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Root system management in winter wheat: practices to increase water and nitrogen use

by

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PART A: ABSTRACT

We aimed to quantify some of the key root-shoot relationships and establish the extent to which agronomy can impact on, or potentially manage, root systems in limiting environments. We targeted crops with small to medium-sized leaf canopies (3 to 8 units of green area index (GAI)) that we expected to be more vulnerable to the extremes of soil conditions and agronomic conditions selected, especially under shallow-rooting conditions. Controlled environment experimentation was used to interpret the field observations and extend the range of environments.

The key messages from the agronomic treatments in this study are: (1) Adjusting seed rate (and hence plant population density) had a large, and significant, effect on the size of the root system. There was also a potentially large, though less consistent, effect of seed rate on increasing root distribution at depth. (2) Adjusting the nitrogen fertiliser programme within a range typical of current practice did not have any consistent benefits for root growth and yield, though there is limited evidence for site-specific benefits in root growth and distribution. (3) There were no agronomically important variations in total root size or root distribution in two contrasting varieties. Nevertheless, we feel that some rooting characteristics could be targeted in crop improvement programmes.

Total root length (TRL) varied from 7 to 28 km m^{-2}, whilst root length density (RLD) ranged from 3 to 6 cm cm^{-3} in the plough layer to generally less than 1 cm cm^{-3} below 40 cm. For moderate to good yields, the relationship between TRL and ear number appears to be conservative at between 30 to 35 m of TRL per ear. TRL per unit of GAI and TRL per tonne of grain increased with an increase in yield. Reducing seed rate affected ear number per m^{-2} more than it did TRL or GAI, and TRL per ear increased significantly with a reduction in seed rate. TRL was weakly associated with the total amount of nitrogen available as either residual soil nitrogen or applied fertiliser nitrogen. Nitrogen offtake was more strongly correlated with RLD in the plough layer (0-20 cm soil depth) than with TRL. At low to moderate yielding sites total root size was small (less than 10-15 km m^{-2}) across a wide range of leaf canopy sizes. As the average site yield increased towards moderate to high yields there was evidence for a trade-off between root growth and shoot growth, such that any given yield could be achieved by further increments in either the root system or the leaf canopy.

We developed simple methods of assessing roots in early spring and related results to actual values of TRL and RLD. At mid-tillering there was a good correlation between root counts at the face of a soil pit and the actual RLD. These simple measures were also related to yield and could be developed for growers and agronomists as measures of root and soil condition that would be particularly useful for identifying remedial action for following seasons, rather than changes in the current season.

PART B: SUMMARY REPORT

1. Introduction

This is one of several HGCA-funded studies focusing on different aspects of cereal root growth. In our project, above and below ground growth were compared in a range of shallow-rooting environments likely to limit root growth and subjected to different agronomic treatments. We quantified some of the key root-shoot relationships and established the extent to which agronomy can impact on, or potentially manage, root systems.

Our crops were characterised by small to medium-sized leaf canopies (i.e. 3 to 8 units of green area index (GAI)) that might be vulnerable to the extremes of soil conditions and agronomic treatments selected. Covering the range of situations experienced by farmers resulted in confounding factors such as differential crop establishment, and rates of growth and development that complicated the analysis. However, the controlled environment studies were used to interpret these complex situations. We feel that this is an important step in taking forward our understanding of root systems and their growth and that our spring-time assessments could be used to benchmark root growth for appropriate remedial action.

With the emphasis on soil conditions that encourage shallow rooting, most of our soil coring in the field trials was to a depth of 80 cm, below which there was negligible root growth, as confirmed by soil coring and root counts in soil pits. To widen the application of our work, controlled environment studies extended this depth to 160 cm. This is important considering that individual roots of cereal crops have been recorded as reaching a depth of over 200 cm.

We examined the influence on rooting of three main agronomic factors:

(1) seed rate and plant population,
(2) nitrogen rate and timing, and
(3) variety choice

2. Root system characteristics

Our field-grown crops had values for total root length (TRL) between 7 to 28 km m^{-2}. This range covers well the wide range of TRL typical of wheat at high yielding sites in the UK (i.e. 12 to 32 km m^{-2}). Some of our crops were more limited in growth, and thus well below this range. The range of root length densities (RLD) was wide: from typical values of more than 3 – 6 cm cm^{-3} in the plough layer to generally less than 1 cm cm^{-3} below 40 cm. Under circumstances of very poor rooting, restricted growth down the soil profile and poor to moderate yield, RLD could less than 1cm cm^{-2} even in the plough layer.

Roots are distributed unevenly with the bulk of their length in the surface layers. Root length decreases down the profile, though not always exponentially. At anthesis, we recorded a wider range of root system distributions (down the soil profile) compared to most other studies.

3. Defining the wheat root system

Our results allowed us draw some general conclusions about root system characteristics typical of low or moderately high yielding sites. The values for root growth and associated leaf canopy in Table 1 represent thresholds above and below which the crop will have a tendency towards either a high or low yield, respectively.

Across a wide range of yields, the relationship between TRL at anthesis and ear number appears to be conservative at about 30 to 35 m of TRL per ear: much above 30 to 35 m ear^{-1} appears to be excessive, whilst TRL much below 30 m per ear was evident in low yielding situations. Certainly, a TRL below 20 m per ear is likely to indicate a serious limitation to yield. Other key points to note are that TRL per unit of GAI and TRL per tonne of grain increased at higher yielding sites.

Table 1. Key measures of the root system and leaf canopy at high and low yielding sites

Crop measure	Yield ($t\ ha^{-1}$) Low $<$ 6 t	High $>$ 9 t	Units
Root system			
Maximum size (TRL)	< 12	> 15	$km\ m^{-2}$
Stem extension root growth	< 5	> 6	$km\ m^{-2}$
RLD in plough layer	< 3	> 4.5	$cm\ cm^{-3}$
RLD at depth	< 0.5	> 0.5	$cm\ cm^{-3}$
TRL per GAI	2.3	3.2	$km\ m^{-2}$
TRL per ear	30	35	$m\ ear^{-1}$
TRL per t grain	1.6	1.9	$km\ t^{-1}$
Associated canopy features*			**Units**
Plant population	< 150	> 150	plants m^{-2}
GAI	< 5	> 5	m^2 (leaf) m^{-2} (soil)
Stem extension GAI increase	< 3.5	> 4.5	m^2 (leaf) m^{-2} (soil)
Ear population	< 330	> 450	ears m^{-2}

*These features need to be considered in relation to the influence of agronomic factors such as seed rate and sowing date on canopy size development, as reported elsewhere

4. Influence of agronomic factors on root systems

4.1. Seed rate and plant population density

Adjusting seed rate had as large an influence on the size of the root system, as it did on the size and structure of the leaf canopy. Our field and controlled environment studies strongly suggest that reduced seed rates can increase root length density and the proportion of the total root system below the plough layer, though the results are not consistent across all sites and years. This was partly due the effect of weather and soil on establishment percentage. At higher plant population densities, roots tended to be increasingly concentrated in the upper part of the soil profile.

It appears that under non-restricting soil conditions, a reduced seed rate (compared to a high seed rate) has the potential for increasing water and/or nitrogen uptake below the plough layer by:

(1) an equal or greater total amount of root (as TRL or RLD) at a soil depth of 0 to 40 cm, and/or
(2) both higher absolute and relative root growth between tillering and anthesis at depths below 40 cm, and/or
(3) a higher proportion of its TRL below 40 cm.

However, where total growth (i.e. root length) was very low or if there is evidence of restricted root growth below the plough layer then the effect on reducing seed rate on root distribution is much reduced or absent. We suggest that shallow rooting as a consequence of either a physical barrier to root growth or a moisture deficit could off-set potential benefits of a reduced seed rate *effect* on improved root distribution and water or nitrogen uptake. Thus the degree of change in the root system through seed rate adjustment may not be sufficient to alleviate restricted growth under severely limiting soil or climatic conditions.

A lower plant population might increase the proportion of the root system at depth, through increased intra-plant competition caused by more tillering and thus the number of nodal root axes initiated.

In our experiments, a reduction is seed rate affected ear number relatively more than it did GAI and TRL. This is a consequence of sowing all treatments at the same date (in the same experiment). Our seed rate and plant population results reinforce the view that a TRL per ear much above 30-35 m ear^{-1} is excessive and much below 30 m ear^{-1} is insufficient for high yield. TRL per unit of GAI was more conservative across the seed rate treatments at a particular site than indicated for the high and low yielding sites (in Table 1). That is, some of the crops at reduced seed rates were relatively high yielding and *vice versa*. Total root length per ear increased significantly with a reduction in seed rate. Interestingly, TRL per tonne of yield was remarkably constant at about 2 km m^{-2} t^{-1}, except when rooting was very poor and/or yield was low.

Potential benefits of a *seed-rate enhancement* for improved root distribution, should be considered in relation to sowing date. Other research has indicated that sowing date is important in increasing the growth of roots at depth, especially in soils that are structurally weak or are likely to have a penetration barrier to root growth. Furthermore, at any given sowing date, a reduction in seed rate affected ear number per m^{-2} more than it did TRL or GAI. Therefore, reducing seed number per m^{-2} should be considered in relation to earlier sowing where this enables individual plants to form more ears, as reported elsewhere.

Sowing date depends on the accessibility of the soil. Rooting of winter crops is generally increased by early sowing, though sowing may be delayed by surface wetness or because of the risk of compacting surface soils. If sowing is too late for these reasons, as occurred in 2000-01, the plant population density will be lower than planned and crops have less capacity for compensation, especially if there is a prolonged wet or cold spell after establishment.

4.2. Nitrogen fertiliser and soil moisture

In our field and controlled environment trials we used rates and timing of nitrogen fertiliser typical of good farming practice. Overall, the effects of timing of nitrogen fertiliser on the growth and distribution of roots were small or inconsistent.

Delayed nitrogen application resulted in a yield penalty and was often associated with smaller root systems and leaf canopies. Overall there was evidence that delaying the main spring nitrogen application increased the amount of rooting below the plough layer compared to the very early (autumn) nitrogen. There was no consistent reason for deviations from this pattern although they seemed to be due to a combination of soil type and season.

