A STUDY OF YIELD, QUALITY AND SUBSOIL WATER UPTAKE OF WHEAT (TRITICUM AESTIVUM L.) CV. KOPARA

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Warwick
Many thanks for your invaluable help to see this through.
Wally 25/3/81.

Hons I 81 May

by

W.S. Dalgliesh

Lincoln College

1981

"Plants speak to men but only in a whisper; their voice can be heard only by those who remain close to them".

- Dr N.E. Borlaug

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PREFACE

Several seasons trials at Lincoln College have helped provide a greater understanding of how the yield components of autumn sown wheat are determined (Dougherty *et al.* 1974, 1975, 1978, 1979, Scott *et al.* 1973, 1977). Notwithstanding the importance of yield, when wheat is destined for bread making in New Zealand a defined level of flour quality must be attained (Hullet, 1964). Previously this aspect had not been studied for wheat growing on moisture retentive soils. Similarly, monitoring plant water uptake from these soils had not been examined. The research reported in this thesis aims to establish more information specific to the points mentioned above.

Chapter 1 deals with changes in yield and yield components that occur when different treatments are imposed during the growing period.

Chapter 2 studies the effects caused by the different agronomic treatments on the various parameters of flour quality.

Chapter 3 monitors the pattern of subsoil water uptake.

These three chapters are not intimately dependent on each other so they have been written as separate and entire units to keep all relevant information together. Chapter 4 is the overall concluding discussion encompassing all work reported in this Thesis.

CHAPTER 1

CHANGES IN WHEAT COMPONENTS OF YIELD AS INFLUENCED BY VARIOUS AGRONOMIC TREATMENTS

1.1 INTRODUCTION

Wheat yield can vary due to many different causes and in each case these are expressed through the harvest yield components. To help interpret yield component relationships, patterns of growth should be analysed.

This chapter describes the trial and examines changes in the yield and yield components that occur when different treatments are imposed during the growing period.

1.2 REVIEW OF LITERATURE

In wheat (*Triticum aestivum* L.) yield is a function of the number and weight of grains per unit area. The four plant parameters controlling yield are ears per unit area, spikelets per ear, grains per spikelet and grain weight and this is also the order in which the components are initiated. However, their final determination can occur in overlapping sequence and this allows the opportunity for component compensation (Evans & Wardlaw 1976) since a much greater capacity is laid down than is ultimately used. The scope for such compensation usually decreases with ontogeny (Rawson & Bremner 1976). Since yield components are determined at different times they can be differentially affected by variations in the environment (Rasmusson & Cannell 1970).

Harvest ear numbers per unit area are derived from tiller numbers which reach their maximum around the end of the vegetative growth phase. In standard wheat cultivars, double ridges and spikelet development commences during the elongation of the shoot apex which is the start of the reproductive phase (Bonnett 1966). The maximum spikelet number is fixed

by the formation of the apical or terminal spikelet but, before this occurs, within spikelet differentiation of those earliest formed spikelets has already started (Fisher 1973). Not all initiated florets continue growth (Langer & Hanif 1973) and undergo fertilisation which is the start of the grain filling process. Grain filling was described by Jenner & Rathjen (1972) as being mainly dependent on the rate and duration of dry matter, or starch accumulation. Over all these physiological stages of plant growth the two main controlling environmental parameters are photoperiod and the gross seasonal change in temperature (Thorne 1973). Besides these, large morphological variations can be induced by altering agronomic management variables such as nitrogen, water supply and plant density. Often the resultant yield will be changed as well.

Although N may be no more essential than other elements required for plant growth, it is consumed in larger amounts than any other element (Viets 1965). It is often the most limiting nutrient and one that may influence all the yield components. Khalifa (1973) found that fertilizer N generally influenced those yield components being determined during the time of its application. Provided N is supplied before stem elongation and inflorescence initiation there will usually be an increase in the number of tillers produced per plant (Jewiss 1972, Batey 1976). Even without N it is known that autumn sown wheat can initiate more tillers than the plant can maintain (Dougherty & Langer 1974). Consequently ear numbers at harvest are determined by tiller survival, rather than tiller production, and this phase occurs during stem elongation (Langer 1979, Clements *et al.* 1974). It involves inter and intra-tiller competition, there being an inverse relationship between final ear number per plant and plant density (Puckridge & Donald 1967, Willey & Holliday 1971). The main stem (the oldest) normally provides the greatest contribution to yield (Rawson, 1971) while the primary tillers contribution to yield and order of

survival follows their pattern of succession (Bunting & Drennan 1966, Fraser 1978).

On a world scale, fluctuations in the amount of soil water available during crop growth is the single most important factor restricting crop yield. Water deficits have a limiting influence on yield (Begg & Turner 1976) and supplying water to alleviate them may promote extra production. The amount of reduction or increase will depend on the degree, duration and stage of crop development. As with N, the plant water status is ultimately reflected through the yield components so that those physiological processes being determined during the times of shortages or additions are the most likely to be affected (Wilson 1974). With autumn-sown wheat in the Lincoln environment, the early tillering stages are not influenced by irrigation on moderately water retentive soils (Scott *et al.* 1973) and it is only from early September that evapotranspiration starts depleting soil water (Walker 1956). Salter & Goode (1967) and Drewitt (1974) acknowledge that if one irrigation is to be used then it should be applied at the time of booting. Here the effect is twofold; it promotes better grain set per ear (Fischer 1973) and it aids tiller survival. Grain weight response can be variable and it has been shown to increase (Drewitt 1974) or decrease (Dougherty & Langer 1974) with irrigation.

The sowing rate for wheat in South Canterbury was determined at between 100 and 200 kg ha^{-1} (McLeod 1960) as this range produced no significant difference in yield. Scott *et al.* (1973) found that as the sowing rate increased from 50 to 150 kg ha^{-1} the number of ears at harvest did also, while spikelets per ear and grain number per spikelet declined. Mean grain weight was heaviest at the 100 kg ha^{-1} rate as was the grain yield.

1.3 MATERIALS AND METHODS

DESIGN: The experiment consisted of a 3 x 2 x 2 x 2 factorial with 2 replicates of each treatment. The 2 x 2 x 2 interaction with 1 degree of freedom was completely confounded so that each block comprised 12 plots i.e. the experiment was arranged in 4 blocks with one replicate in the first two blocks and the other in the next two blocks. The four treatments and their levels were as follows:

Early Nitrogen	E0	None
	E1	45 kg ha^{-1}
	E2	90 kg ha^{-1}
Late Nitrogen	L0	None
	L1	45 kg ha^{-1}
Irrigation	I0	None
	I1	Irrigated
Sowing Rate	S0	250 viable seeds m^{-2}
	S1	500 viable seeds m^{-2}

LOCATION AND HISTORY: The site was on the Lincoln College Henley Research farm and previous ground cover was a fair stand of six year old lucerne. In early autumn this was skim rotary hoed, ploughed and top worked to produce the seedbed.

SOIL TYPE: The trial site was mapped as a Templeton silt loam complex by Cox *et al.* (1971) and a detailed analysis of this soil was undertaken by Hart (1978). Evidence indicates that the soil was derived from flood alluvial sedimentation of the Waimakariri river system and this may have been further complicated by contemporary aeolian deposition. There was a contrast of textural properties between the relatively fine sandy to silt loam in the

30 - 50 cm depth, to the lensoid sandy, silty and clay deposition in the lower profile region.

SOWING: Planting took place on 16 June 1977. Kopara seed treated with an organomurcuric fungicide was drilled using a modified Duncan 700 Seedliner having 10 coulters at 15 cm spacing. This was calibrated according to the manual with the final sowing rates being adjusted for viability and seed weight factors. Sowing depth was around 3 cm and the final plot size was 1.5 m wide by 50 m long. Between each plot was a buffer plot to limit the influence of lateral movement of irrigation water or nitrogen. Drilling 250 viable seeds m^{-2} represented approximately 100 kg ha^{-1}, the normal sowing rate for this area (Scott *et al.* 1973). Kopara is an autumn standard height New Zealand bred cultivar and has been described by Copp & Cawley (1974

FERTILISATION: A basal application of superphosphate equivalent to 250 kg ha^{-1} was drilled with the seed at sowing. N as ammonium sulphate (21% N) was hand broadcast (0, 45, 90 kg ha^{-1}) at the start of tillering and during early stem elongation (0, 45 kg ha^{-1}) on 23 August and 2 November respectively. The rates of N applied in August were established by Dougherty & Othman (pers. comm.) using the soil N analysis and predictive procedures of Ludecke (1974).

IRRIGATION: Irrigated plots were reticulated with a microtube trickle system gravity fed from a header tank elevated 3.0 m above ground level. There were three main lines (inside diameter 13 mm) running lengthwise through each plot and off each at 30 cm intervals on alternating sides were 25 cm long microtubes (inside diameter 0.05 mm) delivering 0.7 ℓ hr^{-1} or 1.88 ℓ m^{-2} hr^{-1}. No attempt was made to exclude rainfall from all plots. Irrigation was first used on 29 November which was 3 days before mid-anthesis. A second was given 14 days later, the amounts applied each

irrigation being 73 and 47 mm respectively.

WEED, PEST AND INSECT CONTROL: The trial was aerially sprayed on 2 September to control leaf blotch (*Septoria tritici*) with a mixture of Benomyl (320 g a.i. ha^{-1}) plus Mancozeb (1280 g a.i. ha^{-1}) and mineral spraying oil (0.5% v v^{-1}). As a preventative precaution a repeat of the above fungicides plus Bandamine (2.5 l a.i. ha^{-1}) for broadleaf weed control was applied on 23 September. Throughout the rest of the growing season the crop was noticeably disease, pest and weed free.

MEASUREMENTS: Establishment population was determined three weeks after sowing when ten random 0.1 m^2 quadrats were counted per plot.

The first destructive plant harvest was on 27 September and thereafter at fortnightly intervals until 3 January. On each occasion only those plots having had their treatments applied were sampled and this was achieved by digging the plant material from a 0.1 m^2 quadrat and removing it to the laboratory for analysis. Measurements recorded were the number of plants, tillers and the leaf and stem fraction dryweights (after drying at 75^{o}C to constant weight). Before drying, a random subsample of ten plants was used to measure leaf area on a planimeter and this was converted, on a dry weight basis, to Leaf Area Index (LAI). Tiller numbers relate to those emerged from their subtending leaf sheath and maintaining at least half their leaf photosynthetically functional. Stem, peduncle, ear elongation and flag leaf area duration were recorded by sampling five main stems from each plot at regular intervals. Samples were taken as required to determine double ridges, ear emergence and anthesis. Dissected mainstems were used to define double ridge stage which is completed by the formation of the terminal spikelet. Anthesis was judged as the first appearance of extruded anthers on 10% of the total plot ears.

At harvest (25 January) 10 separate random 0.1 m^2 quadrats per plot were cut at ground level. Average height and ear number were determined then the ears were severed at the node beneath the basal spikelet so the heads and straw of each plot could be pooled. Sterile and fertile spikelets were counted from a random subsample of 20 ears per plot before threshing. After 1000 grain weights were obtained, grain number per spikelet was calculated by dividing grains m^{-2} by spikelets m^{-2}. Grain and straw yields were expressed at 14% moisture content. All samples taken during the wheat growing period were confined to the same half of each plot as the other half was used to determine combine harvester yields. Harvest Index (HI) refers to the grain weight : grain plus straw weight ratio.

The wheat quality tests are outlined in Section 2.3 and the soil water measurements in Section 3.3.

1.4 RESULTS

The population establishment counts were similar to the averaged plant numbers obtained from the 8 destructive harvests carried out during the trial. However the resultant populations were around 10% lower than those originally desired, with the low and high rates being 223 and 445 plants m^{-2} respectively (S.E. = 11.4).

The trial treatment application dates and the important physiological periods encompassing yield component derivation and determination are recorded in Fig. 1.1.

PLANT MORPHOLOGICAL CHANGES: Morphological plant height changes were recorded during the stem elongation period (Figs. 1.1, 1.2). Higher rates of early N did not alter final peduncle length but increased stem and ear length (Table 1.2). Late N had no effect on any of these measurements even though it was applied during the period of stem and ear elongation and before peduncle growth. The higher seeding density increased stem length extension while reducing it for ear length with the peduncle length being

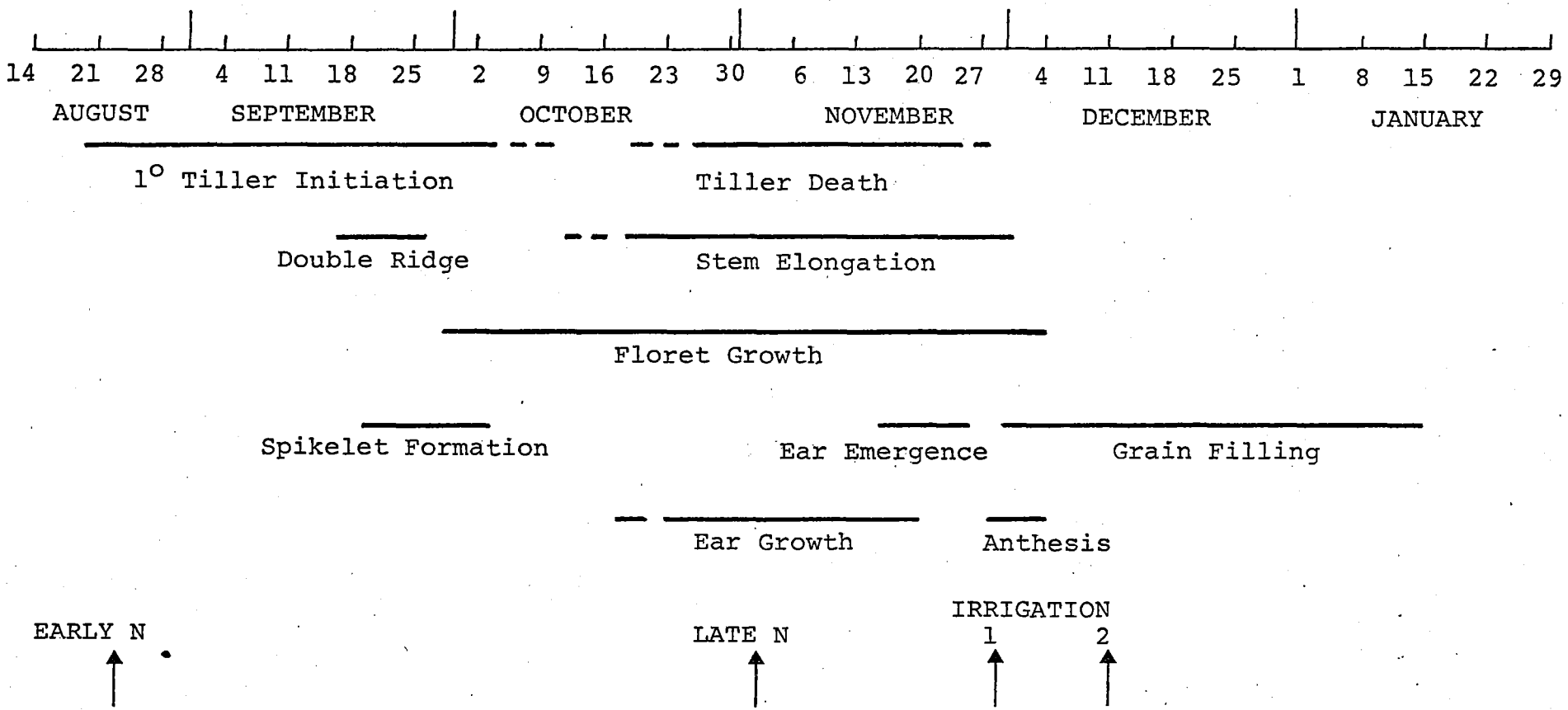

Fig. 1.1: Time scale for the recorded plant physiological events and the trial treatments.

Table 1.1 Grain yield components at harvest for all main treatments.

		Ears m^{-2}	Spikelets per ear	Grain no. per spikelet	Grain no. per ear	Grain wt. (mg)	Grain yield per ear (g)	Grain yield (gm^{-2})
Early Nitrogen								
	E0	480	18.1	2.13	38.5	38.9	1.50	706
	E1	535 L	18.7 L	2.06 L	38.6 NS	37.8 L	1.46 L	775 L
	E2	611	18.9	1.97	37.3	36.0	1.34	819
Late Nitrogen								
	L0	542 NS	18.6 NS	1.98 **	36.9 **	37.7 NS	1.39 **	744 *
	L1	542	18.5	2.13	39.4	37.4	1.48	789
Irrigation								
	I0	531 NS	18.4 NS	2.02 *	37.3 **	37.3 *	1.39 **	728 **
		549	18.7	2.09	39.0	37.8	1.48	809
Sowing Rate								
	S0	493 **	18.8 **	2.19 **	41.1 **	38.0 **	1.56 **	763 NS
	S1	591	18.3	1.93	35.2	37.1	1.30	770
S.E.		45	0.50	0.11	1.95	0.97	0.08	69
C.V. %		8.3	2.7	5.3	5.1	2.6	5.4	9.0
Significant interactions		None	None	ExS **	ExS **	None	ExS **	None

NS = $P > 0.05$ * = $P < 0.05$

L = Linear response $P < 0.01$ ** = $P < 0.01$

unaffected (Table 1.2).

Table 1.2 Final stem, peduncle and ear lengths (all in cm) as influenced by the applied treatments.

		Stem (cm)		Peduncle (cm)		Ear (cm)	
Early Nitrogen							
	E0	51.7		31.1		8.3	
	E1	57.0	Q	30.1	NS	8.7	q
	E2	56.9		29.1		8.7	
Late Nitrogen							
	L0	55.5	NS	29.9	NS	8.6	NS
	L1	54.9		29.6		8.5	
Sowing Rate							
	S0	53.3	**	29.4	NS	9.0	**
	S1	57.1		30.2		8.2	
S.E.		2.3		1.5		0.2	
C.V. %		4.2		5.0		2.8	

There were no significant interactions.

NS = Non significant P > 0.05
q = Quadratic response P < 0.05
Q = Quadratic response P < 0.01
* = P < 0.05
** = P < 0.01

In all sequential harvests of biomass the two earliest applied treatments, sowing rate and early N, clearly produced the most differences in plant growth. The middle early N treatment will be omitted since it was consistently intermediate between the other two. As the early N and sowing rate treatments produced some interactions (Table 1.1), the E x S interactions were used for Figs. 1.3 to 1.7. Early N raised tiller numbers

(Fig. 1.3), biomass and LAI (Figs. 1.5, 1.6, 1.7). There was only one exception and that was the low sowing rate where, in the absence of early N, tiller dry weight at maturity was highest (Fig. 1.4).

The sowing rate treatment was reflected in the morphological parameters when they are studied on a per plant basis because of the variance in plant populations. For example, dry matter per plant at the low seeding rate irrespective of N level, tended to be about twice that of the higher density (Fig. 1.5). On a per unit area basis however, the sowing rate difference was not nearly so marked as can be seen by the biomass m^{-2}, tillers m^{-2} and LAI (Figs. 1.6, 1.3, 1.7).

Late N and irrigation was applied at later stages of plant growth. No significant effect was observed by the late N until the last sampling (3 January) when it extended LAI (Fig. 1.7). Similarly, by that date the only effect irrigation had was to cause an increase in dry weight per tiller and extend leaf area duration (Table 1.3, Fig. 2.1, Table 1.7).

The harvest biomass data are presented in Table 1.3. With increasing rates of early N, straw and grain plus straw yields were significantly boosted. HI declined however, as the increases in grain were less than those obtained with the straw. Using late N or irrigation significantly increased HI. In the case of late N, straw and grain plus straw yields were unaltered while with irrigation both these parameters were significantly increased. At the high sowing rate, more straw was produced for the same level of grain per unit area so that the HI was lower (Table 1.1, 1.3).

HARVEST YIELD COMPONENTS: Harvest yield demonstrated a significant linear increase to additional rates of early N (Table 1.1) while late N and irrigation also raised the final level. Despite the large difference in plant populations the final yields from both treatments were not significantly different.

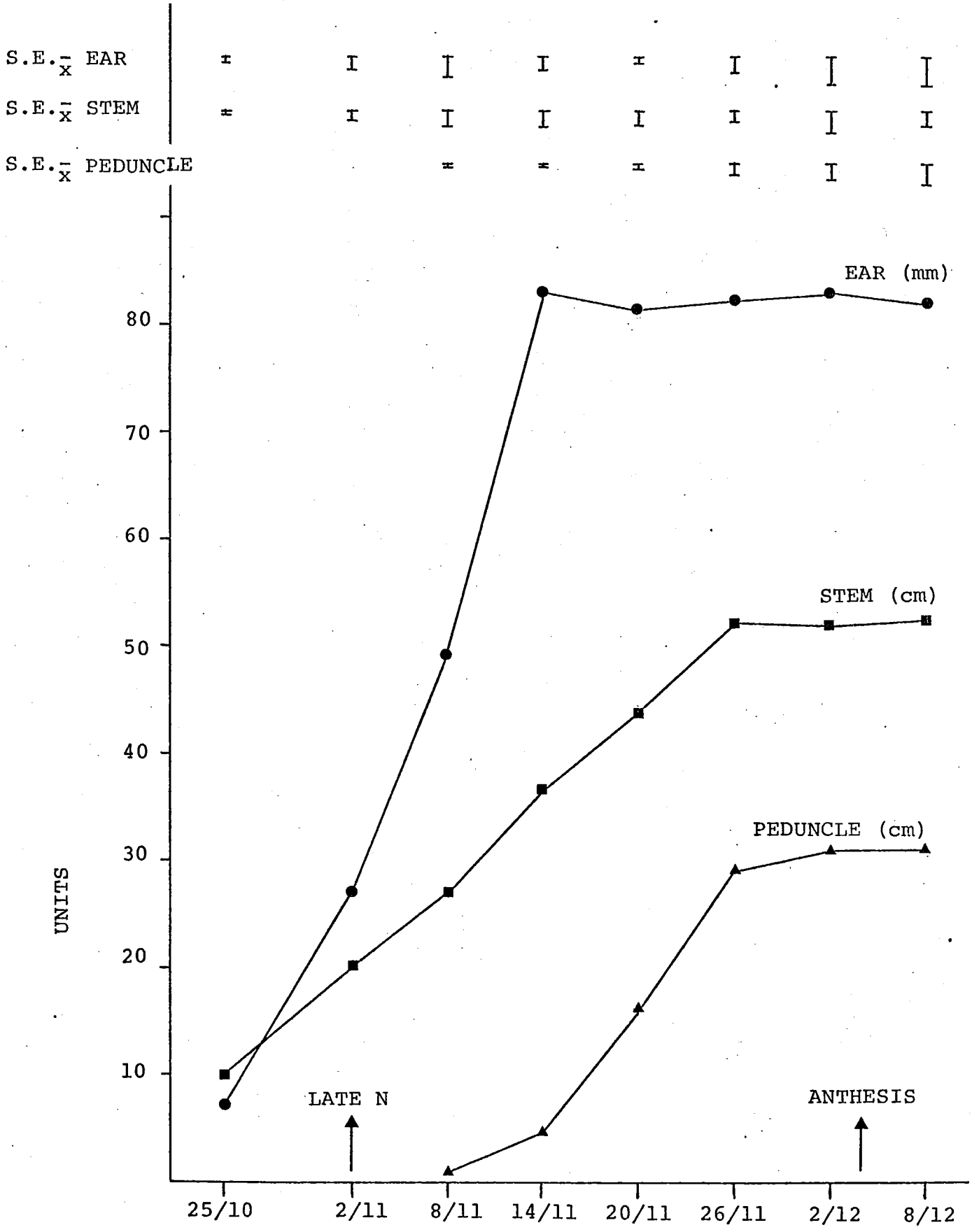

Fig. 1.2: Changes in the ear (mm), stem (cm) and peduncle (cm) length for the nil rate of early N (EO) treatment means over 8 sequential harvests.

