatures increase the rate of grain-fill (Warrington, Dunstone and Green, 1977; Nicolas et al., 1984) the duration of grain-fill is decreased (Wardlaw, Sofield and Cartwright, 1980; Wiegand and Cuellar, 1981). The rate of grain-fill appears to reach a maximum at relatively low temperatures (Sofield et al., 1977a; Sofield et al., 1977b) with the result that increasing rates of grain-fill do not compensate for decreasing durations of grain-fill with increasing temperatures. The optimum temperature for maximum grain yields is about 15-18°C average (Sofield et al., 1977a; Chowdhury and Wardlaw, 1978; Wardlaw et al., 1989a). Yields decline by 3-4% for each 1°C rise in average temperature above this optimum (Wardlaw et al., 1989a; Wardlaw et al., 1989b).

Increasing temperatures over the grain-fill period increase leaf senescence and decrease leaf area duration, often resulting in high positive correlations between leaf area duration and grain yield (Warrington, Dunstone and Green, 1977). This led to the suggestion that increased senescence was the cause of the reduced duration of grain-fill, and consequently, reduced yield (Ford and Thorne, 1975; Spiertz, 1977). However Chowdhury and Wardlaw (1978) found that at the completion of grain-fill, a source of carbohydrate was still available in wheat flag leaves subjected to rising temperatures. Other studies have found adequate supplies of sucrose available in the grain in situations where increasing temperatures have reduced grain size and yield (Nicolas, Gleadow and Dalling, 1984). Similarly Sofield et al., (1977a) found that low levels of irradiance reduced the rate of photosynthesis in the flag leaves. This in turn reduced grain growth

more in the upper florets than the lower florets, indicating competition for assimilates. However temperature reduced final grain weight evenly at all floret positions, suggesting that temperature was affecting the synthetic processes in the grain rather than the availability of assimilates. This was also demonstrated by Jenner (1991a) who found that exposure of ears of wheat in the field to elevated temperatures, for short periods (up to 7 days), resulted in reduced grain growth rates compared to control ears, after the heated ears had been returned to ambient conditions.

Increased respiration losses have been suggested as the mechanism for the decline in grain weights with increasing temperature (Asana and Williams, 1965). While contributing to the reduction in grain weights, enhanced respiration accounts for approximately 25% only of this reduction (Wardlaw, Sofield and Cartwright, 1980). Elevated temperatures also reduce the number of late initiated, small starch granules (B-type) in wheat grains, but again, do not account for all of the reduction in grain weight (Bhullar and Jenner, 1985). Working with wheat endosperm isolated from ears exposed to elevated temperatures, Bhullar and Jenner (1986) concluded that there were two direct effects of temperature on the grain endosperm. One was that starch synthesis is optimised at relatively low temperatures and the other was that exposure of developing ears of wheat to elevated temperatures irreversibly reduces the capacity of the endosperm to convert sucrose to starch.

A partial explanation for the decrease in starch deposition resulting from elevated temperatures is the fall off in activity of the enzyme regulating starch synthesis, starch synthase (Caley, Duffus and Jeffcoat, 1990). Increasing temperatures also decrease the concentration of the precursor for starch synthesis (ADP-glucose) which may also contribute to the decrease in starch deposition (Jenner, 1991a).

The sensitivity of wheat to increasing temperatures over the grain-fill period has been found to vary with irradiance (Sofield *et al.*, 1977a; (Spiertz, 1977; Wardlaw *et al.*, 1989a), humidity (Tashiro and Wardlaw, 1990), regional origin of cultivar (Wardlaw *et al.*, 1989b) and moisture status (Nicolas, Gleadow and Dalling, 1984).

CHAPTER III

MATERIALS AND METHODS

3.0   Introduction

To investigate the use of late (Feekes G.S.9, described by Large, 1954) applications of N to raise protein content and yield in milling wheat three field trials were conducted in 1989/90 at different sites in the Manawatu. The sites were chosen on the basis of yield potential and altitude. Only high yield potential sites were selected. This was done to minimise the risk of having treatment effects masked by factors limiting yield and because high yielding sites are more likely to produce wheat with a low protein content. This is due to the inverse relationship between yield and protein content when nitrogen supply is constant (Martin *et al.*, 1989). Sites at different altitudes were chosen to achieve a different temperature regime at each site. This was required in order to investigate the effect temperature, over the period of grain-filling, has on the relationship between grain protein and baking quality. Mean temperature over the grain-filling period has been positively correlated with protein quality (Stevenson, 1987a).

The field trials were carried out in commercial wheat crops sown in early spring 1989. The cultivar used was Rongotea in each case. Rongotea was bred by the Crop Research Division of the DSIR Palmerston North as a spring wheat. The first commercial Rongotea crops were harvested in the 1981 harvest year. It has been described by McEwan and Vizer (1979) and Mitchel and Cross (1977). Rongotea is on the Recommended List for wheat in the southern North Island and is the highest yielding milling wheat listed (Anon., 1990b). The Manawatu Mills utilise Rongotea to produce strong biscuit flour and represents about 40% of the purchases of locally grown milling wheat (G Georgiou, pers. comm.).

3.1   Trial Sites

The location of trial sites is detailed in Figure 3.1.

FIGURE 3.1: Map of Manawatu with site locations
(Burgess, 1988)

Site 1

Site 2

Site 3

Plate 1: View of the three trial sites.

SITE 1:

Plant population:	350 plants/m^2	
Sowing date:	8 August 1989	
Location:	Property of Mr D Gorton, Wilson Road, Waituna West	
Soil type:	Kiwitea silt loam	
Soil test:	pH	5.6
(15 cm cores)	Olsen P	11 micrograms/g (air dry)
	Exch K	0.67 meq/100 g (air dry)
	SO$_4$	12.8 micrograms/g (air dry)
Altitude:	260 m above sea level	
Paddock history:	1988/89	Wheat
	1987/88	Peas
	1986/87	Pasture
	1985/86	Pasture
	1984/85	Pasture
Fertiliser appln:	At sowing: 11 kg N/ha	
	At Feekes GS5:22 kg P/ha, 35 kg N/ha, 8 kg K/ha	

SITE 2:

Plant population:	350 plants/m^2	
Sowing date:	20 August 1989	
Location:	Property of Mr I Gorton, Almadale Road, Almadale	
Soil type:	Manawatu sandy loam	
Soil test:	pH	5.3
(15 cm cores)	Olsen P	27 micrograms/g (air dry)
	Exch K	0.64 meq/100 g (air dry)
	SO$_4$	9.3 micrograms/g (air dry)
Altitude:	160 m above sea level	
Paddock history:	Permanent pasture	

Fertiliser appln: At sowing: 18 kg N/ha

                                   20 kg P/ha

                                   2 kg S/ha

Paddock was sprayed with glyphosate herbicide prior to cultivation to help control perennial weeds and as part of a chemical fallow. N was applied to the seedbed to ensure establishing wheat seedlings were not N deficient as a result of a reduced fallow period.

SITE 3:

Sowing rate:	150 kg/ha	
Sowing date:	12 September 1989	
Location:	Property of Mr R Green, Lockwood Road, Kairanga	
Soil type:	Kairanga fine sandy loam	
Soil test:	pH	5.7
(15 cm cores)	Olsen P	22 micrograms/g (air dry)
	Exch K	0.72 meq/100 g (air dry)
	SO_4	8.1 micrograms/g (air dry)
Altitude:	10 m above sea level	
Paddock history:	Permanent pasture	
	1988/89	Ryegrass Seed
	1987/88	Barley
	1986/87	Red Clover Hay
	1985/86	Peas
	1984/85	Wheat
Fertiliser appln:	At sowing: 30 kg N/ha	
	20 kg P/ha	
	20 kg K/ha	
	14 kg S/ha	

3.2 **Treatments**

The treatments at each trial were four rates of nitrogen applied at Feekes G.S.9. Treatments were arranged in a complete randomised block design with six replicates

re-randomised at each site. Nitrogen treatments were 0, 20, 40 and 80 kg N/ha applied as ammonium sulphate (21% N) by hand broadcasting. Because of different sowing dates and environments, treatment application occurred at different dates for each site. Nitrogen was applied on 9 November 1989 at site 1, 16 November 1989 at site 2 and 23 November 1989 at site 3. A wide range of N application rates was used to determine the response curve of grain protein content and grain yield to late applications of N. Ammonium sulphate was the preferred source of N even though on a cost per kg of N basis, it is more expensive than other N fertilisers. Compared to urea for example, there is a reduced risk of N loss through ammonia volatilisation with ammonium sulphate especially if irrigation is not available (Theobald and Ball, 1984). The other consideration was the known effect of reducing grain protein quality in milling wheat from inadequate sulphur supply (Wrigley, *et al.*, 1984). Two sites had low/medium sulphur reserves so ammonium sulphate was used to help ensure sulphur deficiency did not restrict protein quality.

3.3 Crop Sampling

Because of the different stages of development, each site was independently sampled. Immediately prior to the application of ammonium sulphate at Feekes G.S.9, each site was sampled for DM. Three 0.1 m^2 cuts were taken at ground level from each plot and bulked. Subsamples were taken for determining DM% and nitrogen content. At anthesis ten ears were collected from each plot. These were used to count the number of spikelets/ear and for future determination of nitrogen content. This was required to determine whether or not N fertiliser applied at Feekes G.S.9 was present in the ear by anthesis and if there was a relationship between N content of the ear at anthesis with grain yield, protein content and the number of grain bearing spikelets at harvest.

After anthesis, ear samples (ten ears/plot) were collected regularly until maturity to enable grain growth rates to be determined. After collection, ears were dried and hand rubbed to release grain. After separation, 100 grains were counted and weighed. During late grain-fill, three successive flag leaf samples were collected (10 leaves/plot) so that any treatment effects on the rate of senescense could be identified.

One week prior to harvesting each plot was sampled for DM with four 0.1 m^2 cuts taken at ground level. Samples were taken back to the laboratory for weighing. The number of ears/m^2 yield component was determined by counting the total number of ears present in the bulked sample. Subsamples were later taken for determining chaff N content. Spikelet numbers/ear were counted from a further subsample of 20 ears/plot. Only grain-bearing spikelets were included. To determine the number of grains/spikelet, the 20 subsampled ears were hand rubbed. Individual kernels were separated from the ear and then counted. The number of grains/spikelet component was calculated by dividing the total number grains/20 ears by the total number of spikelets from these ears. Harvest index (HI) was calculated from total DM at harvest (sampled prior to harvest) and grain yield (machine harvest). While it is normal practice to calculate HI directly, by threshing the sample used to calculate total crop DM, this was not possible due to lack of suitable threshing machinery. Grain yields from hand-threshed samples have been found to be very similar to yields achieved from machine harvest (Hampton, 1981). Nitrogen harvest index was calculated from total crop N at harvest, and total grain N. Total crop N is the sum of total grain N and total chaff N.

Final grain yields were obtained by harvesting a 1.3 m wide strip from each plot with a Wintersteiger plot harvester. The plots were initially 8.5 m long but were trimmed to 8.0 m immediately prior to harvest. The area of each harvested strip was adjusted down by 0.4 m^2 for calculating yield. This was done to compensate for the removal of samples immediately prior to harvest. Site 1 and 2 were harvested on 6 February 1990 and site 3 on 5 February 1990. Grain from each plot was weighed in the paddock and a 1.2 kg subsample taken. From this subsample further samples were drawn for determining grain moisture content, grain N content, grain weight and sodium dodecyl sulphate (SDS) sedimentation volumes. In addition, 1 kg of grain from two replicates from each site (8 samples per site) were sent to the Wheat Research Institute (WRI) for test baking.

3.4 **Crop Management**

SITE 1:

Weed control: Glean/Broxoxynil applied at G.S.4.

Disease control: A single application of a systemic fungicide 'Tilt' to control stripe rust (*Puccinia striiformis*) which appeared in the crop in low levels at early ear emergence (Feekes G.S.10.2). Fungicide was applied at that time. Both stripe rust and brown rust (*Puccinia recondita*) infected the crop during late grain-fill (Feekes G.S.11.2). No control measures were taken because such late infections have very little influence on grain yield (Harvey and Hedley, 1985).

Pest control: Small numbers of rose grain aphid (*Metopolophium dirhodum*) were present in the crop up until maturity. No control measures were taken.

SITE 2:

Weed control: Glean/Bromoxynil applied at Feekes G.S.4. This paddock was cultivated from long term pasture and annual broadleaf weed populations were low. Glean was used to provide residual control of Californian thistles which were prevalent.

Disease control: Stripe rust appeared in the crop while it was in 'boot' (Feekes G.S.10). It was sprayed with 'Tilt' during early ear emergence (Feekes G.S.10.2). Stripe rust and leaf rust reappeared in the crop 10 days after flowering had finished. No control measures were taken because of the poor yield response to control of such late infections. Barley Yellow Dwarf Virus infection was evident in the crop and was severe in patches.   As the crop matured small patches of heavy take-all (*Gaeumannomyces graminis*) infection appeared with the whole crop showing signs of mild infection. These signs included the characteristic blackening of the stem bases and areas of the crop with advanced maturity. Ears from these areas consequently developed the secondary infections typical of take-all, eg sooty moulds.

Pest control: Rose grain aphids were present but numbers were too low to consider

taking control measures. This crop suffered some damage from slugs during the early grain-fill period when conditions were damp. Damage occurred on the top two or three leaves (see Plate 3).

SITE 3:

Weed control: Glean/Bromoxynil applied at Feekes G.S.4.

Disease control: Due to early infection of stripe rust, an application of the systemic fungicide 'Cereous' was made in a tank mix with the herbicide. A second application was made with 'Cereous' at Feekes G.S.7 in mid November, also for stripe rust. By late ear emergence stripe rust was again building up in the crop so a fungicide was applied for the third time at early flowering. The third application was of a new product, 'Folicur'. Good control was achieved. Stripe rust reappeared again in the crop during the late stages of grain-fill. Some infection of the heads occurred at this time.

Pest control: Low numbers of rose grain aphid were present. No control was undertaken.

3.5 Field Measurements

At each site, rainfall, maximum, minimum and average temperatures, total solar radiation as well as soil gravimetric water contents were measured. All recordings began at Feekes G.S.9 and finished at harvest.

Rainfall was recorded with a standard 250 mm capacity gauge. Readings were taken whenever the site was visited and at the end of each month to accurately determine monthly rainfall.

Temperature and solar radiation data was collected with an Omnidata DP219 datapod. This is a miniature, battery-powered field potential evapotranspiration computer. Solar radiation is measured with a LiCor Li200S pyranometer and temperature with an Omnidata TP10V temperature probe. Recordings are taken every ten minutes and stored at the end of the day. Up to nine months data can be stored before having to download.

Plate 2: Stripe rust infection at site 3.

Plate 3: View of canopy at site 2 showing slug damage (striped feeding pattern) and early senescence of flag leaves soon after anthesis.

Temperature and radiation data is recorded in degrees Fahrenheit and Langleys respectively. These were later converted to degrees Celsius and megajoules/m^2/day. The datapod and temperature probe were housed in standard Stevenson screens one metre above the ground.

Soil gravimetric water content was measured at Feekes G.S.9, and subsequently, whenever a site was visited to collect crop samples, through until crop maturity. Soil samples were collected with a corer to a depth of 15 cm.

3.6 Laboratory Procedures

All crop samples bought into the laboratory were weighed and then subsampled for drying and calculation of DM. Subsamples were dried at 85°C for 24 hours.

Soil gravimetric water contents were also determined using subsamples, after thorough mixing. Soil samples were dried at 85°C for 48 hours or until no further weight loss could be detected. Soil analysis for pH, Olsen P, exchangeable K and SO$_4$ were conducted at the Fertiliser and Lime Research Centre, Massey University.

Grain samples taken shortly after harvest to determine grain moisture content were weighed and then dried at 85°C for 24 hours. Grain yields were subsequently adjusted to 14% moisture content. Grain weights were determined by electronically counting 500 kernels, drying at 85°C for 24 hours and weighing. Grain weights have been presented on a dry basis.

The N content of crop samples and grain at final harvest was determined by micro Kjeldahl digestion. All samples, after drying, were ground in a Cyclotec sample mill using a 1 mm sieve and sent to Crop Research Division of the DSIR, Palmerston North where the analysis for N content was undertaken. All samples were repeated, with a blank and a standard included in each batch.

All N contents reported are on a dry weight basis. However grain N content was converted to a protein content, using a conversion factor of 5.7 (Jones, 1926), and then

adjusted to 14% moisture content. All grain protein contents reported are on a 14% moisture basis.

3.7 Baking Quality

Standard 125 g MDD bake tests were carried out on a selected number of grain samples from each site by the WRI, Christchurch. This test was introduced by the WRI in 1973 as a result of bakers switching to a mechanical dough development process (Cawley, 1979).

Because the cost of having all plots test baked was prohibitive, only two replicates from each site were tested, giving 24 plots test baked from the total of 72 plots. All plots were subjected to an alternative small scale test used for assessing baking quality, the SDS sedimentation test (Griffin, 1983b). The bake tests were used to establish the validity of the SDS sedimentation test.

The SDS sedimentation test was carried out using a 6 g sample of wholemeal flour from each plot. This is added to 50 mls of distilled water in a graduated measuring cylinder and mixed by shaking for 15 seconds. Shaking is repeated after two and four minutes. After the last shaking 50 mls of SDS-lactic acid reagent (2.0% SDS, w/v and 0.196% lactic acid, v/v) is added to the cylinder. Mixing was achieved by inverting the cylinder five times and repeating again at two, four and six minutes. After the cylinders had been left to stand for fifteen minutes, the volume of the sediment was recorded. The SDS sedimentation test is temperature sensitive (Griffin, 1983a) so testing was carried out in an internal laboratory with temperature closely monitored. Although this laboratory had no temperature control mechanism, its temperature was more stable than laboratories with temperature control located on the outside of the building.

3.8 Analysis of Data

Statistical analysis was carried out on computer with the SAS software system. For the analysis of variance each site was initially analysed separately. However a combined analysis was undertaken for yield and grain protein. This was done to test the overall treatment effect and to determine if there were significant interactions between treatment

and site for these two attributes. The model for the combined analysis was as follows:

$$X_{ijk} = U + A_i + B_{j(k)} + S_K + (AS)_{ik} + E_{ijk}$$

U	=	overall mean
A	=	treatment effects
B	=	block effects
S	=	site effect
AS	=	interaction
E	=	residual (unexplained variation)

i	=	1 to 4
j	=	1 to 6
k	=	1 to 3

For a combined analysis of variance to be valid the error variances for each site must be homogeneous (Cochran and Cox, 1957). This was tested for using the Chi-square test outlined in Steel and Torrie (2nd Edition) p 471 before the combined analysis was undertaken.

All effects in the model are assumed to be random. Because the SAS statistical programme does not allow for the use of complex F tests nor provide the appropriate degrees of freedom for calculating Least Significant Differences (LSD's) needed for this model, this part of the combined analysis was calculated manually.

Results have been presented with F test significances, LSDs and coefficients of variation (CV's). Those results with F test significances greater than 5% (ie there is a greater than 5% chance of wrongly rejecting the null hypothesis) have been reported as non-significant (NS). Where the F test indicated differences amongst treatment means, LSDs have been calculated using the one tailed t test (unless otherwise stated), to separate treatment means.

For those attributes for which site comparisons were required, a two-tailed t test was used to test for differences amongst the three site means.

The closeness of the association between many of the variables recorded in this series of experiments has been measured by simple correlation analysis. Correlation coefficients which are statistically significant are marked with either one or two asterisks. The level of significance which is indicated by this means may vary between different analyses. Significance levels are given in each case. Correlations with significance levels above 5% have been declared non significant.

Linear regression has been used to determine the relationship between some variables and to test whether or not the relationship between variables has been influenced by site. Sites have been compared by testing for differences in the intercept and the slope of the lines describing a relationship at each site.

CHAPTER IV

RESULTS AND DISCUSSION

CLIMATIC DATA, CROP GROWTH AND DEVELOPMENT

4.0 Introduction

This chapter will summarise temperature, rainfall and solar radiation for each site during the period from Feekes G.S.9 to crop maturity. Crop DM and herbage N% at Feekes G.S.9 plus subsequent growth and development in response to climate and N fertiliser over the same period, will also be described.

4.1 Climate

4.1.1 Temperature

Daily maximum, minimum and average temperatures over the total recording period are detailed in Appendix 3. Mean daily maximum, minimum and average temperature for the two months of December 1989 and January 1990 are presented in Table 4.1. Comparisons with 10 year mean (1970-1980) temperatures was only available for site 3, which is in close proximity to the DSIR recording station at Kairanga.

As expected, temperatures generally declined as altitude increased. The decline in average temperature with increasing altitude over the period 10 November/31 January was 0.55°C/100 m of altitude. This is comparable to the figure of 0.6°C/100 m increase in altitude regarded as being applicable over central New Zealand (Burgess, 1988).

Temperatures in December 1989 were below the 10 year means, particularly the minimum temperature. The average temperature for site 3 was 0.7°C below the 10 year mean. The low minimum temperature was due to a period of very cool night temperatures early in the month, with light ground frosts occurring at sites 1 and 2 on 9 December and at all three sites on 10 December (Appendix 3).

Temperatures in January 1990 were more variable with maximum temperatures being 0.9°C above the 10 year mean while minimum temperatures were 1.0°C lower. Average temperature was very close to the 10 year mean.