There was no evidence of agronomically significant interactions between water availability and nitrogen timing. In the field experiments there was less impact of experimental manipulation of water availability (via contrasting soil texture, or a combination of guttering to allow water to run-off plots and irrigation) on crop growth than expected, though for equivalent sized root systems a non-irrigated treatment or higher soil moisture deficit was generally associated with a significant yield penalty.

In the controlled environment experiments, which removed much of the inherent variability in soils and climate, there were much larger differences in TRL and the distribution of RLD between different nitrogen timings and drought *versus* non-drought conditions. It appears that early spring nitrogen supply resulted in more root growth above 80 cm by growth stage 33, whilst delaying the main application resulted in less root growth in the plough layer at this stage. Although differences were small by anthesis, most of the crop nitrogen had already been taken up by that time. Previous research looking at a wider range of nitrogen treatments has indicated stronger responses of root systems to soil nitrogen availability and applications of nitrogen fertiliser.

Across all field trials TRL was weakly associated with the total amount of nitrogen available as either residual soil nitrogen or applied fertiliser nitrogen: increasing from an average of 10 km m^{-2} at a total N supply of 200 kg ha^{-1} to 18 km m^{-2} at 290 kg N ha^{-1}.

Nitrogen offtake above-ground (i.e. leaves + stems) at anthesis was weakly correlated with TRL but increased by approximately 3.5 kg N (offtake) ha^{-1} per km m^{-2} increment in TRL, between a range of TRL from 5 to 25 km m^{-2}. Nitrogen offtake at anthesis was positively correlated with RLD in the plough layer (0-20 cm soil depth), though below 20 cm no trend was apparent. As expected, GAI and yield were strongly related to nitrogen offtake across all our site and season combinations.

4.3. Variety choice and potential for crop improvement

This project compared two genotypes, Consort and Malacca which were respectively two of the most popular nabim Group 3 and Group 1 varieties. There did not appear to be agronomically significant differences in rooting between these two varieties. In the field, differences in root growth and distribution between Consort and Malacca were relatively small, and tests of these, and other, varieties under a wide range of climatic and soil conditions would be required for any significant differences to be identified. In the controlled environment, Consort had a higher total root length and evidence of a higher RLD than Malacca at soil depths of 60 to 100 cm.

Other work on much wider selections of genotypes in wheat (and barley), suggest that there is significant variability in root traits. This is evident even in modern wheat varieties recently on the Recommended Lists, as reported elsewhere and suggested by the controlled environment studies here. Genotypic differences in root morphology and physiology (including nutrient acquisition and allocation of root-shoot resources) reported in the literature have mainly been linked to differences in yield under unfavourable growing conditions. A variety with at least a two-fold increase in the amount of rooting at depth, i.e. equivalent to the degree of change in our seed rate experiments, may be a useful target for a future breeding programme.

5. Relationships between root and shoot growth

Although effects of changes in root characteristics on yield were difficult to establish because of the ways in which the changes in rooting on yield were mediated through the more direct influence of the leaf canopy, it is possible to establish some important benchmarks for TRL, RLD and GAI.

Of most interest is the relationship between the root system and leaf canopy. It is clear that root-shoot relationships differ between sites. At low to moderate yielding sites (6 to 8 t ha^{-1}) total root size may be small i.e. less than 10-15 km m^{-2} across a wide range of leaf canopy sizes. As the average site yield increases towards moderate to high yields (8 to 10 t ha^{-1}) there is evidence for a trade-off between root and shoot growth, such that any given yield could be achieved by further increments in either the root system or the leaf canopy. This does not appear to be the case at lower yielding sites. As such there could be a negative correlation between root system size and leaf canopy size. Thus the general trend for yield to be associated with increases in both total root length and GAI across all sites was rather weak.

By contrast, the correlation between yield and TRL is much stronger, particularly when TRL is measured at mid-tillering (GS23). This is consistent with the view that yield stability is correlated with TRL, though under different conditions similarly yielding crops could have different sized root systems. Although TRL per unit of GAI was quite conservative across many of our treatment, this hides some significant variation between sites and seasons. On average, TRL per unit of GAI increases with mean site yield.

At anthesis, GAI was strongly related to RLD in the plough layer (0-20 cm). Thus there was a good correlation between root length density in the plough layer and yield. Although RLD at depth was less related to yield in these field trials, this may not be the case in higher yielding crops in deeper soils or soils prone to late drought, in which rooting below the plough layer is important for maintaining high yields. Furthermore, our results suggest that the amount of change in either total root length or GAI or both during stem extension is positively correlated with yield potential.

6. Measuring root systems and implications for crop and soil assessment

We were able to investigate how simple measures of root growth could:

(1) relate to actual values of TRL or RLD estimated from the more time consuming and expensive research methods,
(2) be used by growers and agronomists as a management tool, and
(3) be more closely linked to yield.

At mid-tillering (GS23), there was a good correlation between root counts at the face of a soil pit and the actual RLD measured at GS23, though the correlation between the two was weaker at GS69. The number of root axes per plant was poorly correlated with TRL and RLD: as expected this measure needs to take into account the plant population density. However, the number of root axes per m^2 can be estimated if the plant population density is known. Although this measurement can be made more quickly than counting roots at various depths in a soil pit, the correlation between the number of root axes per m^2 and RLD at GS23 was relatively weak.

Positive relationships between root growth and yield suggested that simple measures of root growth at early to mid tillering could be used by farmers and agronomists to trigger action either in the current season, or more likely in the following one, to alleviate poor crop growth.

The number of root axes per m^2 was moderately correlated with yield, whereas the actual RLD was strongly correlated with yield. The robustness of the correlation between RLD (estimated at mid-tillering) and yield across different soil types and seasons, suggests that a simple measure of RLD would be helpful to advise on crop and soil condition.

The relatively simple methods we have described should help to better quantify existing scoring systems for root abundance and soil condition. If proven to be robust across other sites and seasons, then a measure that is correlated with RLD would be a good index of at least the upper root system density and should assist in quantifying soil fertility and physical condition. It would also provide a way of monitoring change in soil quality over time. Early spring root measurements may only diagnose a problem rather than lead to remedial action in the same season but may benefit management in following seasons. Appropriate root measurements and soil inspection can help in appraising the risks of adverse soil conditions such as compaction.

7. Concluding remarks

The key messages from the agronomic treatments in this study are:

(1) Adjusting seed rate (and hence plant population density) has a large, and significant, effect on the size of the root system. There is also a potentially large, though less consistent, effect of seed rate on improving root distribution down the soil profile. However, this must be considered in relation to sowing date so as not to compromise on leaf canopy size and ear population.

(2) Adjusting the nitrogen fertiliser programme within a range typical of current practice does not have any consistent in-season benefits for root growth and yield, though there is limited evidence for site-specific benefits in root growth.

(3) At present, variety choice offers limited scope for inducing agronomically significant variations in total root size or root distribution. Nevertheless, research from this project and elsewhere has suggested some candidate rooting traits that could be targeted in crop improvement programmes.

Our data showing the wide variation in root system size and distribution independent of canopy size, mean that the concept of root limitation is difficult to quantify. Because there may be differences in the relative resource availability between sites, a root system which can supply the shoot adequately in one place may be limiting in another.

Our results support the view that it is not the absolute size of the root system which determines a limitation to leaf canopy growth because a root system which is usually adequate may become limiting with a change in soil conditions e.g. drought. Soil limiting conditions such as poor soil structure tend to show most in late-sown autumn crops where root systems are less extensive, or in spring crops where the shorter period of growth and greater overlap of shoot and root growth reduce the range of plant responses.

TECHNICAL REPORT

Introduction

Research in agronomy and crop physiology funded by the Home-Grown Cereals Authority has emphasised the prime importance of leaf area in determining growth rate and yield, and has resulted in the identification of a target leaf (green) area index and management practices that can be used to achieve it (i.e. Canopy Management). The HGCA-funded review on 'Management of Cereal Root Systems' (Lucas, Hoad, Russell & Bingham; HGCA Research Review No. 43 identified the need for: (1) a better understanding of root systems in UK crops and (2) establishing the potential for managing cereal root systems so that crops are better able to cope with soil limitations. It was felt that benefits to the whole crop are most likely where roots can be modified to improve water and nitrogen use under circumstances of poor soil exploration because of shallow root development or under soils prone to drought and thus inefficient use of nitrogen.

While the contribution of canopy structure to yield is now well understood, much less is known about how yield is affected or limited by the root system. We know that some management decisions such as sowing date, and cultivations that improve soil structure, can affect the rooting pattern of cereals, but it is not clear what the circumstances would be, if any, in which changes to other practices such as seed rate and variety choice would be beneficial under UK conditions.

The effects of farming practices on rooting can be direct or mediated through changes in the soil or on the above-ground parts of the crop. There is a complex and incompletely understood functional inter-dependence of the shoot and root. Much of our lack of understanding about the potential for manipulating roots in the field is because we do not know enough about the target root size for optimum crop growth. We know that some management practices have benefits for the root environment or roots themselves. Cultivation methods such as sub-soiling are used to alleviate problems of soil structure and root growth, and some PGRs have been shown to increase root proliferation and resistance to lodging. Other practices such as rotational position, seed rate and time of sowing also affect the growth of a root system, and there is and there is evidence for genotypic variation in water use and nitrogen use (e.g. Lucas et al. 2000). However, as yet, we have not explored the potential for general agronomic approaches to root management that have benefits for crop growth and yield similar to those provided by 'Canopy Management'.
In our project we examined the influence on rooting of three main agronomic factors:

(1) seed rate and plant population,
(2) nitrogen rate and timing, and

(3) variety choice

Plant population could affect root development in several ways, for example higher plant densities roots may increase the concentration of roots in the upper part of the soil. We need to establish if modification to plant population by adjustments to seed rate can provide opportunities to influence root growth so that by early spring the crop has greater potential to respond to soil and climatic changes later in the season. Likewise, nitrogen can affect the growth and structure of roots (Lucas et al. 2000), but we need establish the potential to manage nitrogen fertiliser in ways to encourage better distribution of roots. For example, if rooting is too shallow we would need to encourage deeper rooting or better root distribution in anticipation of future water availability problems. Conversely, we need to discourage excessive proliferation under situations where the root system is already adequate.

The overall aim of this project was to examine the potential for managing root systems, especially in a range of shallow-rooting, or potentially dry environments likely to limit root growth and the uptake of water and nitrogen uptake.