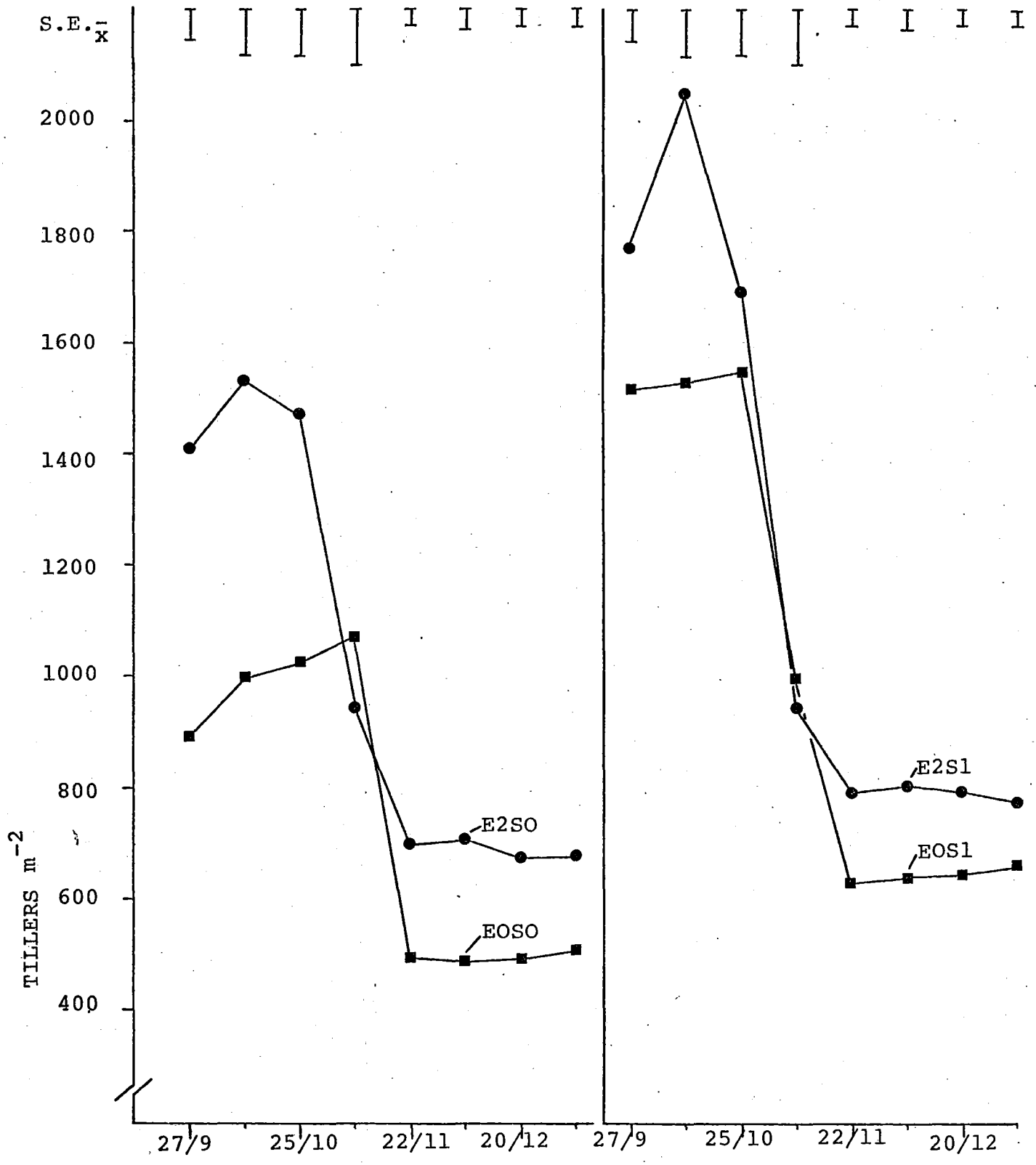

Fig. 1.3: Changes in tillers m^{-2} for the early N by sowing rate (E x S) interaction treatment means over 8 sequential harvests.

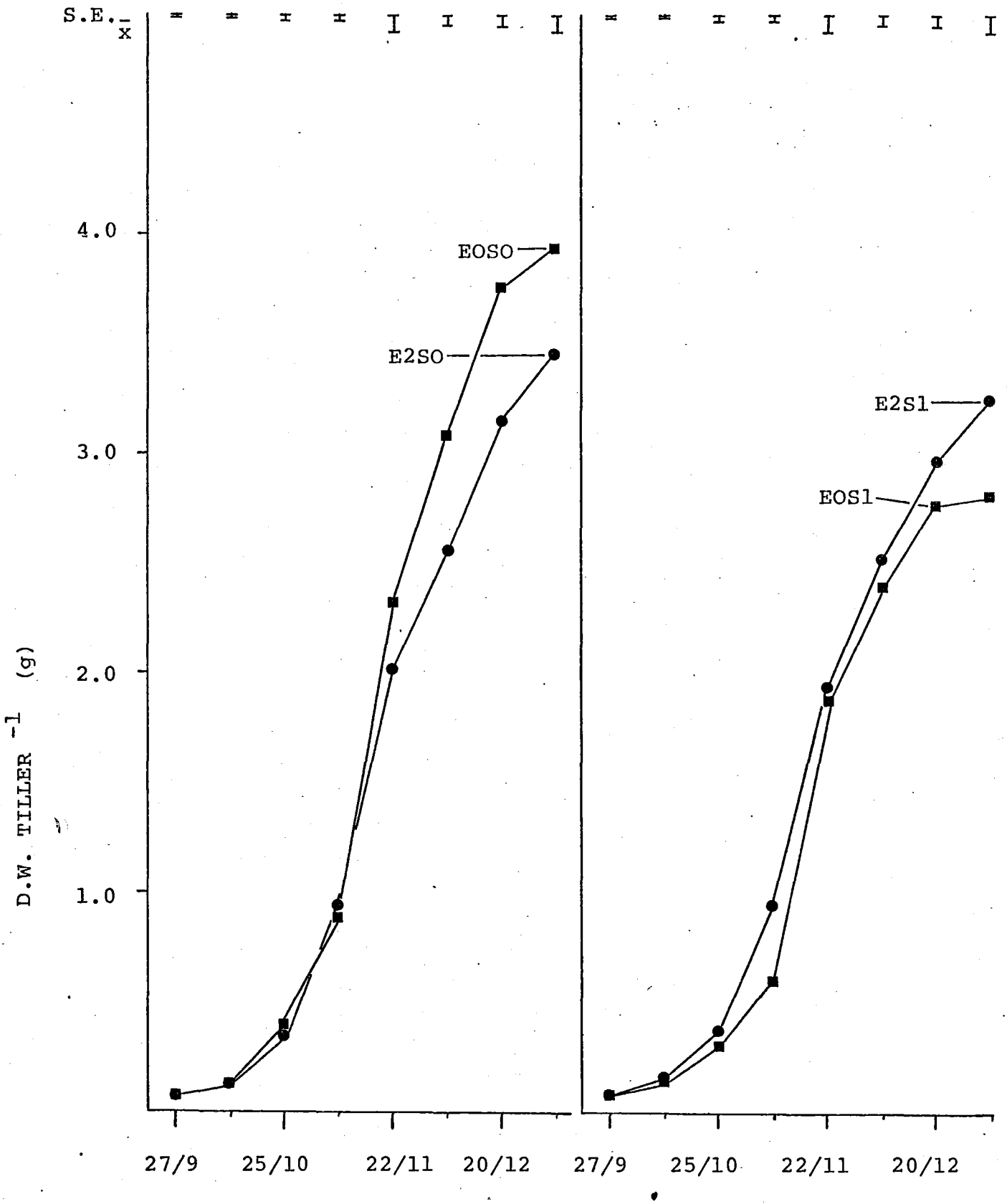

Fig. 1.4: Changes in dry weight per tiller for the early N by sowing rate (E x S) interaction treatment means over 8 sequential harvests.

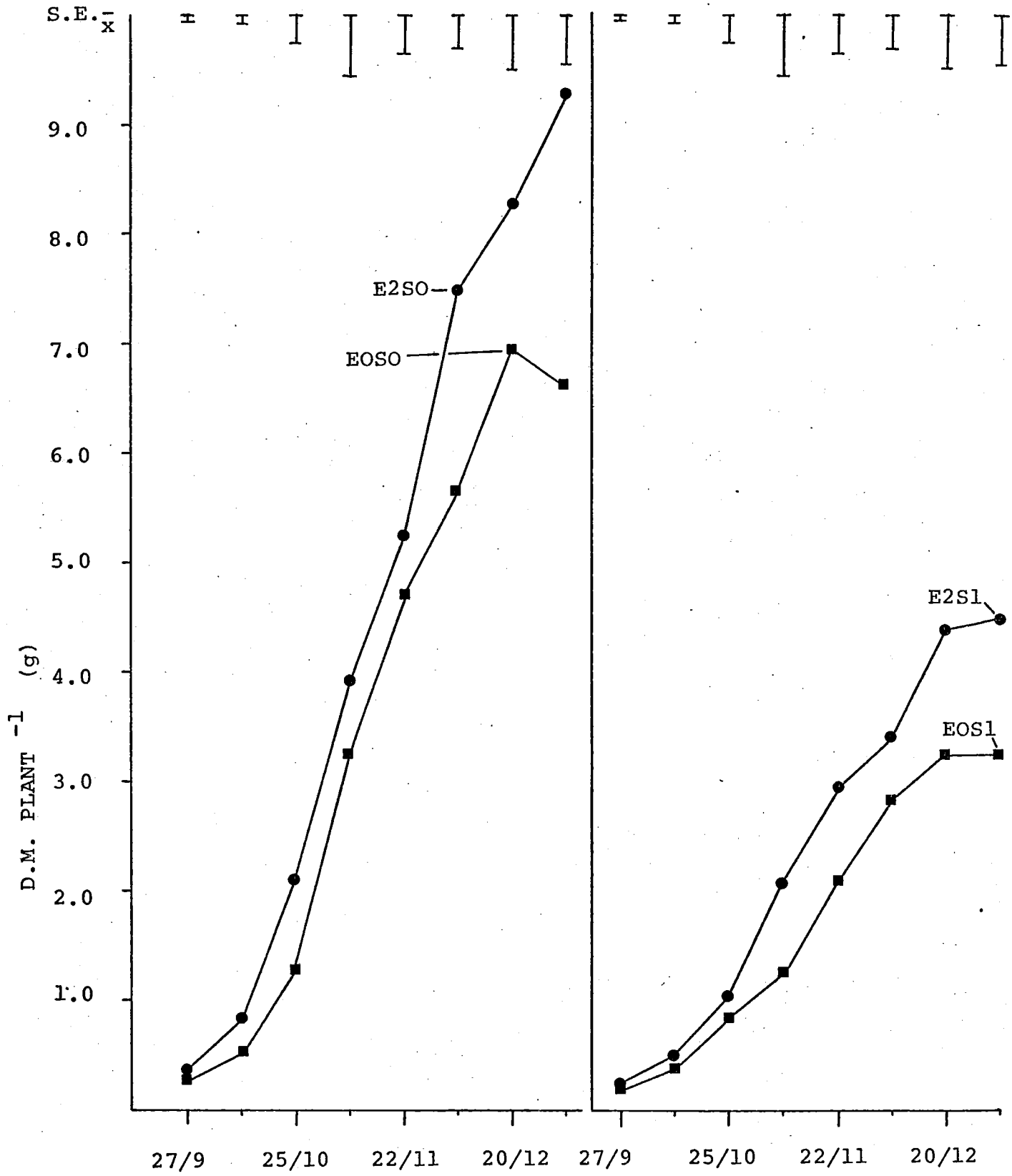

Fig. 1.5: Changes in dry matter per plant for the early N by sowing rate (E x S) interaction treatment means over 8 sequential harvests.

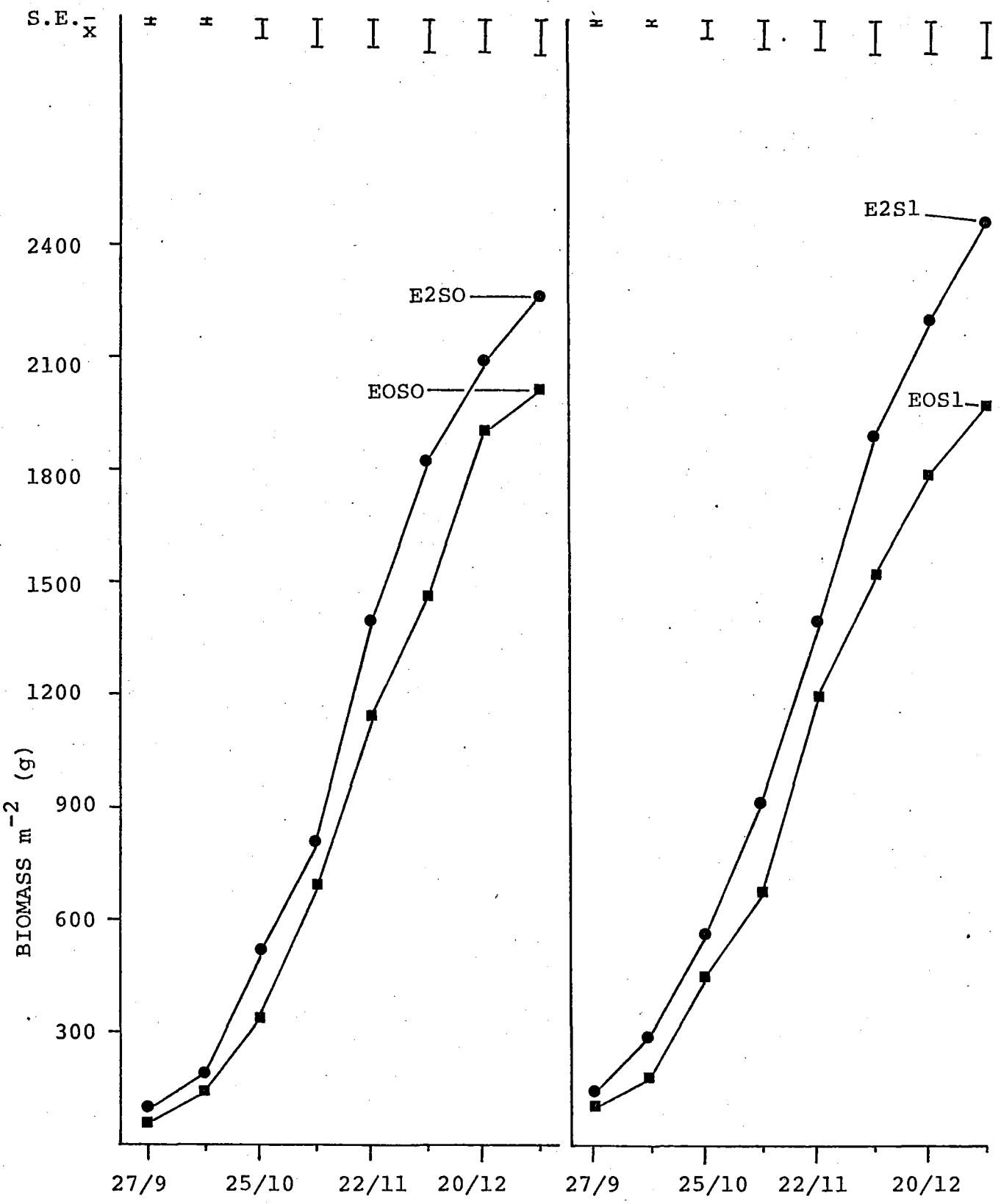

Fig. 1.6: Changes in biomass m^{-2} for the early N by sowing rate (E x S) interaction treatment means over 8 sequential harvests.

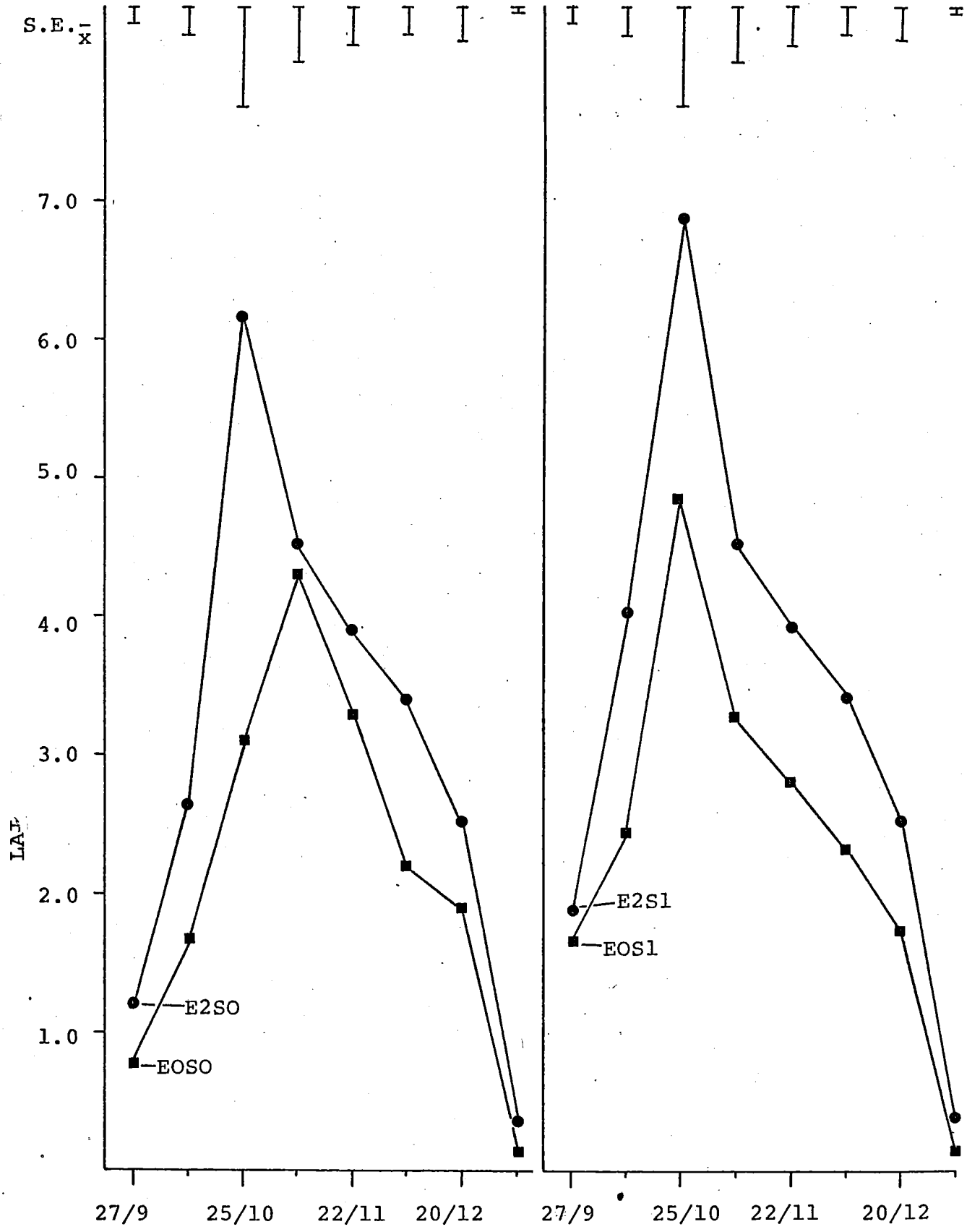

Fig. 1.7: Changes in LAI for the early N by sowing rate (E x S) interaction treatment means over 8 sequential harvests.

Table 1.3 Straw, grain and straw and harvest index for all main treatments at harvest.

		Straw (gm^{-2})		Grain and straw (gm^{-2})		HI (%)	
Early Nitrogen							
	E0	730		1436		49.2	
	E1	846	L	1621	L	47.8	L
	E2	933		1752		46.7	
Late Nitrogen							
	L0	833	NS	1576	NS	47.3	**
	L1	840		1629		48.5	
Irrigation							
	I0	809	*	1533	**	47.3	**
	I1	864		1672		48.5	
Sowing Rate							
	S0	812	*	1574	NS	48.6	**
	S1	861		1632		47.3	
S.E.		75		140		1.0	
C.V. %		9.0		8.8		2.1	

There were no significant interactions.

NS = Non significant P > 0.05
L = Linear response P < 0.01
* = P < 0.05
** = P < 0.01

Increasing rates of early N caused the initiation of more tillers (Fig. 1.3) with the result that significantly more survived at harvest (Table 1.1). More spikelets per ear were produced, although the extra spikelets present were sterile (Table 1.4). There was also a significant linear decline in grain number per spikelet and mean grain weight (Table 1.1).

Table 1.4 Sterile, fertile and total spikelet numbers per ear at harvest.

		Sterile spikelets per ear		Fertile spikelets per ear		Total spikelets per ear	
Early Nitrogen							
	E0	1.79		16.29		18.05	
	E1	2.08	L	16.66	NS	18.73	L
	E2	2.23		16.69		18.92	
Late Nitrogen							
	L0	2.08		16.55		18.62	
			NS		NS		NS
	L1	1.99		16.55		18.51	
Irrigation							
	I0	2.07		16.39		18.43	
			NS		NS		NS
	I1	2.00		16.71		18.70	
Sowing Rate							
	S0	1.92		16.94		18.85	
			*		**		**
	S1	2.15		16.15		18.28	
S.E.		0.34		0.55		0.50	
C.V. %		5.6		3.3		2.7	
Significant interactions		ExS*		None		None	

NS = $P > 0.05$
L = Linear response $P < 0.01$
* = $P < 0.05$
** = $P < 0.01$

Late N was used after the completion of maximum tiller production and spikelet formation (Fig. 1.1). Neither of these two components were influenced by this treatment (Table 1.1) even though the tiller mortality phase had not ended. Floret growth was occurring when the late N was

applied and a significant increase was obtained in harvest grain numbers per spikelet (Table 1.1).

Irrigation commenced just prior to anthesis and again two weeks later. At the time of the initial application, near the end of tiller mortality and floret growth, there was no visual evidence of plant water stress such as flaccidity or rolling of leaves. Irrigation had no effect on ear populations at harvest or spikelet number per ear but it did increase grain number per spikelet and grain weight (Table 1.1).