TABLE 4.1:   Maximum, Minimum and Average Daily Temperatures (°C)

December 1989

	10 year mean	site 1	site 2	site 3
Maximum	20.7	18.3	19.0	20.0
Minumum	10.9	8.1	8.1	9.6
Average	15.8	13.5	14.0	15.1

January 1990

	10 year mean	site 1	site 2	site 3
Maximum	22.5	22.9	23.4	23.4
Minimum	12.4	10.6	10.3	11.4
Average	17.5	16.4	16.9	17.4

TABLE 4.2:   Average Daily Temperature over the Grain Fill Period (°C)

	site 1	site 2	site 3
Average temperature	14.6	15.1	15.7

TABLE 4.3:   Average Monthly Rainfall (mm)

	29 year mean	site 1	site 2	site 3
December	80.0	62.0	56.5	45.3
January	74.0	164.5	140.0	120.5

TABLE 4.4:   Mean Daily Global Solar Radiation (MJ/m^2/day)

	26 year mean	site 1	site 2	site 3
December	24.6	21.5	20.6	22.7
January	24.6	24.1	22.8	24.0
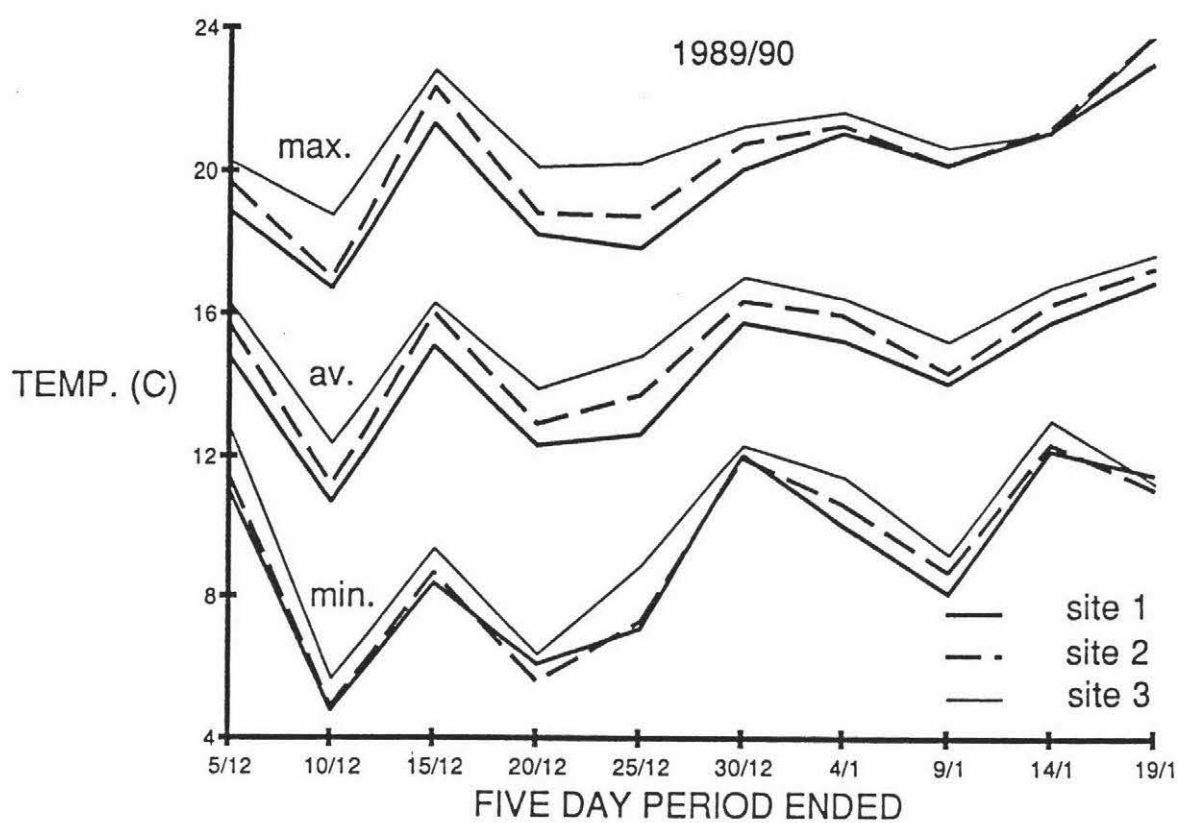
FIGURE 4.1: Temperatures over the grain fill period

Average temperatures over the grain-fill period are detailed in Table 4.2. They have been averaged over the period from the beginning of anthesis until the last sampling date at each site. In addition, maximum, minimum and average temperatures over the grain fill period for each site are shown in figure 4.1. The temperatures in figure 4.1 have been averaged across consecutive 5 day periods. Minimum temperatures show the greatest variation across time but were similar between sites, particularly site 1 and site 2. The reverse pattern occurred with maximum temperatures.

Average temperature over the grain-fill period has declined with increase of altitude although the rate of decrease was 0.44°C/100 m which is less than that recorded over the total measurement period. This was due to anthesis at sites 2 and 3 occurring at the beginning of a period of cold temperatures during the second week of December.

4.1.2 Rainfall

Total rainfall recorded over the measurement period is shown in Appendix 1. Rainfall over December/January is shown in Table 4.3 with a comparison of the 29 year mean rainfall available for site 3. December rainfall for all sites was considerably below the long term mean for site 3. Rainfall has increased with altitude which is consistent with long term observations on the influence of altitude on rainfall in the Manawatu (Burgess, 1988). It is safe to conclude therefore that December rainfall was considerably below average at all 3 sites.

However, in January, rainfall was higher than the long-term mean at site 3 with rainfall again increasing with altitude. It must be noted though that the January figure was inflated by a large rainfall event recorded on 31 January (Appendix 2). At site 3 for example, 63.5 mm of rain was recorded. Up until this rainfall event, the monthly total for January was at about the long-term average. This rain also fell too late to benefit crop growth. Its major influence, was in fact, to delay harvest.

4.1.3 Radiation

Daily radiation receipts for each site are detailed in Appendix 4. Mean daily radiation for December 1989 and January 1990 are shown in Table 4.4. The nearest radiation

recording station is at Ohakea Aerodrome (Figure 3.1). The 26 year average (1954-1980) from Ohakea is provided for comparison. Radiation levels are similar at sites 1 and 3. Site 2 is slightly lower than the other sites while all 3 sites are lower than the long-term mean for December and similar for January. This is consistent with long-term annual sunshine hours found in the Manawatu with highest totals being recorded close to the coast and declining in inland areas. Ohakea receives over 2000 hours of sunshine/ annum while site 1 and 3 are in a band receiving between 1900 and 2000 hours and site 2, 1800-1900 hours (Burgess, 1988). There is a close relationship between sunshine hours and global solar radiation (de Lisle, 1966).

4.2   Crop Development and Grain Growth

After the application of N at Feekes G.S.9, regular ear sampling of the crops at each site was started. The first samples were collected at anthesis. Anthesis dates, with number of days between treatment application and anthesis in brackets were: site 1, 30 November (21 days); site 2, 5 December (19 days) and site 3, 7 December (12 days). The site differences in the time between Feekes G.S.9 and 10.5.1 (anthesis) are the result of differences in average temperature at each of the sites. These temperature differences were due to both altitude (Table 4.1) and sowing date (Chapter III). Average temperatures between Feekes G.S.9 and 10.5.1 were: site 1: 13.3°C, site 2: 14.4°C and site 3: 14.6°C. Increasing temperatures decrease the duration of the vegetative and reproductive phases in wheat (Marcellos and Single, 1971). The difference in average temperature between sites 2 and 3 is very small and seems unlikely to have produced the difference in the duration of the Feekes G.S.9 to 10.5.1 period. However, site 3 was dry at Feekes G.S.9 with soil gravimetric content being only 12.4% (Appendix 2). Soil moisture contents of this level on a fine sandy loam (Chapter III) would have significantly influenced crop growth (Horne, Massey University, pers. comm.). Development is accelerated in crops suffering moisture stress compared to unstressed crops (Drewitt and Dyson, 1987).

The course of grain development and an approximation of the length of the grain fill period (beginning of anthesis to maximum dry weight of grain) can be seen from Figure 4.2. Precise determination is not possible as grain samples could not be collected on

a daily basis. However, based on the moisture content of the grain at the last date of sampling prior to the final harvest, it was assumed that maximum grain dry weight had been achieved at all 3 sites. Maximum grain dry weights occur at about 40% grain moisture content (Jennings and Morton, 1963). Grain moisture contents in this study at the final sampling date prior to harvest were just under 40% at site 1 and just over 30% at sites 2 and 3 (data not presented).

Grain growth shows a typical lag phase immediately after anthesis, followed by a period of linear growth. Subsequently, grain growth levels off, just before the achievement of maximum grain dry weight (Gallagher and Biscoe, 1978b; Sofield *et al.*, 1977a; Spiertz and van de Haar, 1978). The achievement of maximum grain dry weight at site 1, 2 and 3 occurred at 55 days, 49 days and 43 days respectively. The length of the grain-fill period has increased with increasing altitude and decreasing temperature. Temperature has a very strong influence on the length of the grain-fill period (Sofield *et al.*, 1977a; Warrington, Dunston and Green, 1977). The difference in average temperature over the grain-fill period between site 1 and site 3 was 1.1°C. There was a 12 day difference in the grain-fill period between these two sites. This reduction in duration of the grain-filling period per degree C increase in average daily temperature is considerably greater than those reported elsewhere. For example, Spiertz (1977) reported a decrease of 3.4 days/°C and Wiegand and Cuellar, 3.1 days/°C. Other factors must therefore have influenced the duration of the grain-fill period. Solar radiation has been shown to influence the duration of the grain-fill period (Welbank *et al.*, 1968), though site differences in this study were small. The effect of solar radiation on the duration of the grain-fill period is usually slight and only detectable at very low levels of radiation (Sofield *et al.*, 1977a).

It is probable that at site 3, moisture availability will have reduced the period of grain-fill (Drewitt and Dyson, 1987; Nicolas *et al.*, 1984) while at site 2 a late infection of take-all (section 3.4, Chapter III) will have shortened the grain-fill period (Harvey, 1979).

The decline in grain weight between the achievement of maximum dry weight and final
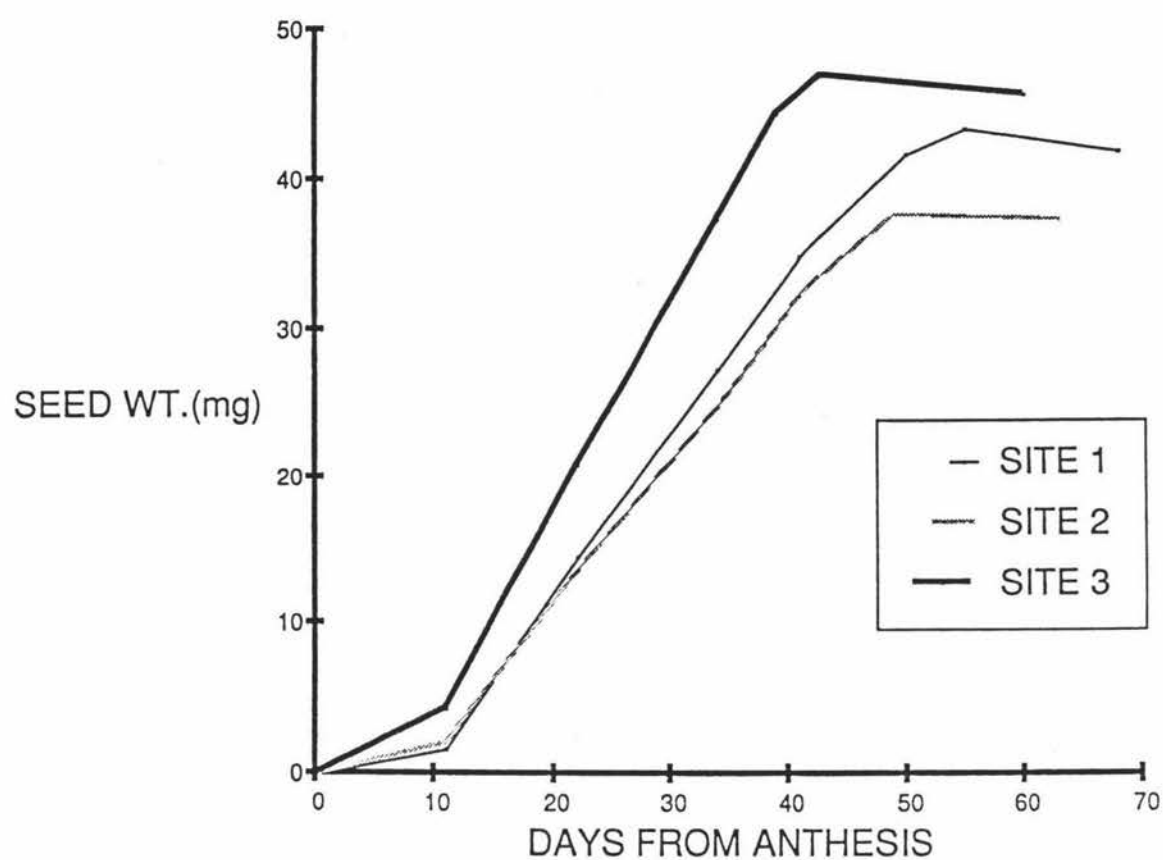
FIGURE   4.2:   The course of grain growth

harvest was probably caused by the damage done to large grains at harvest. Many of these grains were broken during threshing and were subsequently excluded from samples used to calculate dry grain weight. At site 2, where grain weights were low (37 mg), there was little change between maximum dry weight and harvest. Respiration losses can also cause a decline in grain weight (Spiertz and van de Haar, 1978).

4.3   Dry Matter and Nitrogen Yield at Feekes G.S.9

Immediately prior to the application of N at Feekes G.S.9, each plot was sampled for DM yield and subsampled for determination of N content. As there were no treatment effects, this data was pooled for each site and a t-test used to determine the significance of any differences between the sites. This data is shown in Table 4.5.

Table 4.5:   Crop Dry Matter and Nitrogen Content at Feekes G.S.9

	site 1	site 2	site 3	
DM @ G.S.9 (kg DM/ha)	6318	5702	4823	*
N Content @ G.S.9 (%)	2.3	3.0	1.9	*
N Yield @ G.S.9 (kg N/ha)	146	169	92	*

* Sites are significantly different from each other at the 5% level of probability
  (two tailed t-test)

For DM, N content and N yield, each site is different from the other two. The differences in crop DM indicated in Table 4.5 are probably mainly due to the differences in the period between sowing and the time of sampling at Feekes G.S.9. Average crop growth rate over this period was 67.9 kg DM/ha, 64.8 kg DM/ha and 65.2 kg DM/ha for sites 1, 2 and 3 respectively. These growth rates are similar but it is reasonable to expect that crop growth rates should increase from site 1 to 3 as declining altitude and delayed sowing dates will have increased average temperatures over the growth period. The rate of DM accumulation in wheat generally increases as temperature increases (Friend, Helson and Fisher, 1962). However the growth duration of wheat declines with increasing temperature, the net effect being that increasing

temperatures decrease DM at any given stage of development (Kolderup, 1979). Nitrogen has a strong influence on the DM accumulation of cereals with crops deficient in N having lower LAI and LAD than crops where N supply is not limiting (Willington and Biscoe, 1982). However, critical N concentrations are difficult to determine because as cereal crops grow and develop, N concentration naturally declines (Moller Nielsen and Friis-Nielsen, 1976). N concentration in the DM at Feekes G.S.9 ranged from 3.0% at site 2 to 1.9% at site 3 with site 1 being intermediate at 2.3%. The lower than expected crop growth rates at sites 2 and 3 may be due to a wide range of environmental and management factors. It seems unlikely that N supply at site 2 was a limiting factor if it is assumed that the N content of total herbage at Feekes G.S.9 reflects the availability of N up to that point. Root damage from take-all seems a more likely reason for a lower than expected growth rate at this site. Low N availability may be a reason for the lower than expected growth rate at site 3.

Olsen and Kurtz (1982) described the plant N contents of a range of agricultural species associated with a designated nutritional status. For spring wheat, a N content of 1.5-2.0% at ear emergence is regarded as 'low' and 2.0-3.0%, 'sufficient'. Herbage N content at ear emergence (Feekes G.S.10.1) is likely to be lower than those at Feekes G.S.9. This indicates that at site 3 and possibly site 1, N content may have been in the low category. Soil moisture availability is a major cause of variation in crop growth (Biscoe and Willington, 1982). At site 3, soil moisture content was low at Feekes G.S.9 (Appendix 2). This will have resulted in a supression of crop growth which will have caused an increase in crop N content through a reduction in the dilution of available N with DM (Olsen and Kurtz, 1982). Under conditions of optimum soil moisture content, the N content of herbage at site 3 may have been lower than 1.9%. The total N yield at site 3 also indicates that N has limited DM accumulation at this site. Moisture stress has a greater influence on crop DM accumulation than it does on N uptake (Dowdell, Crees and Christian, 1982). The low N yield at site 3 is not necessarily due to moisture stress therefore.

4.4 Nitrogen Uptake and Canopy Senescence

After the application of N at Feekes G.S.9, ear samples were collected at each site at the beginning of anthesis. This was done to assess the speed at which applied N was taken up and became available in the ear and also to determine whether differences in N content of the ears were associated with possible differences in grain set amongst the treatments.

Table 4.6 shows the effect of late N on the N content of the ears at early anthesis for each site. At sites 1 and 3, late N had significantly increased the N content of the ears. Although ear N content at site 2 tended to increase with increasing rates of late N, these results were not significant.

Table 4.6:   N Content of the Ears at Anthesis (%)

kg N/ha	site 1	site 2	site 3
0	1.52	1.69	1.43
20	1.51	1.74	1.46
40	1.59	1.75	1.50
80	1.65	1.76	1.55
significance	0.0025	NS	0.0007
LSD	0.06	-	0.04
CV	3.6	3.9	2.7

The period between application of late N at Feekes G.S.9 and ear sampling at the beginning of anthesis ranged from 21 days at site 1 to 12 days at site 3 (section 4.2). At all 3 sites rain fell within 1-2 days after the application of N. This has allowed rapid uptake except at site 2 where take-all infection adversely affected the crop's ability to absorb nutrients. However even at site 2 which was a high fertility site, the increase in the N content of the ears indicated in Table 4.6 is probably real, given that both straw N% and grain protein were significantly increased by late N at site 2.

When ammonium sulphate is applied to soils, the ammonium is usually rapidly oxidised to nitrate (nitrification) if soil conditions are favourable (warm and near neutral pH)

(Keeney and Gregg, 1982). Once in the soil solution, it may be only a matter of hours before this N can be measured in plants growing in this soil (Minotti, Williams and Jackson, 1969). The low pH at site 2 (Chapter III) may also have contributed to the slow uptake of N fertiliser compared with other sites.

Canopy senescence was measured by sampling ten flag leaves from each plot and recording the average dry weight at 34 and 41 days after the beginning of anthesis. Dry weights were used as an indirect measure of the loss of nutrients, particularly N, from the flag leaves. There is a reliable relationship between the dry weights of various canopy components during the anthesis to grain maturation period and the N content of these canopy components (Spiertz and De Vos, 1983).

Table 4.7: Dry Weight of Flag Leaves at 34 and 41 days after Anthesis(g)

Treatment kg N/ha	site 1		site 2		site 3	
	34 days	41 days	34 days	41 days	34 days	41 days
0	1.38	1.07	1.32	1.25	0.667	0.597
20	1.31	1.12	1.32	1.15	0.612	0.581
40	1.56	1.24	1.30	1.25	0.673	0.576
80	1.54	1.26	1.36	1.31	0.758	0.659
significance	0.011	0.012	NS	NS	0.002	0.0025
LSD	0.13	0.10	-	-	0.053	0.034
CV	8.8	8.6	9.7	8.5	7.7	5.6

Table 4.7 shows that late N has reduced the rate of DM loss from the flag leaves at sites 1 and 3. Because the developing grain is such a strong sink for N (Sinclair and de Wit, 1975), N is remobilised from the vegetative structures if sufficient N is not able to be taken up from the soil to meet the requirements of the grain. The application of late N has probably increased the availability of soil N, increasing uptake and therefore reducing the remobilisation of N from the flag leaves, which results in delayed senescence (Spiertz and Ellen, 1978). Late N did not influence the rate of flag leaf senescence at site 2, probably because the site was a high fertility site anyway and also because take-all was influencing crop development by this time.

Plate 4: The visual response (green pigmentation and delayed leaf senescence) resulting from the application of late N at site 3. On the right, a plot which received 80 kg N/ha compared to a plot receiving 20 kg N/ha, on the left.

The relative loss of DM between 34 and 41 days after anthesis, across all treatments was 19% at site 1 and 10.5% at site 3. This difference is almost certainly due to the fact that at site 3 the flag leaves had almost finished senescing at 41 days, with only 2 days until maximum grain weight, whereas at site 1 this sampling time was still 2 weeks away from maximum grain weight.

The rate of senescence of flag leaves is an import determinant of final grain weight as the fractional loss of N from leaves is related to the maximum rate of photosynthesis of these leaves (Gregory, Marshall and Biscoe, 1981). For example Biscoe, Scott and Monteith (1975) found that light saturation in the final week of the grain-fill period occurred at about 200 W/m^2 compared to 800 W/m^2 in the first week and that the maximum rate of photosynthesis was only 15% of the original maximum value.

Therefore at sites 1 and 3 the application of late N resulted in a delay in senescence and increased assimilate supply to the developing grain.

4.5 Grain Growth Rates

Grain growth rates at the beginning of the linear phase of grain growth (11 days after beginning of anthesis) were just under 0.2 mg/grain/day for sites 1 and 2 and 0.4 mg/grain/day for site 3 (Figure 4.2). Subsequently, grain growth rates at all sites showed a similar pattern of increase followed by a plateau before declining. Actual growth rates at sites 1 and 2 were very similar. The highest growth rates occurred at site 3, peaking at 1.5 mg/grain/day. Senescence was very rapid at site 3 and this can be seen in the steep decline in grain growth rates after 39 days post anthesis. At all 3 sites there was a decline and subsequent small recovery in grain growth rate between about 20 and 40 days post anthesis. This was likely to have resulted from a decline in temperatures experienced at all sites from 6 December to 12 December (Apppendix 3).

Environmental factors influencing the rate of grain growth include both temperature and radiation. At site 3, higher average temperatures (Warrington,Dunstone and Green, 1977) and greater radiation levels (Spiertz, 1977) may have contributed to the higher growth rates at this site compared to the other two. The source : sink balance can also
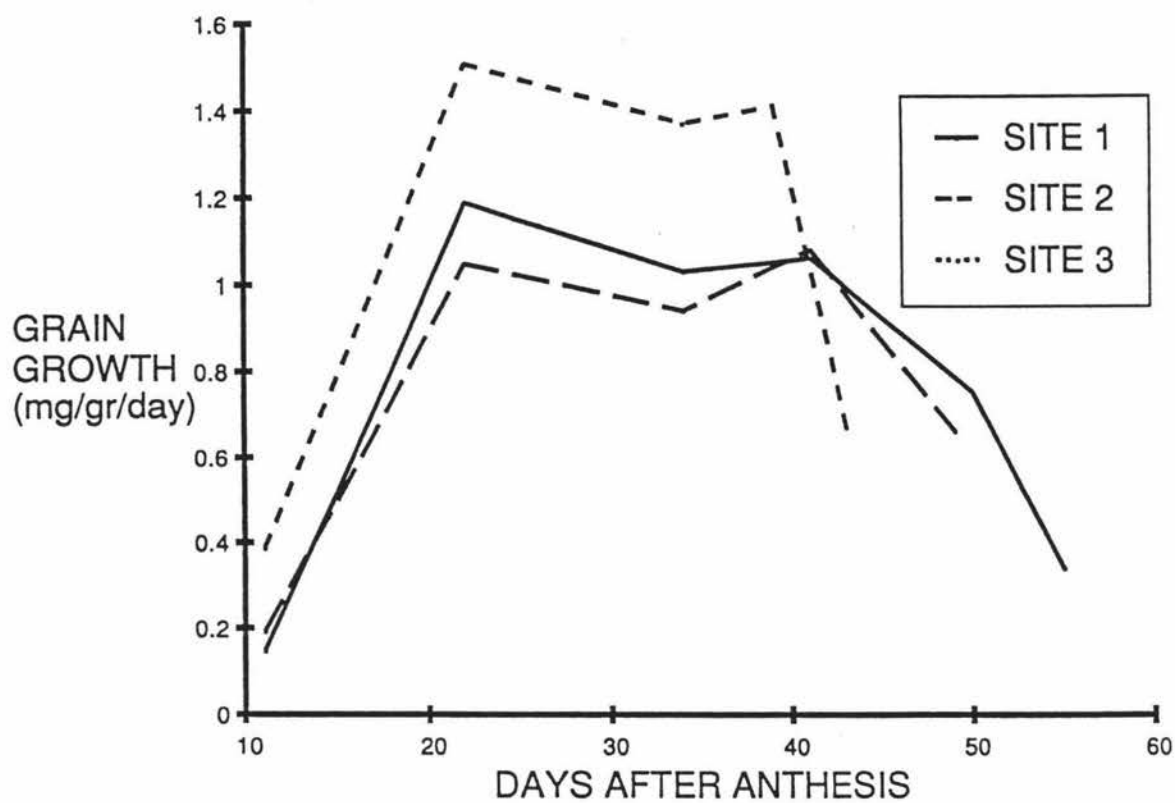
FIGURE 4.3: Grain growth rates

influence grain growth rates (Evans and Rawson, 1970). Spiertz, 1977 found a considerable interaction between temperature and radiation on the growth rate of grains. High radiation levels increased growth rates more at high temperatures than low. The demand for assimilates by the grain is greater at higher temperatures so that any imbalance between source and sink will be increased. The decline in average temperatures during the second week of December was primarily caused by low night temperatures with light ground frosts occurring at all sites (Section 4.1.1). Low temperatures at dawn have been shown to reduce the rate of photosynthesis in creals. Fukai, Koh and Kumura (1976) found that dawn temperatures of between 0° and 5°C depressed net daily photosynthesis by 4-11% compared to dawn temperatures above 5°C. Dawn temperatures were likely to have been at 5°C or less on 5 consecutive nights at site 1 and 2, and for 3 consecutive nights at site 3 (Appendix 3).