Specific objectives were:
(1) To define the characteristics of winter wheat root systems under a wide range of conditions through a twin-track approach of field trials and controlled environment studies.
(2) Examine effects of seed rate (plant population density) on root characteristics across a range of soil conditions, and test how far seed rate can be used as a tool to modify roots.
(3) Examine effects of nitrogen supply and soil type or soil moisture on root characteristics
(4) To establish relationships between the leaf canopy, root growth and yield.
(5) To establish the extent to which a visual assessment of the root system in the spring can be used as a basis for management decisions.

This project used a twin-track approach of field and controlled environment studies. We believed this to be the most effective way of establishing the wide range of growing conditions necessary for a better understanding of root systems and to define, or benchmark, root system growth in relation to canopy growth and yield.

MATERIALS AND METHODS

General details and introduction to field studies (A to F) and controlled environment studies (G to I)

The objectives were addressed using a twin-track experimental approach of field trials and controlled environment studies. The experimental approach focused on agronomy and physiology to provide levels of detail for: (1) understanding of root systems in the field and (2) guidelines or benchmarks for root system measurement and potential management. The range of methods employed reflected the need to develop in-depth understanding as well as practical advice.

A series of nine experiments – six field trials and three controlled environment experiments – were carried out over three years, 2000-01, 2001-02 and 2002-03. SAC and Harper Adams University College conducted field experiments and the University of Edinburgh carried out glasshouse studies (Table M1). The experimental programme was designed to investigate the effect of agronomic factors on the growth of root systems and their relationship with leaf canopies and yield. In each experimental year, a series of core treatments or main factors was included in the work of each partner. Furthermore, each partner had responsibility for other treatments and different measurements of the root system and crop growth.

Most of the work was carried out on the variety Consort. This nabim Group 3 variety was selected because of its importance in terms of the UK wheat area at the time of commencement of the Project. In the final year, Malacca, a nabim Group 1 variety, was added for comparison.

General agronomic information, sites details, experimental design, measurements and analysis are provided in the individual experimental reports below.

Table M1. Details of the main experimental treatments across the programme of work on effects on agronomic factors on the growth of root systems and their relationship with leaf canopies and yield.

Experiment code	Lead partner and location	Year	Main treatments and other factors
A	SAC, East Lothian	2000-01	Seed rate and soil type
B	SAC, East Lothian	2001-02	Seed rate, nitrogen timing and soil type
C	SAC, Midlothain	2002-03	Seed rate, nitrogen timing and variety
D	HAUC, Newport	2000-01	Seed rate plus withholding water on yield
E	HAUC, Newport	2001-02	Nitrogen timing plus seed rate and irrigated water supply on yield
F	HAUC, Newport	2002-03	Nitrogen timing and variety plus irrigation and withholding water on yield
G	University of Edinburgh	2000-01	Plant population density limiting/non-limiting water
H	University of Edinburgh	2001-02	Nitrogen timing and limiting/non-limiting water
I	University of Edinburgh	2002-03	Variety choice

Root and shoot growth in the field - Led by SAC and HAUC

Trial locations at the two main sites (SAC, Edinburgh and HAUC, near Newport) were selected on the basis of soil type and the potential for variation in growth and development of root and shoots. To meet our objectives we needed to establish crops with root systems representing the ranges of root size and root distribution typical of those in farmers' fields, and especially those in areas of shallow rooting and/or drought prone soils.

Soil types were chosen to maximise the range of root system responses to dry soils and the changing availability of water and nitrogen. At both sites there were opportunities to compare either light or shallow soils that are freely drained with more moisture retentive soils or to use procedures to limit water supply through its restriction to plots or by irrigation.

The main agronomic treatments were seed rate and nitrogen programme (rate and timing). Seed rate, and thus plant population density, was used to create different root systems and canopy growth and yield in contrasting soil types. The effects of nitrogen fertiliser on the growth of root systems was studied by adjusting the rate and/or timing of nitrogen applied in the autumn or spring.

The main measurements on root systems were total root length (TRL) (km m^{-2}), root length density (RLD) (cm cm^{-3}), root counts per section of soil profile down a soil pit (at HAUC) and the number of visible root axes (at SAC).

Field experiments were designed to establish the range root growth and yield responses to plant population density and soil type, and to also link root growth to assessments of canopy size.

In the spring and post-anthesis, deep soil pits were used with image analysis to produce maps of root distribution throughout the rooting depth (at HAUC). In the spring-dug shallow soil pits (HAUC and SAC) were used in conjunction with counts of root axes (SAC) to establish a methodology for visual assessment that could be used by farmers and crop consultants. This should allow decisions to be based at least on observations of the plough layer and localised canopy and root growth, even if soil pits have not been dug to expose the sub-soil.

Soil cores were be taken from field experiments using either a tractor-mounted corer (at HAUC) or hand-held corer and petrol-driven hammer (at SAC). Harvesting of roots were be done using a specially-designed root washing facility (Root Washer, Delta-T Devices). Roots were measured either by an area meter (type RLS, Delta-T Devices) or bespoke image analysis system.

Crop and root measurements from the field experiments were cross-referenced to the controlled environment studies.

Controlled environment studies:- Led by University of Edinburgh

Work in controlled environments has three advantages which allow it to complement the field trials: 1) conditions can be controlled more closely so that extraneous factors do not complicate the interpretation of the results, 2) the risk of adverse weather is avoided, 3) root system development can be monitored at regular intervals without damaging the crop.

The controlled environment work, in effect, provides the detailed understanding of the functional balance between roots and shoots necessary to interpret the field observations. Observations were carried out on model systems using long columns of soil with a differentiated "plough layer" and "subsoil" as in the field. Where appropriate, the uptake and losses of water and nitrogen will be measured as well as the size of the root system and shoots. Methods for assessing root system size and distribution included image analysis on soil sections throughout the growth of the plants and measuring weight and length after root washing at the end of the experiment, as described for the field work. More detailed sampling will be possible on the plants growing in the controlled environment than in the field.

The work can be divided into: (1) Further interpretation of field studies to define operational and optimal root sizes for the uptake of water and nitrogen under a range of conditions, (2) detailed measurements of how plant population density affects whole plant growth via changes in the root system, (3) Establishing how changes in nitrogen rate and timing affect root characteristics in the spring (e.g. mass, length and distribution) with benefits for subsequent crop growth and (4) Examination of root traits that may be used to develop the visual or quantitative assessments of root systems. This work is essential for correlating visual assessments (for use in the field) with changes in root structure and function according to crop growth stage and agronomic practice.

Experiment A: Effects of soil type and seed rate on the growth of roots and shoots (SAC)

Experimental design

The experiment consisted of two blocks: one in each of a sandy loam and clay loam part of the same field, approximately 100 m distance. In each block the variety Consort was sown at three seed rates, 80, 320 and 640 seeds m^{-2}, replicated in three sub-blocks of nine plots, making a total of 27 plots per block.

Agronomic details

Table M2 shows the agronomic details for the trial of winter wheat (variety: Consort) at Chapel, North Berwick, East Lothian in 2001.

Table M2: Experiment A: Site and agronomic details

Location	Chapel, near North Berwick, East Lothian	
Soil series	Dreghorn	
Soil texture	Clay loam and sandy loam	
Previous crop	Oilseed rape	
Plot size	20 m x 2m	
Sowing date		01 November 2000
Fertiliser	55 kg N ha^{-1} (Extran)	02 April 2001
	47 kg N ha^{-1} (Extran)	09 April 2001
	52 kg N ha^{-1} (Extran)	21 May 2001
Herbicide	0.9 kg ha^{-1} Platform S	11 May 2001
	1.63 l ha^{-1} MCPA	11 May 2001
Growth regulator	None required	
Fungicide	0.4 l ha^{-1} Unix	22 May 2001
	0.4 kg ha^{-1} Opus	22 May 2001
	0.75 l ha^{-1} Landmark	08 June 2001
	0.27 l ha^{-1} Amistar	05 July 2001
	0.32 l ha^{-1} Folicur	05 July 2001
Harvest date		03 Sept. 2001

Soil measurements

A soil sample across the trial site was taken and analysed for pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M3). Soil cores to 90 cm were taken for determination of soil mineral nitrogen (Table M4).

Soil moisture measurements were made and soil moisture deficit (SMD) estimated using a Soil Profile Probe (Delta-T Devices) at weekly intervals from 27 June 2001 (see Results). Access tubes were installed in 3 plots of both the clay loam and sandy loam blocks.

Table M3. Experiment A: Routine soil analysis results at Chapel, North Berwick, East Lothian, sampled to 20 cm on 20 February 2001.

		Index
pH	6.9	-
Phosphorus (mg l^{-1})	32.6	4
Potassium (mg l^{-1})	254	3
Magnesium (mg l^{-1})	123	3
Sulphur (mg l^{-1})	3.5	Mod
Organic matter (%)	3.4	-

Table M4. Experiment A: Soil mineral nitrogen content for Chapel, North Berwick, East Lothian. Sampled on 9 March 2001. Each sample is the bulked sample of three cores at three depths across in the clay loam and sandy loam blocks.

Sample	Sample depth (cm)	Soil mineral nitrogen* (kg N ha^{-1})	Total
Sandy loam A	0-30	36.0	
	30-60	19.4	
	60-90	17.4	72.8
Sandy loam B	0-30	35.2	
	30-60	23.6	
	60-90	17.9	76.7
Clay loam A	0-30	45.2	
	30-60	26.4	
	60-90	17.4	89.0
Clay loam B	0-30	39.6	
	30-60	25.3	
	60-90	23.1	88.0

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

Plant population counts were done at GS 12-13. The number of plants in the row each side of a 0.5 m rule were counted to give the number of plants per metre row. From this the number of plants per metre squared was calculated as ((plants counted * 100cm)/11.5 cm (the row width)). Twelve plants were tagged in two plots. The number of leaves on the main stem and the number of tillers were monitored weekly from tillering to flag leaf emergence. At GS23 and GS69 two shallow soil pits per treatment combination were dug of approximately 90 cm wide and 30 cm deep. Green area index (GAI) was also measured

Soil cores were taken using a 110 cm long corer with an internal diameter of 8cm and a hand-held petrol-driven hammer. Twelve cores were taken per treatment combination (i.e. four cores in three replicated plots), giving a total of 72 cores per sampling date at GS23 and GS69. Before each core was taken a leaf sample for GAI was cut at ground level inside a $0.1m^2$ grid. The root core was taken adjacent to the $0.1\ m^2$ grid. After sampling each core was chopped into 20 cm lengths and frozen until further analysis.