The sowing rate difference was the only treatment applied at planting. At the high density, harvest ear population was significantly increased while the other three yield components all had significant decreases compared to the lower sowing rate treatment.

Significant interactions from tables presented in this Chapter are detailed in Appendix 1.

1.5 DISCUSSION

A high level of yield was maintained over all treatments with the grand mean being 7.7 t ha^{-1} or more than twice the national average (Anon. 1976). The main objective was achieved insofar than many yield component significant differences were induced through the treatments used. When studying the harvest results (Table 1.1) a high degree of plasticity can be observed between the agronomic treatments and the harvest yield components, although final yield may not necessarily have been quantitatively altered. Yield component compensation is a feature of wheat crops (Dougherty *et al.* 1974, 1975, Scott *et al.* 1973, 1977) and this phenomenon will be analysed further, together with the changes in yield.

Development of each yield component commenced at a different stage of plant growth but due to variation in their duration and cessation, over-

lapping phases occurred (Fig. 1.1). Although tillering was initiated first, the number of spikelets is determined before final ear populations are established. Final ear and floret numbers were largely determined at anthesis. In all cases, except grain weight, there was an excess initiation of components compared to their final harvest number. This was illustrated clearly for tiller number in Fig. 1.3. With spikelet number per ear it is expressed through the number of sterile spikelets (Table 1.4). No record of the over - initiation of floret numbers per spikelet was made, but Langer & Hanif (1973) have verified its occurrence. Thus these three components all rely more on survival once initiated rather than initiated numbers *per se*. While grain numbers can vary, the only change each grain can undergo is in its accumulation of dry weight. Yield depends on the weight of the number of grains per unit area, this being a function of all preceding inter and intra-plant competition. Grafius & Thomas (1971) termed any buffering occurring between yield components as a sequential strategy of the plant in the deployment of limiting resources. They believed it to be largely environmentally controlled through the determination of the initial component of the series. In this trial, ear number significantly dominated the harvest components of yield (Table 1.5) and this has been found in similar trials (Dougherty *et al*. 1974, 1979). Further evidence to support this is shown in Table 1.1 for the sowing rate treatment, where the high density reduced spikelets per ear before the harvest ear number itself was finalised.

Individual analysis of the influence of these agronomic treatments supports the generally held view on yield component compensation. By applying early N at the start of tillering, the earliest derived tillers would have received most benefit. These would be the mainstem, tiller one and sometimes tiller two and these are the best ones to promote since they

have the highest survival rate and heaviest yield (Fraser 1978). Tiller death occurred from late October to late November and mortality rates were not significantly different for the 3 early N rates, averaging 64% (S.E. = 1.1) which is in agreement, although considerably more than Scott *et al.* (1973). Therefore early applications of N ensured a greater number survived and these also had more spikelets (Table 1.4). Since successive higher order tillers contain fewer spikelets per ear, the N effect must have carried on through the double ridge stage notwithstanding that the extra spikelets produced were all sterile. N probably raised the potential spikelet number by increasing the inception rate of leaf primordia on the elongating shoot apex (Rawson & Bremner 1976) and while the maximum number is signified by the formation of the terminal spikelet, whether they will be fertile or sterile is determined during the phase of ear growth. Sterile spikelets occur when all florets within the spikelet fail to develop and these are mainly confined to the basal spikelets probably because of incomplete morphological development (Langer & Dougherty 1976). As floret development coincides with the period of tiller mortality (Fig. 1.1), increasing rates of N may cause declining grain set per spikelet due to the excessive promotion of vegetative sinks to the detriment of reproductive ones (Dougherty *et al.* 1975). N should not have been limiting hence it is likely that the mechanism causing reduced grain set operated by inducing a carbohydrate deficiency (Dougherty *et al.* 1974, 1979); this also being evident in the grain weights (Tables 1.1, 2.2). Batey (1976) referred to the inverse relationship between increasing early N rates and declining grain weights as being a common one. Fischer *et al.* (1977) simply stated that this result is due to a dilution - like effect insofar that more grains per unit area receive less assimilate at grain filling. Again between the mainstem, tiller one and tiller two, large differences are known to occur

in grain set and grain weight (Fraser & Dougherty 1978). In this experiment, grain set per spikelet was the second most important yield component (Table 1.6).

Table 1.5 Correlation matrix for harvest components of yield.

	Component	1		2		3		4	
1	Ears m^{-2}	1.00							
2	Spikelets ear^{-1}	+0.07	NS	1.00					
3	Grains $spikelet^{-1}$	-0.59	**	+0.08	NS	1.00			
4	Grain weight	-0.70	**	-0.16	NS	+0.41	**	1.00	
5	Grain yield	+0.66	**	+0.37	**	+0.14	NS	-0.33	*

NS = $P > 0.05$
* = $P < 0.05$, $r = 0.28$
** = $P < 0.01$, $r = 0.37$

Table 1.6 Stepwise multiple regression for the harvest components of yield.

Variable	Coefficient	S.E. of coefficient	Cumulative r^2
(Constant -2068.6)			
Ears m^{-2}	1.45	0.05	44
Grains $spikelet^{-1}$	333.52	15.67	86
Spikelets ear^{-1}	33.42	3.66	91
Grain weight	19.89	2.43	97

Sowing rate produced a large difference in tiller numbers both before and after the mortality period (Fig. 1.3). Assuming no losses from plant establishment, then the harvest low and high sowing rate would have comprised

on average 2.21 and 1.33 ears per plant. Tiller mortality rates were significantly different with the percentages between peak initiation and harvest numbers being 56 and 63 ($S.E._{\bar{X}} = 1.86$) for the low and high treatment respectively. This indicates that tillers in the high density treatment succumbed after more inter and intra - plant competition and it is known that mechanisms controlling tiller senescence can begin before any visual confirmation is seen (Williams & Langer 1975). Since the first determined yield component, total spikelets per ear (Table 1.4), was reduced at the high sowing rate, intense competition must have been occurring at that period or before. Except for ear number at harvest, all other yield components were beset by limiting plant resources at the high sowing density (Table 1.1). From Table 2.2, it appears that protein and carbohydrate were both restricted at times during grain development.

Late N, applied after double ridges were completed, did not alter ear number per unit area or spikelets per ear (Table 1.1). When applying N at the start of tiller mortality, Dougherty *et al.* (1979) found harvest ear numbers were slightly raised and lowered for plant populations above and below 375 per m^{-2} respectively. Lower populations were used in this trial but there was no plant biomass response at all (Table 1.2, 1.3). Timing of the late N may influence this result, as in this trial the late N was applied at least one third of the way through tiller mortality (Fig. 1.1) whereas Dougherty *et al.* (1979) applied it before any visual decline in tiller numbers occurred. Since increased N was available, the lack of response supports MacDowall (1973) who considered tiller survival was regulated by carbohydrate distribution. Although tiller numbers were declining during this period (Fig. 1.3), the overall vegetative carbohydrate demand was increasing since dry matter accumulation per tiller, per plant, and per unit area (Figs. 1.4, 1.5 and 1.6 respectively) was steadily rising.

Supplying late N increased grain numbers per spikelet as this component was the developing sink at the time of its application and this response is in agreement with Langer & Liew (1973). Grain number per ear increased because of more grains per spikelet but grain weight was not influenced. Thus no carryover effect into individual grain weight accumulation was evident even though on 3 January the late N fertilised treatment had significantly more LAI to support extra grain filling. In fact more assimilate was translocated, as more grains were filled to the same capacity.

Irrigation was applied just before anthesis and was too late to influence spikelets per ear or ear number but it did significantly increase grain numbers per spikelet (Table 1.1), presumably by promoting a number of the later developing florets to achieve fertilisation and subsequent grain growth (Langer & Hanif 1973). Fisher (1973) showed that even minor degrees of plant water stress prior to anthesis could cause large reductions in grain numbers per spikelet while having no appreciable effect on photosynthetic area. This result is associated with cell growth since it is particularly sensitive to even slight degrees of plant water stress (Hsiao 1973). When irrigation was used, 75% of the plant available water in the 25 - 100 cm root zone had been removed (Fig. 3.3), culm growth had just peaked (Fig. 1.2) and LAI was declining (Fig. 1.7) but final floret development would have been proceeding rapidly (Langer & Hanif 1973). Grain weight responded to irrigation and this would largely be due to longer leaf area duration (Table 1.7), especially for the flag leaf (Fig. 2.1), the main leaf supplier of assimilate to the grain (Yoshida 1972). Irrigation, through extending leaf area duration, was responsible for the increased dry weight per tiller (Table 1.7) due to the extra grain and straw accumulation, which was also recorded as a higher HI for this treatment (Table 1.3).

Table 1.7 The effects of no irrigation (I0) and irrigation (I1) on LAI and dry weight per tiller for the last three biomass harvests.

	6/12/77		20/12/77		3/1/78	
LAI						
I0	2.69	NS	1.63	**	0.02	**
I1	2.96		2.66		0.43	
S.E.	0.11		0.13		0.03	
C.V.%	19		30		69[a]	
Dry Weight per Tiller (g)						
I0	2.80	NS	3.09	**	3.32	*
I1	2.49		3.30		3.49	
S.E.	0.03		0.04		0.06	
C.V.%	6		6		8	

NS = non significant; $p > 0.05$

* = $P < 0.05$

** = $P < 0.01$

[a] C.V. % high due to some of the treatments having zero value

In the yield analysis of this trial (Table 1.1) component compensation was very evident for sowing rate and early N, the two earliest applied treatments. Each resulted in an increase in one or more components but some of this benefit was lost through a decline in other components. The late N and irrigation treatments were imposed at a later stage and each caused component increases without reducing other components. In all cases, except sowing density, the applied treatment increased yield, with the heaviest rate of early N giving the largest response. This yield was due to the early N producing a higher final ear population even though it was broadcast five months before harvest. At that time, the mainstem and tiller one would be the main sink utilizing

the N, largely to boost their own size. Decline in other components caused by this treatment was probably due to their rate of growth not being maintained throughout subsequent development presumably due to rising levels of intra and inter-plant competition. The result that ear population at harvest was the most important component in this experiment is similar to that found in previous field trials at Lincoln on moisture retentive soils (Dougherty *et al.* 1974, 1979). In these situations, future research needs to be directed at the possibility of securing high harvest ear populations while improving grain set per spikelet, the second most important component (Table 1.6) and the one most affected during the period of rapid growth prior to ear emergence (Dougherty *et al.* 1975, Scott *et al.* 1975).

CHAPTER 2

THE EFFECT OF DIFFERENT AGRONOMIC TREATMENTS ON THE FLOUR QUALITY OF KOPARA WHEAT

2.1 INTRODUCTION

New Zealand is the only country in the world to test bake samples from its entire national wheat crop and previous wheat cultivar releases have generally shown good breadmaking quality (Meredith 1970a). In the 1977 national harvest (Anon. 1977) Kopara represented 34% of the total wheat area grown and had a very good bulk fermentation baking score average of 37.0. However, comparatively little is known about the quality aspects for high yielding wheat crops grown on moisture retentive soils. This Chapter deals with the effect of different agronomic treatments on the various parameters of flour quality.

2.2 REVIEW OF LITERATURE

Before the final grain weight is determined, several interacting physiological processes are involved. Not all operate within the grain-filling period although the most important probably do. Thorne (1965) conclusively established that most of the grain carbohydrate resulted from post-anthesis photosynthesis. Bingham (1971) related grain yields to the photosynthetic capacity of the crop at flowering, the duration of that photosynthetic area and on the ability of the grain to store the potential supply of assimilate. Throughout the period of grain growth, uptake of grain nitrogen is linear (Dalling *et al.* 1976) as is dry weight accumulation (Meredith & Jenkins 1976). There can be a certain amount of elasticity between growth rate and duration of grain filling (Sofield *et al.* 1977)

with the carbohydrate and protein fractions of the wheat kernel differing in their pattern of deposition with time. From the data of Jennings & Morton (1963) it can be calculated that in the last half of endosperm growth protein content is doubled while carbohydrate volume is trebled.

Wheat flour quality cannot be defined without correlation to its end use. In New Zealand, about 60% of wheat flour is made into bread (Cawley 1967), so quality is usually specified in relation to this context.

The primary factors in determining the baking quality of wheat flour are protein quantity and quality (Stewart 1976, Pratt 1971) and also the degree of structural damage that occurs during milling. The quantitative expression of crude protein is related to total organic nitrogen in the flour, whereas quality evaluations relate specifically to physicochemical characteristics of the gluten - forming component. The mixture of proteins called gluten make up about 80% of the total flour protein content so it is both the quantity and quality of gluten that is the most important part of wheat flour (Cawley 1967). By using chemical and rheological measurements, the prediction relating to the flours' end performance is enhanced as the latter assessment allows a texture judgement of the baked loaf which can lead to the detection of faults concealed by the former assay. In New Zealand, quality of the protein is especially important in cases such as sprout (Meredith 1967) and bug (Meredith 1970b) damage, where often protein quantity is unchanged but the quality is drastically lowered rendering the flour useless for baking purposes. According to Scott *et al.* (1957) maximum protein quality is obtained prior to full ripeness when the grain is around 40% moisture content. Loaves baked from developing grains by Finney & Yamazaki (1967) 24 days before they were ripe but containing 11.5% protein, failed to rise yet nine days later maximum loaf volume was achieved.

It would, therefore, appear that the gluten fraction of the protein was synthesised during the mid to three-quarter phase of grain growth. After the half way stage of grain filling there is relatively little change in total protein content and the gluten transformation is assumed to arise from increases in the molecular size and complexity of the proteins (Pomeranz 1971).

Since the initiation of testing all wheat lines by the Wheat Research Institute for the milling industry, baking score has gradually been adopted as the criteria of quality. Mitchell (1977) considers it is the ultimate standard, while not being infallible, against which other analytical procedures are judged. Several factors have contributed to the reliance on test-baking. When performed under standard conditions it is the only method that brings together all aspects of baking quality into one test (Tipples 1979). To try and obtain the same information from a multiplicity of tests would take far more work and time. Therefore although the Wheat Research Institite carries out six tests on each line, attention is mainly focused on the outcome of two only, loaf volume and crumb texture which are combined to give the total score index.

Under the old system of the bulk fermentation test (Anon. 1956), the final baking score was the aggregate of the points alloted for the loaf volume (maximum 28), texture (14) and flour colour (8). As a rule, those wheats scoring 30 or more were suitable for milling and subsequent baking, while those attaining less than 30 were destined to be feed wheats (Cawley 1967). With the introduction of the mechanical dough development (MDD) process, total score (loaf volume plus crumb texture) will replace the role of baking score. A new cut-off value will need to be determined as a different scale of marking is used. This has tentatively been set at 15 (Cawley pers. comm.).

Wheat quality is complex and even with a moderate-to-high genetic control its level cannot be fixed due to the strong environmental influence (Schmidt 1974). Protein quantity can fluctuate with yield although the qualitative composition is much less affected (Bushuk & Wrigley 1974).

When studying agronomic factors affecting baking quality, Wright (1969) and Malcolm (1977) established that the nature of the preceeding crop had a major influence on the baking score. Wheat following pasture had higher scores than when it succeeded other crops. Johnson *et al.* (1973) with autumn, and Kolderup (1974) with spring sown varieties, have raised grain N contents with increasing rates of N broadcast during tillering in early spring. In a similar trial McNeal *et al.* (1971) correlated the increasing grain protein percentages to higher loaf volume and crumb texture scores. The grain protein content can also be greatly affected by the availability of N during ear emergence and flowering (Stewart 1976). Terman *et al.* (1969) noticed that the later N was applied towards anthesis, the smaller the effect on biomass growth but the greater the increase in the grain protein content. On light soils at Winchmore using autumn-sown wheat, Drewitt (1967, 1974) reported that irrigation during the reproductive phase reduced grain protein and the flour baking quality. In some cases lower quality varieties were abated to below milling standard. Six seeding rates were used by Pendleton & Duncan (1960) with four autumn sown wheats differing in morphological characteristics. In the three years the trial lasted, there was no seeding rate - grain protein interaction.

When comparing the results obtained from different researchers it is noticeable that some relate to nitrogen content and some to protein content. Also some data are based on the whole grain and some on its flour sample only. Nitrogen contents are readily changed to protein levels by a

standard conversion (Kjeldahl nitrogen x 5.7) while Bushuk & Wrigley (1974) and McNeal *et al.* (1971) concluded that the protein content of the whole grain sample is generally around 1% higher than that of its flour. This is due to the protein content being slightly higher in the germ, bran and outer endosperm layers which are largely removed in the milling process.

2.3 MATERIAL AND METHODS

The trial was outlined in detail in Section 1.3. All grain samples (1 kg) forwarded to the Wheat Research Institute for analysis were taken from the combine harvested portion of the plots. These were randomly sampled from the final bulk plot yield. In the calculation of the flour quantity components and carbohydrate to protein ratio (Table 2:2) flour fat content was assumed to be negligible and was omitted (Inglett & Anderson 1974).

The breadmaking procedure used for the test bake was the MDD process (Cawley 1974) and the whole operation is rigidly standardised to facilitate comparisons between the flours used (Cawley 1977, 1979, Mitchell 1976, Dougherty *et al.* 1981). The Wheat Research Institute routinely carries out six tests on each wheat sample and these are described below.

Flour extraction is defined as the percentage of flour derived from milling a known weight of wheat. The mill used was a Brabender Quadramat Junior with the sample size of wheat being 250 g.

Flour protein percentage was derived from a Technician InfraAlyzer using the infrared reflection principle calibrated against a series of known Kjeldahl determined standards.

Flour water absorption is the quantity of water required to yield a dough of predetermined consistency. A flour sample of 125 g (at 14% moisture content) was mixed with water and the derived results are in percentages of water used.

Loaf volume is based on the specific loaf volume (ml g^{-1}) according to the formula:

$$(\text{Specific loaf volume} - 3) \times 10$$

In practice the score is read directly from the volume displaced in a suitably calibrated box filled with rape seed.

Crumb texture is assessed visually from the test bake loaves on a poor to good (0 - 14) scale.

Dough work input requirement is empirically determined during the mixing process on equipment designed at the Wheat Research Institute. Work input is calibrated against time, the optimum value is measured in units of Watt-hours kg^{-1}, usually referred to as counts.

A total score figure is also reported on the Institute recording sheets, this being the combination of the loaf volume plus crumb texture indices.

2.4 RESULTS

All agronomic treatments returned good (greater than 15) total scores. Irrigation lowered and late N raised the total score value (Table 2.1) but these results reflect alterations only to loaf volume since crumb texture was indifferent to all treatments. Only two other cases of significant differences were recorded; high sowing density reduced flour extraction, while the use of late N produced flour with a higher protein content. For all flour quality parameters early N caused no significant main effect differences.

Combine mean grain weight (Table 2.1) displayed the same trends as those of the cut quadrat grain weights (Table 1.1). In all cases the combine mean grain weights were slightly higher probably due to smaller sized grains being screened out during the harvesting process.

Table 2.1 Flour quality parameters, loaf characteristics and grain weight of Kopara.

		Flour Extraction (%)		Flour protein (%)		Flour water absorption (%)		Loaf volume		Crumb texture		Total score		Dough work requirements (Counts)		Grain weight (mg)	
Early Nitrogen																	
	E0	67.8		10.02		59.6		12.38		7.25		19.63		6.69		39.1	
	E1	67.8	NS	10.23	NS	60.1	NS	11.88	NS	7.06	NS	18.94	NS	6.41	NS	38.4	L
	E2	68.2		10.33		59.4		12.32		7.13		19.44		6.37		37.1	
Late Nitrogen																	
	L0	67.9	NS	9.92	**	59.4	NS	11.62	*	7.21	NS	18.83	*	6.36	NS	38.4	NS
	L1	68.0		10.46		60.1		12.75		7.08		19.83		6.62		38.1	
Irrigation																	
	I0	68.1	NS	10.15	NS	59.7	NS	12.79	**	7.17	NS	19.96	**	6.34	NS	37.9	*
	I1	67.8		10.23		59.8		11.58		7.13		18.71		6.64		38.5	
Sowing Rate																	
	S0	68.5	**	10.20	NS	60.1	NS	12.50	NS	7.08	NS	19.58	NS	6.39	NS	38.5	*
	S1	67.4		10.18		59.4		11.88		7.21		19.08		6.59		37.8	
S.E.		1.10		0.42		1.52		1.34		0.49		1.32		0.78		0.97	
C.V. %		1.6		4.1		2.5		11.0		6.8		6.8		12.0		2.5	

There were no significant interactions.

NS = $P > 0.05$ L = linear response $P < 0.01$

* = $P < 0.05$ ** = $P < 0.01$

2.5 DISCUSSION

Grain weight was the least influential component in the yield analysis detailed in Chapter 1 (Table 1.6) and this affect also applies for most of the grain flour quality characteristics (Section 2.4). Flour water absorption, crumb texture and work input were not altered by any of the treatments (Table 2.1). From the milling and baking viewpoint, a wheat flour exhibiting a high degree of constancy over a wide range of agronomic treatments is most desirable.

As referred to earlier (Section 2.3) total score is the main guide used for flour quality. In this experiment crumb texture displayed remarkable stability over all treatments (Table 2.1) so the total score results parallel those of loaf volume. Hence loaf volume was the real indicator of flour quality and this is largely dependent on the quantitative amount of flour protein (Table 2.3). These two parameters will be discussed together.

The relationship between flour protein content and the resultant baked loaf volume was extensively studied by Finney & Barmore (1948). Within a single variety protein content was the major factor accounting for variation in loaf volume. For various wheats with a flour protein range of 8 - 18% the baking score response was linear and positive. Each cultivar produced a characteristic slope so that the vertical distance between gradients at any protein percentage value reflected genetic variation in protein quality. The data relates to crops grown on the Great Plains of U.S.A. where yields are lower and the period of grain-filling shorter by comparison with the Lincoln environment. By judging on protein content *per se* the simple relationship of Finney & Barmore (1948) ignores what is happening to the carbohydrate or the carbohydrate to protein ratio. At given grain protein percentage levels these can vary widely. For example,

under Australian conditions Williams (1966) noticed with later planted wheat, total grain yield and mean grain weight declined but grain protein percent increased. These results were due to the mid-summer heat causing premature senescence of the photosynthetic area. As the grain was incompletely filled there was a converging ratio of starch to protein which was reflected as an increase in grain protein percent. Conversely Drewitt & Rickard (1973) and Drewitt (1974) at Winchmore had significantly increased yields with irrigation largely due to increased grain weights but grain nitrogen, flour protein percentages and baking quality all declined. Calculating from the data of Drewitt & Rickard (1973) the extra weight in the grain was mainly carbohydrate leading to a higher carbohydrate to protein ratio. In the present experiment, the protein and carbohydrate contents of the flour and the carbohydrate to protein ratio were analysed (Table 2.2) to see if either formed a closer relationship with flour protein or loaf volume (Table 2.1). Essentially no evidence was found to support this hypothesis and the carbohydrate to protein ratio gave similar results to that of flour protein percentage. Thus for all treatments except irrigation the relationship stated by Finney & Barmore (1948) holds true. Irrigation effects were non-significant for all three tests (Table 2.2) indicating the basis for its poorer loaf volumes (Table 2.1) must be qualitative rather than directly related to the measured flour constituents. However, this is contradictory to the crumb texture assessments of this treatment (Table 2.1) which indicate no change. The fact that irrigation reduced loaf volume without appearing to alter flour protein percent or the baked loaf crumb texture is unexplainable from the data presented.