CHAPTER V

RESULTS AND DISCUSSION

GRAIN YIELD AND YIELD COMPONENTS

5.1 Introduction

The results in this chapter will initially be presented separately for each site. The discussion which follows will make site comparisons where appropriate. Linear correlation was used to measure the intensity of association between yield and yield components. This was done separately for each site. A combined analysis of grain yield is presented.

5.2 Results

The yield and yield components for each site are detailed in Table 5.1. The theoretical yields in this study were 18.6%, 21.6% and 18.4% higher than header yields for site 1, 2 and 3 respectively and are comparable with differences achieved by other workers (Hampton, 1981). The grains/ear component is the product of spikelets/ear and grains/spikelet and the grains/m^2 component is the product of grains/ear and ears/m^2. Both of these components were calculated on an individual plot basis (see equation 1 below). Therefore the treatment means in Table 5.1 for these two components are not simply the product of the treatment means of their respective factors.

$$\bar{x} \; = \; \frac{\sum a_i}{n} \; \times \; \frac{\sum b_i}{n}. \quad i=1....n \qquad (1)$$

5.2.1 Site 1

The late application of N has significantly increased grain yields at each successive rate. This increase was primarily the result of an increase in ears/m^2 at harvest. Ear numbers at 80 kg N were 15% higher than plots receiving no N, resulting in a 13% increase in yield. The increase in ear numbers resulted in a similar increase in grains/m^2, the overall measure of sink size. There appeared to be a response to N in the grains/

TABLE 5.1: Grain Yield, Yield Components, Total Dry Matter and Harvest Index by site

	Yield (t ha^{-1})	Ears m^{-2}	Spikelets ear^{-1}	Grains spikelet^{-1}	Grains ear^{-1}	Grains m^{-2}	Grain weight (mg)	Total DM at harvest (t ha^{-1})	Harvest Index
SITE 1									
kg N/ha									
10	6.39	521	13.83	2.15	29.7	15453	41.8	14.3	0.385
20	6.67	542	13.57	2.17	29.4	15956	41.2	14.9	0.388
40	6.96	585	13.75	2.16	29.8	17387	42.3	15.9	0.378
80	7.23	598	13.57	2.23	29.8	17812	41.8	17.1	0.374
signif- icance	0.0001	0.0078	NS	NS	NS	0.008	NS	0.0082	NS
LSD	0.22	37	-	-	-	1163	-	1.3	-
CV%	3.2	6.5	5.0	3.2	3.6	6.9	1.7	8.1	10.0
SITE 2									
kg N/ha									
10	5.91	557	15.4	1.94	29.8	16589	37.6	15.4	0.333
20	5.57	527	15.6	1.84	28.8	15119	36.6	14.6	0.331
40	5.91	560	15.5	1.96	30.5	17121	37.1	15.0	0.338
80	6.0	552	15.5	1.97	30.6	16894	37.7	15.2	0.341
signif- icance	NS	NS	NS	NS	NS	NS	0.0481	NS	NS
LSD	-	-	-	-	-	-	0.71	-	-
CV%	5.3	7.5	2.4	6.3	7.1	9.3	1.9	8.6	8.2
SITE 3									
kg N/ha									
10	6.12	432	15.3	2.05	31.3	13563	43.6	12.6	0.419
20	6.19	421	15.2	2.15	32.7	13732	44.6	12.3	0.435
40	6.50	436	15.7	2.16	33.9	14766	46.1	13.7	0.416
80	6.94	436	15.6	2.28	35.6	15507	47.9	13.8	0.436
signif- icance	0.0001	NS	NS	NS	NS	NS	0.0001	NS	NS
LSD	0.25	-	-	-	-	-	0.75	-	-
CV%	3.8	11.9	3.9	6.8	9.7	17.7	1.6	12.2	11.7

spikelet components, however it was not significant. There were no differences in the spikelets/ear, grains/ear or grain weight components. Total crop DM at harvest responded to late N. However, because late N also increased yield, HI was unaffected.

5.2.2 Site 2

Grain yield was unreponsive to late N. This may have been due to the high fertility of site 2 but may also have been caused by the disease and pest problems encountered at this site (Chapter 3). Treatment 2 (20 kg N/ha) had the lowest level of all the treatment means for the components listed in Table 5.1, with the exception of spikelets/ear. However only for the grain weight component was this depression significant. This was probably caused by a higher incidence of take-all in those plots receiving 20 kg N (Appendix 5). Although the differences in the proportion of discoloured ears in Appendix 5 are not significant, the severity of take-all infection was not measured. Visually, two plots from treatment 2 appeared to suffer more damage than other plots.

5.2.3 Site 3

Grain yield responded to late N at 40 kg N and 80 kg N. However the mechanism for this yield response was an increase in grain weight. Late N increased grain weight at all rates (Table 5.1). There were no significant differences in any of the other yield components, total DM at harvest and HI. There appears to have been a response in the grains/ spikelet component to late N with the control treatment averaging 2.05 grains/spikelet compared to 2.28 grains/spikelet at the highest rate of N (an 11% increase). Although declared non-significant at the 5% level of probability, it was significant at the 8% level.

5.3   Discussion

5.3.1 Yield

The yield response to late N at site 1 and site 2 was 10.5 kg grain/kg N and 10.25 kg grain/kg N respectively at 80 kg late N/ha. It is not possible to compare the grain yield response from late applications compared to early applications in this study. However, other workers have found responses to late N similar to those in this study but which

were generally well below responses achieved from early applications (Spiertz and Allen 1978; Withers, 1986). At site 2 an infection of take-all limited yield, primarily by reducing grain weight which was lowest at site 2. Take-all is a soil-borne fungus which causes a crown and root rot, severely restricting uptake of nutrients into the plant (Harvey, 1979). Although take-all can survive on a number of pasture species, (Anon., 1978) it is not normally regarded as a serious problem in paddocks out of long term pasture. However, at site 2 there was a moderate infestation of couch *(Agropyron repens)* which can act as a host for take-all. Control of couch with glyphosate (as at site 2) can significantly increase the risk of take-all infection in subsequent wheat crops (Harvey, Hedley and Braithwaite, 1982).

At Feekes G.S.9, there was no visible sign of take-all. It was not until the early grain-fill period that symptoms became noticeable (accelerated senescence). There were no differences in the numbers of spikelets/ear between normal and discoloured ears whereas both grains/spikelet and grain weight were significantly depressed in discoloured ears (Appendix 6) indicating a relatively late infestation of take-all.

Although there were no significant differences between treatments in proportion of discoloured ears, two plots from treatment 2 appeared to be more severely infected than the others, suffering depressed yields (data not given) and lowering the average yield for treatment 2.

The incidence of discoloured ears in each plot could have been used as a covariat and used to adjust the yield and yield components for each plot (Steel and Torrie, 1981), however as take-all had limited any potential response to N for all treatments, this would not have provided additional information.

5.3.2 Ear Numbers/m^2

Yield responses to late N have primarily been achieved through an increase in grain weight (Drewitt and Dyson, 1977; Martin, 1987; Langer and Liew, 1973). However late applications of N can increase ear numbers (Stephen *et al.,* 1985; Withers, 1986). In both of these studies, an increase in ear numbers at harvest, in response to late
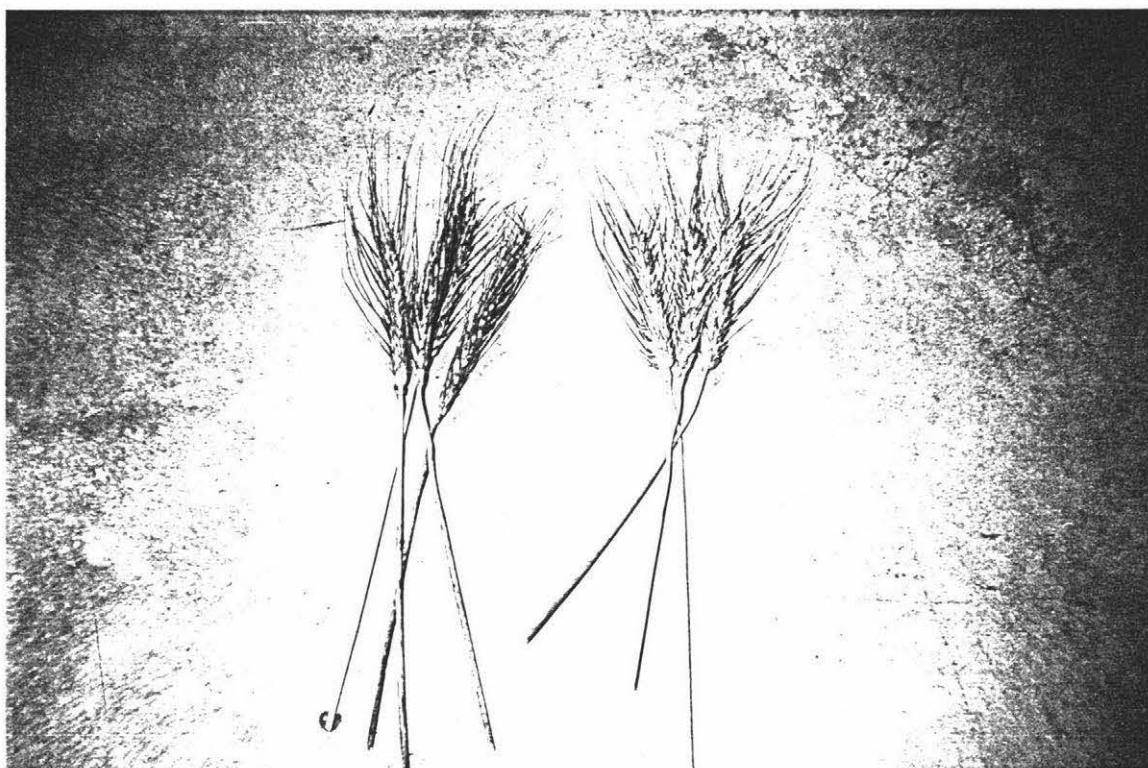
Plate 5: The effects of take-all at site 2. The discoloured ears on the left are from diseased plants while the normal ears on the right are from healthy plants.

applications of N, was attributed to favourable growing conditions. In particular, adequate soil moisture allowed secondary tillers to respond to late N.

The response to late N at site 1 in this study was probably also the result of very favourable growing conditions. Site 1 was the earliest sown and coolest site in this study, meaning crop development was slower than at either site 2 or 3 (Chapter IV). Rainfall and soil moisture contents were also highest at site 1 and probably meant moisture was not limiting crop growth at any stage after the application of late N (Appendix 2). In contrast, a greater rate of development and less favourable soil moisture status at site 3 were limiting factors, preventing secondary tillers responding to the increased N supply.

These factors, plus a probable limitation due to N deficiency (Chapter IV) has resulted in ear numbers at site 3 being low compared to the other two sites (Table 5.1). As a consequence grain numbers are also lower at site 3 compared to the other sites (Section 5.3.5).

The relationship between ears/m^2 and yield as well as with other yield components will be discussed later in this chapter.

5.3.3 Spikelets/Ear and Grains/Spikelet

Late N has had no effect on the number of grain-bearing spikelets at any site. Although spikelet initiation occurs well before Feekes G.S.9 (Brooking, 1979) and therefore unlikely to be influenced by application of N at this time, the number of viabile florets in each spikelet can be influenced by increased N supply prior to Feekes G.S.10.1 (Langer and Liew, 1973). Most wheat cultivars will produce at least 8-10 floret primordia per spikelet with subsequent death, occuring until anthesis (Feekes G.S.10.5), reducing this number substantially (Brooking, 1979). In this study there were also no differences in grain numbers/spikelet amongst the treatments, although at site 3, the differences shown in Table 5.1 just failed to be statistically significant. Site 3 was probably being limited by available N at the time of the late N application (Chapter IV).

At site 1 any response in grain-bearing spikelets/ear and grains/ spikelet may have been complicated by the increase in ear numbers with late N. Some workers have found a negative correlation between these two components and ear numbers (Hampton, 1981). The major reason for this is that tillers have fewer grains in each spikelet compared to the mainstem (Fraser and Dougherty, 1978). Where an early application of N fertiliser has resulted in an increase in ear numbers, there may be a positive relationship between these yield components (Dougherty, Love and Mountier, 1978). The response in ear numbers at site 1 can only have occurred as the result of increased survival of later formed tillers. These tillers will not have been as mature as the primary tillers in the crop at Feekes G.S.9 so that the application of late N may have been sufficiently early to increase the number of grain-bearing spikelets on these tillers. Langer and Liew (1973) found that increased N supply between floret initiation and ear emergence sharply increased the number of grain-bearing spikelets, particularly in the basal positions. That the increase in ears per m^2 at site 1 did not depress the number of grain-bearing spikelets is probably due to the increased survival of florets in the basal spikelets in those tillers which developed to maturity in response to late N.

5.3.4 Grains/m^2

The number of grains/m^2 in a wheat crop is the product of the individual yield components determined by the end of anthesis, ie ears/m^2, spikelets/ear and grains/spikelet. Grains/m^2, together with grain weight determines final yield. However, because grain weight is a relatively stable component (Section 5.3.5) it is the number of grains/m^2 which has the greatest influence on yield (Fischer and Laing, 1976; Kolderup, 1978).

The number of grains/m^2 at site 1 and 2 were similar with average numbers being 16,652/m^2 at site 1 and 16,430/m^2 at site 1. At site 3 grain numbers were below this level at 14,392/m^2. The major reason for the difference being the lower ear numbers at site 3 compared to the other sites (Table 5.1).

Yield generally increases as the number of grains/m^2 increase. Fischer, Aguilar and Laing (1977) found that under conditions of adequate fertility and moisture, yield

continued to increase at grain numbers well above $30,000/m^2$. Grain weight decreased as grains/m^2 increased however, sometimes to less than 30 mg. Langer (1980) also reported similar results when grain numbers exceeded $20,000/m^2$. However, Spiertz and Ellen (1978) reported grain weights of over 42 mg at grain numbers of over $20,000/m^2$ in a favourable year for grain yields.

In this study, the greatest grain numbers occurred at site 1 with the application of 80 kg N/ha of late N. Just under 18,000 grains/m^2 were present. There were no detrimental effects on grain weight as a consequence of increased grain numbers (Table 5.1), indicating that late N has not significantly altered the source : sink balance. At site 3 there may have been a small increase in grain numbers in response to late N, primarily through an increase in the number of grains/spikelet (Section 5.3.4). However, the treatment differences indicated in Table 5.1 were not significantly different, mostly due to the large CV for this characteristic.

5.3.5 Grain Weight

Grain weight in milling wheat is an important characteristic because it is a major determinant of final yield and an important quality characteristic. Small grains, weighing below 35 mg at 14% moisture content, tend to have reduced flour extraction rates when milled (Simons and Meredith, 1979). Given that the grain weights listed in Table 5.1 are on a zero moisture basis, they are well above this level.

Only at site 3 did individual grain weight respond to the application of late N. Although there was no response in grain weight from late N at sites 1 and 2, the reasons for this were different for each site.

At site 2 the only influence on grain weight appeared to be the level of take-all present. Overall, depressed grain weight at site 2 is the major reason for the low yield at this site compared to the other sites. Grain numbers/m^2 were similar to those at site 1. The low grain weights at site 2 are consistent with the effects of a late infection of take-all. Green and Ivins (1984) reported at 36.3% decrease in grain weight after a late infection of take-all. At site 2 there was a 42% decrease in grain weight between normal and

discoloured ears (Appendix 6). The lack of response of seed weight to late N at site 1 is probably due to an increased sink capacity resulting from a significant increase in grain numbers/m^2 in response to late N. It is also possible that late N may have improved the survival of secondary tillers which did not mature. These tillers will have acted as another sink competing for available assimilates. Any affect late N has had on increasing the source capacity of the crop at site 1 has been matched by an increase in the sink capacity, resulting in grain weights remaining unchanged.

At site 3, late N did not begin to influence grain weight until some-time between 34 days and 39 days after the beginning of anthesis (Figure 5.1). N appears to have increased the duration of the linear phase of grain growth rather than increased the maximum rate of grain growth. There does not appear to have been any effect on the grain-filling period. This is consistent with the findings of Spiertz and van de Haar (1978) and Spiertz and Ellen (1978). Spiertz and van de Haar (1978) found that late N increased the LAD of wheat which allowed photosynthesis to occur at higher rates during the later stages of the grain-fill period, increasing the availability of assimilate to the grain, thereby increasing grain weight. This is the mechanism proposed as the explanation for the increased yields in response to late N at both sites 1 and 3 (Chapter IV). At site 1, the increase in the LAD or source capacity was balanced by an increase in the sink (grains/m^2) whereas at site 3, sink size was not affected. This resulted in an increase in grain weight.

Yield responses to late N, resulting from an increase in LAD, are not necessarily proportional to the increase in LAD achieved with the application of late N (Thomas, Thorne and Pearman, 1978). Spiertz and van de Haar (1978) concluded that late N increased grain yields not only through an increase in the source capacity of the crop but also through an improvement in the translocation of assimilates from vegetative structures to the grain, that is, by an improvement in the HI.

Grain weight is a relatively stable yield component compared to other yield components (Stoskopf and Reinbergs, 1966). This has arisen through natural and artificial selection which favours large grain. The response of the crop to any stress prior to the
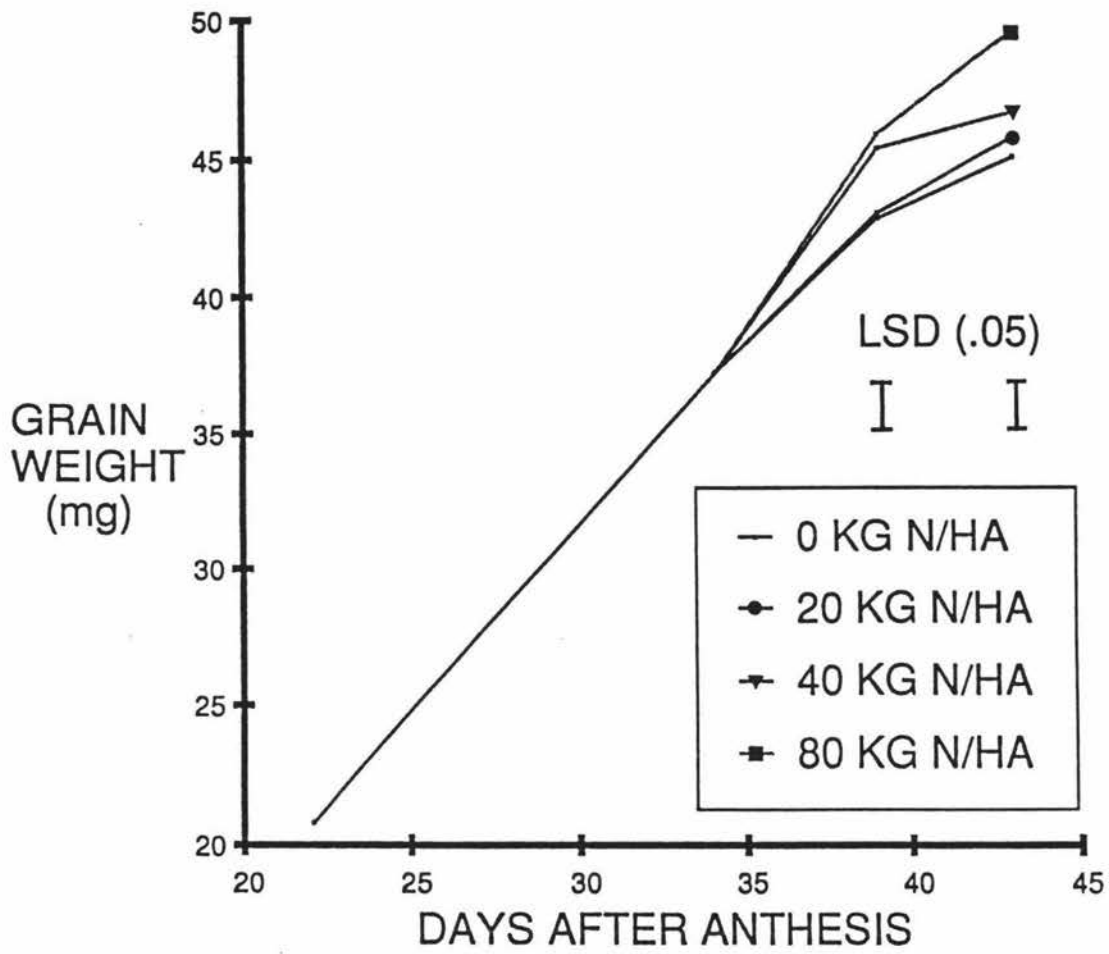
FIGURE 5.1: The effect of N on grain weight at site 3

determination of grain numbers at anthesis is to reduce grain numbers so that grain size is maintained (Fischer, Aguilar and Laing, 1977). The wheat plant also has a capacity to partially compensate for reduced assimilate availability, due to stress, by mobilising reserves of carbohydrate from the stems (Gallagher and Biscoe, 1978b).

Factors influencing the balance between grain number/m^2 and the photosynthetic capacity of the crop e.g. disease prevalence (Daly and Dyson, 1987), moisture availability (Baier and Robertson, 1967), temperature (Spiertz, 1977) and N supply (Pearman *et al.*, 1977) can all cause variation in grain weight.