Samples were washed from the core sections (volume of each 20 cm section was $1005.3\ cm^3$) using a Delta-T Root Washer (Delta-T Devices Ltd, Cambridge, UK). The clean root samples sample was then floated on a shallow water filled tray and sub-sampled at 10 – 50 % depending on the amount of roots present. The sub-sample was copied onto acetate sheets and scanned into a digital analysis system using a standard monochrome output camera connected to a Matrox frame grabbing PC mounted imager board. The acetate sheets were back lit and root lengths were recorded as threshold light segments. The sum of the individual root lengths was determined using a library-based length determination algorithm. Calibration was done using standard lines drawn onto an acetate sheet. The error between the actual and estimated lengths was less than 0.3%

Leaf area was measured using a leaf area meter (LiCor 2100). Samples were cut up into leaves and stems and analysed using the conveyor system to give estimates of leaf area. Green area index was calculated. Samples were dried at 80ºC for three days to estimate above ground dry matter. Non destructive leaf area measurements were made in the field using a canopy analysis system (Delta-T).

Just before harvest, the number of ears per $0.1m^2$ were counted at four positions per plot per treatment combination. Stem height was measured at six positions per plot. At harvest the grain yield (as 15% dry matter), and thousand grain weight were measured.

Statistical analysis

ANOVA was used to determine if there were any significant differences (as Least Significant Difference, LSD) in root and canopy growth and yield at any seed rate and soil type combinations.

Experiment B: Effects of soil type, nitrogen fertiliser and seed rate on the growth of roots and shoots (SAC)

Experimental design

The experiment consisted of two blocks: one in each of a sandy loam and clay loam part of the same field, approximately 100 m distance. In each block the variety Consort was sown at two seed rates, 90 and 360 seeds m^{-2}. For each seed rate there were three nitrogen fertiliser treatments: autumn N plus standard programme (210 kg N ha^{-1} in total), standard N programme (160 kg N ha^{-1} in total) and delayed N programme (160 kg N ha^{-1} in total. The six seed rate x N treatment combinations were replicated in five sub-blocks of six plots, making a total of 30 plots per block. The different N treatments were paired in each sub-block. Site and agronomic details are given in Table M5. Full details of the N treatments are given in Table M6.

Agronomic details

Table M5 shows the agronomic details for the trial of winter wheat (variety: Consort) at Chapel, North Berwick, East Lothian in 2001.

Table M5: Experiment B: Site and agronomic details

Location	Chapel, near North Berwick, East Lothian	
Soil Series	Dreghorn	
Soil texture	Clay loam and sandy loam	
Previous crop	Spring barley	
Plot size	20 m x 2m	
Sowing date		24 Sept. 2001
Fertiliser	Refer to Table below	
Herbicide	0.9 l ha^{-1} Panther	16 November 2001
	0.49 l ha^{-1} Optica	16 November 2001
	1.0 l ha^{-1} Cheetah Super	02 May 2002
Growth regulator	2.5 l ha^{-1} 3C Cycocel	16 April 2002
Fungicide	0.4 l ha^{-1} Mirage	16 April 2002
	0.2 kg ha^{-1} Menara	16 April 2002
	0.4 kg ha^{-1} Unix	02 May 2002
	0.4 l ha^{-1} Opus	02 May 2002
	1.0 l ha^{-1} Opera	01 June 2002
	0.33 l ha^{-1} Amistar	28 June 2002
	0.33 l ha^{-1} Folicur	28 June 2002
Harvest date		01 Sept. 2002

Table M6. Experiment B: Nitrogen treatments: Rates, growth stages and dates of application.

N treatment	Seed bed	GS 23	GS 30-31	GS 32
Autumn + Standard N	50 kg N ha^{-1}	50 kg N ha^{-1}	55 kg N ha^{-1}	55 kg N ha^{-1}
Standard N		50 kg N ha^{-1}	55 kg N ha^{-1}	55 kg N ha^{-1}
Delayed N			80 kg N ha^{-1}	80 kg N ha^{-1}
Application date	26 September 2001	16 March 2002	12 March 2002	02 May 2002

Soil measurements

A soil sample across the trial site was taken for analysis of pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M7). Soil cores to 90 cm were taken for determination of soil mineral nitrogen after drilling before seedbed N application (Table M8) and in early spring avoiding plots that had received seedbed N in the autumn (Table M9).

Soil moisture measurements were made and soil moisture deficit (SMD) estimated using a Soil Profile Probe (Delta-T Devices) at weekly intervals from 27 June 2001 (see Results). Access tubes were installed in 3 plots of both the clay loam and sandy loam blocks.

Table M7. Experiment B: Routine soil analysis results at Chapel, North Berwick, East Lothian, sampled to 20 cm on 1 February 2002.

		Index
pH	6.7	-
Phosphorus (mg l^{-1})	54	4
Potassium (mg l^{-1})	223	2
Magnesium (mg l^{-1})	134	2
Sulphur (mg l^{-1})	3.8	Mod
Organic matter (% m m^{-1})	3.2	-

Table M8. Experiment B: Soil mineral nitrogen content for Chapel, North Berwick, East Lothian. Sampled: 22 September 2001. Each sample is the bulked sample of three cores at three depths across in the clay loam and sandy loam blocks.

Sample	Sample depth (cm)	Soil mineral nitrogen* ($kg\ N\ ha^{-1}$)	
			Total
Sandy loam A	0-30	43.3	
	30-60	33.7	
	60-90	29.4	106.4
Sandy loam B	0-30	41.8	
	30-60	324	
	60-90	26.5	100.7
Clay loam A	0-30	49.6	
	30-60	44.1	
	60-90	20.3	114.0
Clay loam B	0-30	46.7	
	30-60	43.7	
	60-90	28.6	119.0

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Table M9. Experiment B: Soil mineral nitrogen content for Chapel, North Berwick, East Lothian. Sampled on 6 March 2002. Each sample is the bulked sample of three cores at three depths across in the clay loam and sandy loam blocks.

Sample	Sample depth (cm)	Soil mineral nitrogen* ($kg\ N\ ha^{-1}$)	
			Total
Sandy loam A	0-30	32.6	
	30-60	20.6	
	60-90	14.7	67.9
Sandy loam B	0-30	33.9	
	30-60	19.5	
	60-90	17.7	71.1
Clay loam A	0-30	42.3	
	30-60	19.3	
	60-90	15.3	76.9
Clay loam B	0-30	40.7	
	30-60	22.9	
	60-90	15.6	79.2

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

Most of the crop assessments were as described in Experiment A. Minor changes are as follows. At GS 23 and GS69 cores were taken from each of the three nitrogen treatments at 90 and 360 seeds m^{-2}

in both the sandy loam and clay loam blocks. Three cores were taken from three replicate plots for each treatment combination.

Above ground biomass was sampled in two replicates per treatment combination for determination of N offtake at GS23 and GS69. Soil moisture measurements were made and SMD estimated using a Soil Profile Probe (Delta-T Devices).

Statistical analysis

ANOVA was used to determine if there were any significant differences in root and canopy growth and yield at any seed rate and nitrogen treatment combination within a soil type.

Experiment C: Effects of nitrogen fertiliser timing and seed rate on the growth of roots and shoots in two varieties, Consort and Malacca (SAC)

Experimental design

The experiment consisted of two varieties, Consort and Malacca sown at two seed rates, 90 and 360 seeds m^{-2} and two nitrogen timings (an early N treatment and a late N treatment). Each treatment was replicated in four randomised blocks.

Agronomic details

Table M10 shows the agronomic details for the trial of winter wheat (varieties: Consort and Malacca) at Boghall Farm, Midlothian near Edinburgh in 2002-03.

Table M10. Experiment C: Site and agronomic details

Location	March Park, Boghall Farm, Midlothian	
Soil series	Winton/Duncrahill	
Soil texture	Loam	
Previous crop	Spring barley	
Plot size	16 m x 2m	
Sowing date		07 October 2002
Nitrogen fertiliser	Early N treatment:	
	100 kg N ha^{-1}	12 March 2003
	50 kg N ha^{-1}	02 May 2003
	Late N treatment	
	50 kg N ha^{-1}	02 May 2003
	100 kg N ha^{-1}	15 May 2003
Herbicide	4.5 l ha^{-1} Swipe	10 April 2003
	0.5 g ha^{-1} Harmony M	15 May 2003
Growth regulator	0.4 l ha^{-1} Moddus	07 May 2003
Fungicide	0.9 l ha^{-1} Sportak Delta	23 April 2003
	0.3 l ha^{-1} Tern	23 April 2003
	0.75 l ha^{-1} Landmark	03 June 2003
	1.0 l ha^{-1} Orka	03 June 2003
	0.8 l ha^{-1} Twist	16 June 2003
	0.4 l ha^{-1} Folicur	16 June 2003
Harvest date		20 August 2003

Soil measurements

A soil sample across the trial site was taken for analysis of pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M11). Soil cores to 90 cm were taken for determination of soil mineral nitrogen (Table M12).

Table M11. Experiment C: Routine soil analysis results at Mark Park, Boghall Farm, Midlothian, sampled to 20 cm on 28 February 2003.

		Index
PH	6.2	-
Phosphorus (mg l^{-1})	18	2
Potassium (mg l^{-1})	357	4
Magnesium (mg l^{-1})	249	4
Sulphur (mg l^{-1})	4.5	High
Organic matter (%)	6.5	-

Table M12. Experiment C. Soil mineral nitrogen content for Mark Park, Boghall Farm, Midlothian on 6 March 2003. Each sample is the bulked sample of three cores at three depths in each of the four blocks.

Sample	Sample depth (cm)	Soil mineral nitrogen* (kg N ha^{-1})	
			Total
Block 1	0-30	33.5	
	30-60	25.2	
	60-90	10.3	69
Block 2	0-30	30.2	
	30-60	20.4	
	60-90	9.5	60.1
Block 3	0-30	31.2	
	30-60	27.5	
	60-90	8.5	67.2
Block 4	0-30	30.6	
	30-60	25.2	
	60-90	10.1	65.9

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

All plant and crop assessments were carried out as described in Experiment A.