The crumb texture scores (Table 2.1) indicate no detectable change was induced into the composition of flour protein for any treatment even if the total protein content was altered. Qualitative protein synthesis occurs

mainly after mid grain-filling (Finney & Yamazaki 1967) and from just prior to that time an obvious difference in flag leaf area occurred between the irrigated treatment plots (Fig. 2.1). From mid-anthesis (2 December) to grain maturity (14% moisture content on 13 January) was a period of 42 days.

Table 2.2 Weight of flour protein and carbohydrate and the carbohydrate to protein ratio per grain.

		Protein (mg)		Carbohydrate (mg)		Carbohydrate : protein ratio	
Early Nitrogen							
	E0	6.64		59.68		9.01	
	E1	6.65	NS	58.38	L	8.80	NS
	E2	6.53		56.70		8.71	
Late Nitrogen							
	L0	6.46	**	58.68	NS	9.11	**
	L1	6.75		57.82		8.57	
Irrigation							
	I0	6.55	NS	57.97	NS	8.88	NS
	I1	6.66		57.82		8.80	
Sowing Rate							
	S0	6.71	*	59.09	**	8.82	NS
	S1	6.50		57.41		8.85	
S.E.		0.31		1.78		0.43	
C.V. %		4.6		3.1		4.8	

There were no significant interactions.

NS = $P > 0.05$
L = linear response $P < 0.01$
* = $P < 0.05$
** = $P < 0.01$

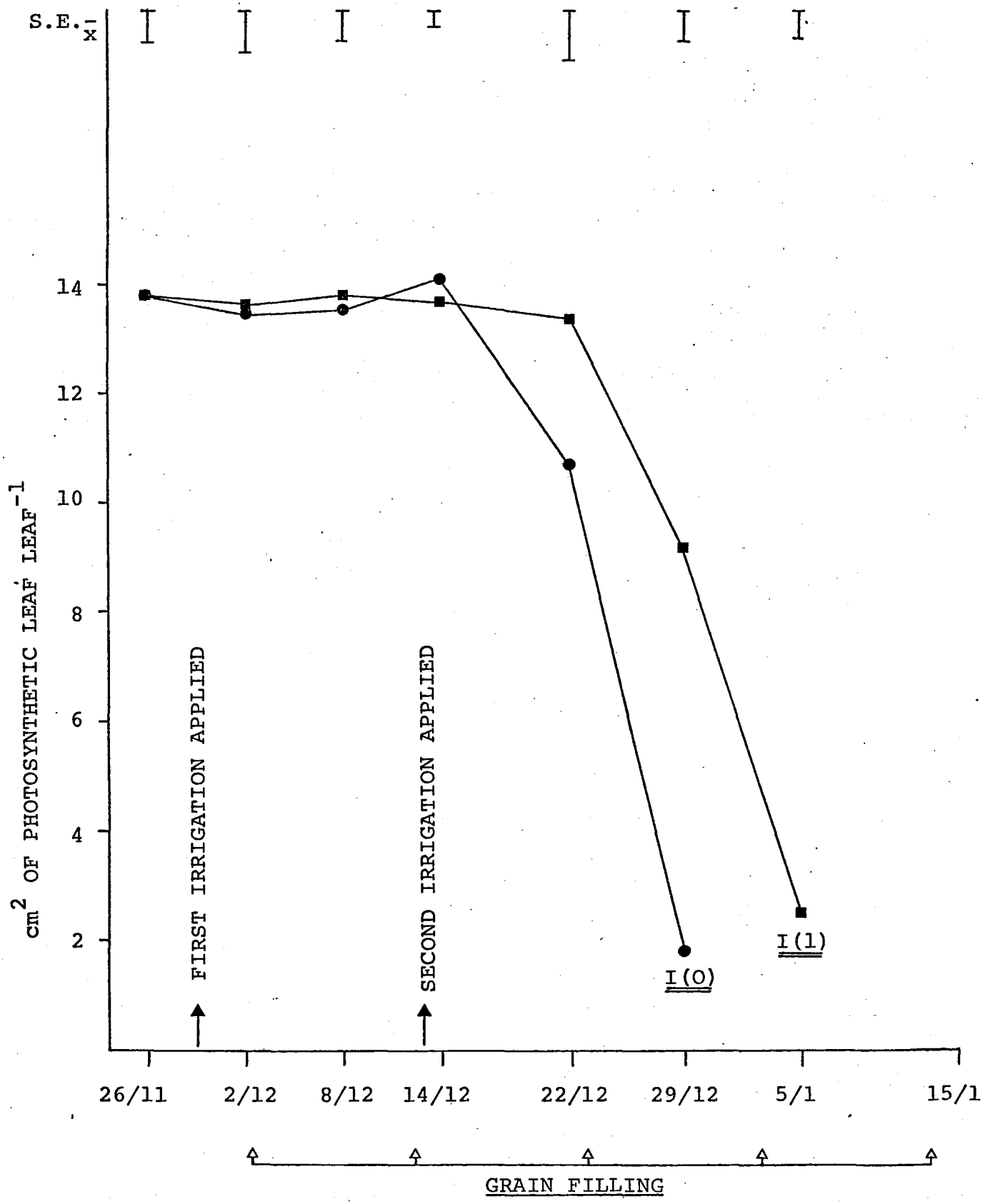

Fig. 2.1: Flag leaf area duration for the irrigation treatment means.

The flag leaf is usually the main leaf source of grain-filling assimilate (Thorne 1973). Those plots receiving irrigation had greater leaf area duration and also higher mean grain weights and total grain yield (Table 1.1). Therefore although irrigation induced plant morphological differences, the crumb texture results indicate that no significant changes occurred in protein composition. This is also substantiated from the stability of the irrigation parameters of Table 2.2. With the late N application, the carbohydrate to protein ratio decreased because of the increased flour protein at stable levels of carbohydrate (Tables 2.1, 2.2). Although this led to an increased loaf volume (Table 2.1) crumb texture was not changed. Increasing rates of early N reduced mean grain weights (Table 2.1) due to less carbohydrate (Table 2.2) but the carbohydrate to protein ratio was unaltered. As expected the corresponding crumb texture values were not significantly different (Table 2.1) and the same applies for the sowing rate treatment.

Crumb texture is a subjective visual assessment so its reliability is largely dependent on the expertise of the examiner (Mitchell 1977). In this trial 73% of the samples received the same value with 6% and 21% being minus or plus one respectively. This narrow range was obtained even though a 0 - 14 scale was used. These results for crumb texture (Table 2.1) indicate that either Kopara wheat has a very stable protein composition with varying agronomic treatments and resultant grain yields or that the visual examinations conducted on the samples were not sufficiently accurate enough to discriminate texture differences. To solve this latter question, further evaluations would need to be completed but unfortunately no duplicate samples were available to allow a rerun with a different examiner.

The agronomic treatments will be dealt with in the order they appear

on Table 2.1 The early N application produced no significant effects on quality. This was contrary to expected (Wright 1969) since the crop followed lucerne and received N fertiliser at early tillering which gave large yield increases (Table 1.2). Johnson *et al.* (1973) under drought conditions in Nebraska, found N broadcast during early tillering caused large increases in grain N. On the light soils at Winchmore, Drewitt (1974) concluded yield responses to N were closely linked to the availability of water. They only occurred in the presence of adequate moisture and where the plant requirement for N was greater than that supplied by soil mineralisation. Terman *et al.* (1969) reports that with adequate water the first effect of applied N is to increase total yield and only if it is absorbed by the plant in excess of its vegetative needs will an increase arise in the protein content of the foliage and possibly the grain. Throughout the very wet winter and spring (Table 3.5) a considerable amount of nitrate leaching probably occurred (Ludecke & Tham 1971) partially negating the lucerne N fertility reserve. N soil tests in early August (Section 1.3) were in general agreement with this. The overall effect of the wet season could have been that the anticipated surplus of soil and fertiliser N did not eventuate, so the grain protein levels were not raised due to increasing rates of early N fertiliser causing the yield to increase (Table 1.2) with no evidence of a yield plateau being reached. This result is in accordance with Terman *et al.* (1969) since soil water did not appear limiting at any time. Schlehuber & Tucker (1967) concluded that on soils limited in N, often moderate rates of N applications raised yields while no change is noticed in their grain protein percentages.

The late N and irrigation results have already been discussed. Dougherty *et al.* (1981) found that N applied during the reproductive phase

caused the grain N levels to rise producing a similar response in the total score and its components. Austin *et al.* (1977) showed that N administered during this period has a more direct route into the developing grain with around 70% of the plant N being present in the grain at maturity.

The precise reason why flour extraction was lower in the high sowing rate was difficult to determine. In general heavier grain weights should return higher flour yields (Shellenberger & Ward 1967). Milling is basically a physical process and with smaller grains it is harder to separate the endosperm from the rest of the grain (Finney & Yamazaki 1967). However lighter grain weights are recorded in the early N treatment (Table 2.1) and no milling difference was observed. Also, both the early N and the sowing rate treatments had significant differences in their amounts of carbohydrate per grain (Table 2.2) but only the sowing rate treatment had a significant flour extraction difference. Besides grain weight, grain shape can be important as it is posible to have short plump or long narrow grains of equivalent weight. Because of this, Bayles (1976) concluded that lightweight grain does not necessarily always produce lower flour yields. These physical grain characteristics were not ascertained in this trial. The exact reason for the lower extraction rate was not pinpointed although it is known that the minature mills used by the Wheat Research Institute are incapable of the refined settings obtained with commercial equipment. In practice, skilful machine adjustment would help eliminate this sowing rate discrepancy (Shellenberger & Ward 1967).

All but one of the flour quality parameters had a poor correlation with grain weight (Table 2.3). The exception, flour protein percent, had a significantly inverse relationship. Thus any agronomic management practice that increases grain weight would tend to have a negative effect on grain

Table 2.3 Simple correlation matrix for all the Wheat Research Institute flour quality parameters, mean grain weight and grain combine yield per hectare.

		1		2		3		4		5		6		7		8		9
1	Flour Extraction	1.00																
2	Flour Protein	0.14	NS	1.00														
3	Flour water Absorption	0.27	NS	0.26	NS	1.00												
4	Loaf Volume	0.09	NS	0.42	**	0.25	NS	1.00										
5	Crumb Texture	-0.17	NS	-0.33	*	-0.46	**	-0.31	*	1.00								
6	Total Score	0.04	NS	0.34	*	0.11	NS	0.95	**	-0.01	NS	1.00						
7	Counts	-0.32	*	0.07	NS	-0.20	NS	0.05	NS	-0.05	NS	0.04	NS	1.00				
8	Grain Weight	-0.22	NS	-0.36	**	-0.02	NS	-0.26	NS	0.27	NS	-0.18	NS	0.10	NS	1.00		
9	Combine Yield	-0.27	NS	0.22	NS	0.17	NS	-0.08	NS	-0.11	NS	-0.12	NS	0.03	NS	-0.40	**	1.00

NS = $P > 0.05$

* = $P < 0.05$, $r = 0.28$

** = $P < 0.01$, $r = 0.36$

protein levels which may in turn lead to lower baking scores. This was the case when Drewitt (1967) used irrigation on a light soil type and found with increasing grain weights there were accompanying reductions in grain N and baking volume. Only irrigation lifted mean grain weight in this experiment and while not reducing flour protein content, it did significantly lower baked loaf volume (Table 2.1). That a similar response should be recorded on the more moisture retentive soil used suggests that it may be better not to irrigate if a high baking score is critical. As there was no late N by irrigation interaction, the use of the former to try and counteract the latter would not be successful. A more positive approach would be to direct attention away from grain size, the least responsive yield component (Table 1.6), and try to raise grain yields without lowering flour baking qualities. This could be achieved by having a yield comprising of an increased number of smaller sized grains but each having proportionally more flour protein (Table 2.3). To accomplish this the most effective treatment to consider would be a late application of N.

CHAPTER 3

THE PATTERN OF SUBSOIL WATER USE IN AUTUMN SOWN KOPARA WHEAT

3.1 INTRODUCTION

In the early 1950's the first satisfactory results were obtained from using the neutron moderation technique to measure soil water content (Gardner & Kirkham 1952). After several years of further research, simple and reliable neutron - scattering moisture devices were being commercially manufactured (McHenry 1963).

Previous wheat crops at Lincoln have been monitored for soil water by gravimetric methods. Due to the physical limitations of this procedure only the top 20 cm soil layer has been regularly sampled (Dougherty *et al.* 1974, Scott *et al.* 1973, 1977) but with a neutron probe subsoil moisture levels can be readily calculated. This chapter relates the pattern of subsoil water use to the period of greatest crop growth.

3.2 REVIEW OF LITERATURE

Use of the neutron probe has several advantages over standard gravimetric methods (Stewart & Taylor 1957, Cope & Trickett 1965, Noble 1973). The most important is that once an access tube is located there is no further disruption of the soil. Therefore soil water content is determined *in situ* on an undisturbed soil volume and without interference to the cover vegetation. Repeated readings can be taken from the same site over a period of time, with several different depths being sampled on each occasion. Accurate results are obtained quickly and easily with a minimum of physical effort.

The fundamental underlying property of neutron moisture probes is that they detect thermal or slow neutrons. Their radioactive source emits fast neutrons which lose energy in elastic collisions with soil matter nuclei, particularly hydrogen. Two phenomena peculiar to hydrogen allow this to operate efficiently. Firstly, due to its low atomic weight, it is many times more effective than any other element in thermalising fast neutrons. Secondly, essentially all the hydrogen in mineral soils is within the water molecule (Gardner & Kirkham 1952). This makes it possible to correlate the backscattering of the moderated neutrons to the soil water content as the number sensed by the detector tube per unit time is proportional to the amount of hydrogen present. By using a preamplifier these are counted and totalled on a ratemeter.

During the operation, the probe's effective center of measurement must be known and equated to the depth being tested. The zone of influence should also be calculated as this delineates the sphere of soil monitored by the probe. Its centre is at the radioactive source and, in effect, this zone operates as an inverse function of the soil water content. Provided the detector lies within the sphere of influence there should be a linear response between captured moderated neutrons and soil water content (van Bavel *et al.* 1956). In soils with abrupt changes in water content a source of error can arise as the probes resolution is not precise enough to detect these differences (Long & French 1967).

For modern probes, the relationship between soil water content and the standard probe counts should be linear with the regression line intercepting the ordinate at the origin (Long & French 1967, Hajdukovic *et al.* 1967, Rawls & Asmussen 1973). If the probe is to be used close to the surface, a separate calibration must be made as the measured

value under-estimates the true value due to neutrons escaping from the soil mass without detection (Stewart & Taylor 1957). Similarly high organic matter situations may require special treatment due to the presence of hydrogen not held in the water molecule. The chemical composition of the soil (Gardner & Kirkham 1952) can also have an effect upon the thermalising of the fast neutrons. On diverse soil types in Hawaii, Shirazi & Isobe (1976) found significant differences between the regression line gradients relating counts and soil water content although McHenry & Gill (1967) report that in practice this is rare. Working with 11 different soils, Rawls & Asmussen (1973) concluded that calibration was independent of soil type and depth and this reinforces the operating principles of Gardner & Kirkham (1952) and van Bavel *et al.* (1956).

Plant water uptake relates closely to root distribution hence root spread, density and depth are important in defining the rooting volume (Wiersum 1966). Water absorption is controlled by the plant rate of water loss, the extent and efficiency of the root system, the soil water potential, and hydraulic conductivity of the soil (Kramer 1969). Water passes through the plant mainly by passive processes caused by transpirational losses (Begg & Turner 1976, Ellis 1976). In moist soil, Kramer (1959) considered that the transpiration rate was controlled by plant factors such as leaf area and structure, extent of stomatal opening, and by such environmental factors as humidity, temperature, solar radiation and wind. More than 95% of the water than enters the roots is lost in this form (Chapman & Carter 1976). As water vapour is given off, gradients of water potential are generated in the plant causing more water from the soil to be absorbed by the roots.

There are large variations in root distribution and soil water

extraction between plant species. Within the single genus *Triticum* , Hurd (1968) noticed differences between cultivars but this was not confirmed by Lupton *et al.* (1974). Besides the plant's genetic potential, many soil chemical and physical conditions influence root distribution and, hence, soil water extraction. The main factors are aeration, pH, nutrition, moisture status and soil structure (Ellis 1976, Wiersma 1959). The mechanical resistance that roots encounter is strongly related to soil density and texture, while texture also affects the amount of water available for root utilization (Eavis & Payne 1969). In mature plants, 75 percent of the roots can be in the top 25 cm of soil (Lupton *et al.* 1974).

Halevy (1969) considered that the advantages of the neutron probe have not been exploited enough in crop - water utilization studies. This in part is verified by the lack of related scientific published reports. Those that are documented cover a wide range of crops and environments, for example: Long & French (1967) with grasses and barley, Danfors & Gustafsson (1967) with potatoes, Draycott (1973) with sugarbeet and Watt (1977) with pasture sward.

3.3 MATERIALS AND METHODS

The experiment was outlined in detail in Section 1.3.

The soil water was monitored at weekly intervals using a neutron moisture meter. Only 24 access tubes were available, so the late nitrogen treatments were omitted. Aluminium alloy tubes were sealed at the bottom end, being 1.25 m in length and having an outside and inside diameter of 44.5 and 44.3 mm respectively. They were inserted during late August after carefully removing by hand auger a column of soil the exact dimensions of the tube. Their position was randomly sited on the longitudinal midline within each plot. Throughout the placement process raised platforms were

used to stand on so the wheat and soil was minimally disturbed.

From 15 September onwards, six half minute readings were taken at each access tube; two standards and one at each of the depths 25, 50, 75 and 100 cm. The standards are used to eliminate errors arising from drift in the efficiency of the measuring system since in all calculations of the count ratios, the standard readings are used as the divisor (Appendix 2). The time taken for all readings on each occasion was around 2.5 hours. Readings presented here were from 6 October onwards. Before this date heavy rainfall in September (Table 3.5) caused water volumes to rise in many of the profiles indicating water quantities possibly in excess of field capacity. It was only from 6 October that the majority of partial profile volumes (25 - 50, 50 - 75, 75 - 100 cm) recorded a water loss. At this stage all partial profiles would have been near to field capacity. No attempt was made to distinguish or measure downward drainage which was assumed to be small in relation to the transpirational use (Hillel 1972). Similarly, the top 25 cm of soil was not monitored due to the difficulty of distinguishing between water loss by soil evaporation and plant transpiration.

The depth moisture gauge used was Model 1257 from Troxler Electronic Laboratories, North Carolina, U.S.A. The probe (Model 105 A) was a $^{10}BF_3$ detector tube that had mounted at the bottom end a radioactive source of Americum ^{241}: Beryllium rated at 100 millicuries. The probes effective centre of measurement was the geometric midpoint of its lithium enriched boron trifluoride gas detector tube. As there was 10 cm between the detector center and the source, the zone of measurement would be less than the zone of influence since only 90-95% of the neutron interactions are detected. This leads to asymetrical source-detector geometry (Bell

& McCullogh 1969). However, according to the Troxler Manual (Anon. 1974) the zone of measurement for this model was a sphere of radius 23 cm at 30 volume percent moisture and 29 cm at half that value. The centre of the sphere influences the measurement much more than the outside as the thermal neutron density is greatest near the neutron source (Long & French 1967). The Troxler scaler - ratemeter used was Model 2651.

Long & French (1967) recommend that the neutron probe should be field calibrated even though a factory standard is usually supplied. A method similar to Rawls & Asmussen (1973) was followed for this purpose. During the installation process, 10 cm soil cores were taken at the depths 30 - 40, 60 - 70, 90 - 100 cm and were determined for soil water content, by oven drying at 105^{o}C to a constant dry weight. Immediately following the access tube placement the corresponding depth neutron probe test counts were taken. The sampled gavimetric soil water contents were converted to a volumetric basis by using bulk density figures from Hart (1978). These figures related to the same trial site and the mean of his 12 determinations were used for each depth. The final regression line was fitted by the least squares method, using the probe standard counts as the ordinate and the volumetric soil water contents as the abscissa. A feature of this probe (Anon. 1974) was that its linear regression line passed through the origin and this characteristic was used to provide the range necessary to formulate the relationship. The calculated linear regression coefficient was $b = +3.06$ ($S.E._b = 0.22$). In the program analysis the slope was assigned the value $b = +3.00$ compared to the factory standard $b = +2.18$.

A Fortran IV computer program was written to convert the neutron probe readings into millimeters of water. This was achieved by integrating the spline function joining consecutive probe depth readings. From this program printout, total water content within the three partial (25 - 50,

50 - 75, 75 - 100 cm) and total (25 - 100 cm) profile zones, was calculated. Weekly water consumption was obtained by subtraction of volumes of successive weeks. Data from 14 consecutive weeks were used starting from when the wheat was at the double ridge stage (6 October) and finishing three - quarters of the way through grain-filling (5 January). A more thorough description of this program is given in Appendix 2 along with a sample printout.

3.4 RESULTS

Towards the end of the vegetative growth in early October, all plots were near to field capacity in subsoil water status. From then until the first irrigation (29 November), only one significant difference in water use occured (Table 3.1) and this was for the 3 November reading, where in the 25 - 50 cm profile the highest rate of early N removed more water (Table 3.1).

Table 3.1: Water extraction (mm) for the 25 - 50 cm profile in the early nitrogen treatment for the period 28 October to 3 November.

Nitrogen level	mm		
E0	4.78	b	B
E1	6.38	ab	AB
E2	7.72	a	A
S.E. $\bar{x}$	0.55		
C.V. %	25		

The lower and upper case letters refer to Duncan's multiple range test for P = 0.05 and P = 0.01 respectively. Values followed by the same letter are not significantly different.

Once the irrigation commenced it caused many significant differences in water status as summarised in Tables 3.2 and 3.3. The first readings following irrigation (1 and 15 December) had significantly more water entering the profiles (Table 3.3; with the exception of the 75 - 100 cm profile on 1 December). All other significant differences related to irrigation (except 50 - 75 and 75 - 100 cm profiles on 8 December) were due to the irrigated treatment having more water extracted (Table 3.3). Throughout the experiment, sowing rate caused no significant differences in water extraction, but the early N treatment did on 3 November and the 1, 8, 15, 22 and 29 December (Tables 3.2, 3.3).