5.3.6 Total Crop Dry Matter and HI

Only at site 1 did the application of late N influence the total DM yield of the crop at maturity (just prior to final harvest). This can be explained by the fact that at site 1 late N increased the number of ears/m^2 at harvest. Unless the density of the crop is increased from an application of late N, total DM responses are likely to be limited to increased in grain weight resulting from a delay in senescence. For those tillers at Feekes G.S.9, an application of N will be too late to influence those canopy structures which determine LAI (Gallagher and Biscoe, 1978b), for example leaf number and size (Langer and Liew, 1973).

At site 3 the yield response to late N occurred from an increase in grain weight. If this increase was the result of increased photosynthesis from greater LAD, then any increase in crop DM would be equal to the increase in grain yield. In this situation the maximum grain yield response was 820 kg/ha. Treatment differences for total DM exceed this, but are not significant.

Increases in crop DM in response to late N are not typical (Spiertz and Ellen, 1978; Strong, 1982; Strong, 1986; Cooper and Blakeney, 1990). However where late N applications have increased the survival of ear bearing tillers, increases in total crop DM have been recorded (Spiertz and De Vos, 1983).

Harvest index did not respond to the application of late N at any site. However there

were large and significant site differences in HI between sites (P = 0.1%). Average HI was 0.380, 0.337 and 0.427 at site 1, 2 and 3 respectively. Each site is significantly different from the other two.

Rongotea was derived from a cross between a Mexican semi-dwarf accession and the standard height Australian cultivar, Raven (McEwan and Vizer, 1979). When comparing the HI of Raven and other standard height cultivars, with semi-dwarf wheats, McEwan (1973) found that Raven had a HI of 0.330 compared to the HI of the semi-dwarf wheats of 0.450, a substantial difference. The HI for Rongotea in this study has varied across this range. Spring sown Rongotea has been found to have a HI which is intermediate between semi-dwarf and standard height cultivars (Drewitt and Quin, 1980).

The HI at site 2 is low compared to the other sites. The probable cause of this is likely to have been the pest and disease problems in this crop (Chapter III), particularly the take-all. One of the effects of take-all infection is premature ripening. At site 2 therefore, the redistribution of assimilates which normally occurs in wheat after anthesis (Gallagher and Biscoe, 1978b) will have been reduced, reducing HI. Any reduction in LAD, resulting from premature ripening, will reduce assimilate supply to the grain and reduce HI.

The difference in HI between site 1 and site 3 may be a result of differences in sowing date. Early sowing (site 1) generally results in a longer period in the vegetative phase, resulting in a greater number of leaves per tiller and more sites for tillers compared with latter sown crops (site 3) (Kirby, 1969). Later sowing also reduces crop height (Stapper and Fischer, 1990a). Therefore, late sowing can result in less competition for assimilates within the crop and a greater reserve of assimilates in the stem prior to anthesis, which results in a greater HI.

5.4   Yield Data Correlation

The simple correlation coefficients between yield components and HI for each site are presented in Table 5.2.

TABLE 5.2: Simple correlation coefficients for yield components, HI and % discoloured ears (site 2 only)

	site 1	site 2	site 3
Yield:			
ears/m^2	0.413*	0.431*	0.382
spikelets/ear	-0.400	-0.482*	0.197
grains/spikelet	0.016	0.296	0.506*
grains/m^2	0.097	0.415*	0.532**
1000 seed weight	0.756**	0.386	0.647**
% discoloured ears	–	-0.660**	–
Ears/m^2:			
spikelets/ear	-0.099	-0.222	0.207
grains/spikelet	-0.159	-0.070	0.116
grains/m^2	0.801**	0.686**	0.813**
seed weight	0.062	0.249	0.068
total crop dry matter	0.894**	0.865**	0.885**
Spikelets/ear:			
grains/spikelet	-0.327	-0.007	0.591**
grains/m^2	0.355	0.103	0.619**
seed weight	-0.337	-0.317	0.345
Grains/spikelet:			
grains/m^2	0.319	0.622**	0.646**
seed weight	-0.397	0.108	0.633**
Grains/m^2:			
seed weight	-0.312	0.184	0.403
Harvest Index:			
ears/m^2	-0.606**	-0.678**	-0.800**

* Significant at 5% level of probability

** Significant at 1% level of probability

The component most closely associated with yield in this analysis for site 1 and 3 is grain weight. For site 3, this is expected because the yield response to late N at this site was the result of increased grain weight. However at site 1, it was ears/m^2 which responded to late N and increased yield. Although the correlation between yield and ears/m^2 at site 1 is significant, it is much weaker than the correlation between yield and grain weight. At site 1 there was a strong block effect on the relationship between yield and yield components. Growth in one block was very dense which eventually resulting in lodging soon after anthesis. As a consequence, the plots in this block had a depressed grain weight at harvest and a low yield. Ear numbers were highest in this block. Removing this block from the correlation analysis resulted in the correlation between yield and ears/m^2 increasing to 0.668** and the correlation between yield and seed weight becoming non significant. At site 2, it was the proportion of take-all infected ears which had the greatest association with yield.

Previous work undertaken in the Manawatu has shown that yield is most closely associated with ears/m^2 (Hampton, 1981; Withers and Pringle, 1981).

There was no association between ears/m^2 and the remaining yield components in this study. Ears/m^2 was strongly associated with number of grains/m^2, indicating that ears/m^2 is the most important component influencing sink size. Grains/spikelet also had a strong influence on grains/m^2 at sites 2 and 3.

At all three sites, HI was negatively associated with ears/m^2. This is probably due to the strong association of total dry matter at harvest on ears/m^2 (Table 5.2). Ears/m^2 was only weakly associated with yield at sites 1 and 2 only. Increasing ear numbers is known to depress grain set in wheat, primarily because of increased competition for assimilates (Dougherty, Love and Mountier, 1978). Although there were negative correlations between ears/m^2 and the components determining grain set at two sites in this study, they were very small and not significant.

5.5   Combined Grain Yield (across three sites)

5.5.1 Treatment Effects

Table 5.3:   Effect of N on Grain Yield

	Treatment (kg N/ha)				Significance	LSD
	0	20	40	80		
Yield (t/ha)	6.14	6.14	6.46	6.72	0.026	0.30

Average grain yields have increased from 6.14 t/ha to 6.72 t/ha with the application of 80 kg N. The 80 kg N treatment was higher yielding than the 40 kg N which in turn yielded more than the control and 20 kg N treatments.   However only the yield differences between the 80 kg N treatment and the control and 20 kg N treatments was significant. The difference between the 40 kg N and 80 kg N treatments just failed to be significant. There was no response to 20 kg N. This was due to the yield depression resulting from take-all infection in this treatment at site 2 (Figure 5.2).

5.5.2 Site Effects

Table 5.4:   Influence of Site on Grain Yield

	site 1	site 2	site 3	Significance	LSD
Yield (t/ha)	6.81	5.85	6.44	0.0015	0.54*

* two-tailed t test

A combined analysis was done to determine the effect of late applications of N across a range of sites.   Site or location has a large influence on the outcome of many agricultural experiments (Steel and Torrie, 1981). The combined analysis allows the treatment effects to be tested against this background of different environments.

Grain yield at sites 1 and 3 are significantly higher than at site 2. The difference between site 1 and site 3 was not significant. Site 2 probably had the highest potential

yield of those three sites because the crop at this site was established into the ground which had been in long-term pasture on a free draining soil type. Ismail and Withers (1984) found that yield potential declines as the number of consecutive crops out of pasture increases. The relatively poor yield at site 2 is almost certainly due to low grain weights, which resulted from a late infection of take-all, as previously discussed (Section 5.3.1).

5.5.3 Treatment and Site Interaction

There was a significant interaction between the effects of late N and site on grain yields (Figure 5.2). The greatest inconsistency in the response of grain yield to late N was the zero response at site 2. Consequently there was a large difference in yield at the highest rate of N between site 2 and both the other sites. However, there was no difference between yields for the control treatment between site 2 and site 3. The lack of response to late N at site 2 may have been caused by take-all, as previously discussed, or by the fact that it was a fertile site. While yield responses to N fertiliser after long-term pasture are uncommon (Wright, 1969), they have been recorded in the Manawatu (Ismail and Withers, 1984). Other studies have shown a negative relationship between the number of years out of pasture and the response to N fertiliser (Schurink, Penman and Withers, 1984). This may be related to the degree of compaction and surface crusting which have been shown to influence the yield response to N fertiliser and are associated with increasing years in crop (Withers and Pringle, 1981).
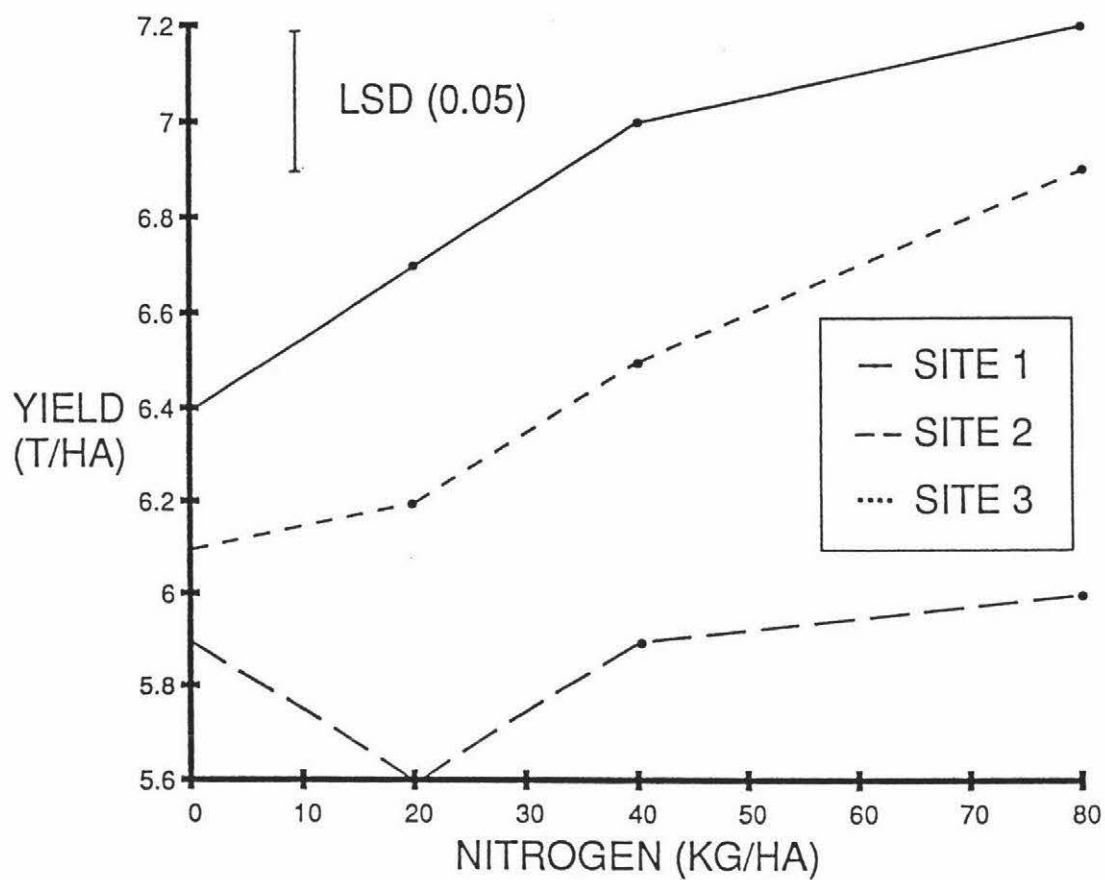
FIGURE 5.2: The interaction of N and site on grain yield

CHAPTER VI

RESULTS AND DISCUSSION

NITROGEN DISTRIBUTION

6.1 Introduction

This chapter will describe the effects of late N on grain protein content and the distribution of N in the crop at final harvest. Again, results are initially presented for individual sites with site comparisons made in the discussion which follows. Nitrogen recovery is also described. Finally, a combined analysis of grain protein is presented. The relationship between grain protein content and baking quality is detailed in Chapter VII.

6.2 Results

Table 6.1 shows the effects of late N on the distribution of N at harvest.

6.2.1 Site 1

Grain protein content has been significantly increased by the application of late N. This, plus the increase in grain yield resulting from the application of late N, has meant that grain N yield has also increased significantly, and, similarly, total N yield. Straw N content and straw N yield did not increase significantly. Nitrogen harvest index was also not affected, meaning that total N yield and grain N yield have increased proportionately.

6.2.2 Site 2

The grain protein content at site 2 was increased by late N, despite the disease problems experienced at this site. However the response was small and only occurred at the highest rate of N. This increase in grain protein content was sufficient to significantly increase grain N yield at the highest rate of N, despite grain yield remaining the same. Treatment differences in straw N content were just significant. The 80 kg N treatment was significantly higher than the control and 40 kg N treatment but was not higher than the 20 kg N treatment. This may reflect the prevalence of the take-all in plots receiving this treatment. Total N yield was not affected by late N so the elevated straw N content

for the 20 kg N treatment is probably due to a reduction in the redistribution of N from the vegetative structures to the grain. This would be indicated by a low NHI for this treatment, though none of the differences indicated in Table 6.1 were significant.

6.2.3 Site 3

There was a marked response in grain protein content to late N at this site. Initial levels were very low, being less than 9.0% protein. The application of 80 kg N increased protein levels from 8.87% to 10.87%. Because of the response of protein content and grain yield (Chapter V) to late N, grain N yield increased significantly.

Neither straw N content or straw N yield was affected by late N, however the increase in grain N yield has resulted in a significant increase in total N yield. NHI at site 3 was very high, indicating a high proportion of redistribution of N from the vegetative structures to the grain. As with the other two sites, there were no treatment differences in NHI.

6.3 Discussion

6.3.1 Grain Protein

The response of grain protein content to late N is shown in graphical form for each site in Figure 6.1. Responses have been greatest at site 3, intermediate at site 1 and least at site 2. The magnitude of response appears to be related to the N yield at Feekes G.S.9. (Chapter IV) and the total N yield at harvest. This is discussed further in Section 6.5. The response appears to be linear at all sites, although at site 2 there was a plateau between the 20 kg N and 40 kg N treatments. In this case, the cause is probably due to the elevated protein content for the 20 kg N treatment as a result of the low yield for this treatment (Martin, 1987).

The linear response to late N is consistent with the results achieved by most workers (Spiertz and Ellen, 1978; Benzian and Lane, 1981; Guy, 1985; Strong, 1986) when applying N late. Early applications of N result in less consistent increases in grain N and may reduce grain protein content in certain situations (Benzian and Lane, 1981).

TABLE 6.1: Treatment Effects on the Distribution of Crop N at Harvest

	Grain Protein (%)	Grain N Yield (kg/ha)	Straw N (%)	Straw N Yield (kg/ha)	Total N Yield (kg/ha)	NHI
SITE 1						
kg N/ha						
0	10.35	115.3	0.47	41.4	156.8	0.74
20	10.54	122.7	0.48	50.4	173.1	0.72
40	10.75	131.3	0.55	48.9	180.2	0.73
80	11.28	142.5	0.56	60.3	202.8	0.70
significance	0.0001	0.0001	NS	NS	0.0028	NS
LSD	0.271	4.9	-	-	17.4	-
CV	2.5	3.8	28.0	31.0	9.6	7.8
SITE 2						
kg N/ha						
0	12.97	134.5	0.85	87.8	218.7	0.62
20	13.19	128.8	0.95	93.5	222.4	0.58
40	13.20	136.8	0.86	85.7	222.5	0.61
80	13.69	144.2	1.02	102.3	246.3	0.59
significance	0.009	0.03	0.05	NS	NS	NS
LSD	0.33	7.9	0.11	-	-	-
CV	2.4	5.8	12.1	19.8	8.9	7.8
SITE 3						
kg N/ha						
0	8.87	95.2	0.24	17.8	113.0	0.84
20	9.22	100.2	0.25	17.2	117.2	0.85
40	9.72	110.8	0.25	21.1	132.0	0.85
80	10.87	132.0	0.27	21.4	153.2	0.86
significance	0.0001	0.0001	NS	NS	0.001	NS
LSD	0.27	4.5	-	-	8.0	-
CV	2.8	4.1	17.1	33.3	6.2	4.7
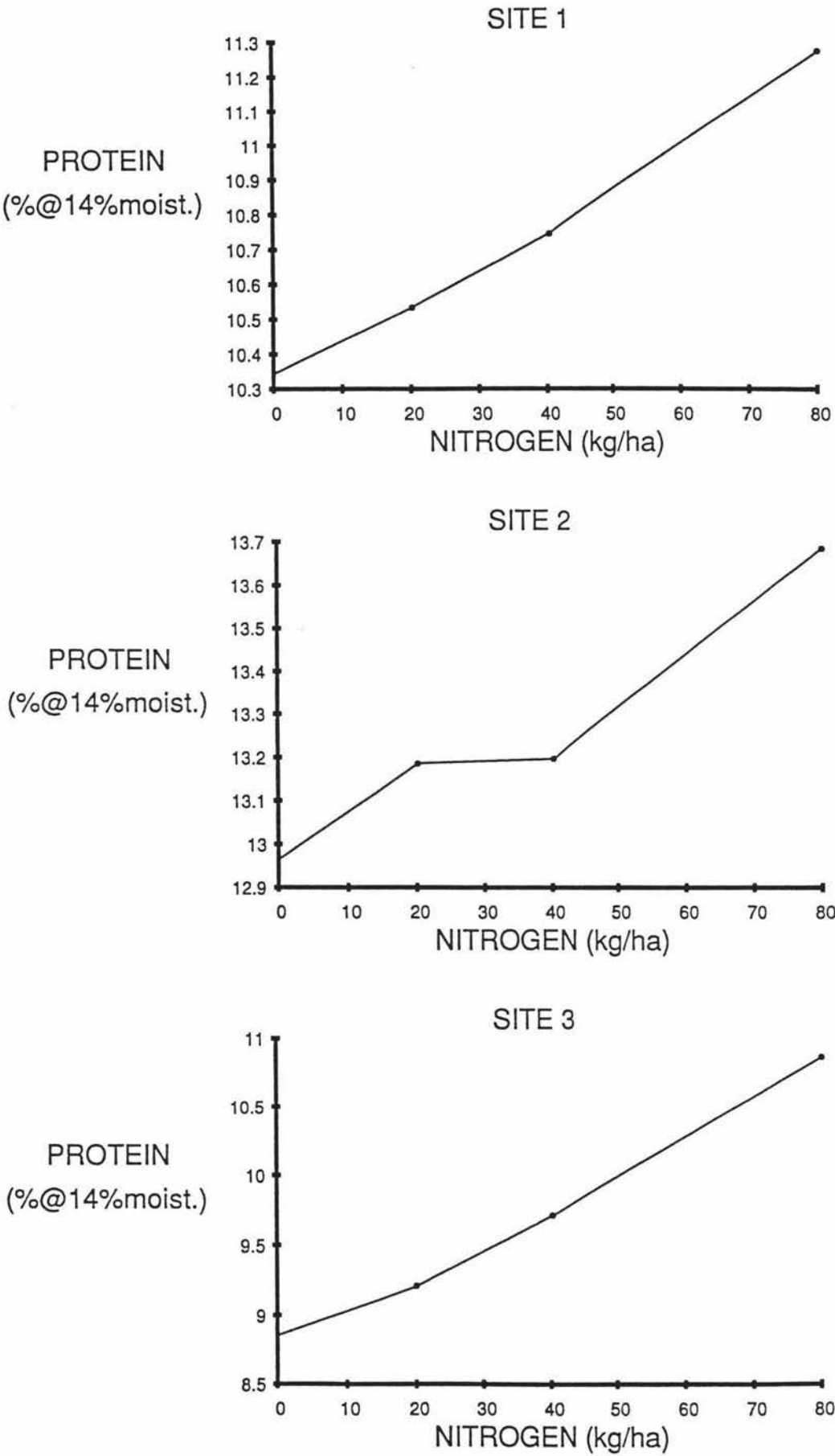
FIGURE 6.1: Effect of N on grain protein content

The rate of response of grain protein content to late N decreases as the available supply of soil N increases (Stevenson, 1987b). At site 3, the least fertile site, a 1% increase in grain protein required an application of 40 kg N/ha. At site 1, 86 kg N/ha was required to increase grain protein by 1% while at site 2, the most fertile site, 111 kg N/ha was required to increase grain protein content by this amount. There may be an interaction between the amount of N applied early and the amount applied late on the effect late N has on grain protein content. For example, Strong (1982), found that late N increased grain protein by 1% for each 35 kg N/ha when no early N had been applied to an infertile soil. The response to late N declined with increasing application rates of early N, so that at 200 kg N/ha applied at sowing, grain protein content increased by 1% for each 50 kg N/ha applied late. Other workers have reported similar responses of grain protein content to late N (Cooper and Blakeney, 1990; Miezan, Heyne and Finney, 1977; McCloy, 1985b).

Late N may increase grain yields without adversely affecting the response of grain protein content to late N (Pushman and Bingham, 1975; Drewitt and Dyson, 1987). However, the greater the yield of the crop, the greater the amount of N which would be required to lift grain protein content by a set amount (Guy, 1985). Variation may arise from the proportion of N which is taken up by the crop and then redistributed to the grain (N recovery). Factors which result in increased uptake of applied N, eg adequate soil moisture (Drewitt and Dyson, 1987) and greater redistribution to the grain, eg adequate pest and disease control (Spiertz and De Vos, 1983) can result in an increased response of grain protein content to late N.

6.3.2   Total Nitrogen Yield and Nitrogen Harvest Index

The high total N yield at site 2 confirms the high fertility status of this site. However, despite significant increases in the components making up total N yield, treatment differences were not significant at site 2, unlike sites 1 and 3. Only at site 1, with the application of 80 kg N/ha, did total N yield approach the levels achieved at site 2. Total N yields of over 200 kg N/ha are usually associated with high grain yields (Spiertz and Ellen, 1978; Clarke *et al.*, 1990). Both of these studies achieved grain yields of over 8.0 t/ha. Grain yields at site 2 were considerably below this, primarily because of a

very low HI. Total N yield can be influenced by soil moisture availability (Drewitt and Rickard, 1972) as well as by fertility (Spiertz and van de Haar, 1978; Stevenson, 1987b).

The NHI varied considerably between individual sites. Each site was significantly different from the other two ($P = 0.1\%$). The average NHI for site 1, 2 and 3 was 0.725, 0.600 and 0.851 respectively. Large variations in NHI within the same cultivar can be caused by a number of factors, including lodging (Canvin, 1976), moisture stress (Campbell, Davidson and McCaig, 1983) and disease (Spiertz and De Vos, 1983). With the exception of site 2, the NHI achieved in this study are of the same order of those reported by other workers (Spiertz and van de Haar, 1978; Clarke *et al.*, 1990). The NHI achieved at site 2 is lower than those achieved in most studies. This low value may be due to the high fertility status of the site which has been shown to reduce NHI (McNeal *et al.*, 1971). The late take-all infection at site 2, which resulted in premature senescence may also have reduced NHI by reducing the period in which N is remobilised. This is supported by the high straw N content at site 2 compared to the other two sites and also the significant treatment differences at site 2. The difference in the NHI between site 1 and site 3 was probably due to the lower fertility at site 3. Although temperature can influence NHI, at the temperatures experienced at these sites, differences due to this factor are unlikely (Campbell, Davidson and McCaig, 1983).