Statistical analysis

ANOVA was used to determine if there were any significant differences in root and canopy growth and yield at any seed rate x nitrogen x variety combination.

Experiment D: Effects of seed rate on the growth of roots and shoots, with implications for yield in withholding water (HAUC)

Experimental design

Two adjacent trials were established, each divided into 9 blocks.

Trial One: Each block was divided into 6 plots, two for each of three seed rates. To imitate low moisture conditions guttering was placed between each row of plants in one block in trial One from mid June. The other eight blocks were used to collect soil cores and make crop assessments as described below.

Trial Two: The blocks were structured as in Trial One for soil coring and crop assessments, but three blocks in Trial Two were irrigated using trickle tape (Access Irrigation, Northampton, UK). Irrigation was set to give 3 mm of water per day over 7 minutes. This was running from 19th June 2001 to mid August.

Agronomic details

Table M13 shows the agronomic details for the trial of winter wheat (variety: Consort) at Harper Adams University College (HAUC), Shropshire in 2001.

Soil measurements

A soil sample across the trial site was taken and sent to ADAS Wolverhampton for determination of pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M14). Soil cores to 90 cm were taken for determination of nitrate and ammonium concentration (Table M15).

Soil moisture measurements were made using a Sentek Diviner 2000 probe (Sentek Pty Ltd, Stepney, South Australia) at weekly intervals from 27 June 2001. Access tubes were installed in 10 plots; 5 in irrigated and 5 in ambient Soil moisture deficits are shown in Results calculated using the Silsoe College Irrigation Scheduling Program (Hess, 1995).

Table M13. Experiment D: Site and agronomic details

Location	Flat Nook field at Harper Adams University College	
Soil texture	Bridgnorth Series: Stoneless sandy loam or loamy sand (Beard, 1988)	Trial One
	Newport Series: Very slightly stony sandy loam or loamy sand (Beard, 1988)	Trial Two
Previous crop	Potatoes	
Plot size	10 m x 1.75 m	
Sowing date	Trial One	11 January 2001
	Trial Two	12 January 2001
Fertiliser	40 kg N ha^{-1} (Extran)	26 April 2001
	90 kg N ha^{-1} (Extran)	17 May 2001
	1l ha^{-1} Manganese	12 April 2001
	1l ha^{-1} Manganese	22 May 2001
Herbicide	1l ha^{-1} Ardent	12 April 2001
	2 l ha^{-1} IPU	12 April 2001
	3 l ha^{-1} IPU	10 May 2001
	20 g ha^{-1} Ally	22 May 2001
	0.5 l ha^{-1} Starane	22 May 2001
	1 l ha^{-1} Cheetah	22 May 2001
Insecticide	0.25 l ha^{-1} Cyperkill	12 April 2001
Growth regulator	0.2 l ha^{-1} Moddus	23 May 2001
	1.25 l ha^{-1} Chlormequat	23 May 2001
Fungicide	0.75 l ha^{-1} Landmark	23 May 2001
	0.4 kg ha^{-1} Unix	23 May 2001
	0.75 l ha^{-1} Landmark	13 June 2001
Harvest date	Trial One	23 August 2001
	Trial Two	27 August 2001

Table M14. Experiment D: Routine soil analysis results at Flat Nook, Harper Adams University College, Shropshire. Soil sampled to 20 cm. Sampled: 6 February 2001.

		Index
pH	6.7	-
Phosphorus (mg l^{-1})	74	5
Potassium (mg l^{-1})	167	2
Magnesium (mg l^{-1})	82	2
Organic matter (% m m^{-1})	2.56	-

Table M15. Experiment D: Soil mineral nitrogen analysis for Flat Nook, Harper Adams University College, Shropshire. Sampled: 9 March 2001. Each sample is the bulked sample of three cores at the three depths across three blocks in a trial.

Sample	Sample	Moisture	Nitrate	Ammonium- N	Total N	Soil mineral

	depth (cm)	(%)	(mg kg^{-1} DM)	(mg kg^{-1} DM)	(% DM)	nitrogen* (kg N ha^{-1})	
							Total
Flat	0-30	15.8	11.1	0.9	0.15	48.0	
Nook	30-60	10.8	4.3	0.7	0.08	20.1	
A	60-90	9.8	2.2	0.2	0.05	9.5	77.6
Flat	0-30	15.6	5.7	0.9	0.16	26.0	
Nook	30-60	12.2	3.7	0.8	0.08	17.7	
B	60-90	10.3	2.3	0.3	0.04	10.1	53.8
Flat	0-30	15.5	9.2	0.7	0.15	39.9	
Nook	30-60	12.3	4.7	1.2	0.08	23.3	
C	60-90	9.4	2.3	0.4	0.05	10.7	73.9
Flat	0-30	14.6	8.7	0.7	0.16	37.7	
Nook	30-60	11.9	3.3	1.3	0.08	18.6	
D	60-90	10.2	1.9	0.2	0.04	8.6	64.9
Flat	0-30	15.4	8.2	1.2	0.15	37.3	
Nook	30-60	11.2	4.8	0.7	0.08	22.3	
E	60-90	8.9	2.4	0.4	0.05	11.1	70.7
Flat	0-30	15.9	10.3	1.1	0.15	45.7	
Nook	30-60	11.8	3.2	0.5	0.08	15.0	
F	60-90	10.4	2.5	0.4	0.04	11.5	72.2

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

Plant population counts were done at GS 12-13. The number of plants in the row each side of a 0.5 m rule were counted to give the number of plants per metre row. From this the number of plants per metre squared was calculated as ((plants counted * 100cm)/15cm (the row width)).

Twelve plants were tagged in one block per trial. The number of leaves on the main stem and the number of tillers were monitored weekly from tillering to flag leaf emergence. At GS 23, GS 31 and GS 69 soil coring, soil pits and measurement of Green Area Index (GAI) were done.

At each growth stage six soil pits were dug of approximately 90 cm wide and up to 120 cm deep. Photographs using a digital camera were taken of the roots. Each photograph covered an area of approximately 30 cm^2. The soil pit was divided into a grid of 15 cm x 15 cm squares and the number of roots per grid were counted. Roots were counted in four categories as very fine (< 1 mm), fine (1-2 mm), medium (2-5mm) and coarse (>5 mm) (Gay *et al.,* 1998). In practice most roots were classified as very fine with a few fine roots. The top soil depth of each pit was measured at three positions and an average taken. Samples for assessments of soil type were taken from the top and sub soil. Soil type was assessed using the hand texture method (Gay *et al.,* 1988).

Soil cores were taken using a tractor mounted corer with an internal diameter of 5.2 cm (Geonor MCL 3 soil sampler system, Geonor AS, Roa, Norway). Two cores were taken per plot in each of three blocks in both trial one and two, giving a total of 72 cores per sampling date. Plots 1- 18 in trial one were sampled at all sampling dates. In trial two plots 1-18 were sampled at GS 23 and 31 and plots 37-54 at GS 69. Before each core was taken a leaf sample for GAI was cut at ground level inside a $0.1m^2$ grid. The root core was taken inside the 0.1 m^2 grid area over one of the wheat plants. After sampling each core was chopped into 20 cm lengths and frozen until further analysis.

Samples were washed using a Delta-T Root Washer (Delta-T Devices Ltd, Cambridge, UK). The sample was scanned with a HP flatbed scanner using the associated software, Deskscan II, and subsequently the Delta-T Scan software (Delta-T Devices Ltd, Cambridge, UK) was used to calculate root length. The protocol for scanning roots involved staining with methylene blue, at a concentration of 50 mg l^{-1}, for 30 minutes, washing off excess stain and mounting in glass tray with a little water and scanning at 200 dpi at 170 brightness. Samples were then dried at 50ºC for three days and root dry weight recorded.

Leaf area was measured using a WinDIAS colour image analysis system (Delta-T Devices Ltd, Cambridge, UK). Samples were cut up into leaves and stems and analysed using the conveyor system to give estimates of leaf area. GAI was calculated as leaf area (m^2) / area sampled (0.1 m^2). Leaf samples were dried at 75ºC for three days and dry weight recorded.

To determine above ground dry matter a metre of crop was cut at five positions per plot. The sample was bulked and the fresh weight recorded. A subsample was taken and dried at 105ºC for 2 days and reweighed.

The number of ears per $0.1m^2$ were counted at four positions per plot. Stem height was measured at six positions per plot.

At harvest the grain yield, moisture content, specific weight and thousand grain weight were measured.

Statistical analysis

ANOVA was used to determine if there were any significant differences between seed rates and irrigated, ambient and guttered.

Experiment E: Effects of nitrogen fertiliser and seed rate on the growth of roots and shoots, with implications for yield in changing water supply to crops (HAUC)

Experimental design

A single site was divided into 12 blocks of plots. Four blocks included a water-with holding treatment: this drought simulation was carried out using guttering placed between each row of plants in a standard N treatment at two seed rates (90 and 360 seeds m^{-2}). Gutters were in place from 22nd May 2002. Rain water was collected from the gutters in two of the plots and was measured using a tipping bucket. The amount of water collected over each 24 hour period was recorded on a data logger.

Four blocks were irrigated using trickle tape (Access Irrigation, Northampton, UK). Irrigation was set to give 3 mm of water per day over 10 minutes for each block, if 1 mm of rain was recorded the length of time the irrigation was running was reduced by 50 %. This was running from 12th June 2002 to mid August.

The remaining four blocks were neither irrigated or guttered (i.e. non-irrigated or ambient).

Agronomic details

Table M16. shows the agronomic details for the trial of winter wheat (variety: Consort) at Harper Adams University College (HAUC), Shropshire in 2002. Table M17 shows the nitrogen treatments.

Soil measurements

A soil sample across the trial site was taken and sent to ADAS Wolverhampton for determination of pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M18). Soil cores to 90 cm were taken for determination of nitrate and ammonium concentration after drilling before seedbed N application (Table M19) and in early Spring avoiding plots that had received seedbed N in the Autumn (Table M20).

Soil moisture deficits (SMD's) were calculated using the Silsoe College Irrigation Scheduling Program (Hess, 1995). Weather data was from the Harper Adams University College Weather Station.

Table M16. Experiment E: Site and agronomic details.