Since irrigation had the most main effect differences, weekly results were analysed according to the irrigation standard order. Fig. 3.1 is the average weekly consumption of water for all non-irrigated treatments (12 plots). Between the three partial profiles, differences in the rate of water consumption varied over time. The trend was for the shallow (25 - 50 cm) zone to initially display the greatest volume removed. Then, as that level declined, the middle (50 - 75 cm) zone replaced it as the main water supply source. Correspondingly as it declined, the deepest (75 - 100 cm) zone became the most important layer. This zone, in common with the other two, declined in water use after anthesis (Fig. 3.1). Weekly data from Fig. 3.1 was converted in Fig. 3.2 to the average cumulative total for each measured profile zone. When readings were terminated in early January, the middle zone had supplied around 2.6 mm more water than the other two which had both lost approximately 36.3 mm of water. The cumulative and average weekly water consumption for the total (25 - 100 cm) monitored soil profile is shown in Fig. 3.3 and Fig. 3.5 respectively. Weekly rainfall totals throughout the soil water monitoring period are shown in Fig. 3.4 and the Lincoln College Metrological

Table 3.2: Weekly water extraction summary for all profile zones and the total profile as affected by the applied treatments.

	Profile zones (cm)			Total
	25 - 50	50 - 75	75 - 100	25 - 100
13 October	NS	NS	NS	NS
20 October	NS	NS	NS	NS
27 October	NS	NS	NS	NS
3 November	E**	NS	NS	NS
10 November	NS	NS	NS	NS
17 November	NS	NS	NS	NS
24 November	NS	NS	NS	NS
1 December	I**	I*	E*, I*	I**
8 December	E*, I**	I**	I**	NS
15 December	I**	I**	E**, I**	I**
22 December	E*, I**	NS	NS	NS
29 December	E*, I**	NS	NS	I**
5 January	I**	I**	I**	I**

Significant Interactions: (detailed in Appendix 3).

8 December, 50 - 75 cm profile: S x I*

15 December, 75 - 100 cm profile: E x I**, E x S**

22 December, 25 - 50 cm profile: E x I*

29 December, 25 - 50 cm profile: E x I**, S x I*

29 December, 50 - 75 cm profile: S x I*

29 December, 25 - 100 cm profile: S x I*

NS Non significant $P > 0.05$

* $P < 0.05$

** $P < 0.01$

Table 3.3: Detailed treatment by profile depth significant differences from the Table 3.2 summary.

Date	Profile depth (cm)	Treatment				$SE_{\bar{x}}$	CV%
1 December	25 - 50	I0 = 3.25	I1 = -19.23			1.80	-*
	50 - 75	I0 = 4.79	I1 = -5.19			1.37	-
	75 - 100	I0 = 5.54	I1 = 3.08			0.58	47
	75 - 100	E0 = 4.65	E1 = 5.68	E2 =	2.59	0.71	47
	25 - 100	I0 = 13.58	I1 = -21.34			3.40	-
8 December	25 - 50	I0 = 2.22	I1 = 6.39			0.55	45
	25 - 50	E0 = 4.25	E1 = 5.72	E2 =	2.94	0.68	45
	50 - 75	I0 = 3.62	I1 = 1.74			0.35	45
	75 - 100	I0 = 4.07	I1 = 1.26			0.59	77
15 December	25 - 50	I0 = 0.10	I1 = -12.34			1.23	-
	50 - 75	I0 = 1.22	I1 = -8.61			0.91	-
	75 - 100	I0 = 2.48	I1 = -3.83			0.46	-
	75 - 100	E0 = -3.54	E1 = 1.04	E2 =	0.48	0.57	-
	25 - 100	I0 = 3.81	I1 = -24.78			2.04	-
22 December	25 - 50	I0 = 0.92	I1 = 7.38			0.52	43
	25 - 50	E0 = 3.31	E1 = 5.74	E2 =	3.40	0.63	43
29 December	25 - 50	I0 = 0.75	I1 = 3.48			0.19	31
	25 - 50	E0 = 1.47	E1 = 2.28	E2 =	2.60	0.23	31
	25 - 100	I0 = 3.75	I1 = 7.80			0.82	49
5 January	25 - 50	I0 = 0.13	I1 = 4.74			0.32	46
	50 - 75	I0 = 0.91	I1 = 3.88			0.34	49
	75 - 100	I0 = 1.63	I1 = 3.09			0.27	39
	25 - 100	I0 = 2.67	I1 = 11.70			0.65	31

* CV% could not be calculated due to the mean being negative.

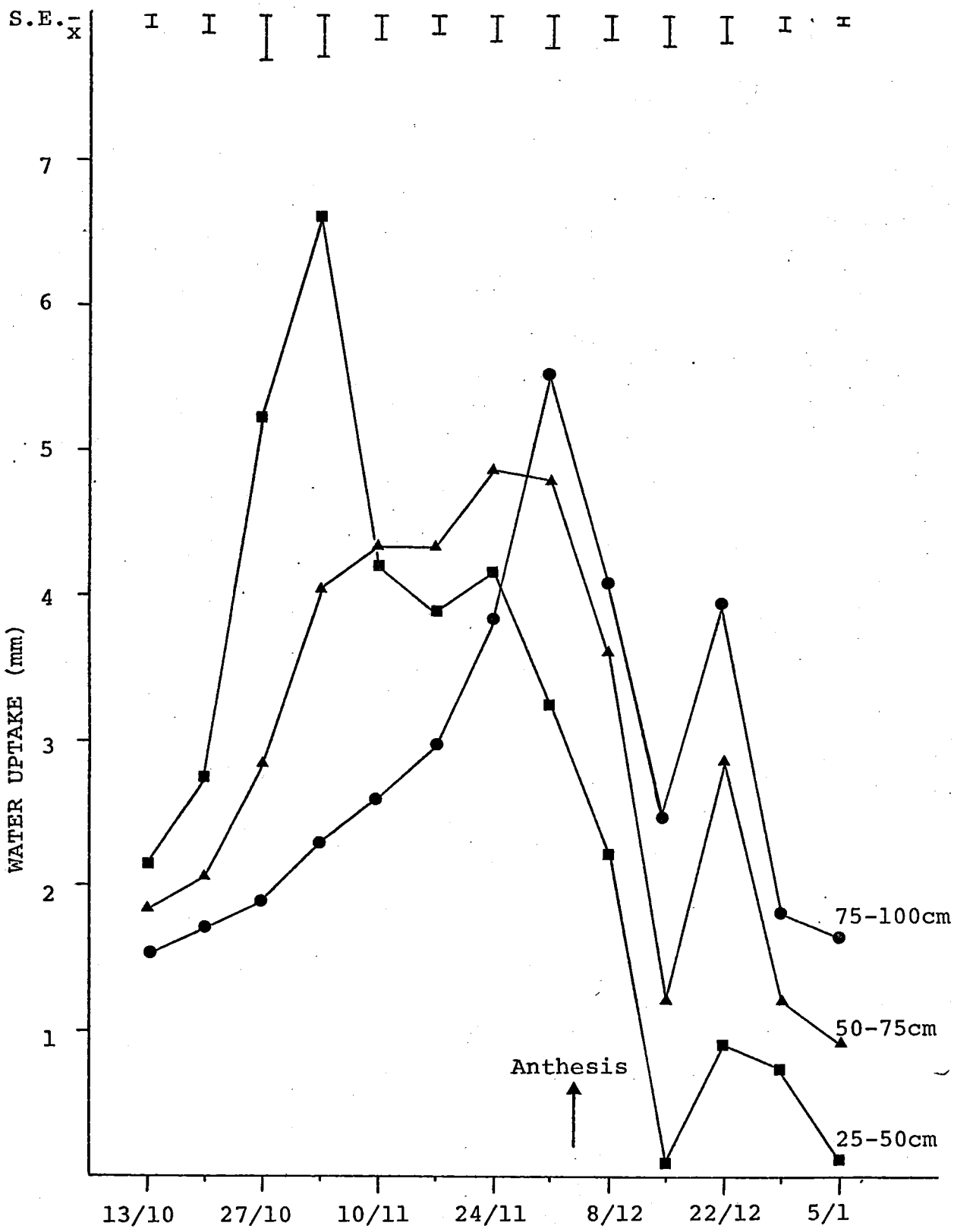

Fig. 3.1: Average weekly uptake of water (mm) for all non-irrigated plots for the three (25-50,50-75,75-100cm) soil profiles.

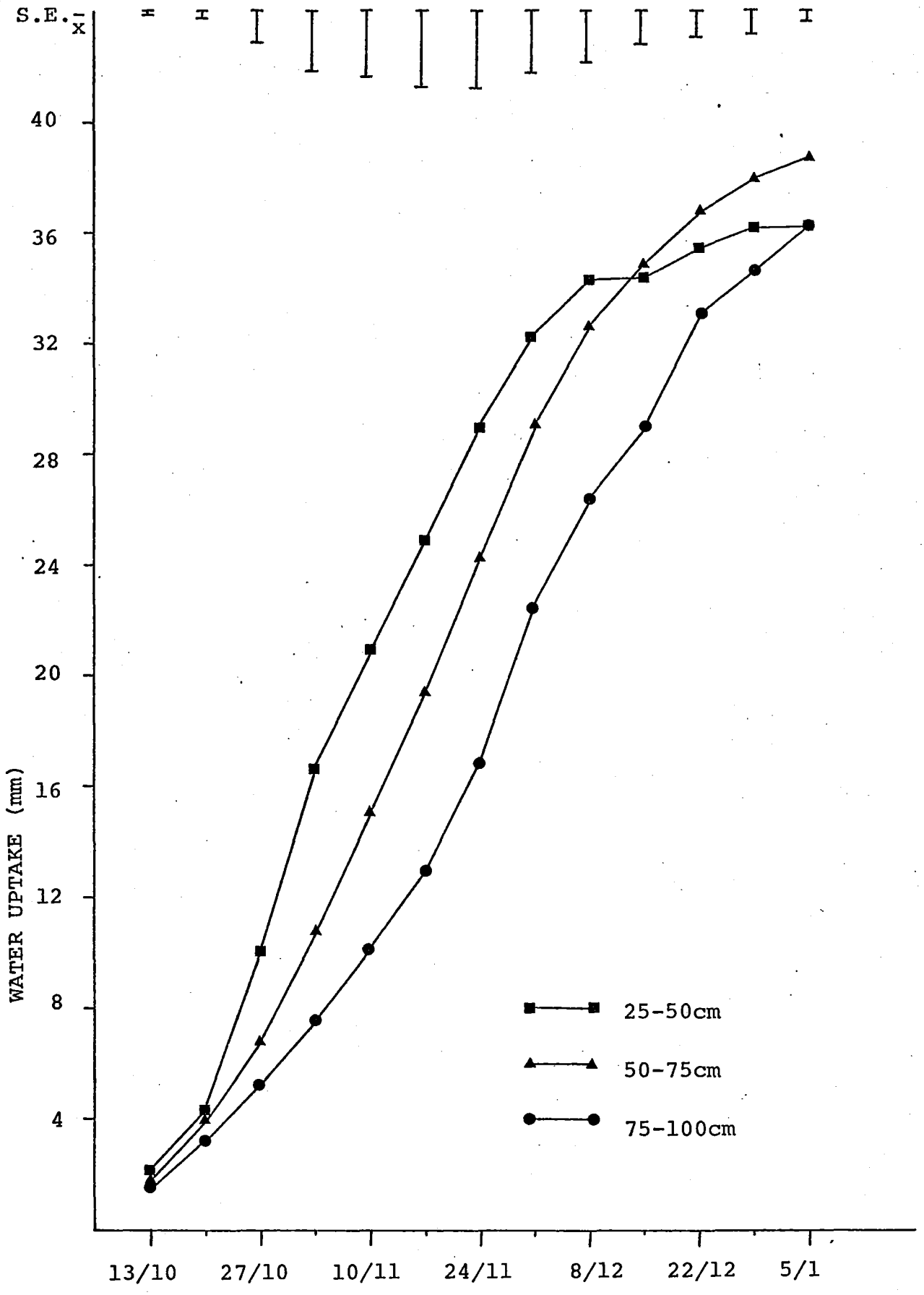

Fig. 3.2: Average cummulative weekly uptake of water (mm) for all non-irrigated plots for the three (25-50,50-75, 75-100cm) soil profiles.

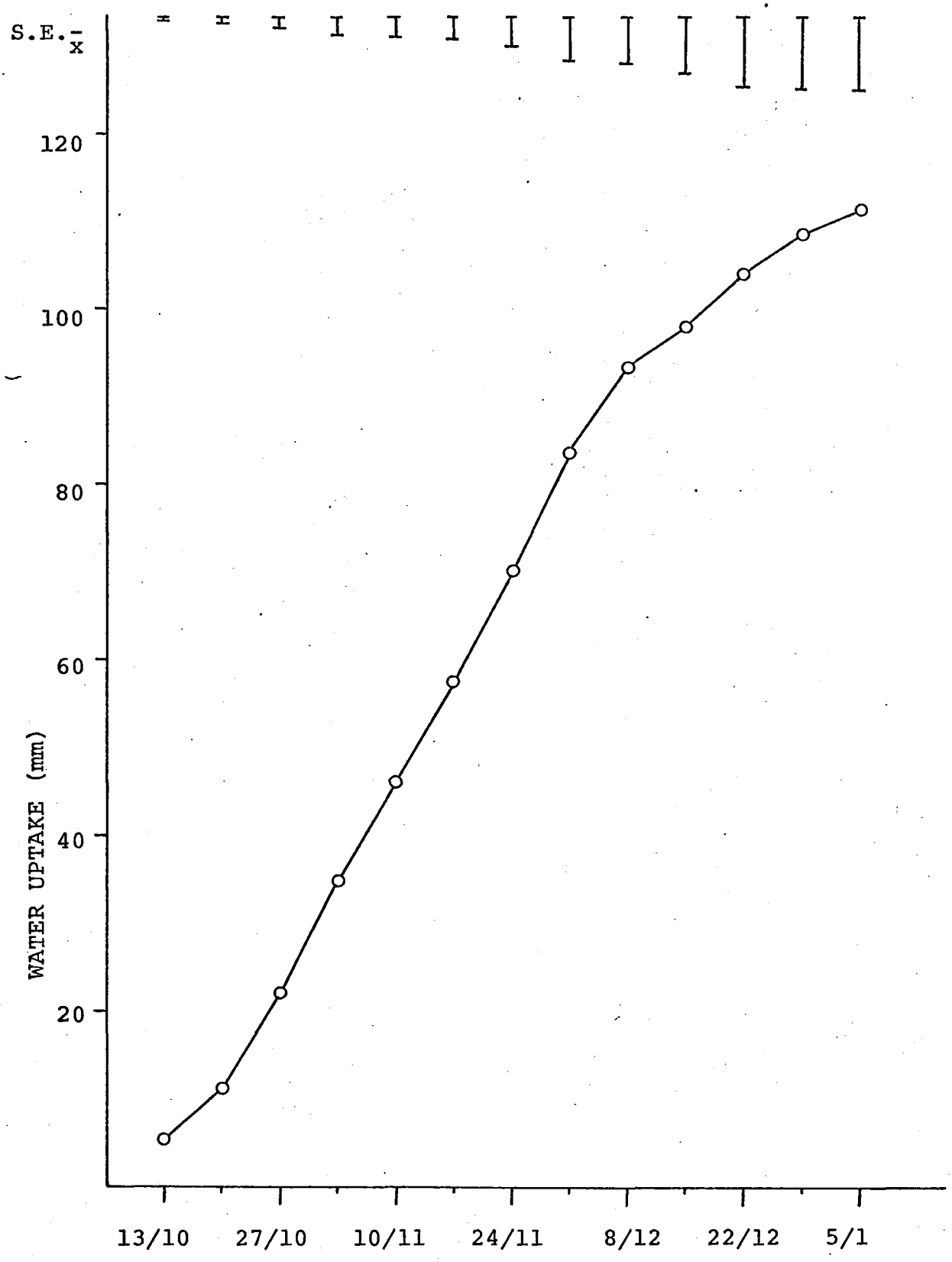

Fig. 3.3: Average total cummulative weekly uptake of water (mm) for all non-irrigated plots for the total (25-100cm) soil profile.

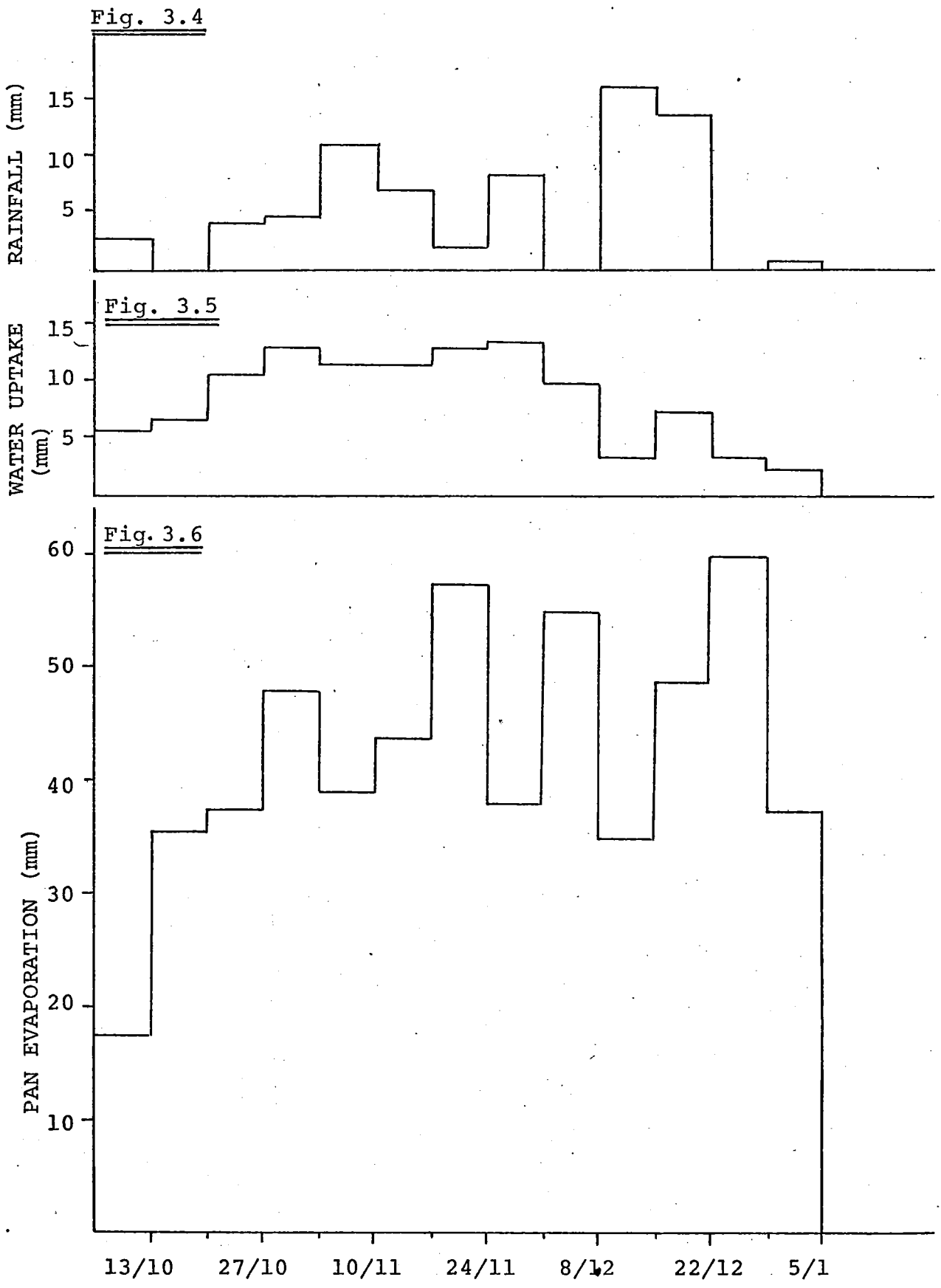

Fig. 3.4: Total weekly rainfall (mm) from 6 October till 5 January.
Fig. 3.5: Average total weekly uptake of water (mm) for all non-irrigated plots for the total soil profile (25-100cm) from 6 October till 5 January.
Fig. 3.6: Total weekly raised pan evaporation (mm) for Lincoln College Metrological Station from 6 October till 5 January.

Station raised pan evaporation totals are shown in Fig. 3.6.

3.5 DISCUSSION

A feature of these results were the high coefficients of variation obtained during the analysis of variance. These arose from large differences being recorded between plots with the same treatment. Even when the irrigated treatment had not been applied and these plots were used as an extra two replications, this did not alleviate the problem. An example of this type of analysis (6 treatments x 4 replications) is shown in Table 3.4.

Table 3.4: The effect of early nitrogen and sowing rate on water uptake (mm) for the 4 - 10 November in the three partial and total profile when using the non-imposed irrigation treatments as two extra replications (i.e.: 6 treatments x 4 replications).

		Profile depth (cm): -						Total	
		25 - 50 mm		50 - 75 mm		75 - 100 mm		25 - 100 mm	
Early Nitrogen									
	E0	3.40		4.01		3.57		10.98	
	E1	4.80	NS	4.23	NS	2.52	NS	11.55	NS
	E2	4.08		3.67		1.60		9.35	
Sowing Rate									
	S0	3.76	NS	3.48	NS	2.14	NS	9.38	NS
	S1	4.42		4.46		2.99		11.87	
S.E.		2.16		1.51		1.83		3.39	
C.V. %		53		38		66		32	

There were no significant interactions.

NS = non significant

This variation was attributed to the textural complexity of the soil and its resultant effect on water holding capacity (Anon. 1968, Hart 1978). Variability was generally greater within individual profile zones than over the whole profile total. This indicates that the plant water extraction pattern was an integrated function of the whole rooting depth rather than being dominated by specific arbitrarily determined soil profile zones.

Soil water storage is largely dependent on the annual depletion and recharge cycle (Walker 1956). Rainfall data over the winter months of this trial was 50% higher than the long term average (Anon. 1973, Table 3.5) and neutron probe readings in late September showed that all subsoil profiles had reached or exceeded field capacity (Section 3.3).

Table 3.5: Lincoln College monthly rainfall data (mm) for the trial.

	1941 - 1970 average mm	1977 mm
May	76	74
June	58	72
July	58	137
August	56	52
September	46	104
Total	294	439
October	48	21
November	53	29
December	58	49
Total	159	99

Plant water demand would not be high before the end of the double ridge growth phase as little biomass is produced (Fig. 1.3) and soil, air temperatures and solar radiation levels are also still relatively low at this time. All these conditions would favour root development near the soil surface rather than subsoil penetration (Evans 1973).

It was throughout the reproductive phase when biomass accumulation was accelerating that the monitored profiles showed water depletion occurring faster than natural recharge. Reicosky *et al.* (1972) noticed that as the dry matter production increased so did the demand for water, and root and shoot growth were found by Lupton *et al.* (1974) to be highly correlated over this phase. Throughout this period less rainfall was recorded (Table 3.5), when compared to the long term average. In unsaturated soil conditions, plant water extraction depends mainly on continued root growth into unexploited moisture reserves of the soil profile (Pearson 1966). Initially the shallowest measured zone was the largest supplier while the deepest provided least but by grainfilling the situation was reversed (Fig. 3.1). This pattern of soil water utilization is in agreement with the findings of Hurd & Spratt (1975). As water is removed from the uppermost layer, the gradient in water potential between soil and root decreases and hydraulic conductivity of the soil declines reducing the water flux. As the level of water in the surface diminishes, a gradual change in extraction pattern occurs to the deeper layers, with higher water potentials and hydraulic conductivities. Each profile trend was very similar in the rate of cumulative water absorption (Fig. 3.2) with the shallowest attaining any given level of water usage first, followed by the middle profile and then the deepest. This held true until 8 December, after which water removal from the 25 - 50 cm profile noticeably declined (Fig. 3.2).