NHI was highly, negatively, correlated with straw N content at all sites (Table 6.2).

Table 6.2:   Simple correlation coefficients for NHI with straw N content and total N yield

NHI	site 1	site 2	site 3
Straw N Content	-0.778**	-0.789**	-0.777**
Total N Yield	-0.823**	-0.743**	-0.300

** Significant at the 0.01% level of probability

NHI was also negatively correlated with total N yield at all sites, although the correlation at site 3 was not significant. This indicates that NHI was influenced by fertility (as measured by total N yield) and is likely to have been a cause of the variation in NHI between sites. The strong association between NHI and straw N % is probably the result of the assocation between total N yield and straw N content (Table 6.3).

Table 6.3:   Simple correlation coefficients for total N yield and straw N content

site 1	site 2	site 3
0.797**	0.724**	0.564*

** Significant at the 0.01% level of probability
 * Significant at the 1.0% level of probability

Where total N yield has been increased, a greater proportion of the N requirements of the developing grain has been able to be met through increased uptake, therefore reducing the need to remobilise N from vegetative structures. This would increase the straw N content and decrease NHI. The positive association between total N yield and the uptake of N from Feekes G.S.9 to maturity, and, the negative association this has with NHI is shown in Table 6.4.

Table 6.4: **Simple correlation coefficients for N uptake after Feekes G.S.9 with total N yield and NHI**

Uptake	site 1	site 2	site 3
Total N Yield	0.614**	0.503*	0.584**
NHI	-0.50*	-0.38	-0.481*

** Significant at the 1.0% level of probability
 * Significant at the 2.0% level of probability

NHI was not correlated with grain protein content, except at site 1. However the significant correlation at site 1 was due to the influence of the lodging occurring in one block. The lodging was due to the high fertility in this block, which resulted in high grain protein content and low NHI. The lack of correlation between NHI and grain protein agrees with some workers (McMullan, McVetty and Urquhart, 1988) but is in contrast with others (Cox, Qualset and Rains, 1986). The poor association of NHI and grain protein content in this study is probably due to variation in the amount of N taken up during the grain fill period.

6.4 Nitrogen Recovery

There were no treatment differences in the proportion of late N recovered with the grain at final harvest. The average rate of recovery for each site is shown in Table 6.5.

Table 6.5: Nitrogen recovery

	site 1	site 2	site 3
Recovery (%)	36.2	11.5*	36.5

** Significantly different from sites 1 and 3 at the 0.1% level of probability (two-tailed t-test)

The effect of fertiliser N on N recovery has been found to be variable (Scarsbrook, 1965). Cooper and Blackeney (1990) found that increasing the rate of late N from 40 kg N/ha to 80 kg N/ha increased N recovery in the grain from 30.8% to 36.4%. This is very similar to the average recoveries achieved at sites 1 and 3. Strong (1986) found that N recovery in the grain initially increased as the rate of N fertiliser increased but subsequently decreased as fertiliser rates increased to over 150 kg N/ha. Other workers have achieved N recoveries comparable to those achieved in this study, from late applications of N (Spiertz and De Vos, 1983).

The timing of N application can influence N recovery rates. Applications of N made prior to sowing may result in lower N recovery than applications which are split between pre-sowing and tillering, especially when application rates are high (Strong, 1986). In a large study of 21 wheat crops, Vaidyanathan (1982) found that average N recovery from early applications of N was 50%. Recoveries of this magnitude from N applied to a growing crop in quantities it is capable of utilising, are regarded as normal (Anon., 1983).

The stage of growth at which late N is applied can also influence N recovery. Strong (1982) found that N recovery decreased from 30% when applied at the 'boot' stage (Feekes G.S.10) to less than 10% when application was delayed until after flowering (Feekes G.S.11.1). Similar results were obtained by Smith and Whitfield (1990) particularly when soil moisture was limiting. Soil moisture has a large influence of the uptake of N (Drewitt and Rickard, 1972).

The low recovery at site 2 may be due to high available supplies of soil N at the time of fertiliser N application and to the influence of the late take-all infection. Take-all will have reduced the ability of the crop to take up fertiliser N (Clarkson *et al.*, 1975) as well as reduced the retranslocation of N from the herbage to the grain (Table 6.1). Spiertz and De Vos (1983) found that the control of foliar fungal diseases greatly increased the recovery of N in wheat. This was due to both increased remobilisation of N to the grain from the vegetative structures and greater N uptake from the soil. Foliar diseases can reduce root length in diseased plants (Balasubramanian and Gaunt, 1985).

While it can be argued that when calculating N recovery, the N content of crop residues should also be considered, these residues make no financial contribution to the crop from which they came. They may contribute significantly to the soil N supply after harvest. However where crop residue is burnt, as is normal practice in the southern North Island, this does not hold. It has also been found that mineralisation of crop residues can result in nitrate pollution of drainage water leaving catchments which have a significant area in crop (Roberts, 1987).

6.5   Combined Grain Protein Content (Across Three Sites)

6.5.1   Treatment Effects

Table 6.6: Effect of N on Grain Protein Content

	Treatment (kg N/ha)				Significance	LSD
	0	20	40	80		
Protein (%)	10.73	10.98	11.22	11.95	0.013	0.78

When averaged across three sites, the treatment effects on grain protein content are significant. Grain protein content increased from 10.73% with no late N to 11.95% with the application of 80 kg N/ha of late N. The 80 kg N/ha treatment was significantly higher than the control and 20 kg N/ha treatments. The difference between the 40 kg N/ha and 80 kg N/ha treatments just failed to be significant. The application

of late N increased total N yield (Table 6.1). Total N yield is a major determinant of grain protein content, along with grain yield (Benzian and Lane, 1979). Table 6.7 shows the correlation between total N yield and grain protein content for each site. At site 1 and 3 grain protein content is strongly correlated with total N yield. At site 2, the correlation is weaker than at the other two sites.

Table 6.7: **Simple correlation coefficients for grain protein content and total N yield**

site 1	site 2	site 3
0.765**	0.417*	0.717**

** Significant at the 0.1% level of probability
 * Significant at the 5% level of probability

6.5.2 Site Effects

Table 6.8: Influence of site on grain protein content

	site 1	site 2	site 3	Significance	LSD
Protein	10.73	13.26	9.67	0.0001	0.73*

* two-tailed t-test

The influence of site on grain protein content in this study was significant, with each site being different from the other two. Site 2 had the highest grain protein content, site 3 the lowest with site 1 intermediate. Site or environment is known to have a large effect on determining grain protein levels (Miezan, Heyne and Finney, 1977; Douglas and Dyson, 1984; Lindley and Humphrey-Taylor, 1987).

The difference in grain protein content betwen the sites appears to be the result of differences in the total N yield at each site (Appendix 7). As with grain protein content, site 2 is ranked highest, site 3 the lowest and site 1 is again intermediate. There was

an assosiation between total N yield and grain protein content for individual sites (Table 6.7). The relationship between grain protein content and total N yield for all three sites combined is shown in Appendix 8. This relationship is strong ($R^2 = 0.82$) confirming that total N yield has had the greatest influence over grain protein content in this study. It can be seen from a comparison of Table 6.6 and 6.8, that the influence of site on grain protein content has been greater than the influence of treatments.

6.5.3 Treatment and Site Interaction

There was a significant interaction between late N application and site on grain protein levels (LSD 0.05 = 0.334% protein). As can be seen from Figure 6.1, there was a difference in the magnitude of the response of grain protein content to late N. For example, at site 2, only at the highest rate of late N was there a significant response in grain protein content. The difference in the responsiveness of each site to late N is due to the fertility difference amongst the sites. The magnitude of response is inversely proportional to the total N yield at each site. There was some evidence that disease may also have influenced the response to late N at site 2, with NHI being generally low (Table 6.1). However the high fertility at site 2 may also have reduced NHI (Section 6.3.2).

CHAPTER VII

RESULTS AND DISCUSSION

BAKING QUALITY

7.0   Introduction

In Chapter VI the effects of late N on grain protein content were described.   In this chapter the relationship between grain protein content and a number of baking quality parameters including SDS sedimentation volume, will be presented.   A strong relationship between bake score and SDS sedimentation volume will be revealed, validating the use of this test to measure baking quality.   Subsequently, the relationship between grain protein content and baking quality (as measured by the SDS sedimentation volume) at each site will be examined.

7.1   Relationship Between Grain Protein Content and Baking Quality

After harvest, grain samples from two replicates at each site were sent to the Wheat Research Institute (WRI), Christchurch to obtain an assessment of bread baking quality. This included the overall bake score as well as optimum work input and water absorption.   A total of 24 samples (8 per site) were tested.   The association between these quality parameters and grain protein content was initially analysed for, using simple correlation.   Table 7.1 details the correlation coefficients for a range of quality parameters including SDS sedimentation volume.
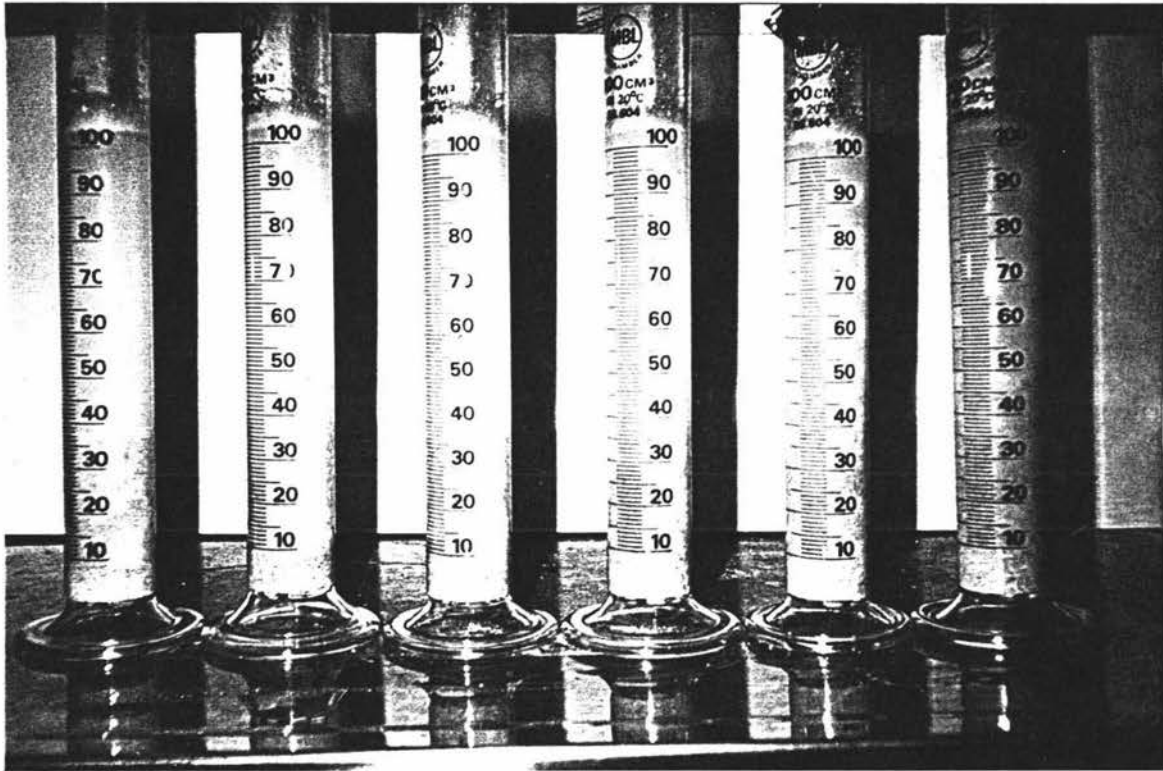
Plate 6: The SDS sedimentation test. These samples are ready to have the sediment volume recorded.

Table 7.1:   Simple correlation coefficients for grain protein content, loaf bake score, SDS sedimentation volume, optimum work input and water absorption

	Grain Protein (%)	Bake Score	SDS Volume	Work Input
Bake Score	0.91**			
SDS volume (mls)	0.91**	0.84**		
Work Input (Wh/kg)	0.87**	0.82**	0.75**	
Water Absorption (%)	0.74**	0.58**	0.84**	0.53*

** Significant at the 0.01% level of probability
 * Significant at the 1.0% level of probability

Grain protein content is strongly correlated with all of the quality parameters in Table 7.1. The correlation between bake score and SDS sedimentation volume is also strong. This indicates that SDS sedimentation volume is an acceptable alternative to bake score as a means of assessing baking quality. The relationship between grain protein content and the four quality parameters in Table 7.1 was examined further through the use of linear regression. These results are presented later in this chapter.

The correlation between grain protein content and SDS sedimentation volume compares with the correlation coefficient of 0.83 obtained by Griffin (1983b), also for Rongotea. In another study, Griffin (1983a), found significant correlations between grain protein content and SDS sedimentation volume across a range of North Island sites. The results from this study and those of Griffin (1983a) and (1983b) are contrary to those of Blackman and Gill (1980) who found no relationship between grain protein content and SDS sedimentation volume.

Similarly, the high correlations between SDS sedimentation volume and bake score in this study is in agreement with the results of Griffin (1983a) and (1983b) as well as those from Blackman and Gill (1980) and Axford, McDermott and Redman (1978).

Most studies have found that SDS sedimentation volume is more closely correlated to bake score than is protein content (Axford, McDermott and Redman, 1979; Griffin, 1983a). This is in contrast with the results from this study.

7.1.1 Bake Score

The relationship between grain protein content and bake score was further analysed using linear regression and is presented in Figure 7.1. The equation describing this relationship is:

Bake score = 1.4 + 1.81(protein)* $R^2 = 0.83$
* significance = 0.01%

Many New Zealand studies have found that, while there is a relationship between grain protein content and bake score, it is not strong enough to be used as a reliable predictor of bake score (Mitchell and Casutt, 1983; Wilson, 1983; Hanson and Wilson, 1985; Mitchell, 1985). This relationship is also cultivar specific and tends to plateau (Douglas, 1987; Stevenson, 1987a). As can be seen from Figure 7.1 the relationship between grain protein content and bakescore was good, with an R^2 of 0.83. This is in comparison with the R^2 of 4.0 achieved by Douglas (1987). There was also no indication of any plateau in bake score across the range of grain protein contents achieved in this study. This agrees with the assertion of Moss (1981) that bread wheat quality increases with protein content at least up to 14.0% protein.

The above studies comprised of a large number of grain samples taken across a range of environments (districts/locations). Both district and season are known to influence the relationship between grain protein content and bake score (Stevenson, 1987a).

Daly and Dyson (1987) found a good relationship between these two parameters when averaged over three seasons but at a single location. The relationship between grain protein content and bake score has been found to be reliable in overseas studies, when using high quality bread wheat cultivars (Preston, March and Tipples, 1982; Cooper and Blackeney, 1990). The latter study achieved an R^2 of 0.79 when investigating the

relationship between grain protein content and bake score in milling wheat samples from New South Wales.

A MDD bake score of 20 was regarded as the minimum for commercial bread production (Mitchell, 1983a). This equates to a grain protein content of approximately 10.5% in the samples used in this study. During the year in which this study was conducted, a protein content of 10.5% was the cut off point for purchase on the Manawatu Mills wheat purchase contract (Chapter I). This minimum was reduced in 1991, presumably because sufficient quantities of high protein content wheat are available to blend these low protein wheats into a composite line of acceptable protein content.

7.1.2 Optimum Work Input

Figure 7.2 shows the relationship between grain protein content and optimum work input. Work inputs have ranged from under 8 Wh/kg to over 20 Wh/kg across the range of grain protein contents sampled from the three sites used in this study. Work input applications of around 8 Wh/kg to 12 Wh/kg are regarded as being in the ideal range for commercial baking (Lindley and Moore, 1979). In this study, this equates to a protein content range of about 10% to 11.5%. For those samples with protein contents of over 13% (site 2), work input requirements are twice those inside the ideal range. However, grain protein contents of 10.0-11.5% are more typical for wheat grown in the Southern North Island. Work input requirements have been known to fall away at very high grain protein contents (>16.0%) in some environments (Tipples, Dubetz and Irvine, 1977). This was also associated with a marked deterioration in baking quality.
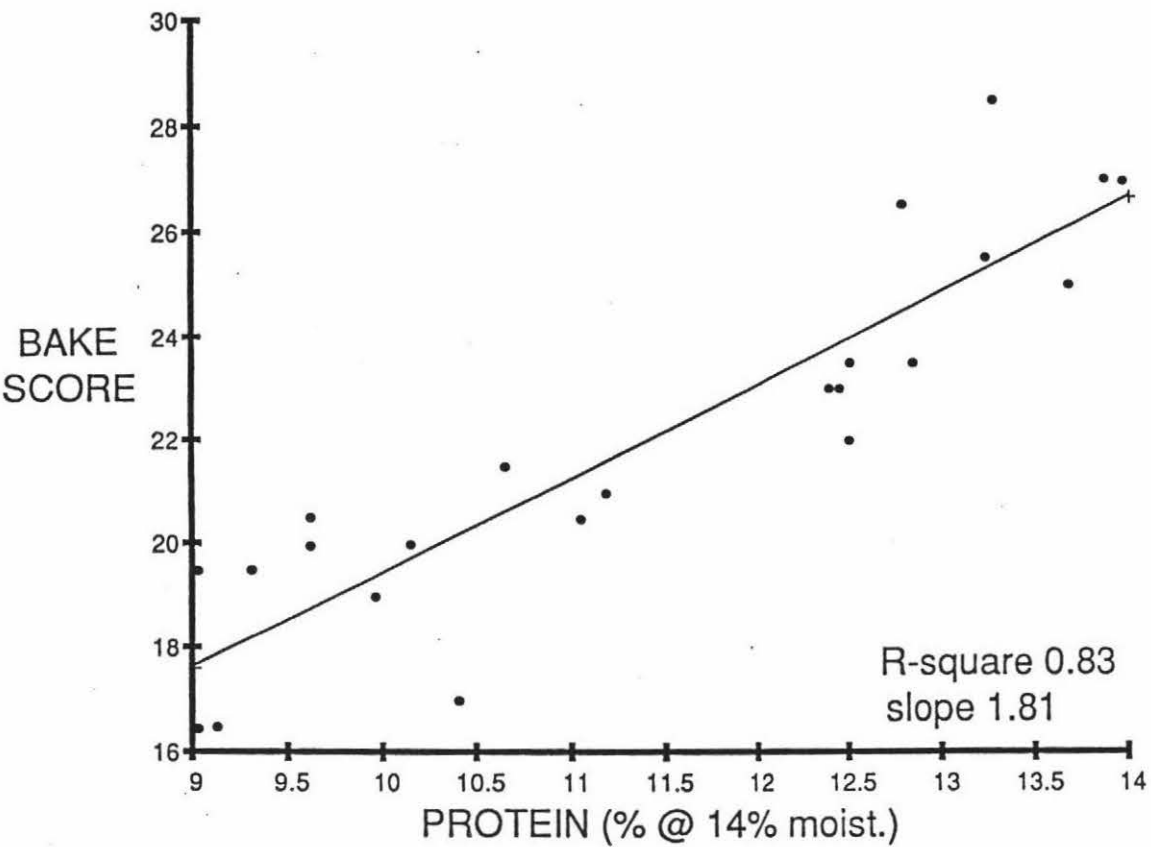
FIGURE 7.1: The regression of bake score on grain protein
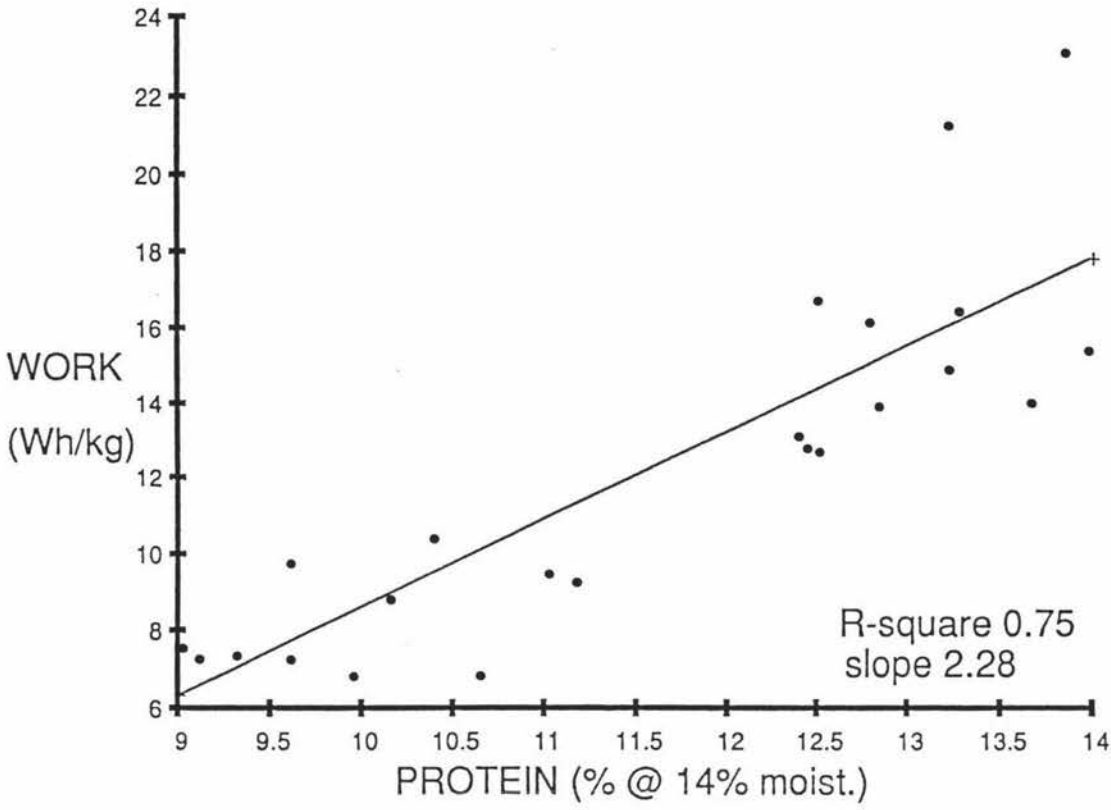
FIGURE 7.2: The regression of optimum dough work input
on grain protein

7.1.3 Water Absorption

Dough water absorption had the weakest relationship with grain protein content of any of the quality parameters used in this study (Figure 7.3), with an R^2 of 0.55. This is comparable to the results of Cooper and Blackeney (1990) who achieved an R^2 of 0.65 for a relationship between grain protein content and absorption. Absorptions have ranged from under 59% to over 63%. This is consistent with water absorptions achieved by most New Zealand milling wheat cultivars at average grain protein levels (Lindley and Humphrey-Taylor, 1987). Unlike work input, high absorptions are regarded as desirable due to the benefits of increased loaf weight and crumb moisture (Lindley and Moore, 1989). However, increasing the moisture content of dough above the optimum does not necessarily decrease bread quality but does present problems of physically handling dough at the bakery, as well as increasing the work requirement of the dough (Larsen and Greenwood, 1991).