Soil texture	Newport Series: Very slightly stony sandy loam or loamy sand	
Previous crop	Potatoes	
Plot size	10 m x 1.75 m	
Sowing date	11 December 2001	
Fertiliser	Nitrogen applications as specified for treatments	
	1 l ha $^{-1}$ Manganese (Manifol)	26 March 2002
	1 l ha $^{-1}$ Manganese (Manifol)	17 May 2002
	1 l ha $^{-1}$ Manganese (Manifol)	12 June 2002
Herbicide	3 l ha $^{-1}$ IPU	26 March 2002
	1 l ha $^{-1}$ Compitox Plus	26 March 2002
	0.7 l ha^{-1} Starane 2	17 May 2002
	15g ha^{-1} Ally	17 May 2002
Insecticide	0.25 l ha $^{-1}$ Toppel	26 March 2002
Fungicide	0.4 kg ha^{-1} Unix	12 June 2002
	1 l ha $^{-1}$ Flamenco	12 June 2002
	0.75 l ha^{-1} Folicur	4 July 2002
	0.75 l ha^{-1} Amistar Pro	4 July 2002
Harvest date		16 August 2002

Table M17. Experiment E: Nitrogen treatments: Rates and dates of application.

N treatment	Seed bed	GS 23	GS 30-31	GS 32
Autumn + Standard N	50 kg N ha^{-1}	50 kg N ha^{-1}	55 kg N ha^{-1}	55 kg N ha^{-1}
Standard N		50 kg N ha^{-1}	55 kg N ha^{-1}	55 kg N ha^{-1}
Delayed N			80 kg N ha^{-1}	80 kg N ha^{-1}
Application date	12 December 2001	2 April 2002	26 April 2002	9 May 2002

Table M18. Experiment E: Routine soil analysis results at Flat Nook, Harper Adams University College, Shropshire. Soil sampled to 20 cm. Sampled: 12 December 2001.

		Index
pH	6.8	-
Phosphorus (mg l^{-1})	68	4
Potassium (mg l^{-1})	153	2-
Magnesium (mg l^{-1})	91	2
Organic matter (% m m^{-1})	2.32	-

Table M19. Experiment E: Soil mineral nitrogen analysis for Flat Nook, Harper Adams University College, Shropshire. Sampled: 12 December 2001. Each sample is the bulked sample of three cores at the three depths.

Sample	Sample depth (cm)	Moisture (%)	Nitrate (mg kg^{-1})	Ammonium- N (mg kg^{-1})	Total N (mg kg^{-1})	Soil mineral nitrogen* (kg N ha^{-1})	
							Total
Flat	0-30	10.0	5.0	0.43	5.43	21.72	
Nook	30-60	10.6	9.4	0.35	9.75	39.00	
A	60-90	14.7	9.0	0.44	9.44	37.76	98.48
Flat	0-30	16.4	9.3	0.40	9.70	38.80	
Nook	30-60	10.9	5.4	0.36	5.76	23.04	
B	60-90	9.1	7.6	0.37	7.97	31.88	93.72
Flat	0-30	15.8	8.1	0.37	8.47	33.88	
Nook	30-60	10.9	8.9	0.32	9.22	36.88	
C	60-90	9.2	6.0	0.24	6.24	24.96	95.72
Flat	0-30	15.6	10.9	0.48	11.38	45.52	
Nook	30-60	12.1	7.9	0.25	8.15	32.60	
D	60-90	9.2	6.0	0.35	6.35	25.40	103.52

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Table M20. Experiment E: Soil mineral nitrogen analysis for Flat Nook, Harper Adams University College, Shropshire. Sampled: 4 March 2002. Each sample is the bulked sample of three cores at the three depths.

Sample	Sample depth (cm)	Moisture (%)	Nitrate (mg kg^{-1})	Ammonium-N (mg kg^{-1})	Total N (% dm)	Soil mineral nitrogen* (kg N ha^{-1})	
							Total
Flat	0-30	14.9	3.2	3.5	0.17	26.6	
Nook	30-60	11.8	3.1	1.1	0.08	16.9	
E	60-90	9.2	3.1	0.3	0.05	13.4	57.0
Flat	0-30	15.1	5.0	1.4	0.16	25.5	
Nook	30-60	10.9	3.5	0.5	0.07	15.8	
F	60-90	8.7	4.0	0.3	0.05	17.2	58.5
Flat	0-30	15.0	5.5	1.2	0.16	26.7	
Nook	30-60	9.6	3.7	0.6	0.07	16.9	
G	60-90	8.8	3.3	0.3	0.05	14.5	58.1
Flat	0-30	13.5	5.4	0.6	0.15	24.0	
Nook	30-60	10.5	4.5	0.6	0.09	20.3	
H	60-90	9.7	4.0	0.3	0.06	17.2	61.4

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

Unless otherwise stated the measurements and assessments are as described in Experiment D.

Four plants in each plot in blocks 3 and 8 were tagged. The number of leaves on the main stem and the number of tillers were monitored weekly from tillering to flag leaf emergence. At GS 23, GS 31 and GS 69 soil coring and measurement of Green Area Index (GAI) were done. At GS 23 and 69 soil pits were dug.

At GS 23 eight soil pits in the ambient plots (blocks 9 and 12) were dug of approximately 90 cm wide and up to 80 cm deep in the autumn + standard N treatment and the delayed N treatment at both the 90 and 360 seed rates. At GS 69 the same eight plots in the ambient blocks were dug and another eight soil pits were dug in the irrigated plots (blocks 10 and 11). Photographs using a digital camera were taken of the roots. Each photograph covered an area of approximately 30 cm^2.

At GS 23 cores were taken from each of the three nitrogen treatments at the 360 seed rate in three of the ambient blocks. Three replicate cores were taken from each of the plots. At GS 31 cores were taken in the standard N treatment plots at the 360 seed rate only. At GS 69 cores were taken in the three ambient blocks and in three of the irrigated blocks. Before each core was taken a leaf sample for GAI was cut at ground level inside a $0.1m^2$ grid. The root core was taken inside the $0.1\ m^2$ grid area over one of the wheat plants. After sampling each core was chopped into 20 cm lengths and frozen until further analysis.

Before harvest the number of ears per $0.1m^2$ were counted at four positions per plot and stem height was measured at six positions per plot.

Statistical analysis

ANOVA was used to determine if there were any significant differences between nitrogen treatments and seed rates separately in the ambient, irrigated, and guttered blocks.

Experiment F: Effects of nitrogen fertiliser timing on the growth of roots and shoots in two varieties, Consort and Malacca, with implications for yield in adjusting seed rate and changing water supply (HAUC)

Experimental design

One block of eight plots was irrigated using trickle tape (Access Irrigation, Northampton, UK). Irrigation was set to give 3 mm of water per day over 10 minutes, if 1 mm of rain was recorded the length of time the irrigation was running was reduced by 50 %. This was running from 10 June 2003 to mid August. To imitate drought conditions, shelters were placed over one block of eight plots. Shelters were in place from 21 May 2003.

Agronomic details

Table M21 shows the agronomic details for the trial of winter wheat (varieties: Consort and Malacca) at Harper Adams University College (HAUC), Shropshire in 2003. Table M22 shows the nitrogen treatments.

Soil measurements

A soil sample across the trial site was taken and sent to ADAS Wolverhampton for determination of pH, phosphorus, potassium and magnesium concentration and percentage organic matter (Table M23). Soil cores to 90 cm were taken for determination of nitrate and ammonium concentration in early Spring (Table M24).

Table M21. Experiment F: Site details and agronomic treatments.

Soil texture	Newport Series: Very slightly stony sandy loam or loamy sand	
Previous crop	Peas	
Plot size	10 m x 1.75 m	
Sowing date	5 November 2002	
Fertiliser	Nitrogen applications as specified for treatments	
	1 l ha $^{-1}$ Manganese (Manifol)	18 March 2003
	1 l ha $^{-1}$ Manganese (Manifol)	24 June 2003
Herbicide	2.52 l ha $^{-1}$ Cordelia 2	18 March 2003
	0.52 l ha $^{-1}$ Trooper	18 March 2003
	0.52 l ha^{-1} Ardent	18 March 2003
	1 l ha^{-1} Starane 2	24 June 2003
	30 g ha^{-1} Ally	24 June 2003
Insecticide	0.252 l ha $^{-1}$ Permasect	18 March 2003
Fungicide	1 l ha^{-1} Eclipse	24 June 2003
Harvest date		14 August 2003

Table M22. Experiment F: Nitrogen treatments: Rates and dates of application.

N treatment	Application rate	Product	Application date
Early N	100 kg N ha^{-1}	Nitroprill	3 April 2003
Late N	50 kg N ha^{-1}	Nitroprill	1 May 2003
	50 kg N ha^{-1}	Nitroprill	5 May 2003

Table M23. Experiment F: Routine soil analysis results at Flat Nook, Harper Adams University College, Shropshire. Soil sampled to 20 cm. Sampled: 20 December 2002.

		Index
pH	7.2	
Phosphorus (mg l^{-1})	77	5
Potassium (mg l^{-1})	161	2
Magnesium (mg l^{-1})	99	2
Organic matter (% m m^{-1})	2.53	

Table M24. Experiment F: Soil mineral nitrogen analysis for Flat Nook, Harper Adams University College, Shropshire. Sampled: 10 March 2003. Each sample is the bulked sample of three cores at the three depths.

Sample	Sample depth (cm)	Moisture (%)	Nitrate-N (mg kg^{-1})	Ammonium- N (mg kg^{-1})	Total N (mg kg^{-1})	Soil mineral nitrogen* (kg N ha^{-1})	
							Total
Flat	0-30	15.8	7.7	1.2	8.9	35.6	
Nook	30-60	14.2	10.9	1.1	12.0	48	
A	60-90	12.6	3.8	0.9	4.7	18.8	102.4
Flat	0-30	16.4	5.6	1.9	7.5	30	
Nook	30-60	14.0	4.9	1.8	6.7	26.8	
B	60-90	11.6	3.5	1.7	5.2	20.8	77.6
Flat	0-30	15.9	8.0	1.8	9.8	39.2	
Nook	30-60	12.6	6.2	1.7	7.9	31.6	
C	60-90	10.2	4.0	1.7	5.7	22.8	93.6
Flat	0-30	15.3	7.8	1.8	9.6	38.4	
Nook	30-60	13.2	7.5	1.7	9.2	36.8	
D	60-90	12.1	4.6	2.1	6.7	26.8	102
						Total	375.6
						Mean	93.9

*Soil mineral nitrogen calculated from soil nitrate and ammonium results.