Following the use of irrigation the water extraction pattern in the three profile zones was markedly changed. Whereas non-irrigated plots were removing more water from the deepest profile zone, the irrigated plots had their greatest loss from the shallowest profile (Fig. 3.7). This trend continued on for three weeks, until testing stopped, and would be due to the irrigation raising water potential gradients more in the surface profiles than the deeper ones (Table 3.6).

Table 3.6: Mean water volumes (mm) being removed or added for the week tested following the two irrigations, for the non-irrigated (I0) and irrigated (I1) treatment means in the three partial and total soil profiles.

		25 - 50 mm	50 - 75 mm	75 - 100 mm	Total 25 - 100 mm
1 December	I0	3.2 **	4.8 **	5.5 *	13.5 **
	I1	-19.2	-5.2	3.1	-21.3
	S.E.$_{\bar{x}}$	1.80	1.37	0.58	3.40
	C.V. %	- [a]	-	47	-
15 December	I0	0.1 **	1.2 **	2.5 **	3.8 **
	I1	-12.3	-8.6	-3.8	-24.7
	S.E.	1.23	0.91	0.46	2.04
	C.V. %	-	-	-	-

[a] C.V. % could not be calculated due to the mean being negative.

* = $P < 0.05$

** = $P < 0.01$

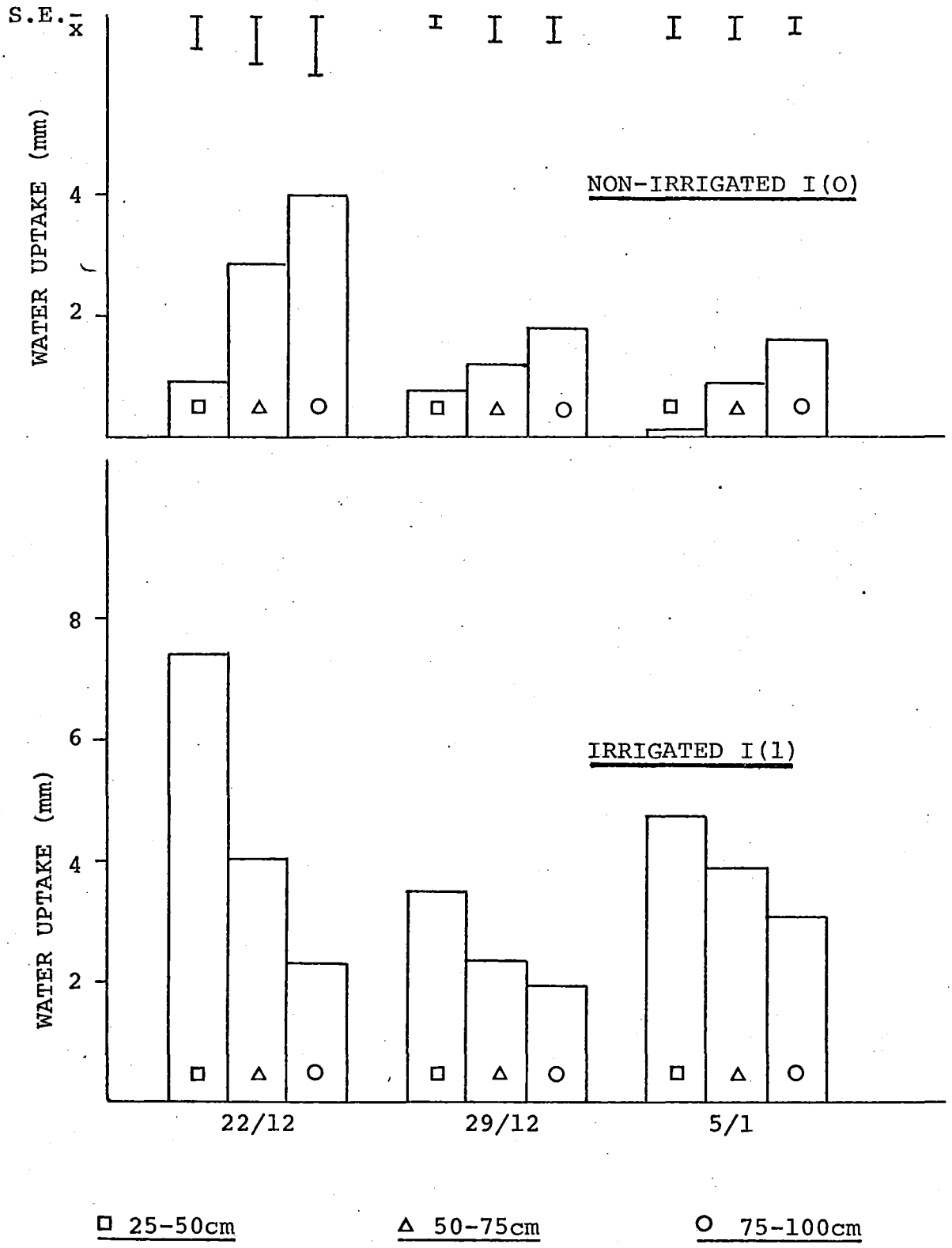

Fig. 3.7: Average weekly water (mm) uptake for the non-irrigated (IO) and irrigated (I1) treatment means for the three (25-50, 50-75, 75-100 cm) soil profiles for the last three weeks monitored.

Summation of the water extracted each week from the three partial profiles (Fig. 3.1) gives the total weekly profile of water utilization (Fig. 3.5). The average total weekly uptake increased until 3 November, fell slightly for the next two weeks, and then rose again for the following two. The first decline could be explained by higher rainfall and lower pan evaporation (Figs. 3.4, 3.5, 3.6) placing a temporarily decreased dependence on subsoil water. Previous research with autumn sown wheat at Lincoln (Scott *et al.* 1973) has indicated that by early December the topsoil 25 cm could be near to wilting point. This layer would include the plants oldest and most suberised roots. Reicosky *et al.* (1972) demonstrated that these roots could still absorb water if it was readily available while Kramer (1933) showed that plants could even take up water through dead root systems. Thus following rain, the roots in the top 25 cm soil layer absorbed and utilized some of it, replacing and conserving water obtained from the deeper subsurface zones. The importance and volumes of water supplied from the topsoil layer to the wheat was not determined. Besides the roots using water from the top 25 cm soil layer, evidence is available to show that winter wheat roots can extract water from as deep as 2.4 m (Kmoch *et al.* 1957). The second decline in the amount of water removed each week from the total profile happened just after anthesis but it cannot be explained in the same way, as it coincided with a period of high pan evaporation and no rainfall (Figs. 3.4, 3.5, 3.6). This reduction in water uptake was probably related to the cessation of root growth known to occur at that time (Hurd 1968, Connor 1975).

The quantities of water removed throughout the recorded period were calculated in Table 3.7.

Table 3.7: Total water removal (mm) from the three individual and total profile zones between 6 October and 5 January.

	Profile (cm)			Total
	25 - 50	50 - 75	75 - 100	25 - 100
Start (mm)	72.67	72.41	73.80	218.88
Finish (mm)	36.35	33.49	36.80	106.64
Difference (mm)	36.32	38.92	37.00	112.24
% Water used	50.0	53.7	50.1	51.3

All profiles lost around 50% of their total water. This was about the expected maximum since the neutron probe measures total soil water which includes capillary and hygroscopic water (Gardner 1975, Buckman & Brady 1969). In normal situations only capillary or plant available soil water can be used and this portion generally amounts to about half the combined total (Dagg 1967, Buckman & Brady 1969). Theoretically, Table 3.7 indicates that approximately all the plant available soil water was removed from the measured profile depths. This demonstrates the importance of root penetration into deeper soil layers for the purpose of extracting water, especially when considering that in the last month monitored, the shallowest to deepest profiles had a total of 1.9, 6.2 and 9.9 mm of water removed respectively (Fig. 3.2).

It is obvious that further improvements could be made to obtain more information from this type of study. Longer access tubes are essential to encompass the plants complete rooting depth. An attempt should be made to estimate water removal in the top 0 - 25 cm soil profile even though considerable problems would be encountered (Painter 1977). But the most important requires finding another site if small, but *real*, differences caused by the treatments are to be detected. Ideally the soil used should have a uniform profile so the soil physical parameters do not vary with depth or between sampling sites.

CHAPTER 4

GENERAL DISCUSSION

In each of the preceding chapters, the discussion has concentrated on the results obtained from that part of the experiment. This was done for ease of writing the Thesis and it does not infer that they are independent in the agronomic sense. The aim of this section is to unite the individual chapter studies together.

Four different treatments, sowing rate, early N, late N and irrigation, were imposed on autumn sown wheat in an attempt to obtain as much variation as possible in the yield components. Previous trials, including Fraser (1978) and Dougherty *et al.* (1979), have been carried out on the same Templeton silt loam soil and their results for components of yield have been similar in that small differences between treatments have often reached a statistical level of significance. Originally the information collected with the neutron probe (Chapter 3) was going to be related to the agronomic treatments but lack of statistically significant differences prevented this (Table 3.2, 3.3). Before anthesis, only one significant difference was detected in the volume of water removed within a monitored profile zone (Table 3.2) and this was due to the high rate of early N causing more water to be lost from the 25 - 50cm depth at the start of November (Table 3.1). At that stage of plant development, early tiller death and stem elongation, no corresponding increase was recorded in biomass m^{-2} or LAI although significant differences were detected before and after that date (Figs. 1.6, 1.7). Thus soil water removal as monitored by individual profile zones did not, in general, form a consistent relationship to the plant biomass m^{-2} or LAI increases caused by the early N. This was

contrary to expected since Kmoch *et al.*(1957) found early N fertilisation in winter wheat increased root weights and subsoil moisture utilization while Rosenburg (1974) related faster rates of soil water depletion to rising LAI's. The poor relationship between soil water and plant biomass or LAI data arose as all individual plot results showed considerable variation and this was attributed to the soil not being uniform over the site. This was noticed while inserting the neutron probe tubes and as the soil properties altered within the measured profiles it is likely that soil variability influenced the water holding capacities (Anon. 1968, Hart 1976), plant root penetration (Evans 1973), and rate of water removal (Ellis 1976). The testing apparatus could not be faulted since repeated readings on the same plots were in close agreement, but errors could have arisen from not having the measurements encompassing the complete rooting depth. In a study such as this, the soil properties must be consistent over the rooting depth if meaningful results are to be obtained for water uptake and then be correlated to biomass growth parameters.

A measurement was made of the severity in water stress that developed between some of the treatments, using the flag leaf as the plant indicator. Kramer (1969) considered plant turgidity the most important aspect in plant-water relations because of its intrinsic involvement in the physiological processes controlling growth quantity and quality, and that plant water potential was the single most useful parameter characterising water stress. It has been widely used and accepted (Slavik 1974), and the method used in this experiment is outlined in Appendix 4. Figure 4.1 shows the difference in flag leaf water potentials between the nil and high early N treatment on the 19 November. From 0630 hours on, the high N plots were significantly lower, a trend that continued until 0500 hours the next morning. Recordings on the 23 and 25 November followed a similar pattern

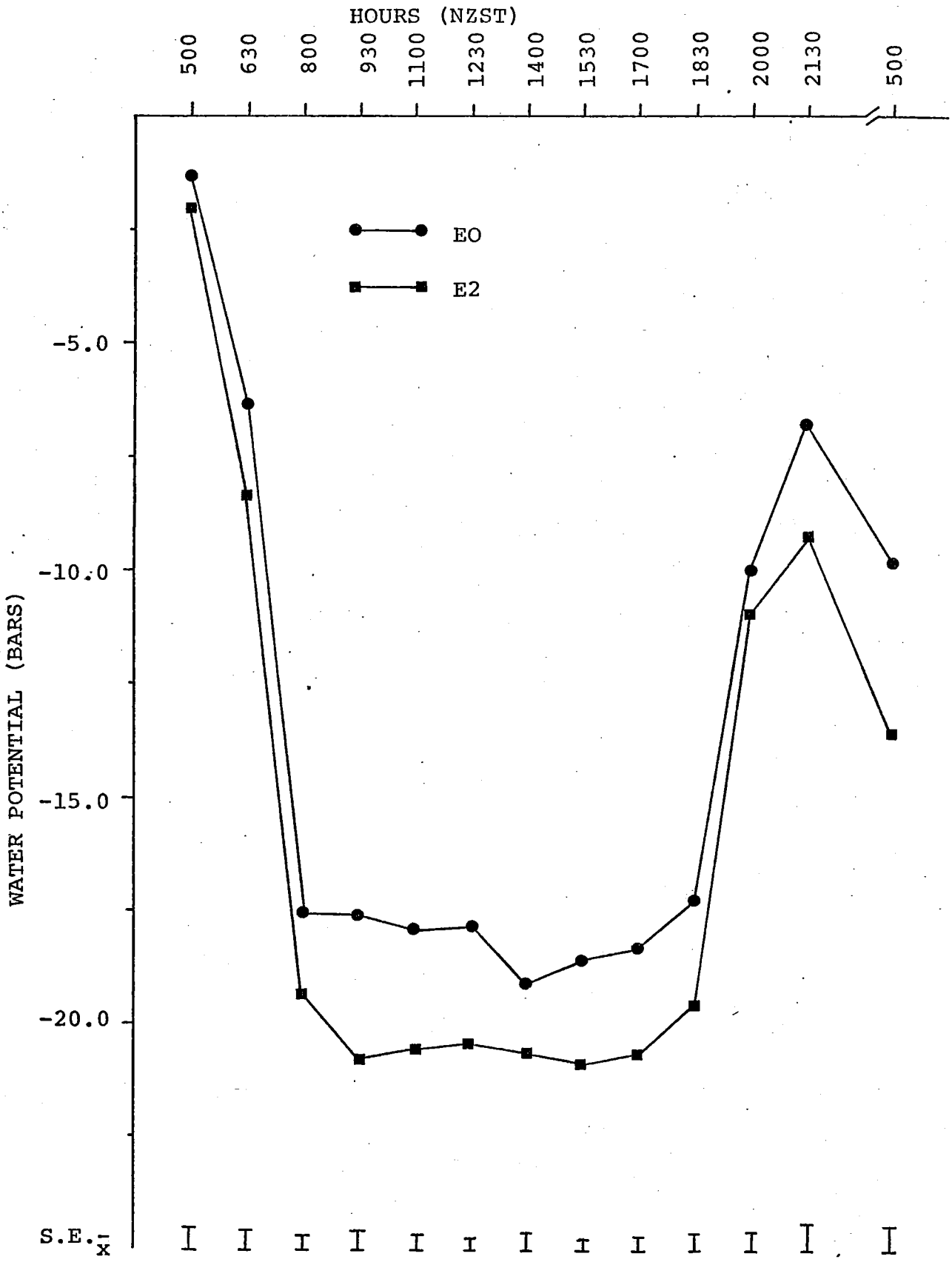

Fig. 4.1: Flag leaf water potentials as affected by early N for the nil rate of late N, non-irrigated, low sowing rate treatment means for the 19 November.

for the main part of the day but throughout late November, no difference in water uptake from the monitored soil zones was noticed between treatments (Table 3.2). Soil moisture availability is not the only factor controlling the plant water status and plant water deficits can arise when transpiration losses exceed the rate of root absorption (Kramer 1959). The high rate of early N produced significantly more leaf area (Fig. 1.7) and this could lead to higher advective and insolation transpiration losses thereby intensifying plant water stress (Dougherty 1973). During the time period over which the leaf water potential measurements were taken, ear emergence was proceeding (Fig. 1.1) and this plant stage is known to be sensitive to water stress, being characterised by a reduction in grain numbers per spikelet when water shortages occur (Fischer 1973, Table 1.1). Scott *et al.* (1973) also commented that high LAI's in November may limit the supply of assimilate to the developing ear. In an extreme example which caused a 30% yield depression mainly due to poor grain set, Dougherty & Langer (1974) attributed the primary cause to pre-anthesis plant deficiencies of carbohydrate. In this experiment there was a significant inverse correlation between ears m^{-2} and grains per spikelet (Table 1.5), therefore, as ear numbers were raised by early N (Fig. 1.3), LAI was also (Fig. 1.7), resulting in lower grain set per spikelet and lighter grain weights (Tables 1.1, 1.5). If larger LAI's predispose higher plant water deficits, there is likely to be less water available for plant processes which would eventually limit photosynthesis resulting in less carbohydrate available for plant utilization (Boyer & McPherson 1975), especially for the rapidly developing pre-anthesis ear (Hsiao 1973).

Irrigation was used for the first time at anthesis since no visual symptoms of plant water stress occurred earlier to warrant bringing its application forward. The aim of applying this treatment at flowering was to

affect grain size and grain flour quality, as irrigation can significantly alter these parameters (Drewitt & Rickard 1971, 1973). After each irrigation, except the days immediately following when water was still entering the monitored profiles, all differences caused by this treatment were due to having more of the added water removed (Tables 3.2, 3.3). For the week ending the 5 January, about two-thirds of the way through grainfilling, all irrigated profile depths had significantly more water extracted from them. Only two of the measured plant biomass parameters, LAI and dry weight per tiller, responded to irrigation (Table 1.7) and the latter is reflected in the yield components as an increase in grain number per spikelet, grain weight, and straw weight (Tables 1.1, 1.3). Plant water potentials determined on the flag leaves were significantly raised (i.e. less negative) by the application of water (Fig. 4.2) and a similar pattern of response was recorded on the 5, 12 and 18 December as well. In all cases, the differences occupied the majority of the day with the irrigated plots regularly around -2 bars more than the non-irrigated ones, being approximately -22 and -24 bars respectively. If these two figures are taken as representing stomatal closure, then the 2 bars difference could reflect accelerated aging brought on by less plant available water (Frank *et al.* 1973). It is erroneous to assume that plant growth is only affected by large soil water deficits (Hsiao 1973), hence irrigation helping to alleviate any deficit would correspondingly uphold a more active leaf area (Fig. 2.1, Table 1.7) and therefore a greater assimilate supply to the plants.

Brocklehurst (1977) correlated grain weight to the number of endosperm cells, which are determined in the first two weeks after fertilisation, but he concluded that grain weight was determined mainly by differences in the supply of assimilate to the developing grains, which in turn regulates the size of grain sink to match the amount of assimilate available.

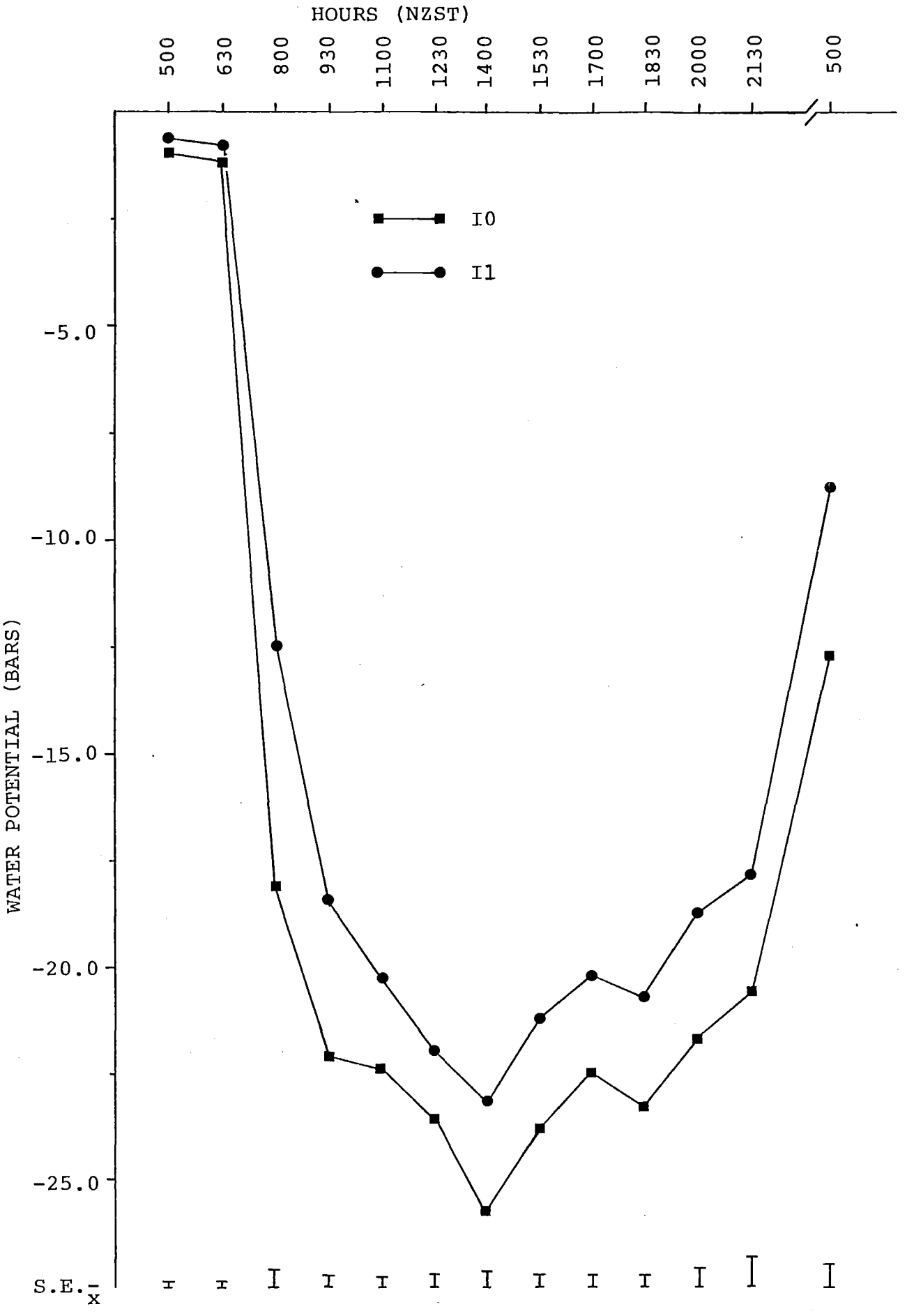

Fig. 4.2: Flag leaf water potentials as affected by irrigation for the high rate of early N, nil rate of late N and low sowing rate treatment means for the 16 December.