Observation of Figure 7.3 suggests that the relationship between grain protein content and water absorption may not be linear. Absorptions appear to decline above 12.5% protein. The inclusion of a quadratic term in the regression increased the R^2 significantly, from 0.55 to 0.72. However it is very likely that the decline in water absorption above 12.5% protein is due to the fact that all of the samples over 12.5% protein are from site 2. Water absorption is influenced by environment (Lindley and Humphrey-Taylor, 1987). Water absorption will respond to grain protein contents well above the levels achieved in this study (Tipples, Dubetz and Irvine, 1977).
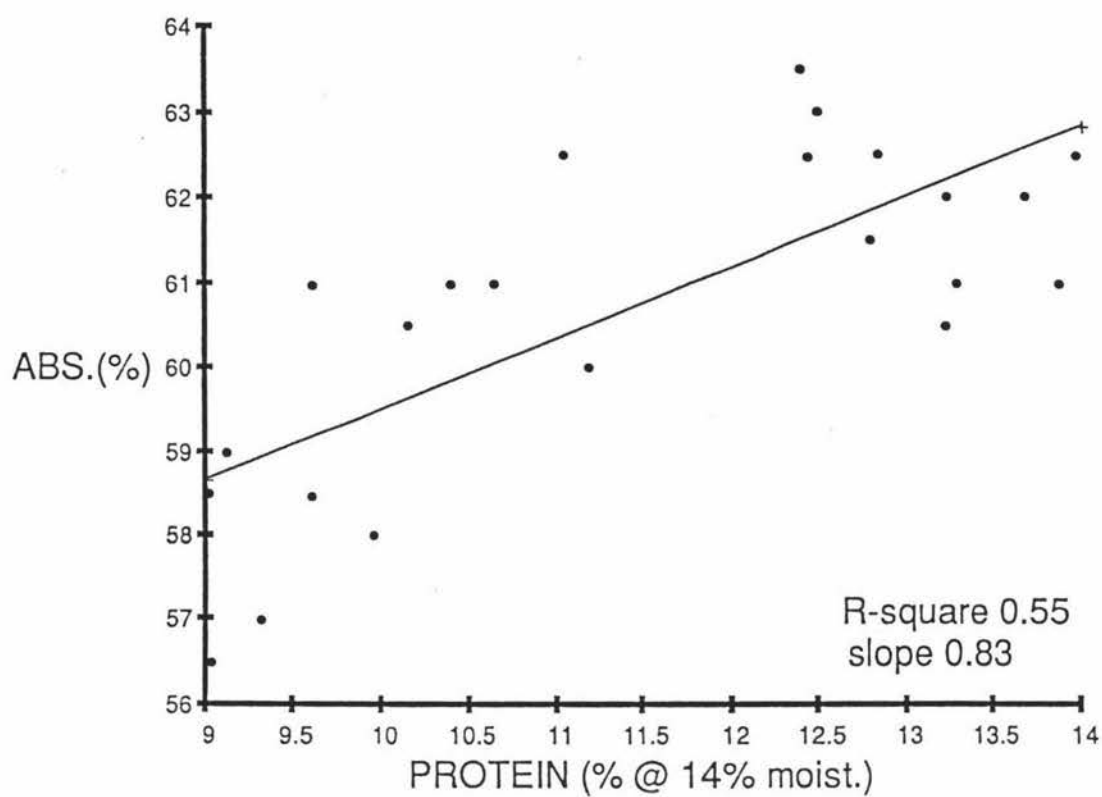
FIGURE 7.3 The regression of dough water absorption on grain protein

7.2   Relationship Between Bake Score and SDS Sedimentation Volume

Sodium dodecyl sulphate sedimentation volume has been found to be a good predictor
of the quality of wheat used for breadmaking (Blackman and Gill, 1980; Griffin,
1983b). The relationship achieved between SDS sedimentation volume and bake score
in this study confirms that this is also the case in the present situation (Figure 7.4). The
strength of the relationship detailed in Figure 7.4 is consistent with the results of other
workers except that in this study grain protein content was found to be as good a
predictor of bake score as was SDS sedimentation volume (Figure 7.1). Grain protein
content has only occasionally been found to be comparable to SDS sedimentation volume
as a means of predicting baking quality (Griffin, 1983b).

Because of the strength of the relationship detailed in Figure 7.4, SDS sedimentation
volume was subsequently used to examine, in greater depth, the relationship between
grain protein content and baking quality in this study.

7.3   Relationship Between Grain Protein Content and SDS Sedimentation Volume
         - Three Sites Combined

The correlation between grain protein content and SDS sedimentation volume, described
earlier in this chapter, was calculated from an incomplete sample, primarily for
comparison with the correlations between grain protein content and other baking quality
parameters. To examine the relationship between grain protein content and SDS
sedimentation volume, data from all three sites was pooled and analysed using linear
regression. Results are presented in Figure 7.5. The regression equation for this
relationship is:

SDS volume = 2.17 + 5.61(protein)

Standard error of estimate	Intercept	3.67
	Slope	0.323

The strength of the relationship between these two quality parameters is in agreement
with the results from the earlier analysis of the limited data set. 81% of the variation
in SDS sedimentation volume is accounted for by variation in grain protein content. The
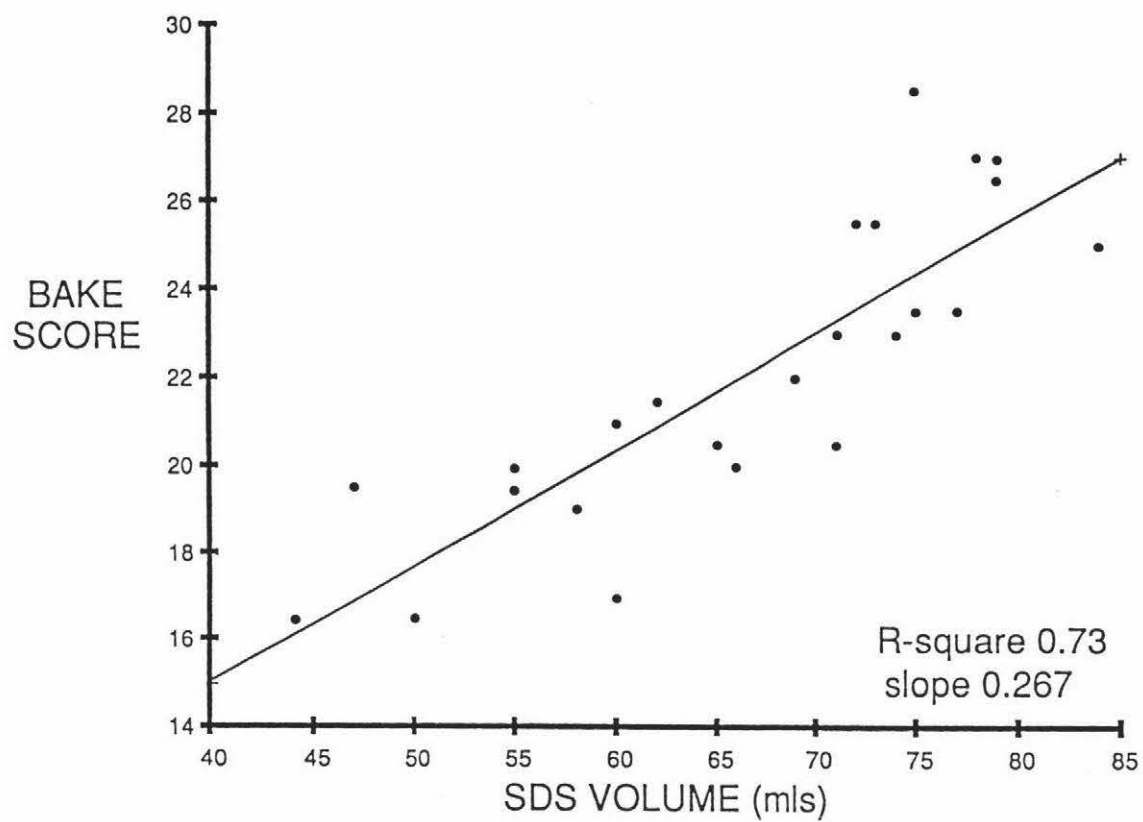
FIGURE 7.4: The regression of bake score on SDS sedimentation volume
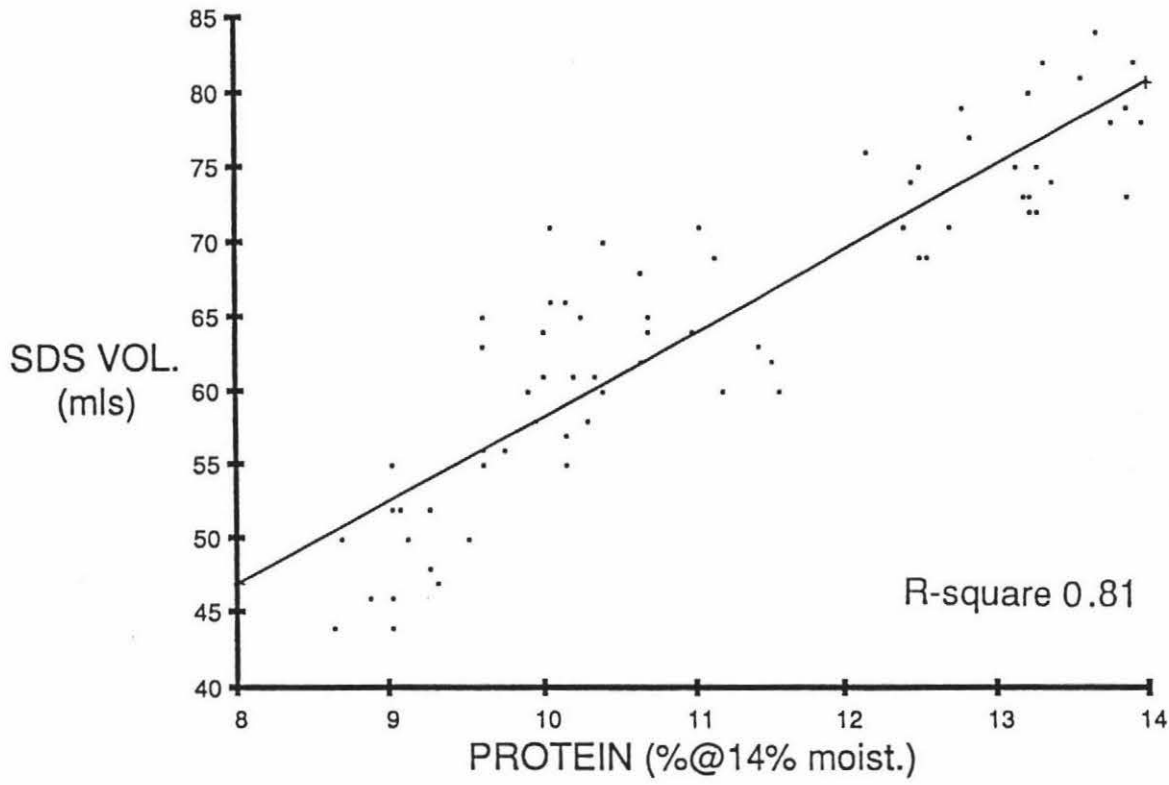
FIGURE 7.5: The regression of SDS sedimentation volume
on grain protein (all sites)

relationship is linear over the range of grain protein contents represented by the samples used in this analysis. Although the data points suggest that the relationship may not be linear, this was discounted for two reasons. Firstly, a graph of the residuals from the linear regression (from Figure 7.5) plotted against grain protein content revealed a random distribution, with no evident relationship. Secondly, the inclusion of a quadratic term in the regression had very little effect on the R^2, increasing it from 0.81 to 0.83.

7.4 Relationship Between Grain Protein Content and SDS Sedimentation Volume - Individual Sites

The linear regression of SDS sedimentation volume on grain protein content was calculated for all three sites, individually. Subsequently, the regressions from individual sites were compared with the pooled regression with sites combined (Figure 7.5).

The individual site regressions are sown in Figures 7.6, 7.7 and 7.8 for site 1, 2 and 3 respectively. The regression equations from each site were:

site 1	SDS volume	= 28.4 + 3.45(protein)
	R^2	= 0.43
	significance	= 0.05%

site 2	SDS volume	= 14.83 + 4.62(protein)
	R^2	= 0.27
	significance	= 1.0%

site 3	SDS volume	= -4.48 + 6.02(protein)
	R^2	= 0.67
	significance	= 0.01%

Standard Error of Estimates:	site 1	site 2	site 3
Intercept	9.10	21.54	9.93
Slope	0.84	1.62	1.02

Although these regressions were all significant, they varied greatly, Only the
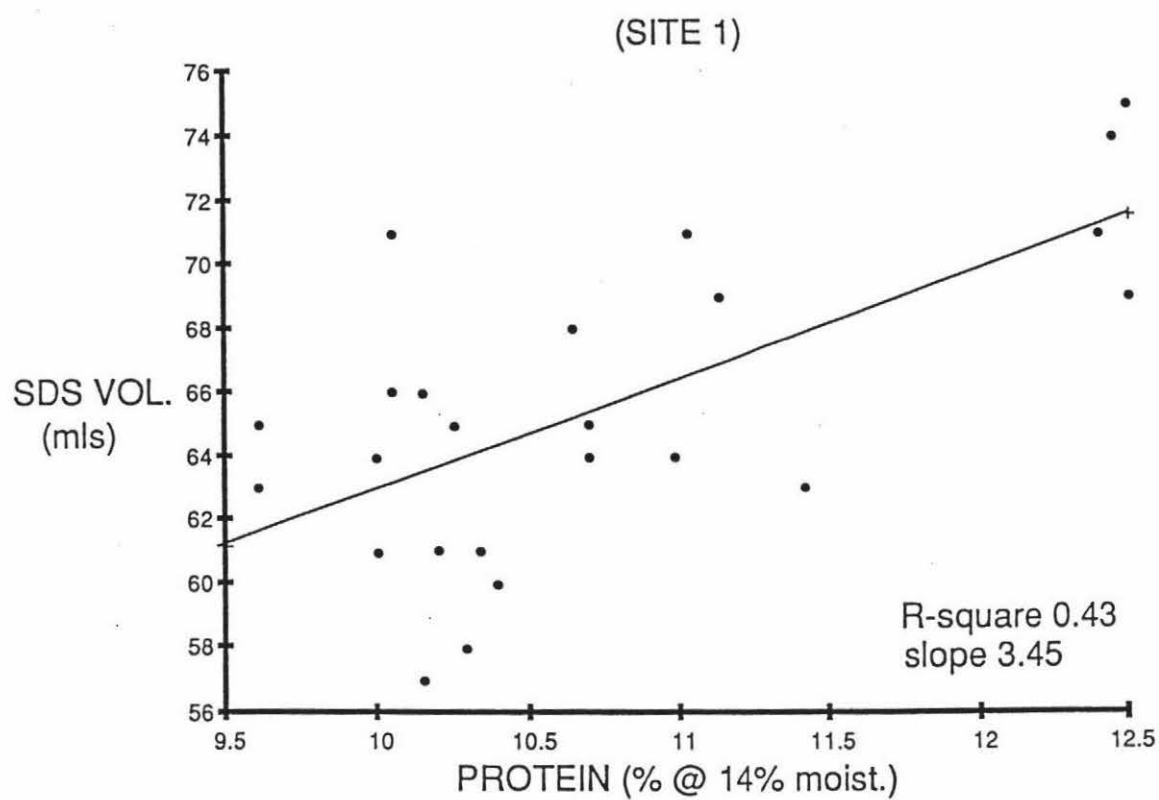
FIGURE 7.6: The regression of SDS sedimentation volume on grain protein, site 1
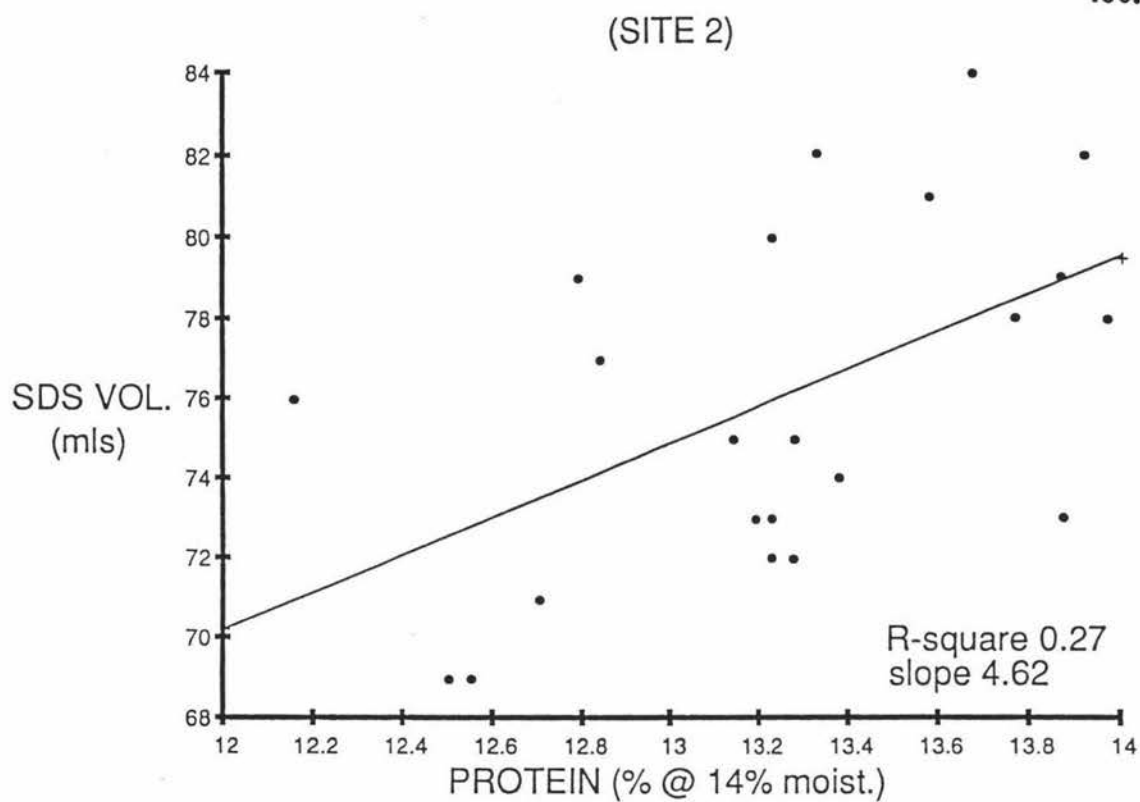
FIGURE   7.7:   The regression of SDS sedimentation volume
on grain protein, site 2
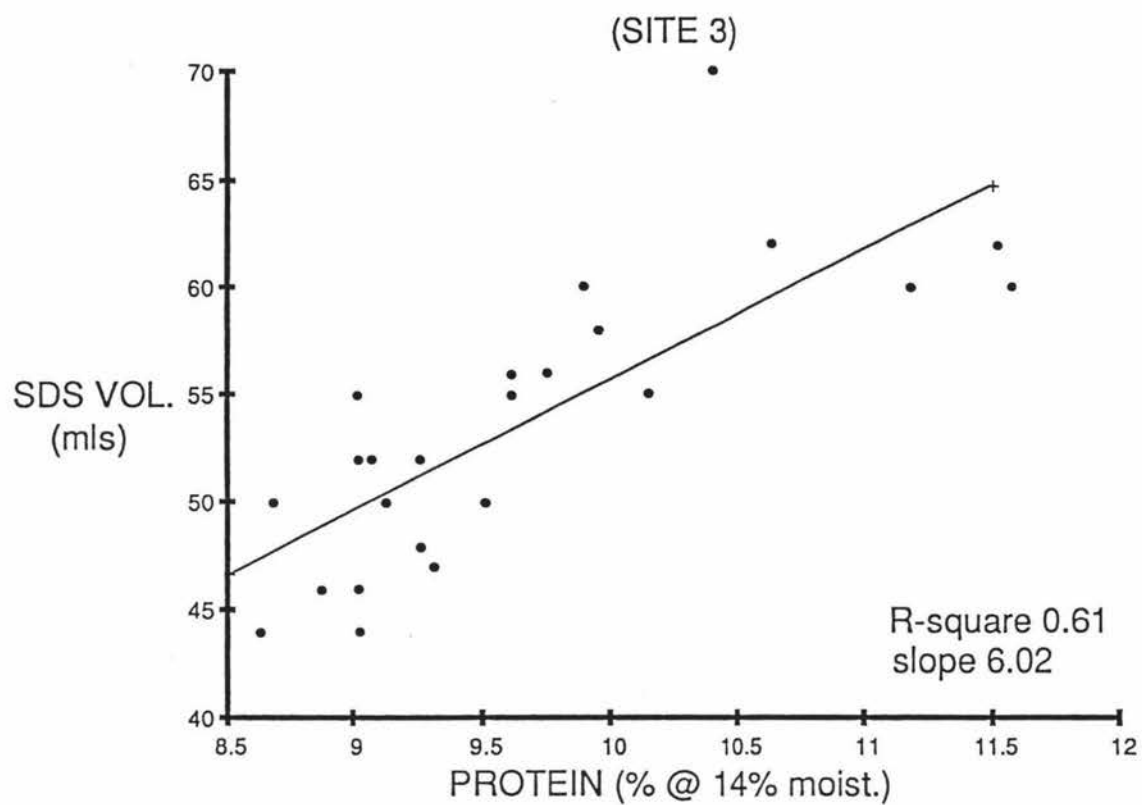
FIGURE 7.8: The regression of SDS sedimentation volume on grain protein, site 3

regression at site 3 approached the strength of the combined regression, with site 1 and site 2 in particular, displaying relatively weak relationships between SDS sedimentation volume and grain protein content. Variation in the relationship between grain protein content and baking quality due to site has been noted previously (Douglas, 1987; Stevenson, 1987a).

The relative strengths of the combined regression and the regressions from the individual sites may be the result of differences in the range of grain protein contents used in each case. The combined regression used grain protein contents which ranged from under 9% to 14% (R^2 = 0.81). At site 3 protein contents ranged from 8.5% to 11.5% (R^2 = 0.61), at site 1, 10% to 12.5% (R^2 = 0.43) and at site 2, 12.5% to 14% (R^2 = 0.27).

Site differences in average grain protein content may also have influenced the R^2 achieved at each site. Preston, March and Tipples (1982) found that the grain protein content of different wheat samples had a strong influence on the ability of SDS sedimentation volume to predict baking quality from those samples. The lower the average protein content of the sample set, the better the ability of the SDS sedimentation test to predict baking quality. However, for wheat from the same sample which had been split into lines differing in protein content, grain protein content was consistent in its ability to predict baking quality. This indicates that grain protein content can influencing the SDS sedimentation test.

The t test (two-tailed) was used to test for differences in both the intercept and slope from the combined regression (Section 7.3) with the intercept and slope from the individual site regressions. Significant differences were found between the regression from site 1 and the combined regression. The intercepts were different at the 1.0% level of probability (t = 2.67). The slopes were different at the 2.0% level of probability (t = 2.38), being 3.45 at site 1 compared with the slope of 5.61 from the combined regression.