Root and shoot measurements

Unless otherwise stated the measurements and assessments are as described in Experiment B.
Four plants in sixteen plots were tagged. The number of leaves on the main stem and the number of tillers were monitored weekly from tillering to flag leaf emergence. At GS 23 and GS 69 soil coring and measurement of Green Area Index (GAI) were done and soil pits were dug. At GS 23 and GS 69 eight soil pits were dug of approximately 90 cm wide and up to 80 cm deep. Photographs using a digital camera were taken of the roots. Each photograph covered an area of approximately 30 cm^2.

At GS 23 and GS 69 cores were taken from each of the nitrogen treatments at the 360 seed rate for the two varieties in three of the ambient blocks. Three replicate cores were taken from each of the plots. Before each core was taken a leaf sample for GAI was cut at ground level inside a 0.1m^2 grid. The root core was taken inside the 0.1 m^2 grid area over one of the wheat plants. After sampling each core was chopped into 20 cm lengths and frozen until further analysis.

Soil moisture deficits were calculated using the Silsoe College Irrigation Scheduling Program (Hess, 1995). Weather data was from the Harper Adams University College Weather Station and the SMD's are shown for the period 01/03/03 to 13/08/03 in Appendix A, Table A1 for the ambient plots and Table A2 for the sheltered plots.

Statistical analysis

A 2x2x2 ANOVA was used to determine if there were any significant differences between nitrogen treatments, seed rates and variety for the number of roots in the soil pits and for the harvest data. As some of the data was non-parametric, this was analysed using a Kruskal-Wallis one way anova.

Experiment G to I: Effects of plant population density, nitrogen, withholding water and variety (Consort and Malacca) on root and shoot growth under controlled environment conditions (University of Edinburgh)

Experimental set-up

Experiments were performed in three years in an unheated glasshouse in Edinburgh which had automatic vents to prevent excessively high temperatures being reached. The wheat plants were grown in long plastic tubes. These were 0.11 m in diameter and 1.20 m tall. In the first year, tubes of 0.16 m diameter were also used to enable a low plant population density to be simulated. The tubes were halved longitudinally and then taped together before being filled with the growing medium. A fine nylon mesh material was stretched over the base of the tubes and held in place with strong rubber bands cut from a car tyre inner tube and a thin layer of sand was added to promote drainage. The aim was to simulate a eutric cambisol which occurs in many of the UK arable areas. This was done by filling the bottom 0.90 m with an artificial soil low in organic matter and the top with the same mix except that the organic matter content was increased to simulate topsoil. The soil mix was improved each year in the light of experience. In the first year, there was too much organic matter which resulted in excessive nitrogen mineralisation. Functionally the soils acted as if they were sandy loam in texture. Filling the tubes was carried out with care, soil being added in about 0.1 m increments, tamped down with a home-made tool and then scarified on the surface before the next layer was added. The tubes were attached to a secure metal frame and stood in pot trays. The tubes were prepared some time before the plants were added and were wetted and allowed to return to field capacity after which time the trays were emptied of water. Once the plants had several leaves, the soil surface was covered with course gravel to prevent damage to the soil surface by watering and to minimise evaporative losses.

In the first year, five blocks of eight tubes (4 long ×2 wide) were arranged round three sides of a rectangle. In the second and third years they were arranged in a south facing row of five blocks of six (2 long ×3 wide). There was a tube width gap between tubes to permit access. In all cases the tubes were closely packed and were surrounded by 50 mm thick expanded polystyrene insulation to minimise diurnal temperature changes in the soil. Nets and reflective panels were used to mimic the effect of a surrounding crop. These were raised as the crop grew to avoid shading the plants. Trays of wheat plants were grown at either end of the line to act as guards.

In the first year, seeds were sown directly into the tubes but the duration of vernalising temperatures in the unheated glasshouse turned out to be insufficiently long for floral initiation. In the two subsequent years, seeds were sown in trays at weekly intervals in February and left outdoors in a cold frame. At transplanting time, the batch nearest growth stage 12 were chosen. These had been exposed as seedlings to three weeks of cool temperatures. Uniform seedlings were selected and randomly allocated one to each tube. Surplus plants were kept until it was clear that all the seedlings had established. In fact, all seedlings thrived. In the first year, tubes with 1, 2 or 3 plants were used to generate a range of plant population densities.

Air temperature was recorded by a shielded thermometer in the roof of the glasshouse and is likely therefore to be an over-estimate. The estimated mean daily temperature typically ranged from 10ºC in March to 17ºC in July. These compare with 6.5ºC and 17ºC for Reading.

The tubes were started were kept at field capacity till the seedlings become well established by adding excess water and allowing the surplus water to drain. This could be verified by examining the drip trays beneath the tubes. The control water treatment was not to keep the plants at field capacity throughout as this was felt not to be typical of the situation in the field. In the east of the UK between March and July rainfall exceeds evapo-transpiration on less than one day in four. Three test plants with the control treatment were grown in half depth tubes that were weighed weekly initially and more frequently as the rate of evapo-transpiration increased due to increased leaf area and the increasing potential rate as the season progressed. The weight loss was converted to a volume of water that was added to both the water controls and the test tubes. Bringing the tubes back to field capacity at the end of each experiment showed that this method tended to underestimate the water loss from the experimental tubes. However, the soil water deficits were not such as to impair the growth of the plants and, in any case, this treatment provides a pattern of soil water deficit typical of a wetter year in the field.

The mixes were estimated to contain the equivalent of 100 kg ha^{-1} of P and K so these elements should not have been limiting and nitrogen was released by mineralisation of the organic matter as well as from added ammonium nitrate which was applied as weighed quantities dissolved in water. The applications were calculated from field rates by scaling down to the surface area of the tubes. Test plants from the discards were used for dissections to identify growth stages 30, 31 and 32.

The treatments were chosen to allow comparison with the field trials, while taking advantage of the opportunity to control the availability of water.

The measurement protocols

In the second and third years, three typical seedlings of each variety were measured at transplanting time. The potting compost was washed from the roots and the plants were placed in a plastic sleeve and photocopied. Leaf area and root length were measured by hand.

On the day when the tubed plants were harvested the tubes were brought back to field capacity. The tubes were laid horizontally over a tube size box with a metal mesh bottom and one half of the tube was carefully removed. A spray of water was used to wash most of the soil from the root systems. Any loose roots remaining on the grid or floating in the water underneath were collected separately. The tops were cut off just above the base of the plant and were taken away for analysis. The intact root systems were placed in a polythene bag in a cold room at 4ºC. The roots could be left like this for at least 14 days without deterioration, production of new roots or fungal colonisation. The tops were analysed by assessing the stage of development of each plant, counting tillers and ears if present and separating the material into leaf and stem. The projected area of leaf blades and sheaths was measured using a LiCor leaf area meter. When there was a large amount of leaf, sub-samples were taken. Fresh weights were taken before the leaf area was measured and dry weights after oven-drying overnight at 80ºC.

The root systems were processed in a random order. First the root systems were washed carefully in a large measuring cylinder so that any losses could be observed. The objective was not to produce completely clean roots but rather to allow the primary axes to be identified. The roots were then spread out on a tray and the main axes, i.e. the seminal and nodal axes, were disentangled as far as possible. The nodal and seminal axes were not distinguished. Water was sprayed on the roots from a bottle whenever it was felt they were vulnerable to drying. The roots were spread out so that they resembled the distribution in the tubes except that roots below 1.20 m were extended. The maximum effective root depth was measured and then the main axes were counted. This was done every 0.20 m in the first year. However, counts were made every 0.10 metres in the subsequent years with the first measurement being taken immediately below the first node. It often proved easier to count the roots at 0.10 m by subtracting the number of main roots that did not extend to that depth from the number at the base of the stem.

Finally, a 50 mm long sample of a typical main axis was taken from the middle of each 0.10 m band and was carefully cleaned under a binocular microscope before being arranged in a Petri dish and photographed over a black background. In the first two years, 35 mm colour slides were taken of the labelled Petri dish with the roots. These were then scanned and input to an Optimas image analysis system. Automatic estimation of root length was not used as it proved impossible to set an accurate threshold. An operator traced the roots on the screen and the image analysis software calculated their length and number. In the final year, high resolution digital photographs were taken, A5 prints were made and the operator used a professional quality digital map measurer (online 5, Kasper & Richter GMBH) to measure the lengths of the roots. First and second order lateral roots were measured separately. Absolute lengths were calculated using either the diameter of the Petri dish (years 1 and 2) or a scale attached to each Petri dish (final year) as a standard. Finally the ratio of lateral root length to main axis length was calculated.

Experimental design and data analysis

The experiments were designed as randomised blocks with the treatments being part-factorial in that all combinations were not represented. The first priority was to develop methods that would allow the identification of differences between treatments with the second being to get good absolute values that could be compared with the data collected in the field. Thus, it was important to ensure that systematic errors between treatments were minimised by randomising the order in which tubes were analysed. Several operators were involved in the measurements and analysis. Wherever possible, one person was responsible for a single operation. Where this was not possible a single written protocol was used and tubes were allocated at random to operators. A sample of root photographs was re-measured at the end of the measurement campaign to check for changes in operator skill over time. In the second and third years, measurements were made at more than one stage of development in order to check the sensitivity of the results to the date of measurement. One complete block was measured on each occasion.

The main axes in the bottom half of the profile were relatively easy to count. However, in some tubes they appeared to become fewer near the surface and this was probably due to shrinkage of the cortex in response to shortage of water. Since the count of roots at the base of the stem was considered rather accurate, the raw data was corrected to ensure that the number of main axes declined from the surface to the maximum rooting depth.

Root length in each 0.10 m layer was calculated as:

$$R_l = L_m \times (1 + L_{1,2} / L_m)$$

where L_m is the total length of main axis in the layer and $L_{1,2}$ is the total length of first and second order lateral roots. The ratio $L_{1,2} / L_m$ was obtained from the sub-samples of primary axis.

Total root length was hypothesised to be a function of stage of development and treatment with a second hypothesis that the treatment effects could be explained through their effect on leaf area. Each year was designed to test particular hypotheses. However, an overall analysis over the three years could also be carried out even though treatments varied from year to year. Although there were differences from year to year in the soil mix, the conditions in the glasshouse and the methodology these were all rather less than would have been the case in the field and have been subsumed into the error term.