Grain weight showed a significant response to irrigation but of the flour quality parameters only loaf volume was altered (Table 2.1). The grain protein to carbohydrate ratio remained the same (Table 2.2) indicating that with increasing grain weights, the proportions of grain assimilate accumulation were unchanged even though irrigation induced an obvious difference in flag leaf area duration (Fig. 2.1). As most grain carbohydrate is derived from flag leaf photosynthesis (Patrick 1971, Yoshida 1972), it may have been anticipated that the grain protein to carbohydrate ratio would decline resulting in poorer flour quality (Drewitt & Rickard 1973). However the balanced uptake of grain protein may have been due to the strong positive correlation that exists at maturity between straw weight and the N in the grain plus straw (Austin *et al.* 1977). Irrigation, by reducing the amount of *in vivo* dry matter that needs to be mobilised (Fig. 2.1, Table 1.7) thereby maintains photosynthetic activity which provides the energy for continued N uptake. It is suggested that heavier tillers (Table 1.7) and more straw (Table 1.3) produced by irrigation, together with delaying leaf senescence (Fig. 2.1, Table 1.7), could have maintained the N to carbohydrate relationship in the developing grain.

There was no point in trying to calculate how much extra soil water the irrigated plots removed, compared to the non-irrigated ones, as this would depend on too many assumptions and estimations. However the 120mm of water put on (Chapter 1.3) resulted in an 11% improvement in yield (Table 1.1). Using the same soil type with autumn sown Kopara wheat irrigated to field capacity on the 7 November and 8 December, Wilson (1974a) obtained a 9% lift in yield. The Templeton silt loam soil was described by Cox *et al.* (1971) as being prone to drying out in drought summers, but as previously mentioned, large soil moisture deficits are not required to initiate yield limitations. In the non-irrigated plots, nearly all the

plant available water was removed from the 75-100cm soil profile depth (Table 3.7) demonstrating that root penetration clearly went deeper. After the very wet winter (Table 3.5), the subsoil below 100cm could have been at saturation capacity and this would be a ready source of water for deep root exploitation (Scott *et al.* 1977), even though the last three months of the year were drier than normal (Table 3.5). Another function of deep root penetration would be the absorption of any leached N since autumn sown wheat can easily take N up from as deep as 150cm (Daigger & Sander 1976).

No significant response was found between yield and any of the measured flour quality parameters (Table 2.3) although under English conditions, it is normal to find an inverse relationship between yield and grain protein (Lupton & Pushman 1975). A positive trend was present in this experiment which may have helped stabilise the flour quality components, as this would infer N was not limited for grain protein development. Similarly, no significant interactions were present for any of the quality results (Table 2.1) indicating that the agronomic treatments had little direct influence on the grain - flour quality relationships irrespective of treatment effects on grain weights. In his comprehensive review of New Zealand wheat N responses Wright (1969) calculated that 94% of the trials gave an improvement in baking score when N was applied, but no substantial yield improvements were noticed at high baking scores. Only moderately high baking scores could be claimed from Table 2.1, while yield response to early N was large (Table 1.1). These results support the general North American response when increasing rates of early N are used in the presence of adequate soil water. In general, there is a yield improvement and the protein effect is minimal until the grain response reaches its maximum (Johnson *et al.*1975). Late N raised flour protein percent (Table 2.1), otherwise all treatments did not influence this parameter which is the

single most important quality component (Finney & Yamasaki 1967).

Results presented in Table 1.1 by the various treatments indicate that there was considerable room for manipulation within each yield component. Although the reaction of each yield component to each agronomic treatment could be looked at in isolation from the rest, it is desirable to try and determine these responses as part of the overall crop development, since component compensation is a regular and intimate part of yield determination (Evans & Wardlaw 1976). In crop plants, the relationship of final component size being positively correlated to those earliest initiated or with the longest period of development, has been noticed before. With wheat, for example, tiller survival follows an hierarchial order with later formed tillers senescing first, while the mainstem or oldest tiller consistently carries greatest proportions of yield (Clements *et al.* 1974, Power & Alessi 1978, Fraser & Dougherty 1978). Scott *et al.* 1975 demonstrated a significant and positive relationship between spikelet dry weight at the early boot stage and final grain set. Failure of upper order florets to set grain was attributed by Langer & Hanif (1973) to their later initiation of development and thus less total growth between conception and fertilisation. Kirby (1974) showed that grain size was positively correlated to the time of floret initiation while Brocklehurst (1977) found grain weight was dependent on the rate of dry matter accumulation which is governed by the number of endosperm cells formed during the first two weeks after fertilisation. This highlights the importance of determining the timing of physiological events (Fig. 1.1) as for all these parameters, treatments increasing initial size may directly result in more yield provided subsequent components are not disadvantaged too severely. When studying developmental plasticity, Adams (1967) referred to it as being synonymous to component compensation, and in this experiment, the yield components can be closely related to

treatment effects applied during early development. N fertiliser broadcast at the commencement of tillering raised harvest ear numbers, late N used midway through floret growth improved grain set per spikelet and irrigation at anthesis resulted in heavier grains (Table 1.1, Fig. 1.1). Decline of later formed components was most noticeable after treatments were used to promote earlier ones and the best example of this was sowing density, where the high rate produced more ears but all succeeding components were reduced (Table 1.1). The reduction of subsequent components does not occur haphazardly but also follows an integrated pattern which is interdependent on their development (Adams 1967) and in the case of sowing rate, increased spike population was completely offset by lower production per ear so harvest yield was unaffected. The above results between components strictly relate only to this experiment, but the principles involved have a far wider application.

In practical terms, the most important treatment of this experiment was early N application as it significantly raised yield through supporting a higher harvest ear population despite large reductions in some of the within-ear components (Table 1.1). Harvest ear number was the most influential yield component (Table 1.5, 1.6) and this has been found before on the soils around Lincoln (Dougherty *et al.* 1974, 1975, 1979). Adequate soil water is necessary for early N fertiliser to sustain high yields, as Drewitt & Rickard (1973) achieved no yield response to early N on a light soil type at Winchmore, due to the increased ear number being counteracted by a grain set and grain weight reduction. On the Templeton silt loam, within any measured subsoil profile zone the cummulative soil water uptake followed a sigmoid curve pattern (Figs. 3.2, 3.3). When studied on a weekly basis, many significant differences resulted between the arbitrary defined profile zones (Fig. 3.1), and the weekly seasonal pattern of water removal

between the measured profiles would be related to their water potential differences (Kramer 1969). Despite large variations in yield (Table 1.1) and subsoil water uptake (Table 3.2) induced by the treatments used in this experiment, flour quality characteristics were relatively stable (Table 2.1).

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Appendix 1: Interactions from Chapter 1.

a) From Table 1.1:

Grain number per spikelet ExS**

	S0	S1
E0	2.39	1.88
E1	2.16	1.97
E2	2.02	1.93

S.E. 0.04
C.V. % 5.3

Grain number per ear ExS**

	S0	S1
E0	43.8	33.3
E1	41.0	36.3
E2	38.6	36.0

S.E. 0.69
C.V. % 5.1

Grain yield per ear (g) ExS**

	S0	S1
E0	1.72	1.28
E1	1.57	1.34
E2	1.40	1.29

S.E. 0.03
C.V. % 5.4

b) From Table 1.4:

Sterile spikelets per ear ExS*

	S0	S1
E0	1.48	2.11
E1	2.04	2.13
E2	2.24	2.23

S.E. 0.12
C.V. % 5.6

Appendix 2: The computer program written to calculate volumes of soil water (mm) from the initial neutron probe readings.

In this experiment, the neutron probe readings were taken at weekly intervals from 7 October until 5 January. For each tube, this involved two standard readings (STD1 and STD2) and one at each of the depths 25, 50, 75 and 100 cm (CM25, CM50, CM75, CM100). This was done for 24 plots, the readings being formated in columns with the plots being the rows. This was termed DATA, and is displayed in the print-out under the heading DATA.

The first subroutine RDC (RAW DATA CONVERSION) converts DATA, the field absolute count rates, into standardised count rates or the standard count ratio (CRATIO). This appears in the print-out under CRATIO.

The second subroutine SDC (STANDARD DATA CONVERSION) is used to convert the CRATIO readings into millimetres of water (MM). This is in the print-out under MM.

The third subroutine VOLUME, takes the field measured point volumes of water as determined by MM (from subroutine SDC) and integrates between them to obtain partial profile volumes (CM25-50, CM50-75, CM75-100) and also the total profile volume (TOTVOL). This is a quantitative method, in that the volume of water measured in the field is now defined as millimetres of water per profile depth, and the results are shown in the print-out under VOLUMES. The integration method relies on two parts - firstly obtaining the curve between all the MM points and secondly calculating the volume of water beneath specific portions of it. The former is achieved by the polynomial intercepts method and the latter by the trapezoidal integration procedure. Also in this subroutine, the files 10 and 11 are written, containing the calculated profile volumes.

At the end of the main program, the differences between successive weeks volume readings are determined by subtraction of the FILE 11 from FILE 10. This therefore gives the change in water status during that week, and is shown in the print-out under the heading DIFFERENCES.

After subroutine VOLUME in the main program, FILE 12 can be used to obtain any treatment means required. By arranging the plots needed onto a DATA NO card at the head of the program, the information requested is taken off FILE 10 and FILE 11 in the main program before FILE 10 is cleared ready for its next weeks values. Unfortunately cards need to be manually changed in the main program every time the DATA NO sequence is altered. The information also shows which plots have been averaged and this appears in the print-out under VOLUME DIFFS and DIFFERENCE DIFFS.

The following provides more detail of the Subroutines used:

SUBROUTINE ONE: SUBROUTINE RDC (DATA, CRATIO)

RDC = RAW DATA CONVERSION

The field DATA is converted into the standard count ratio (CRATIO). The formula was: $P = K / SC$

where: P = Count ratio

K = Field count rate of measurement (counts minute^{-1})

SC = Field standard count rate of measurement (counts minute^{-1}).

In this case 0.5 minute field readings with two standard readings were used therefore:

P = DATA (I,J) *2 / DATA (I,1) + DATA (I,2)

where: J = 3,6

The results of this calculation were called CRATIO, and is the standardised neutron probe data form.

SUBROUTINE TWO: SUBROUTINE SDC (CRATIO, MM)

SDC = STANDARD DATA CONVERSION

The subroutine SDC is used to convert the neutron probe standard counts (CRATIO) to moisture contents (MM). The regression line between these two was calculated as detailed in Section 3.3 and is given by:

CR = B*X

where: CR = Count ratio (CRATIO)

B = 3.0

X = moisture content in kg l^{-1} (MM)

This was rearranged so that MM = (CRATIO) / 3.0 and the array MM was calculated.

SUBROUTINE THREE: SUBROUTINE VOLUME (MM,L)

VOLUME = calculates the soil water volumes (mm).

MM are the point moisture contents at the depths tested and L is the counter indicating what weeks DATA is being used.

A, B, C and D are the profile depths as listed. The curve of the line through the MM points is calculated according to the algebraic intercept methods and is represented by the equation TOTMM. Calculation of the volume integrated beneath this was carried out by the trapezoidal method, in a series of iterations. This computation is carried out in kg l^{-1} but the result of VOLS is required in mm cm^{-1} so a multiplication factor of 10 is used.

Two files are written in this subroutine, although both are actually operated at the end of the main program. FILE 10 minus FILE 11 gives the differences (DIFF) between successive weeks volumes as seen in the print-out under DIFFERENCES.

The following 9 pages contain the programe written in Fortran, for the Burroughs 6700 computer, and an example of print-out.

```
      ************************************************
      * *                                          * *
      ***  THIS PROGRAM IS FOR CONVERTING NEUTRON  ***
      ***  PROBE READINGS INTO SOIL WATER VOLUMES  ***
      ***                                          ***
      ***  IT WAS WRITTEN BY WALLY DALGLIESH 1978  ***
      * *                                          * *
      ************************************************

FILE  10=WEEK1,UNIT=DISK,AREA=24,RECORD=4
FILE  11=WEEK2,UNIT=DISK,AREA=24,RECORD=4
FILE  12=AVERAGES,UNIT=DISK,AREA=12,RECORD=8

      REAL MM(24,4)
      DIMENSION DATA(24,6),CRATIO(24,4),SUM(4),ASUM(4),DIFF(4),
     * DATA2(24,7),NO(24),DIFF1(4),DIFF2(4)

   SORTING OF THE DATA INTO THE "DATA NO" ORDER

      DATA NO/11,26,17,48,22,37,4,33,5,25,15,42,
     *        14,39,2,30,8,27,13,46,18,40,12,29/
         DO 99999 L=1,14
         DO 10 I=1,24
       READ(5,900)(DATA2(I,J),J=1,7)
  900  FORMAT(8X,I2,5X,2F5.0,5X,4F5.0)
         DO 11 J=1,24
      IF(DATA2(I,1).NE.NO(J)) GO TO 11
         DO 12 JJ=1,6
      DATA(J,JJ)=DATA2(I,JJ+1)
   12 CONTINUE
   11 CONTINUE
   10 CONTINUE

      CALL RDC(DATA,CRATIO)

      CALL SDC(CRATIO,MM)

       WRITE(6,901) L
  901
         DO 13 I=1,24
       WRITE(6,902) NO(I),(DATA(I,J),J=1,6),(CRATIO(I,J),J=1,4),
     2 (MM(I,J),J=1,4)
  902
   13 CONTINUE
       WRITE(6,903) L,L-1
  903

      CALL VOLUME(MM,L,NO)

      IF(L.EQ.1)  GO TO 99999
```

CALCULATION OF THE WEEKLY "VOLUME DIFFS" & THE "DIFFERENCE DIFFS"

```
      KK=2
         DO 14 I=1,24
      READ(10'I) (SUM(K),K=1,4)
      READ(11'I)(ASUM(K),K=1,4)
         DO 15 J=1,4
      DIFF(J)=SUM(J)-ASUM(J)
      DIFF1(J)=DIFF1(J)+ASUM(J)
      DIFF2(J)=DIFF2(J)+DIFF(J)
   15 CONTINUE
       WRITE(6,904) NO(I),(ASUM(K),K=1,4),(DIFF(J),J=1,4)
      IF(I.EQ.KK)  WRITE(12'KK/2) (DIFF1(K),K=1,4),(DIFF2(K),K=1,4)
      IF(I.LT.KK) GO TO 14
         DO 16 J=1,4
      DIFF1(J)=0.0
      DIFF2(J)=0.0
   16 CONTINUE
      IF(I.EQ.KK) KK=KK+2
   14 CONTINUE
       WRITE(6,905) L,L-1
         DO 17 N=1,12
      READ(12'N) (DIFF1(K),K=1,4),(DIFF2(K),K=1,4)
       WRITE(6,906) NO(N*2-1),NO(N*2),(DIFF1(J)/2.0,J=1,4),
     * (DIFF2(J)/2.0,J=1,4)
   17 CONTINUE
         DO 18 J=1,4
      DIFF1(J)=0.0
      DIFF2(J)=0.0
   18 CONTINUE
         DO 19 N=1,24
      READ(11'N) (ASUM(J),J=1,4)
      WRITE(10'N)(ASUM(K),K=1,4)
   19 CONTINUE
99999 CONTINUE
```

FORMAT CARDS

```
  901  FORMAT('1',5X,'WEEK',I3/25X,'DATA',40X,'CRATIO',37X,'MM'//
     1 1X,'PLOT',2X,'STD1',3X,'STD2',3X,'CM25',3X,'CM50',3X,'CM75',3X,
     1 'CM100',12X,'CM25',4X,'CM50',4X,'CM75',4X,'CM100',11X,'CM25',4X,
     1 'CM50',4X,'CM75',4X,'CM100'//)
  902  FORMAT(1X,I2,3X,6F7.0,8X,4F8.5,8X,4F8.5)
  903  FORMAT(1X,/////////32X,'VOLUMES',56X,'DIFFERENCES',3X,'WEEK',
     3 I2,'-',I2//4X,'PLOT',6X,'VOLUME',7X,'VOLUME',7X,'VOLUME',7X,
     3 'TOTVOL',18X,'DIFF',9X,'DIFF',9X,'DIFF',9X,'TOTDIFF'/
     3 13X,'CM25-50',6X,'CM50-75',6X,'CM75-100',4X,'CM25-100',
     3 18X,'CM25-50',6X,'CM50-75',6X,'CM75-100',5X,'CM25-100'//)
  904  FORMAT(5X,I2,4F13.4,11X,4F13.4)
  905  FORMAT('1',6X,'PLOTS',23X,'MEAN VOLUMES',38X,'MEAN DIFFERENCES',
     5 3X,'WEEK',I2,'-',I2//)
  906  FORMAT(5X,2I3,4F12.4,10X,4F12.4/)
       STOP
       END
```

```
      SUBROUTINE RDC(DATA,CRATIO)
      RDC = RAW DATA CONVERSION , FROM THE FIELD DATA TO STANDARD DATA

      DIMENSION DATA(24,6),CRATIO(24,4)
         DO 20 I=1,24
         DO 21 J=3,6
      CONVER=DATA(I,J)*2/(DATA(I,1)+DATA(I,2))
      N=J-2
      CRATIO(I,N)=CONVER
   21 CONTINUE
   20 CONTINUE
      RETURN
      END




      SUBROUTINE SDC(CRATIO,MM)
      SDC = STANDARD DATA CONVERSION , FROM COUNT RATES TO MM OF WATER

      REAL MM(24,4)
      DIMENSION CRATIO(24,4)
         DO 30 I=1,24
         DO 31 J=1,4
      MM(I,J)=CRATIO(I,J)/3.0
   31 CONTINUE
   30 CONTINUE
      RETURN
      END




      SUBROUTINE VOLUME(MM,L,NO)
      VOLUME = INTEGRATION OF MM OF WATER TO OBTAIN TOTAL PROFILE VOLUME

      REAL MM(24,4)
      DIMENSION SUM(3),NO(24)
      TOTVOL=0.0
      A=25.0
      B=50.0
      C=75.0
      D=100.0
         DO 40 I=1,24
         DO 41 K=1,3
         DO 42 J=25*K,25*(K+1)
      TOTMM=(((MM(I,1)*(J-B)*(J-C)*(J-D))/((A-B)*(A-C)*(A-D)))+
     *       ((MM(I,2)*(J-A)*(J-C)*(J-D))/((B-A)*(B-C)*(B-D)))+
     *       ((MM(I,3)*(J-A)*(J-B)*(J-D))/((C-A)*(C-B)*(C-D)))+
     *       ((MM(I,4)*(J-A)*(J-B)*(J-C))/((D-A)*(D-B)*(D-C))))
      IF(J.EQ.(25*K))     TOTMM=TOTMM*0.5
      IF(J.EQ.25*(K+1))   TOTMM=TOTMM*0.5
      SUM(K)=SUM(K)+TOTMM
   42 CONTINUE
      SUM(K)=SUM(K)*10
      TOTVOL=TOTVOL+SUM(K)
   41 CONTINUE
      IF(L.EQ.1)   WRITE(10'I)(SUM(K),K=1,3),TOTVOL
      IF(L.GT.1)   WRITE(11'I)(SUM(K),K=1,3),TOTVOL
      IF(L.GT.1)   GO TO 44
       WRITE(6,940) NO(I),(SUM(K),K=1,3),TOTVOL
  940  FORMAT(5X,I2,4F13.4)
   44    DO 43 K=1,3
      SUM(K)=0.0
   43 CONTINUE
      TOTVOL=0.0
   40 CONTINUE
      RETURN
      END
```

WEEK 5

DATA

PLOT	STD1	STD2	CM25	CM50	CM75	CM100
11	24193.	23753.	14987.	15280.	18205.	22124.
26	23757.	23603.	13395.	17957.	18910.	16837.
17	23864.	23891.	15207.	17574.	17798.	21591.
48	23060.	23167.	14243.	18577.	18187.	14253.
22	23971.	23564.	15398.	19418.	19212.	22115.
37	23825.	23807.	14646.	17189.	14883.	21391.
4	23896.	23531.	15547.	15221.	12564.	22337.
33	23574.	23648.	14573.	17504.	16869.	18918.
5	23504.	23836.	13907.	17520.	18715.	20692.
25	23285.	23543.	13476.	18636.	18688.	18558.
15	23181.	24023.	14013.	16645.	18556.	21984.
42	23528.	23730.	12925.	17971.	17068.	21812.
14	23450.	23560.	13409.	17147.	19213.	21180.
39	23588.	23693.	14164.	17426.	18853.	18090.
2	24179.	23839.	14269.	17514.	17650.	19275.
30	23342.	23543.	14563.	15027.	19422.	18728.
8	24317.	23575.	13745.	14445.	19412.	22871.
27	23841.	24118.	13788.	17776.	17231.	20797.
13	24251.	24217.	12712.	17261.	11416.	21759.
46	23571.	23583.	12740.	16746.	19141.	21364.
18	24175.	23486.	14147.	17224.	20014.	20361.
40	23921.	23221.	13082.	17428.	20443.	20501.
12	24351.	23703.	13538.	18175.	18375.	20935.
29	23918.	23465.	13824.	18279.	19820.	19551.