Differences in the relationship between grain protein and baking quality at different environments/locations have been attributed to differences in average temperature over

the grain-filling period (Martin, 1987; Stevenson, 1987a). Randall and Moss (1990) found that increasing temperature produced qualitative changes in grain protein resulting in increased response of baking quality to increases in grain protein, as temperature increased.

The altitude differences between the three sites resulted in differences in average temperature (Chapter IV). Site 1 was the coolest site, site 3 was the warmest and site 2, intermediate. One of the objectives of this study was to compare the response of baking quality to grain protein content from these three sites. If increasing average temperature has improved grain quality then the slopes of the site regressions of SDS sedimentation volume on grain protein content from warm sites may be greater than those from cooler sites. The slope of the regression from site 1 was significantly greater than that from site 3 ($P = 0.05$). The slope from the regression at site 2 was intermediate but was not significantly different from site 1 or site 3. While this tends to support the argument that increasing temperature increases baking quality, temperature was not the only environmental factor which varied among the sites. Other factors, such as moisture have been shown to also influence baking quality (Bunker *et al.*, 1989).

CHAPTER VIII

FINAL DISCUSSION

8.0 Introduction

The final discussion will build on the preliminary discussions presented earlier in the result chapters and whenever appropriate links issues arising from different chapters.

8.1 Yield and Yield Components

The grain yields achieved in this study (6.8 t/ha, 5.8 t/ha and 6.4 t/ha for site 1, site 2 and site 3 respectively) are above the long term mean of 4.5 t/ha for milling wheat in the Manawatu (Mitchell, 1990). They are also above the mean yield recorded for the 1989/90 season (the season in which this work was undertaken) of 4.69 t/ha (Anon., 1991). This confirms the high yield potential of these three sites. The environmental factors which can influence grain yields do not provide an explanation for site differences, particularly the low yield at site 2. The effect of temperature and rainfall have been discussed previously (Chapter IV). There were small differences in total solar radiation received with site 2 receiving less radiation than the other two sites in both December and January. Photosynthesis increases linearly as solar radiation increases, but at about 17.0 MJ/m2/day the relationship becomes curved as it approaches the asymptote (Wellbank, Witts and Thorne, 1968). Radiation levels at all three sites were above this (Chapter IV) and given the small difference between sites, are unlikely to have significantly influenced yield. Grain yield has been found to be relatively insensitive to irradiance levels during the grain-fill period. The period during influorescence development, when sink size is determined, has been found to be the most sensitive (Evans, 1978).

The major reason for the relatively low yield at site 2 was the effect of disease, primarily take-all, on grain weight. The proportion of ears showing visible symptoms of take-all at harvest was significantly correlated with grain yield (Chapter V). The correlation with grain weight (r = -0.40) just failed to be significant. The effect of take-all on grain yields can be described using linear regression (Rosser and Chadburn,

1968). At site 2, the equation describing the effect of take-all on yield was:

yield =   6.91 - 0.037 (% infected ears)*

         * significant at 0.04% level of probability

         $R^2 = 0.44$

The intercept term is an estimate of grain yield (t/ha) in the absence of take-all and has a standard error of 0.26 t/ha. This indicates that grain yields at site 2 may have been similar to those at the other two sites in the absence of take-all.

Grain yield in wheat is strongly related to the ear/m² component of yield (McCloy, 1980). Work in Canterbury has shown that an ear population of 600-800 ears/m² is required for maximum yield (Scott, 1978a). Similar results were reported by Hampton (1981). Ear populations in this study were generally below this range, particularly at site 3. Only the 40 kg N/ha and 80 kg N/ha treatments at site 1, achieved ear populations approaching this range. This was the only site for which ear numbers responded to late N. It is likely that further yield increases would have resulted from further increases in ear populations at site 1 because there was no indication that other yield components were declining in response to increasing ear populations (Nourafza and Langer, 1979).

High wheat yields have been obtained with ear numbers below the levels regarded as being necessary for maximum yields (Scott, 1978b). In the above study, the high yields were attributed to the grains/spikelet component being high. In this study, the high yields achieved at site 3 were primarily due to high seed weights (55.7mg at 80 kg N/ha on a 14% moisture basis). This demonstrates that a limitation in one yield component may not always result in poor yields, provided the crop is able compensate through an increase in the other components. The flexibility of the yield components in wheat has been demonstrated previously (Nourafza and Langer, 1979; Hampton, 1981).

Grain weight is an important yield component in milling wheat because of its influence on both yield and acceptability (Drewitt and Dyson, 1987). The Manawatu Mills Limited Premium Wheat Purchasing Contract (1991) specifies a minimum grain weight

of 38.0 mg for Rongotea at 14.5% moisture content. Grain weights at all three sites were above this level when adjusted to a 14.5% moisture content basis.

The application of late N increased grain weight at site 3 but had no effect at site 1 and 2. The application of early N to wheat has often resulted in a decrease in grain weights, which reduces its quality for milling (Dougherty, Scott and Langer, 1975; Fraser and Dougherty, 1978; Drewitt and Dyson, 1987). However, the effect of early N on grain weight interacts with other environmental factors particularly soil moisture (Drewitt, 1979). Late N has often increased grain weights in those situations where early N has decreased grain weights (Dougherty, Love and Mountier, 1978; Stephen, Saville and Kemp, 1985). This occurs because of an increase in source capacity relative to sink size (Langer and Liew, 1973). The lack of response of grain weight at site 2 can be attributed to the high fertility and disease problems encountered. At site 1, late N significantly increased sink size (grains/m^2) so that the associated increase in source capacity was balanced leaving grain weight unaffected. Early N will also increase the source capacity but when applied in large amounts may result in competition between vegetative and reproductive components, reducing grain set and grain yield (Dougherty and Langer, 1974). It is possible that the low grain yield at site 2 was partly caused by high fertility, compounded by the addition of N fertiliser at sowing. Greenwood (1979) found that N fertiliser reduced grain yields in spring wheat in 75% of paddocks cultivated from permanent pasture. Although fertiliser N was used at sowing to alleviate the possibility of low mineral N availability (resulting from a short fallow), it has been shown that the use of herbicides prior to cultivation (as was the case at site 2) can completely overcome the detrimental affects of a shortened fallow (Palmer, MacKay and O'Connor, 1972).

8.2   Grain Protein Content

Chapter VI described the effects of site and late N application on grain protein content. The grain protein content for Rongotea from the last two nationwide wheat surveys was 10.2% in 1982 and 10.8% in 1983 (Chapter I). The average protein content at site 1 (10.73%) was intermediate to these values. Site 2 (13.26%) achieved an average protein content well in excess of these values, while site 3 (9.67%) was below. It was only at

the highest rate of application of late N did grain protein contents at site 3 achieve the Manawatu Mills Limited minimum of 10.0%. Purchase is optional below this level (Appendix 9). At the other extreme, grain protein contents for all treatments at site 3 were above the upper cut-off point allowing increased price premiums for increasing protein content (Appendix 9).

8.3   The Relationship between Grain Yield and Grain Protein Content

At any given level of N availability there is a negative relationship between yield and protein content (Drewitt, 1979; Martin, 1987). This is because at a given level of available N, there is a constant protein yield which is diluted as grain yield increases. Increasing the availability of N early in the development of a wheat crop may result in an increased yield but a decrease in protein content (Benzian and Lane, 1979). The objective of applying N late in the development of the crop is to increase grain protein content and grain yield. Figure 8.1 shows the effect of different rates of late N on grain yield and grain protein content. At site 1 and site 3, late N has increased both yield and protein content. At site 2 yields have remained static and the protein content has increased slightly. This is in agreement with the findings of most workers. That is, late N increases protein content, almost linearly to very high application rates, and may increase grain yields, depending on soil fertility and rate of late N applied (Benzian and Lane, 1981; Drewitt and Dyson, 1987; Stevenson, 1987b; Martin *et al.*, 1989).

Early N can also increase both grain yield and grain protein content, particularly when applied at high rates, but it is more likely to reduce grain weight than late N (Drewitt and Dyson, 1987; Guy, 1987). This is because of the relatively large effect early N has on sink size compared to late N (Strong, 1986).

In this study, late N significantly increased grain protein content at site 1 and 2 but had no effect on grain weight. At site 3, both parameters were increased by late N. At site 1, late N increased the sink capacity of the crop, negating any potential increase in grain weight. At site 2, late N had no effect on either sink size or source capacity.
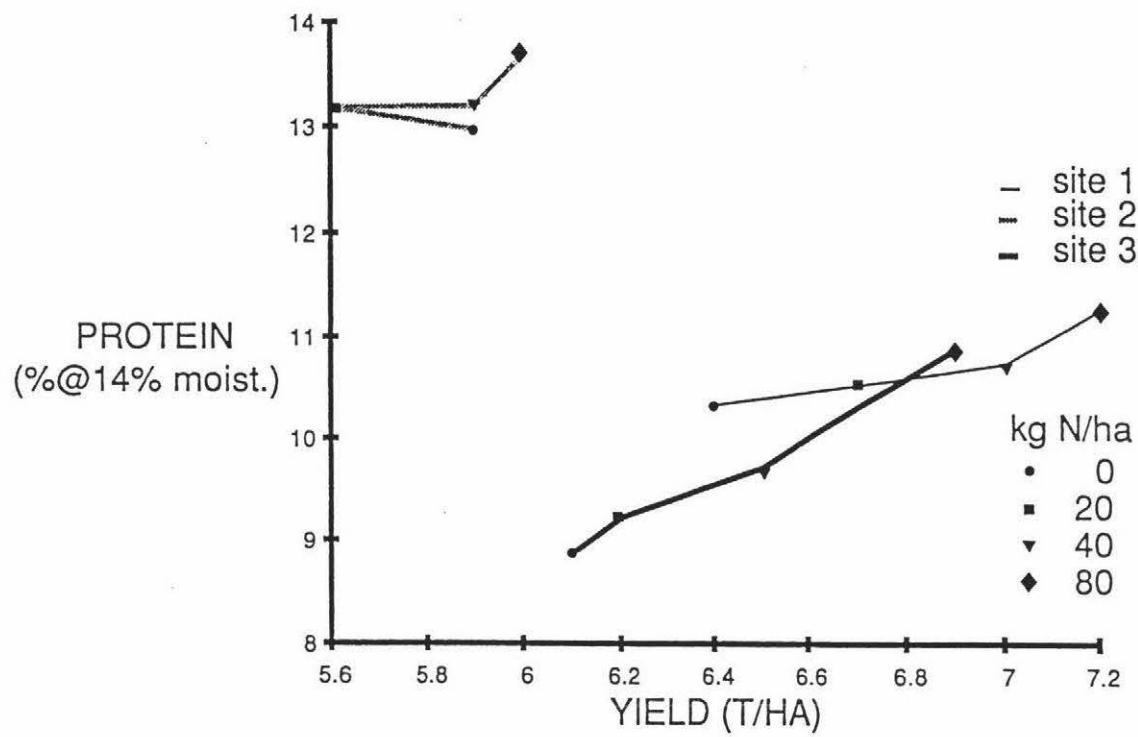
FIGURE 8.1: The effect of N on the relationship between grain yield and grain protein content

8.4 The Relationship between Harvest Index and Nitrogen Harvest Index

Strong correlations between HI and NHI have resulted in suggestions that these two processes may be related (McMullan, McVetty and Urquhart, 1988). Spiertz and Ellen (1978) concluded that the removal of carbon and N components from the vegetative organs to the grain is interrelated due to the fact that the average N content of amino acids is 16%, meaning that for every kg of N translocated to the grain, 6.25 kg of carbohydrate is also translocated.

The correlation coefficients between HI and NHI achieved in thus study are given in Table 8.1.

Table 8.1: Correlation Coefficients between HI and NHI

site 1	site 2	site 3
0.54*	0.71**	0.68*

* Significant at the 0.1% level of probability

** Significant at the 0.01% level of probability

The degree of association between HI and NHI was similar for all sites. These correlations are less than that achieved by McMullan, McVetty and Urquhart (1988) (r = 0.83), but similar to those obtained by other workers (Anderson, 1985).

These correlations indicate that the remobilisation of DM and N during grain-fill are related. However, evidence of a relationship between HI and NHI is conflicting. Jenner, Ugalde and Aspinal (1991) concluded that the deposition of starch and protein in wheat grains are independent events. For example, increasing temperatures generally decrease the total amount of starch deposited whereas protein deposition is largely unaffected (Bhullar and Jenner, 1985). However, both NHI (MacKown and Van Sandford, 1988) and HI (Perry and D'Antuono, 1989) will respond positively to an increase in sink size (grain number), indicating that starch and protein deposition may be influenced, in a similar manner, by a common factor.

Clarke *et al.*, (1990) found that HI and NHI responded to moisture availability with values of both parameters being low at low and high moisture availability. High moisture availability is likely to result in increased accumulation of post anthesis DM and nutrients, reducing the need for remobilisation to the grain. However in dry years or in a stressed crops (from disease for example) N accumulation and DM accumulation may cease shortly after anthesis (Gregory, Marshall and Biscoe, 1981).

8.5 **Baking Quality**

The baking scores achieved in this series of experiments ranged from 16 to 28. However all of the treatments scoring less than 20 were from site 3 and had low protein contents (< 10.0%). Although a bake score of 20 has been regarded as a minimum by New Zealand bakeries (Moss, 1981), the introduction of improved cultivars, particularly Otane and Kotare has resulted in the national average bake score now being well above this level (Lindley, 1989). Otane has a higher bake score than Rongotea at the same protein content (Martin, 1987). At site 3, the use of a high quality cultivar, such as Otane, may have increased the low bake scores achieved to a level where they would be acceptable to millers.

The strength of the relationship between bake score and grain protein content found in this study is unusual in New Zealand. Most studies have found the relationship to be poor (Mitchell and Casutt, 1983; Wilson, 1983; Hanson and Wilson, 1985; Douglas, 1987). Because of the size of these studies the effects of different environments may have influenced the relationship between bake score and grain protein content. However Stevenson, (1987b) found no relationship between bake score and grain protein content for the cultivars Rongotea, Oroua, Otane and Kotare grown in the same environment. It can be argued that the poor relationship found between these two quality parameters is partly because of the relatively poor quality of the wheat cultivars grown in New Zealand in the past (Griffin,1985). However , Otane and Kotare are high quality cultivars which are internationally competitive in terms of baking quality (Lindley, 1989).

The strong relationship between bake score and grain protein content in this study

supports the use of protein content, in conjunction with cultivar, sprout damage and screenings, to assess the quality of milling wheat which may be purchased by the Manawatu Mills Limited, Palmerston North.

Despite the strong relationship between bake score and grain protein content in this study, there were site differences in apparent baking quality. Baking quality, as measured by the SDS sedimentation test, responded differently to increases in grain protein content at different sites. It is very likely that site or location influences the relationship between baking quality and grain protein content by altering the composition of the wheat storeage proteins. Environmental factors are known to influence not only the protein content of wheat but also the composition and hence the physical properties of these proteins (Fowler and De La Roche, 1975). Increasing temperatures can increase the proportion of gluten in the wheat storage proteins (Kolderup, 1975). It is gluten that gives dough its visco-elastic properties. Temperature (Blumenthal *et al.*, 1991b) and moisture (Bunker *et al.*, 1989) have been shown to influence the gliadin : gluten ratio in wheat, and as a consequence, baking quality.

8.6 The feasibility of using late N on milling wheat crops in the Manawatu

It is technically feasible to apply N fertiliser to wheat in the latter stages of crop development. Although Manawatu mixed-arable farmers do not use tramlines in their crops, allowing vehicles to travel across the crop at any stage of growth, aerial application means that this can be achieved very quickly and at short notice. The decision on whether or not to apply late N to milling wheat crops will be almost entirely dependent on the likely economic benefits to the farmer.

At the current price of ammonium sulphate, the applied cost of N in this study was $39.00/ha, $63.00/ha and $110.00/ha at 20 kg N/ha, 40 kg N/ha and 80 kg N/ha respectively. The response in grain yield and protein content achieved in this study was used, in conjunction with the above costs, to calculate financial returns from the application of late N. The 1991 Manawatu Mills Limited base price of $295.00/tonne @ 100 index points was applied. The index points were allocated according to schedule 2 of Appendix 9. Financial returns are shown in Table 8.2.

Table 8.2: Net return from the application of late N ($/ha)

	site 1	site 2	site 3*
20 kg N/ha	80	-39	-13
40 kg N/ha	177	-63	38
80 kg N/ha	228	-110	254

* Assumes that wheat below 10.0% protein content is accepted by the Manawatu Mills Limited

Table 8.2 shows that for site 1 and site 3 the combined benefits of increasing yield and protein content has resulted in margins of $228.00/ha and $254.00/ha respectively, from the use of late N. The economic benefits have increased with the rate of application. At site 2, where there was no yield response and protein contents were above the upper threshold for obtaining price premiums, increasing application rates have increased the financial losses. At site 3, only the 80 kg N/ha application rate resulted in a grain protein content above 10.0% (Chapter VI). If grain below 10.0% protein content was rejected by the Mills, then it would have to be sold as feed wheat. This may involve additional cartage and storage costs as well as accepting a price discount normally received for feed wheat.

Although ammonium sulphate was used in this study, urea may be equally as effective (Withers, 1986). Potential disadvantages of urea are high volatilisation losses in warm dry conditions (Theobald and Ball, 1984) and for sites with low soil sulphur(S) levels, a widening of the N:S ratio which may result in decreased protein quality (Gooding, Kettlewell and Hocking, 1991). On a cents/kg N basis, urea has traditionally cost less than ammonium sulphate in New Zealand (Rogers and Little, 1982).

It is possible to apply N as a foliar spray, usually with water solutions of urea or diammonium phosphate (Ozanne and Petch, 1978). The effectiveness of foliar application has been found to be variable. Strong (1982) found that foliar applications at the boot stage were not as effective as soil applications but were more effective if late N was applied after anthesis. This may have been due to low soil moisture levels reducing uptake with the later soil application. Cooper and Blakeney (1990) found that foliar applications of urea were significantly less effective at increasing grain protein content than soil applied ammonium nitrate applied to irrigated wheat near anthesis. Pushman and Bingham (1976) concluded that, although foliar liquid urea was effective at increasing grain protein content, this did not necessarily result in an increase in baking quality. Another problem resulting from the use of foliar fertilisers is the risk of leaf scorch (Sylvester-Bradley and Dampney, 1982; Strong, 1986).

The recovery of late N applied to the crops in this series of experiments was low, particularly at site 2 (Chapter VI). Because excessive quantities of nitrate N in the soil is a potential environmental hazard, low recovery of N fertiliser is not desirable. Some of the N which was not recovered in the grain in this study can be accounted for in the straw. As stubble was burnt at all three sites this N was not returned to the soil. Nitrogen not accounted for may have been lost from the soil through leaching and denitrification or may still be present, either in mineral or organic form (Allison, 1966). Losses of N from the soil-plant system can range from virtually nothing to 35% (Addiscot and Powlson, 1992) with losses due to denitrification being generally twice as large as those from leaching. Rainfall has a strong influence on the proportion of applied N lost from the soil-plant system with losses being higher with higher rainfall (Powlson et al., 1992). Losses in this study may have increased with site altitude because of the trend of higher rainfall at higher altitudes (Appendix 1).

The use of late N (Feekes G.S.8-9) to increase yield and protein content of milling wheat is a common practice in Europe (Needham, 1982). McCloy (1981) did not recommend the use of late N on milling wheat in New Zealand because of uneconomic yield responses. Although the ability of late N to increase grain protein content was recognised, there were no variable payments based on protein content. Payment for

milling wheat prior to the deregulation of the New Zealand Wheat Board was based on bake score (Logan, 1985). Because of the relatively poor relationship between grain protein content and bake score, increasing protein contents did not necessarily result in an increase in bake score (Wilson, 1983). However, with premiums now available for grain protein content alone, this is no longer a constraint for Manawatu wheat producers.

Late N has been recommended for Southland milling wheat crops (Christie, 1989). In the Manawatu, Withers (1986) found that late N could be profitable. In the above study late N increased both yield and protein content in a wet year. Low soil moisture reduces the effectiveness of late N (Needham, 1982). In this study, rainfall during the month of December (early grain-fill) was well below the long term average (Chapter IV), indicating that for the soil types represented by the sites used in this series of experiments, soil moisture levels are likely to be adequate even in years of low rainfall. At site 3 for example, the December rainfall total of 45.3 mm is approaching the 10 percentile value of 36 mm (Burgess, 1988).

Yield responses to late N tend to be much less reliable than increases in grain protein content (Pushman and Bingham, 1976; McCloy, 1985b; Drewitt and Dyson, 1987; Christie, 1989). In this study, the net return from applying late N would have been much reduced if the response was confined to grain protein content only. However, if grain yield had not responded to late N, then the grain protein contents achieved would have been greater because of the lack of dilution resulting from yield increases (Pushman and Bingham, 1976). Under this scenario the net returns achieved at site 1 and site 3 would have been similar to those in Table 8.2.

The economic benefits of late N are likely to be the greatest in crops which are high yielding but with restricted N supply, particularly during the latter stages of development (Martin et al., 1989). Any factor limiting crop growth, such as disease (Spiertz and De Vos, 1983) or moisture stress (Drewitt and Dyson, 1987) will limit economic benefits. Moisture stress has a negative effect of grain yield resulting in high grain protein contents. Any response in grain protein content from the application of late N may not

necessarily result in price premiums if the upper threshold limit for grain protein content is achieved.

Effective use of N fertiliser requires an objective means of determining the potential response to late N. In this study, there was a strong correlation ($r=0.96$) between N content of the crop at Feekes G.S.9 and grain protein content amongst those plots not recieving late N. This suggests that crop N content may be of use as a means of identifying crops likely to produce low protein wheat. However there was no relationship between N content of the crop at Feekes G.S.9 and grain yield. While some studies have found a relationship between crop N content and grain yield (Olson and Kurtz, 1982), the relationship between N supply and grain protein content is much more reliable than that between N supply and grain yield (Benzian and Lane, 1981).

The nitrate sap test (Withers and Palenski, 1984) may be of use as a more convenient means of identifying paddocks which will produce an economic increase in grain yield and grain protein content in response to late N. Withers (1986) found a good relationship between sap nitrate levels during stem elongation in wheat and barley and subsequent grain protein content. Crops with low sap nitrate levels at stem elongation may still produce grain with a high protein content at low yielding sites. The most responsive sites are likely to be those with low sap nitrate levels but with a high potential yield. Sap tests were taken at each site prior to the application of N at the beginning of this study. However the results were extremely variable with many test strips failing to change colour at each site. As a consequence, no meaningful data was obtained. Withers (1982) found that the relationship between sap test levels at Feekes G.S.9 and grain yield was poor. Withers and Palenski (1984) suggested that the sap test would be of greatest use as a tool to monitor trends in sap nitrate levels rather than as a once only test. The nitrate sap test can be used at Feekes G.S.6-7 to monitor the N status of a crop and depending on potential yield, N fertiliser applied to the crop as appropriate. This will allow potential yield to be achieved while maintaining adequate levels of grain protein (Anon., 1988a).

CHAPTER IX

CONCLUSIONS

1. There were significant differences among the sites in grain protein content. There was a strong, positive relationship between grain protein content and total N yield. Average protein contents were 10.73%, 13.26% and 9.67% for site 1, 2 and 3 respectively, mean of all treatments.

2. Late N significantly increased grain protein content at all three sites. Although the response was linear at all sites, the response rate differed among the sites, being inversely proportional to the average grain protein content and the total N yield.

3. The response of grain protein content to late N was greatest at site 3 with 40 kg N/ha required to lift grain protein content by 1.0%. Responses were least at site 2, with 111 kg N/ha required to lift grain protein content 1% and intermediate at site 1 where 86 kg N/ha was required.

4. N recoveries in this study were generally comparable to those achieved by other workers when applying late N. However, they were below the N recoveries achievable from early applications of N.

5. Grain protein content was strongly related to MDD bake score. The response of bake score to increasing grain protein content was linear across the range of grain protein contents sampled (9.0%-14.0%). This is in contrast to other studies in New Zealand and may be due to the limited number of sites and small geographical range used in this study.

6. There was a strong, positive relationship between grain protein content and SDS sedimentation volume.

7. SDS sedimentation volume was strongly and positively related to bake score, allowing it to be used as an alternative measure of baking quality.

8. There were site differences in the relationship between protein content and baking quality, as measured by SDS sedimentation volume.

9. Late N significantly increased grain yields at sites 1 and 3. However the response mechanism differed between these sites. Late N increased ear numbers at site 1 whereas at site 3 it increased grain weight. There was no response at site 2.

10. Late N delayed the senescence of the flag leaves at sites 1 and 3.

11. Grain yields at site 2 were depressed by a late infection of take-all. The proportion of ears showing symptoms of take-all damage was negatively correlated with grain yield.

12. Average site temperatures declined with increasing altitude, at a rate of 0.55°C/100 m of altitude. Average temperature for the 1989/90 season was close to the long term mean.

13. Rainfall during the early grain-fill period was below the long term mean.

14. The combined benefits of increased grain yield and grain protein content at site 1 and 3 (from the application of late N) resulted in the use of late N being highly profitable.

15. Responsive sites are most likely to be those that have been previously cropped and where the yield potential is high.

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APPENDIX 1: Recorded rainfall from time of N application till harvest (mm)

Date		Site 1	Site 2	Site 3
November	16	6.0		
	22	2.5	2.5	
	30	30.5	20.0	13.0
December	05	9.5	12.5	18.0
	07	5.5	3.5	0.0
	11	1.5	1.5	
	16		0.0	
	18			4.8
	22	20.5	14.0	
	27	35.0	25.0	
	29			22.5
January	03	53.5		
	08		71.0	
	10	25.5		39.5
	19	25.5		17.5
	23		15.0	
	31	30.0	54.0	63.5
December	Total	62.0	56.5	45.3
January	Total	164.5	140.0	120.5

APPENDIX 2: Gravimetric Soil Water Content (%)

Date		Site 1	Site 2	Site 3
November	09	36.8†		
	16		20.5†	
	25			12.4†
	30	42.6*		
December	05		23.6*	
	07			21.5*
	11	40.8		
	16		16.4	
	18			13.6
	22	37.6		
	27		51.5	
	29			17.0
January	03	43.7		
	08		30.9	
	10	41.6		17.9
	15		24.7	
	19		16.8	

† Application of N (Feekes G.S.9)

* Beginning of Anthesis (Feekes G.S.10.5.1)

APPENDIX 3: Daily maximum, minimum and average temperature (°C)

DATE	MAXIMUM			MINIMUM			AVERAGE		
	SITE1	SITE2	SITE3	SITE1	SITE2	SITE3	SITE1	SITE2	SITE3
NOV10	17.2	18.3	18.9	10.0	11.1	12.8	13.9	15.0	15.6
NOV11	15.6	16.7	17.8	6.7	6.1	7.8	11.7	12.2	14.4
NOV12	18.9	20.6	21.1	6.7	5.6	5.6	12.2	13.3	13.3
NOV13	17.2	18.9	20.0	8.3	8.9	12.2	12.8	13.9	15.6
NOV14	20.0	20.0	20.0	7.8	7.2	8.3	14.4	14.4	15.0
NOV15	18.3	19.4	18.9	9.4	7.8	12.8	15.0	15.0	15.6
NOV16	18.9	20.0	20.6	8.9	7.2	11.7	12.3	13.9	15.6
NOV17	21.7	21.7	22.2	9.4	11.1	7.8	15.6	16.1	16.1
NOV18	20.6	21.1	22.2	10.0	10.6	11.7	15.0	15.6	16.1
NOV19	19.4	18.9	18.9	9.4	9.4	11.1	14.4	15.0	15.6
NOV20	16.1	15.6	18.9	8.3	9.4	9.4	12.2	12.8	13.9
NOV21	13.3	13.9	15.6	7.2	7.8	8.3	9.4	10.6	11.7
NOV22	18.3	18.3	17.8	2.8	1.7	4.4	11.1	11.7	12.2
NOV23	21.1	21.1	23.3	8.3	9.4	10.6	13.9	14.4	16.1
NOV24	24.4	24.4	25.0	7.8	9.4	13.9	16.7	18.3	18.9
NOV25	25.6	23.3	24.4	12.8	12.8	15.6	17.8	17.8	18.9
NOV26	21.1	21.1	22.0	11.7	11.1	12.8	16.1	16.1	17.2
NOV27	18.3	19.4	20.6	9.4	10.0	12.2	13.9	15.8	15.6
NOV28	13.3	14.4	16.1	6.1	5.0	4.4	10.0	11.1	12.2
NOV29	15.0	16.1	17.2	1.7	1.7	2.2	8.9	9.4	10.6
NOV30	14.4	16.1	17.8	7.8	6.1	5.0	11.7	12.2	12.8
DEC1	17.8	18.9	19.4	11.1	12.2	12.2	13.9	15.0	15.6
DEC2	20.0	20.6	20.0	10.6	8.3	13.9	15.6	16.1	16.7
DEC3	18.9	20.0	21.1	12.2	13.3	13.9	15.6	16.7	17.2
DEC4	21.1	21.1	21.7	12.2	13.3	12.2	15.6	16.7	17.2
DEC5	16.7	17.8	19.4	8.9	10.0	11.7	13.3	13.9	15.0
DEC6	15.6	16.7	17.2	6.7	7.2	7.2	10.6	11.1	12.2
DEC7	15.0	16.1	18.9	7.2	8.3	5.0	10.6	11.7	12.8
DEC8	14.7	17.2	18.3	5.0	3.9	8.9	11.1	11.7	13.3
DEC9	18.3	18.3	19.4	2.2	2.2	5.6	10.0	11.1	12.2
DEC10	17.8	16.7	20.0	2.8	2.8	1.7	11.1	10.6	11.7
DEC11	21.1	22.2	23.3	4.4	5.0	3.3	12.8	13.9	13.3
DEC12	20.0	20.6	21.7	3.9	5.0	5.0	13.3	13.9	14.4
DEC13	20.0	21.7	21.7	10.6	11.1	13.9	15.0	16.1	17.2
DEC14	23.3	23.3	23.9	10.0	11.7	12.8	16.7	17.2	18.3
DEC15	22.2	23.9	23.3	13.3	10.6	12.2	17.8	18.9	18.3
DEC16	26.1	21.7	20.6	11.1	11.1	13.3	16.7	17.8	18.3
DEC17	15.6	17.2	18.9	10.0	7.8	8.9	12.2	12.2	13.9
DEC18	15.0	15.6	18.9	3.9	5.0	5.6	10.0	11.1	12.8
DEC19	20.0	19.4	20.6	0.6	1.1	0.0	10.6	11.1	11.1
DEC20	20.0	20.0	21.7	5.0	2.8	4.4	12.2	12.2	13.3
DEC21	22.2	22.2	23.9	4.4	2.8	5.0	13.9	14.4	16.1
DEC22	20.6	21.1	21.7	8.9	10.0	10.6	15.6	16.1	16.1
DEC23	16.1	17.2	18.9	8.3	9.4	10.0	11.1	11.7	12.9
DEC24	13.9	15.6	17.8	6.1	7.2	10.0	10.0	11.1	13.9
DEC25	16.1	17.2	18.9	7.8	7.2	8.9	12.2	13.3	13.9
DEC26	16.7	18.3	20.0	10.6	11.7	13.3	12.8	14.4	16.1
DEC27	21.7	22.2	22.8	11.7	11.1	9.4	16.1	16.1	17.2
DEC28	23.3	23.9	23.9	15.0	15.0	13.9	18.3	18.9	18.3
DEC29	18.3	18.9	18.9	12.2	11.7	13.3	16.1	16.7	17.2
DEC30	20.0	20.0	20.6	10.6	10.0	11.7	15.0	15.6	16.1
DEC31	17.8	18.9	18.9	11.1	12.2	12.2	13.9	14.4	14.4
JAN1	21.1	21.7	22.2	9.4	10.0	12.2	15.6	16.7	17.2
JAN2	22.0	22.2	22.2	7.8	8.3	8.9	15.6	15.0	16.1
JAN3	21.1	21.1	21.1	12.8	13.3	12.8	15.6	16.7	17.2
JAN4	22.2	22.2	23.3	8.9	8.9	11.1	15.6	14.7	17.2
JAN5	17.2	17.8	18.3	10.0	10.0	11.7	13.9	14.4	15.6
JAN6	21.1	19.4	20.6	7.2	8.3	9.4	13.9	13.9	15.0
JAN7	21.7	21.7	21.7	6.1	6.1	6.7	12.9	14.4	14.4
JAN8	19.4	20.0	20.0	6.7	7.2	6.1	13.3	13.3	13.9
JAN9	21.1	21.7	22.2	10.6	11.7	12.2	15.0	15.6	17.2
JAN10	20.0	20.0	21.7	10.0	9.4	9.4	13.9	15.0	15.6
JAN11	21.1	21.1	20.0	7.8	7.8	8.3	14.4	15.0	15.0
JAN12	20.6	20.6	21.1	13.3	13.3	14.4	16.1	16.1	16.7
JAN13	21.1	21.1	18.9	13.9	15.0	16.1	16.1	.16.7	17.8
JAN14	22.2	22.8	23.3	13.6	16.1	16.7	17.8	18.3	18.3
JAN15	21.7	22.0	23.3	12.2	12.8	15.0	16.1	17.2	18.3
JAN16	24.4	24.4	24.4	10.6	10.0	10.0	17.2	17.2	17.8
JAN17	26.7	27.8	27.2	15.6	15.6	15.6	20.6	20.6	20.6
JAN18	18.9	19.4	20.6	10.0	8.9	8.9	15.0	15.6	16.1
JAN19	22.8	23.9	22.0	8.9	7.8	6.7	15.0	15.6	15.6
JAN20	26.1	26.7	26.7	8.3	8.3	8.9	18.3	18.3	18.3
JAN21	25.6	26.1	25.6	11.7	11.1	14.4	18.9	19.4	20.0
JAN22	23.9	24.4	22.0	10.6	9.4	10.0	17.2	17.2	17.2
JAN23	22.0	23.9	24.4	11.7	11.1	12.8	16.7	17.2	18.3
JAN24	21.1	22.2	24.4	9.4	9.4	7.2	15.6	16.7	16.7
JAN25	27.2	28.3	27.2	6.7	5.6	5.6	16.7	16.7	17.8
JAN26	26.1	27.2	27.8	11.1	7.8	7.8	18.3	17.0	17.2
JAN27	26.7	27.2	26.7	12.8	11.1	15.6	19.4	20.0	20.6
JAN28	25.0	26.1	26.1	15.0	14.4	15.6	18.9	18.9	20.0
JAN29	27.8	29.4	25.0	15.0	16.1	17.8	21.1	22.2	21.7
JAN30	22.2	23.3	23.9	11.7	10.0	13.3	17.2	17.8	18.9
JAN31	27.2	27.8	27.2	6.7	6.1	11.7	17.2	17.2	18.9
FEB1	26.1	26.7	26.1	13.3	12.3	13.3	19.4	20.0	20.0
FEB2	27.8	28.3	27.2	11.7	11.7	11.1	19.4	19.4	18.9
FEB3	26.7	26.7	26.1	13.3	13.9	15.6	20.0	21.1	21.1
FEB4	27.8	28.3	27.2	11.1	11.7	11.7	19.4	19.4	18.9
FEB5	26.1	26.1	26.1	14.4	15.0	14.4	19.4	20.0	19.4

APPENDIX 4:   Daily solar radiation (MJ/m^2/day)

DATE

	SITE 1	SITE 2	SITE 3
NOV10	152.4	136.6	150.0
NOV11	157.8	146.4	164.3
NOV12	151.2	150.7	147.6
NOV13	129.0	117.7	129.7
NOV14	85.0	71.6	69.3
NOV15	168.4	146.1	147.1
NOV16	158.8	138.7	141.8
NOV17	134.0	155.2	160.5
NOV18	120.6	111.8	145.2
NOV19	59.7	58.7	55.2
NOV20	105.5	89.6	109.8
NOV21	116.5	125.8	155.7
NOV22	179.1	175.5	175.3
NOV23	119.4	123.0	127.5
NOV24	175.3	166.2	180.1
NOV25	134.0	133.5	131.3
NOV26	138.0	136.1	141.8
NOV27	106.7	124.4	114.9
NOV28	83.1	80.2	73.1
NOV29	179.3	177.9	148.7
NOV30	81.7	89.1	106.2
DEC1	79.3	78.3	76.9
DEC2	174.8	163.6	154.7
DEC3	81.0	111.5	159.0
DEC4	103.2	115.1	100.3
DEC5	73.8	80.2	93.4
DEC6	134.9	107.2	143.3
DEC7	115.6	106.5	139.5
DEC8	143.3	119.6	177.2
DEC9	149.3	148.1	138.7
DEC10	156.7	99.1	138.5
DEC11	174.8	166.2	163.3
DEC12	145.4	139.0	145.2
DEC13	147.1	134.9	157.8
DEC14	154.7	146.4	172.9
DEC15	101.7	110.8	93.4
DEC16	59.5	64.5	78.1
DEC17	93.4	100.5	125.1
DEC18	116.1	131.1	114.6
DEC19	178.1	158.8	163.3
DEC20	191.5	181.0	184.6
DEC21	182.9	170.7	185.3
DEC22	136.6	134.7	137.1
DEC23	92.4	95.0	117.3
DEC24	112.0	104.4	146.9
DEC25	119.9	124.9	139.5
DEC26	70.2	90.0	88.6
DEC27	122.5	111.8	107.0
DEC28	115.1	91.0	80.2
DEC29	46.3	46.3	65.0
DEC30	174.3	159.8	173.8
DEC31	55.4	52.1	59.7
JAN1	173.4	157.4	168.1
JAN2	173.4	158.1	176.7
JAN3	131.8	114.9	155.9
JAN4	125.1	113.7	115.3
JAN5	88.1	85.5	126.1
JAN6	156.4	124.4	131.6
JAN7	187.9	155.7	163.1
JAN8	122.0	119.2	122.3
JAN9	145.9	138.7	163.8
JAN10	130.1	136.8	114.4
JAN11	157.8	129.0	94.6
JAN12	131.6	111.3	145.2
JAN13	86.7	65.9	52.5
JAN14	102.0	104.8	111.8
JAN15	88.8	92.7	130.6
JAN16	152.6	147.6	155.9
JAN17	79.8	99.6	67.6
JAN18	146.9	141.4	145.7
JAN19	178.9	166.2	185.1
JAN20	176.7	177.2	182.9
JAN21	149.3	145.2	176.5
JAN22	168.8	152.4	132.3
JAN23	118.2	123.2	130.6
JAN24	140.2	122.0	146.4
JAN25	182.0	174.3	180.3
JAN26	163.3	158.8	168.4
JAN27	135.9	136.4	143.3
JAN28	70.9	69.7	94.8
JAN29	139.0	129.0	95.8
JAN30	84.5	87.6	79.3
JAN31	179.6	170.7	174.6
FEB1	145.7	136.6	159.3
FEB2	155.2	152.4	167.6
FEB3	142.3	125.4	151.1
FEB4	171.9	161.2	156.9
FEB5	124.7	115.6	121.5

APPENDIX 5: The proportion of discoloured and healthy ears at site 2

Treatment	% Discoloured
0	27.0
20	32.5
40	27.9
80	25.6
Significance	NS

APPENDIX 6: Paired comparison of healthy and diseased (discoloured) ears for yield component differences, at site 2

|	spikelets/ear (at anthesis)	grains/spikelet	1000 seed wt (g)
Normal Average	16.2	2.23	40.7
Diseased Average	17.3	1.77	23.5
Difference	-1.1	0.46	17.2
Significance	NS	5%*	1%*

* Two tailed t test

APPENDIX 7: The effect of site on the total N yield at harvest

	Site 1	Site 2	Site 3
Total N yield (kg N/ha)	178.2	227.5	128.8 *

All sites are significantly different from each other at the 0.1% level of probability

APPENDIX 8: The regression of grain protein content on total N yield at harvest
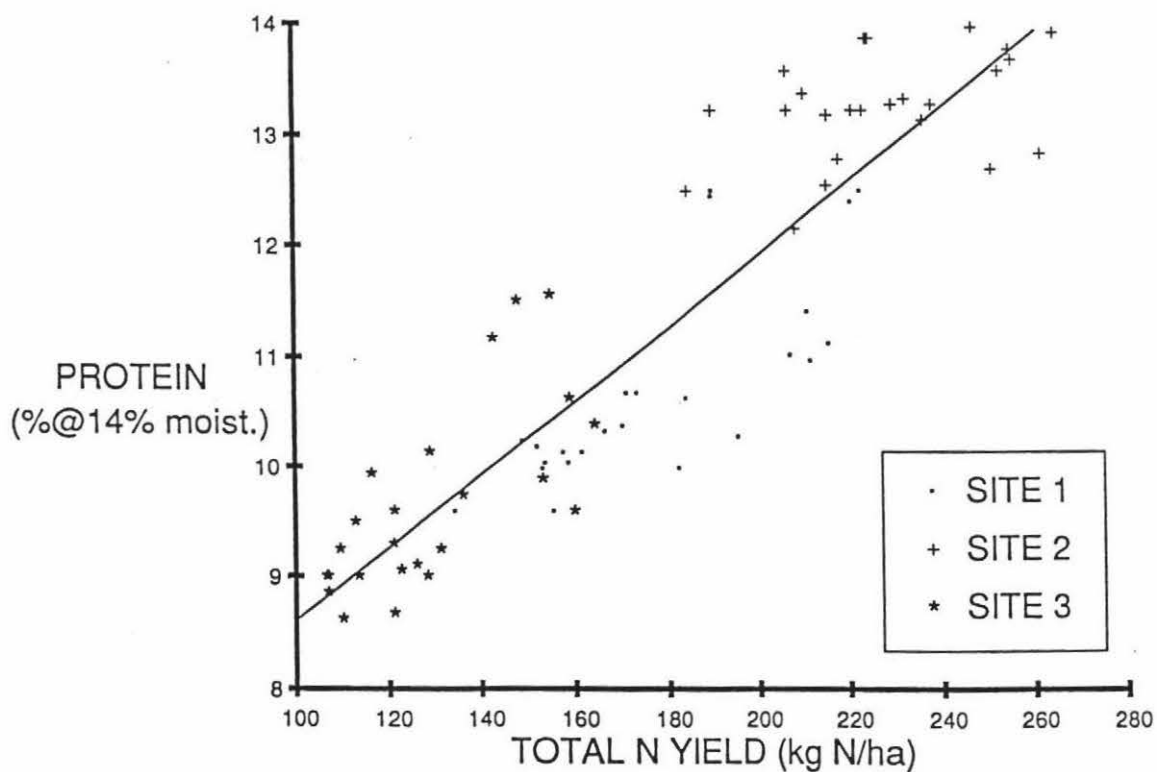
Protein = 5.3 + 0.0332(total N yield)
R^2 = 0.82

APPENDIX   9:

MANAWATU MILLS LTD NORTH ISLAND MILLING CONTRACT
PREMIUM WHEATS 1991-92

SCHEDULE 1

Quality Specifications
(a) MOISTURE maximum 14.5%.
(b) TEST WEIGHT min 72kgs/HL
(c) KERNEL-WEIGHT (grams per 1000 kernels clean wheat)
     Oroua min 34 grams per 1000 Otane min 40 grams per 1000. All other wheats min 38 grams per 1000.
(d) FALLING NUMBERS
     ALL WHEATS min 250 (option to purchase to 180, below 180 rejected)
(e) BLACK POINT NUMBER maximum 5 by M.A.F. scale.
(f) APPEARANCE — all wheat shall be sound, sweet and clean, free from foreign grains, smut, decay, insect and grain storage pests, vermin, visible sprout, and any other blemish or damage

SCHEDULE 2

(a) **Quality Index**

Premium Wheats		Bread Wheats	
OTANE	87 points	NORSEMAN	83 points
OROUA	85 points		
RONGOTEA	85 points		

(b) **Protein Index**

Premium Wheats		Bread Wheats	
12.9% and above	+ 22 points	12.9% and above	+ 22 points
12.6-12.8%	+ 20 points	12.6-12.8%	+ 20 points
12.3-12.5%	+ 18 points	12.3-12.5%	+ 18 points
12.0-12.2%	+ 16 points	12.0-12.2%	+ 16 points
11.7-11.9%	+ 14 points	11.7-11.9%	+ 14 points
11.4-11.6%	+ 12 points	11.4-11.6%	+ 12 points
11.1-11.3%	+ 10 points	11.1-11.3%	+ 10 points
10.8-11.0%	+ 8 points	10.8-11.0%	+ 8 points
10.5-10.7%	+ 6 points	10.5-10.7%	+ 6 points
10.2-10.4%	+ 4 points	Below 10.5% option to purchase	
10.0-10.1%	+ 2 points		
Below 10% option to purchase			

(c) **Screenings** All weed seeds & foreign matter fully deductible
     Up to 2% — no deductions
     2% to 5% — deduction by weight of 1% or part thereof for each 1% percentage part thereof of screenings.
     Above 5% — option to purchase

SCHEDULE 3

Storage Index
13 cents per tonne per day as from 1/4/92.

SCHEDULE 4

Testing Procedures
Tests may be carried out by any recognised method provided test results can be standardised against the following Standard Laboratory methods used by Northern Roller Milling Laboratory Auckland
(a) **Telarc Registered Test Methods**
     (i) PROTEIN No. AACC 4608 on wheat meal at 14% m.b.
     (ii) SCREENINGS NRM CO 2 CARTER DOCKAGE 2mm.
     (iii) MOISTURE No. AACC 44-15A AIR OVEN
     (iv) FALLING NUMBER No. AACC 56-81B on unsieved wheatmeal
(b) **Unregistered Test Methods**
     (i) TEST WEIGHT NRM HO 2 Kilograms per Hectolitre of dirty wheat
     (ii) KERNEL WEIGHT Grams per 1000 kernels of clean wheat
     (iii) BLACK POINT NUMBER M.A.F. scale