CRATIO

CM25	CM50	CM75	CM100
0.62516	0.63738	0.75940	0.92287
0.56567	0.75832	0.79856	0.71102
0.63688	0.73601	0.74539	0.90424
0.61622	0.80373	0.78686	0.61665
0.64786	0.81700	0.80833	0.93047
0.61496	0.72174	0.62492	0.89818
0.65562	0.64187	0.52982	0.94195
0.61721	0.74135	0.71446	0.80124
0.58754	0.74018	0.79066	0.87419
0.57555	0.79593	0.79815	0.79260
0.59372	0.70524	0.78620	0.93145
0.54700	0.76055	0.72233	0.92310
0.57047	0.72950	0.81740	0.90108
0.59914	0.73712	0.79749	0.76521
0.59432	0.72948	0.73514	0.80282
0.62122	0.64102	0.82850	0.79889
0.57400	0.60323	0.81066	0.95511
0.57499	0.74130	0.71857	0.86728
0.52455	0.71226	0.47107	0.89787
0.54036	0.71027	0.81185	0.90614
0.59365	0.72277	0.83985	0.85441
0.55500	0.73938	0.86729	0.86976
0.56345	0.75644	0.76476	0.87131
0.58350	0.77154	0.83659	0.82523

MM

CM25	CM50	CM75	CM100
0.20839	0.21246	0.25313	0.30762
0.18856	0.25277	0.26619	0.23701
0.21229	0.24534	0.24846	0.30141
0.20541	0.26791	0.26229	0.20555
0.21595	0.27233	0.26944	0.31016
0.20499	0.24058	0.20831	0.29939
0.21854	0.21396	0.17661	0.31398
0.20574	0.24712	0.23815	0.26708
0.19585	0.24673	0.26355	0.29140
0.19185	0.26531	0.26605	0.26420
0.19791	0.23508	0.26207	0.31048
0.18233	0.25352	0.24078	0.30770
0.19016	0.24317	0.27247	0.30036
0.19971	0.24571	0.26583	0.25507
0.19811	0.24316	0.24505	0.26761
0.20707	0.21367	0.27617	0.26630
0.19133	0.20108	0.27022	0.31837
0.19166	0.24710	0.23952	0.28909
0.17485	0.23742	0.15702	0.29929
0.18012	0.23676	0.27062	0.30205
0.19788	0.24092	0.27995	0.28480
0.18500	0.24646	0.28910	0.28992
0.18782	0.25215	0.25492	0.29044
0.19450	0.25718	0.27886	0.27508

VOLUMES

PLOT	VOLUME CM25-50	VOLUME CM50-75	VOLUME CM75-100	TOTVOL CM25-100
11	51.6080	57.6748	70.0439	179.3267
26	56.3081	65.8415	63.7001	185.8497
17	58.6550	61.5177	66.8689	187.0416
48	60.7586	67.5145	59.3656	187.6387
22	63.3384	67.8850	70.4733	201.6967
37	59.0965	55.5336	58.9075	173.5376
4	56.9015	47.3443	55.5319	159.7776
33	58.5715	60.7880	61.4480	180.8076
5	56.4984	64.0246	68.6710	189.1940
25	59.3872	67.2036	65.6061	192.1969
15	54.6638	62.0265	70.7944	187.4847
42	57.9279	61.8310	65.2016	184.9605
14	54.8910	64.7156	71.4008	191.0073
39	56.1639	64.5324	65.8068	186.5031
2	56.7199	61.2596	62.9880	180.9675
30	50.0967	61.4008	70.6467	182.1443
8	46.9798	58.5126	74.8462	180.3387
27	57.4058	60.8890	63.6390	181.9338
13	58.3103	48.4769	48.6054	155.3926
46	52.7947	63.6838	71.4218	187.9003
18	54.6208	65.5063	71.6185	191.7455
40	54.0852	67.5756	73.4860	195.1467
12	57.2565	63.6832	66.5081	187.4478
29	57.4745	67.6966	69.6106	194.7817

DIFFERENCES WEEK 5- 4

DIFF CM25-50	DIFF CM50-75	DIFF CM75-100	TOTDIFF CM25-100
6.3270	4.8140	2.0847	13.2257
5.5051	1.5768	2.5424	9.6244
5.6246	3.1518	1.8657	10.6420
3.3452	3.6752	4.6624	11.6828
3.6253	1.4415	1.2052	6.2719
3.6389	5.7435	6.0043	15.3866
4.6716	6.2062	5.3877	16.2655
5.4138	2.4161	4.2418	12.0717
6.6009	2.8701	0.9440	10.4150
6.1098	2.8431	2.1427	11.0955
5.9529	2.4579	-0.5148	7.8960
3.3739	2.7863	3.3904	9.5506
8.3361	3.3422	0.7190	12.3973
7.3844	4.1004	1.5774	13.0622
6.1220	4.3837	2.8666	13.3723
7.1288	2.3763	-1.5641	7.9410
12.0492	8.0778	0.6176	20.7447
7.7872	5.6977	5.3198	18.8047
8.2070	4.9842	1.8010	14.9922
8.4591	5.7243	2.7455	16.9289
6.8085	3.2916	2.7818	12.8819
6.7724	2.2935	0.8908	9.9567
7.0567	5.0670	1.8127	13.9364
4.5825	0.9381	0.4754	5.9961

PLOTS	VOLUME DIFFS				DIFFERENCE DIFFS			
11 26	53.9581	61.7581	66.8720	182.5882	5.9161	3.1954	2.3136	11.4250
17 48	59.7068	64.5161	63.1173	187.3402	4.4849	3.4135	3.2640	11.1624
22 37	61.2175	61.7093	64.6904	187.6171	3.6321	3.5925	3.6047	10.8293
4 33	57.7365	54.0661	58.4900	170.2926	5.0427	4.3112	4.8148	14.1686
5 25	57.9428	65.6141	67.1386	190.6955	6.3554	2.8566	1.5433	10.7553
15 42	56.2958	61.9287	67.9980	186.2226	4.6634	2.6221	1.4378	8.7233
14 39	55.5274	64.6240	68.6038	188.7552	7.8603	3.7213	1.1482	12.7298
2 30	53.4083	61.3302	66.8174	181.5559	6.6254	3.3800	0.6512	10.6566
9 27	52.1928	59.7008	69.2426	181.1362	9.9182	6.8878	2.9687	19.7747
13 46	55.5525	56.0803	60.0136	171.6465	8.3330	5.3543	2.2732	15.9605
18 40	54.3530	66.5409	72.5522	193.4461	6.7904	2.7926	1.8363	11.4193
12 29	57.3655	65.6899	68.0594	191.1148	5.8196	3.0026	1.1441	9.9662

WEEK 6

DATA

PLOT	STD1	STD2	CM25	CM50	CM75	CM100
11	24040.	23496.	14244.	13314.	17543.	21849.
26	23939.	23576.	12382.	16756.	18582.	16084.
17	23448.	23860.	14328.	16131.	16804.	20320.
48	23151.	23853.	13310.	18030.	16327.	13492.
22	23729.	23323.	15049.	18675.	18925.	22002.
37	23628.	23223.	13732.	16106.	12399.	20993.
4	24043.	23272.	14566.	13860.	11481.	21270.
33	24198.	23853.	13441.	17074.	15242.	16911.
5	23345.	23758.	13276.	16673.	17648.	19561.
25	23786.	23218.	12650.	18037.	17639.	17804.
15	24162.	23487.	13615.	14678.	17684.	21610.
42	23387.	23539.	11929.	17115.	15842.	21354.
14	23764.	23327.	12298.	15854.	18517.	20547.
39	23798.	24059.	12692.	15799.	18312.	17512.
2	23557.	23853.	13735.	15087.	16764.	18463.
30	24156.	23429.	13161.	13158.	19049.	17769.
8	23932.	23343.	12884.	11925.	18577.	22347.
27	23984.	23470.	12678.	16494.	15855.	20209.
13	23944.	23604.	12279.	15852.	10172.	21514.
46	23345.	23492.	12049.	14049.	18066.	20538.
18	24187.	23564.	13137.	16863.	18992.	19581.
40	23103.	23537.	12334.	16468.	20405.	20009.
12	23730.	23791.	12761.	17065.	17603.	20521.
29	23954.	23456.	12661.	17200.	19277.	19312.

CRATIO

CM25	CM50	CM75	CM100
0.59929	0.56016	0.73809	0.91926
0.52118	0.70529	0.78215	0.67701
0.60573	0.68196	0.71041	0.85905
0.56633	0.76717	0.69471	0.57408
0.63968	0.79380	0.80443	0.93522
0.58620	0.68754	0.52929	0.89616
0.61570	0.58586	0.48530	0.89908
0.55945	0.71066	0.63441	0.70388
0.56370	0.70794	0.74934	0.83056
0.53825	0.76747	0.75053	0.75755
0.57147	0.61609	0.74226	0.90705
0.50842	0.72945	0.67519	0.91011
0.52231	0.67333	0.78643	0.87265
0.53041	0.66026	0.76528	0.73185
0.57941	0.63645	0.70719	0.77887
0.55316	0.55303	0.80063	0.74683
0.54507	0.50449	0.78591	0.94540
0.53433	0.69516	0.66823	0.85173
0.51649	0.66678	0.42786	0.90494
0.51451	0.59991	0.77144	0.87700
0.55023	0.70629	0.79546	0.82013
0.52890	0.70617	0.87500	0.85802
0.53707	0.71821	0.74085	0.86366
0.53411	0.72559	0.81320	0.81468

MM

CM25	CM50	CM75	CM100
0.19976	0.18672	0.24603	0.30642
0.17373	0.23510	0.26072	0.22567
0.20191	0.22732	0.23680	0.28635
0.18878	0.25572	0.23157	0.19136
0.21323	0.26460	0.26814	0.31174
0.19540	0.22918	0.17643	0.29872
0.20523	0.19529	0.16177	0.29969
0.18648	0.23689	0.21147	0.23463
0.18790	0.23598	0.24978	0.27685
0.17942	0.25582	0.25018	0.25252
0.19049	0.20536	0.24742	0.30235
0.16947	0.24315	0.22506	0.30337
0.17410	0.22444	0.26214	0.29088
0.17680	0.22009	0.25509	0.24395
0.19314	0.21215	0.23573	0.25962
0.18439	0.18434	0.26688	0.24894
0.18169	0.16816	0.26197	0.31513
0.17811	0.23172	0.22274	0.28391
0.17216	0.22226	0.14262	0.30165
0.17150	0.19997	0.25715	0.29233
0.18341	0.23543	0.26515	0.27338
0.17630	0.23539	0.29167	0.28601
0.17902	0.23940	0.24695	0.28789
0.17804	0.24186	0.27107	0.27156

VOLUMES

PLOT	VOLUME CM25-50	VOLUME CM50-75	VOLUME CM75-100	TOTVOL CM25-100
11	46.0646	53.3304	69.7752	169.1702
26	51.5876	62.9797	62.3194	176.8867
17	54.5672	57.7642	63.9786	176.3099
48	58.2379	62.0259	52.4196	172.6834
22	61.6372	66.6739	70.7382	199.0493
37	57.5926	49.7810	53.0329	160.4066
4	52.5837	43.0938	52.0883	147.7658
33	55.7920	56.3280	53.4579	165.5779
5	54.1925	60.9382	65.0584	180.1892
25	57.0479	64.0202	61.7344	182.8025
15	48.7673	56.1813	68.6024	173.5510
42	55.4431	58.4784	62.0926	176.0141
14	50.1197	61.0484	69.2767	180.4448
39	49.3895	59.9635	63.7342	173.0872
2	50.5215	55.9343	61.9570	168.4128
30	42.4700	56.5886	68.4709	167.5296
8	39.9604	53.0734	74.5224	167.5562
27	53.9108	56.7290	60.4921	171.1319
13	55.8327	44.4772	46.7378	147.0476
46	45.3096	57.0698	69.6697	172.0491
18	52.8270	63.0283	67.7551	183.6105
40	50.9053	66.5557	74.1122	191.5732
12	54.2988	60.9964	65.2635	180.5587
29	53.2687	64.7749	68.3643	186.4079

DIFFERENCES WEEK 6- 5

DIFF CM25-50	DIFF CM50-75	DIFF CM75-100	TOTDIFF CM25-100
5.5434	4.3444	0.2687	10.1565
4.7205	2.8618	1.3807	8.9630
4.0878	3.7536	2.8903	10.7317
2.5206	5.4886	6.9461	14.9553
1.7012	1.2111	-0.2649	2.6473
1.5039	5.7526	5.8746	13.1311
4.3178	4.2504	3.4436	12.0119
2.7795	4.4600	7.9901	15.2297
2.3058	3.0864	3.6126	9.0049
2.3393	3.1834	3.8717	9.3944
5.8964	5.8452	2.1920	13.9336
2.4848	3.5526	3.1090	8.9465
4.7713	3.6672	2.1241	10.5625
6.7743	4.5689	2.0727	13.4159
6.1983	5.3254	1.0310	12.5547
7.6267	4.8122	2.1758	14.6147
7.0195	5.4392	0.3238	12.7825
3.4950	4.1600	3.1469	10.8019
2.4776	3.9997	1.8676	8.3449
7.4851	6.6140	1.7521	15.8512
1.7938	2.4779	3.8633	8.1351
3.1799	1.0199	-0.6262	3.5735
2.9576	2.6868	1.2447	6.8892
4.2058	2.9217	1.2463	8.3738

PLOTS		VOLUME DIFFS				DIFFERENCE DIFFS			
11	26	48.8261	58.1550	66.0473	173.0284	5.1320	3.6031	0.8247	9.5597
17	48	56.4026	59.8950	58.1991	174.4967	3.3042	4.6211	4.9182	12.8435
22	37	59.6149	58.2275	61.8856	179.7279	1.6025	3.4818	2.8049	7.8892
4	33	54.1878	49.7109	52.7731	156.6718	3.5487	4.3552	5.7169	13.6208
5	25	55.6202	62.4792	63.3964	181.4959	2.3226	3.1349	3.7422	9.1996
15	42	52.1052	57.3298	65.3475	174.7825	4.1906	4.5989	2.6505	11.4401
14	39	49.7546	60.5059	66.5054	176.7660	5.7728	4.1181	2.0984	11.9892
2	30	46.4958	56.2615	65.2139	167.9712	6.9125	5.0688	1.6034	13.5847
8	27	46.9356	54.9012	67.5073	169.3441	5.2572	4.7996	1.7353	11.7922
13	46	50.5712	50.7735	58.2038	159.5484	4.9813	5.3069	1.8099	12.0981
18	40	51.8661	64.7920	70.9337	187.5918	2.4869	1.7489	1.6186	5.8543
12	29	53.7838	62.8856	66.8139	183.4833	3.5817	2.8043	1.2455	7.6315

WEEK 7

DATA

PLOT	STD1	STD2	CM25	CM50	CM75	CM100
11	23447.	23776.	13649.	11424.	16978.	21979.
26	23731.	23454.	11867.	15794.	17726.	15528.
17	23326.	23595.	13752.	15318.	15866.	18306.
48	23291.	23842.	12565.	16781.	14744.	12351.
22	23887.	23777.	14643.	17872.	17830.	21394.
37	23867.	23092.	13381.	14072.	10713.	20634.
4	24086.	23228.	13733.	11441.	10739.	20766.
33	24102.	23303.	12556.	16393.	14012.	15276.
5	23727.	23321.	12896.	14977.	16303.	18525.
25	24058.	23091.	12028.	16837.	16309.	17241.
15	24138.	23713.	12592.	12896.	17415.	20890.
42	23792.	24024.	11635.	16105.	14017.	20969.
14	23788.	23339.	11675.	15372.	17702.	19777.
39	23649.	23652.	12054.	14446.	17756.	16991.
2	23550.	23459.	13297.	12775.	15997.	17189.
30	23859.	23336.	12267.	11816.	18411.	16670.
8	23247.	23519.	12244.	10693.	17832.	21993.
27	24019.	23369.	12123.	15924.	14531.	19891.
13	23868.	23791.	11652.	14556.	9022.	20672.
46	23384.	23573.	11422.	11770.	17613.	19258.
18	23627.	23762.	12814.	16508.	17677.	18279.
40	23300.	23770.	11869.	15147.	19777.	19583.
12	23351.	23129.	12177.	15873.	16464.	19346.
29	23892.	23583.	12136.	16370.	18548.	18878.

CRATIO

CM25	CM50	CM75	CM100
0.57807	0.48383	0.71906	0.93086
0.50300	0.66945	0.75134	0.65818
0.58618	0.65293	0.67629	0.78029
0.53317	0.71207	0.62563	0.52409
0.61443	0.74992	0.74815	0.89770
0.56990	0.59933	0.45627	0.87881
0.58050	0.48362	0.45395	0.87780
0.52973	0.69161	0.59116	0.64449
0.54821	0.63667	0.69304	0.78749
0.51021	0.71420	0.69181	0.73134
0.52630	0.53901	0.72788	0.87313
0.48666	0.67362	0.58629	0.87707
0.49547	0.65236	0.75125	0.83931
0.50967	0.61081	0.75077	0.71842
0.56572	0.54351	0.68059	0.73131
0.51984	0.50073	0.78021	0.70643
0.52363	0.45730	0.76261	0.94056
0.51165	0.67207	0.61328	0.83950
0.48897	0.61084	0.37861	0.86750
0.48649	0.50131	0.75018	0.82024
0.54080	0.69670	0.74604	0.77144
0.50431	0.64359	0.84032	0.83208
0.52397	0.68300	0.70843	0.83244
0.51126	0.68963	0.78138	0.79528

MM

CM25	CM50	CM75	CM100
0.19269	0.16128	0.23969	0.31029
0.16767	0.22315	0.25045	0.21939
0.19539	0.21764	0.22543	0.26010
0.17772	0.23736	0.20854	0.17470
0.20481	0.24997	0.24938	0.29923
0.18997	0.19978	0.15209	0.29294
0.19350	0.16121	0.15132	0.29260
0.17658	0.23054	0.19705	0.21483
0.18274	0.21222	0.23101	0.26250
0.17007	0.23807	0.23060	0.24378
0.17543	0.17967	0.24263	0.29104
0.16222	0.22454	0.19543	0.29236
0.16516	0.21745	0.25042	0.27977
0.16989	0.20360	0.25026	0.23947
0.18857	0.18117	0.22686	0.24377
0.17328	0.16691	0.26007	0.23548
0.17454	0.15243	0.25420	0.31352
0.17055	0.22402	0.20443	0.27983
0.16299	0.20361	0.12620	0.28917
0.16216	0.16710	0.25006	0.27341
0.18027	0.23223	0.24868	0.25715
0.16810	0.21453	0.26011	0.27736
0.17466	0.22767	0.23614	0.27748
0.17042	0.22988	0.26046	0.26509

VOLUMES

PLOT	VOLUME CM25-50	VOLUME CM50-75	VOLUME CM75-100	TOTVOL CM25-100
11	40.7382	49.0594	70.1322	159.9298
26	49.1246	60.0996	60.2573	169.4815
17	52.3602	55.2547	59.7015	167.3164
48	54.5922	56.7099	47.1425	158.4446
22	58.7995	62.3708	66.5278	187.6982
37	52.4727	42.6206	49.1481	144.2414
4	45.2118	37.2600	51.0056	133.4774
33	54.1509	53.8253	48.9767	156.9529
5	49.8356	55.3836	61.1814	166.4006
25	53.5865	59.1539	57.8689	170.6093
15	42.4043	52.3277	67.7733	162.5053
42	52.5086	52.1365	56.0900	160.7351
14	48.3923	58.7224	66.1845	173.2992
39	45.6858	57.1952	63.1426	166.0236
2	44.2621	50.7516	60.2796	155.2933
30	38.1940	53.5620	66.6524	158.4083
8	36.5654	49.9825	73.5779	160.1257
27	52.5894	53.3280	56.8082	162.7256
13	52.0081	39.9546	43.1937	135.1564
46	38.1043	51.9537	68.1049	158.1629
18	52.5879	60.5665	63.1079	176.2624
40	46.5215	62.3413	72.0143	180.8771
12	52.0217	58.0980	62.7148	172.8345
29	50.6678	61.8621	66.2036	178.7334

DIFFERENCES WEEK 7- 6

DIFF CM25-50	DIFF CM50-75	DIFF CM75-100	TOTDIFF CM25-100
5.3264	4.2710	-0.3570	9.2404
2.4630	2.8801	2.0621	7.4052
2.2070	2.5094	4.2770	8.9935
3.6457	5.3160	5.2771	14.2388
2.8377	4.3030	4.2104	11.3511
5.1199	7.1604	3.8848	16.1651
7.3719	5.8338	1.0827	14.2884
1.6411	2.5027	4.4812	8.6250
4.3569	5.5546	3.8770	13.7885
3.4615	4.8663	3.8655	12.1932
6.3630	3.8536	0.8290	11.0457
2.9345	6.3419	6.0026	15.2790
1.7274	2.3260	3.0922	7.1456
3.7037	2.7683	0.5916	7.0636
6.2594	5.1827	1.6774	13.1195
4.2761	3.0266	1.8186	9.1212
3.3950	3.0909	0.9446	7.4305
1.3214	3.4010	3.6839	8.4063
3.8246	4.5226	3.5441	11.8913
7.2053	5.1161	1.5648	13.8862
0.2390	2.4618	4.6472	7.3481
4.3838	4.2144	2.0979	10.6961
2.2771	2.8984	2.5486	7.7242
2.6009	2.9128	2.1607	7.6745

PLOTS	VOLUME DIFFS				DIFFERENCE DIFFS			
11 26	44.9314	54.5795	65.1947	164.7056	3.8947	3.5755	0.8526	8.3228
17 48	53.4762	55.9823	53.4220	162.8805	2.9264	3.9127	4.7771	11.6162
22 37	55.6361	52.4957	57.8380	165.9698	3.9788	5.7317	4.0476	13.7581
4 33	49.6813	45.5427	49.9911	145.2151	4.5065	4.1682	2.7820	11.4567
5 25	51.7111	57.2688	59.5252	168.5050	3.9092	5.2104	3.8713	12.9909
15 42	47.4565	52.2321	61.9317	161.6202	4.6488	5.0978	3.4158	13.1623
14 39	47.0390	57.9588	64.6635	169.6614	2.7156	2.5471	1.8419	7.1046
2 30	41.2280	52.1568	63.4660	156.8508	5.2678	4.1046	1.7480	11.1204
8 27	44.5774	51.6552	65.1930	161.4257	2.3582	3.2460	2.3142	7.9184
13 46	45.0562	45.9541	55.6493	146.6596	5.5150	4.8193	2.5545	12.8888
18 40	49.5547	61.4539	67.5611	178.5697	2.3114	3.3381	3.3726	9.0221
12 29	51.3447	59.9800	64.4592	175.7840	2.4390	2.9056	2.3547	7.6993

Appendix 3: Interactions from Chapter 3.

a) From Table 3.2:

8 December, 50 - 75 cm profile : SxI*

	I0	I1	
S0	4.05	0.77	S.E. 0.35
S1	3.18	2.72	C.V. % 45

15 December, 75 - 100 cm profile : ExI**

	I0	I1	
E0	2.04	-9.12	S.E. 0.57
E1	3.34	-1.26	C.V. % -
E2	2.08	-1.12	

ExS**

	S0	S1	
E0	-0.49	-6.59	S.E. 0.57
E1	0.20	1.88	C.V. % -
E2	0.05	0.91	

22 December, 27 - 50 cm profile : ExI*

	I0	I1	
E0	1.20	5.42	S.E. 0.63
E1	0.95	10.54	C.V. % 43
E2	0.61	6.20	

29 December, 25 - 50 cm profile : ExI**

	I0	I1	
E0	0.96	1.98	S.E. 0.23
E1	0.87	3.69	C.V. % 31
E2	0.43	4.77	

SxI*

	I0	I1	
S0	1.20	3.18	S.E. 0.19
S1	0.31	3.77	C.V. % 31

50 - 75 cm profile : SxI*

	I0	I1	
S0	1.54	1.36	S.E. 0.40
S1	0.85	3.37	C.V. % 78

25 - 100 cm profile : SxI*

	I0	I1	
S0	4.50	5.72	S.E. 0.82
S1	3.00	9.88	C.V. % 49

Appendix 4: Leaf water potential measurements.

All flag leaf water potentials were determined using the pressure chamber method similar to Dougherty (1973). Plant samples were collected at 0500 hours and thereafter at 0130 hour intervals until 2130 hours and again at 0500 hours the next morning to complete the 24 hour period. For each sample, 6 mainstems were taken from the two treatments being compared, a total of 24 in all. After severing, the ear-bearing culms were placed inside a plastic bag from which most of the air was expressed and these were placed into an ice cooled chilly bin where they were held until prepared for the pressure chamber. Immediately before a reading was to be taken, the flag leaf was cut from the culm at the leaf and sheath junction. Then two perpendicular cuts were made, one on either side and to within 1.5mm of the midrib, approximately 15mm up from the leaf base, so the lamina outside the midrib projection could be removed. The exposed leaf midrib was then placed through the silicon rubber gland of the pressure chamber lid, the gland tightened to hold the leaf and the lid screwed onto the chamber. Nitrogen gas was then released into the chamber at a rate of 0.6 bars $^{-1}$, which is a similar rate to that used by others (Slavik 1974).

All work was completed on the trial site as the apparatus was housed in a transportable shed. At each sampling time, collection of the material took approximately 5 minutes and each subsequent preparation and reading required around one minute per flag leaf. All sampling times refer to NZST (New Zealand Standard Time).