Experiment G (2000/01):

The aims of experiment G were to examine the effect of plant population density (PPD) on rooting and to test the methods employed. Four PPDs were used with on, two or three plants in a standard sized tube and one plant in the large diameter tube. Uniformly distributed wheat plants in the field should give similar yields for the highest three PPDs while 50 m^{-2} should show a significant reduction. Two contrasting environments were used: a) no water for 12 days and a low dose of ammonium nitrate and b) keeping the soil water deficit at less than 20 mm and applying a high rate of ammonium nitrate. As the plants turned out not to have been vernalised, the tubes were harvested on a date equivalent to anthesis.

Treatments	
Plants m^{-2}	P1 = 50
	P2 = 106
	P3 = 213
	P4 = 319
Variety	Consort
Water	W1 = water withheld for 12 days after GS 31
	W3 = soil water deficit < 20 mm
Nitrogen (kg/ha)	N1 = 25@GS 31
	N2 = 150@GS 31
Treatments	W1N1P1, W1N1P2, W1N1P3, W1N1P4, W3N2P1 W3N2P2, W3N2P3, W3N2P4
GS sampled	29+

Management	Details	Growth Stage	Date
Sowing			Apr-5
Topsoil (volumes)	50 Levington F2: 30 sand: 20 perlite		
Subsoil (volumes)	33 Levington F2: 40 sand: 27 perlite		
Fertiliser	No additional fertiliser applied		
Herbicide	None		
Fungicide	None (grew away from low level mildew)		
Insecticide	Soil-incorporated Intercept® 5R		

	(active ingredient imadocloprid)		
Plant growth regulator	None		
Harvest		29+	Jul-4

Experiment H (2001/02):

W1 Watered twice a week according to the weight loss of three standard plants with treatment W1N2. Mark with a white tag with the full treatment name (e.g. W1N1).

W2 No watering till the test plants have lost a cumulative total of 700 g. Then add 600 ml and restart the accumulation. The three nitrogen treatments factorially combined with the two water treatments were based on an application of 100 kg/ha. Treatments N1 and N2 were the same except that N1 included an additional early application of 50 kg/ha. N3 increased the later applications at the expense of the one at mid-tillering.

Treatments	
Plants m^{-2}	106
Variety	Consort
Water	W2= Soil water deficit allowed to reach 70 mm
	W3= Soil water deficit kept < 20 mm
Nitrogen (kg/ha)	N3E = 50 @ GS12, 33 @ GS 23, 33 @ GS31, 33 @ GS32
	N2E = 0 @ GS 12, 33 @ GS 23, 33 @ GS31, 33 @ GS32
	N2 = 0 @ GS 12, 0 @ GS 23, 50 @ GS31, 50 @ GS32
Treatments	W2N3E, W2N2E, W2N2, W1N3E,W1N2E, W1NE
GSs sampled	21,

Management	Details	Growth Stage	Date
Transplanting		21	Mar-26
Topsoil (volumes)	100 John Innes No. 1		
Subsoil (volumes)	50 John Innes No 1: 50 sand		
Fertiliser	No additional fertiliser applied		
Herbicide	None		
Fungicide	None		
Insecticide	Soil-incorporated Intercept® 5R (active ingredient imadocloprid)		
Plant growth regulator	None		
Anthesis (GS 65)			

Experiment I (2002/03):

All plants were given the same water treatment. They were well watered till just before GS 30 so that water drained through the tubes and they were at field capacity. Any excess water was then removed and the plants were watered weekly according to the weight loss of three standard plants. This resulted in an increasing deficit being built up by the end of each week and the tubes being brought back to near field capacity. The nitrogen treatments were more extreme than the previous year with a zero treatment, all applied early or a split application at the normal growth stages.

Treatments	
Plants m^{-2}	50, 106, 213, 319
Variety	V1 = Consort V2 = Malacca
Water	W3 = Soil water deficit < 20 mm
Nitrogen (kg/ha)	N0 = no nitrogen applied N2VE = 100 @ GS 23 N2 = 0 @ GS 23, 50 @ GS 31, 50 @ GS 32
Treatments	V1W3N0, V1W3N2VE, V1W3N2 V2 W3N0, V2W3N2VE, V2W3N2
GSs sampled	23, 27, 32, 59,

Management	Details	Growth Stage	Date

Transplanting	22 Apr-04
Topsoil (volumes)	100 John Innes No. 1
Subsoil (volumes)	50 John Innes No 1: 50 sand
Fertiliser	No additional fertiliser applied
Herbicide	None
Fungicide	None
Insecticide	Soil-incorporated Intercept® 5R (active ingredient imadocloprid)
Plant growth regulator	None
Anthesis (GS 65)	

Treatment summary

Environment	Variety	PPD	Water	Nitrogen
01	Consort	50	Early drought	25
01	Consort	106	Early drought	25
01	Consort	213	Early drought	25
01	Consort	319	Early drought	25
01	Consort	50	Well-watered	150
01	Consort	106	Well-watered	150
01	Consort	213	Well-watered	150
01	Consort	319	Well-watered	150
02	Consort	106	Well-watered	100
02	Consort	106	Well-watered	100 early
02	Consort	106	Well-watered	150 early
02	Consort	106	Late drought	100
02	Consort	106	Late drought	100 early
02	Consort	106	Late drought	150 early
03	Consort	106	Well-watered	0
03	Consort	106	Well-watered	100 very early
03	Consort	106	Well-watered	100
03	Malacca	106	Well-watered	0
03	Malacca	106	Well-watered	100 very early
03	Malacca	106	Well-watered	100

RESULTS

Results are presented for each Experiment as described in the Materials and Methods.

Experiments A, B and C at SAC 2000/01 to 2002/03

Experiments D, E, and F at HAUC 2000/01 to 2002/03

Experiments G, H and I at University of Edinburgh 2000/01 to 2002/03

Some further joint-analyses of results are presented the Discussion.

Experiment A: Effects of soil type and seed rate on the growth of roots and shoots (SAC)

Root axes

There were no significant differences in the number of seminal root axes per plant between treatments, though the number of axes tended to be reduced at the highest seed rate compared to the lowest seed rate (Table R1). There was approximately a four-fold increase in the number of nodal root axes between GS23 and GS37. At each growth stage, the number of nodal axes significantly reduced with an increase in seed rate and plant population density (Tables R1 and R2).

Table R1. Experiment A: Effects of soil type and seed rate on production of root axes per plant in Consort at North Berwick, in 2000-01. Data are for GS23. LSDs are for comparing any treatment combinations.

Soil type	Sandy loam			Clay loam			LSD
Seed rate (seeds m^{-2})	80	320	640	80	320	640	
Seminal axes	4.5	3.7	4.1	4.8	4.5	4.1	0.41
Nodal axes	8.5	7.4	4.0	8.8	6.1	6.0	1.69
Number of main stem leaves	5.4	5.3	5.1	5.3	5.0	5.0	0.25
Number of tillers	4.0	3.6	2.2	3.8	3.1	2.0	0.96
Plant population density (plants m^{-2})	74	265	474	35	124	207	37.5
Root number m^{-2}	966	1978	1925	313	762	1245	215

Table R2. Experiment A: Effects of soil type and seed rate on production of root axes per plant in Consort at North Berwick, in 2000-01. Data are for GS 31. LSDs are for comparing any treatment combinations.

Soil type	Sandy loam			Clay loam			LSD
Seed rate (seeds m^{-2})	80	320	640	80	320	640	
Seminal axes	4.9	4.1	4.1	4.3	4.8	4.0	0.32
Nodal axes	25.4	16.4	10.0	20.4	18.1	16.1	4.6
Number of main stem leaves	8.0	6.9	6.5	7.7	7.3	7.6	1.2
Number of tillers	4.3	4.0	2.6	4.9	4.0	2.8	0.81
Plant population density (plants m^{-2})	67	257	472	31	115	223	32.3
Root number m^{-2}	2027	5271	6674	771	2631	4935	657

Table R3. Experiment A: Effects of soil type and seed rate on production of root axes per plant in Consort at North Berwick, in 2000-01. Data are for GS 37. LSDs are for comparing any treatment combinations.

Soil type	Sandy loam			Clay loam			LSD
Seed rate (seeds m^{-2})	80	320	640	80	320	640	
Seminal axes	4.8	4.8	3.8	5.0	5.4	4.5	0.42
Nodal axes	37.3	22.1	17.1	39.8	34.6	22.8	5.1
Number of main stem leaves	9.8	8.1	8.0	9.3	9.5	7.8	0.96
Number of tillers	5.0	3.3	2.5	4.5	4.5	3.4	1.21
Plant population density (plants m^{-2})	71	249	456	29	110	215	45.1
Root number m^{-2}	2982	6505	9519	1298	4400	5859	774

Root length density (RLD) and total root length (TRL)

At GS23, TRL was significantly higher on the clay loam compared to the sandy loam: the differences were most pronounced at the earlier growth stage (Table R4). At GS23, RLDs were always higher (at each soil layer and at each seed rate) in the clay loam compared to the sandy loam. The proportion of the total root system at 40-60 cm depth was higher at 80 seeds m^{-2} than at 640 seeds m^{-2}.

The TRL approximately doubled between GS23 and GS69 (Table R5). At soil depths of 40-80 80 cm, RLDs were relatively high in the clay loam compared to the sandy loam, and at the lowest seed rate compared to the high seed rate (on both soil types).

Crop growth and yield

Plant establishment on the sandy loam was high, ranging from 76% to 86% from the high to low seed rate (Table R4). By contrast, establishment on the clay loam was poor, ranging from 13% to 35%. Consequently, GAIs at GS23 were higher on the sandy loam compared to the clay loam. By GS69 the differences in GAI were less pronounced, though there remained significant differences between the seed rates (Table R5).

There were significantly more ears m^{-2} on the sandy loam compared to the clay loam, and a significant increase in ear number with seed rate (Table R5). TGW was higher on the sandy loam than on the clay loam, but there was significant seed rate effect. Yield significantly increased with an increase in seed rate. At each seed rate, yield was higher on the sandy loam than on the clay loam.

Table R6 show the average soil moisture deficits (SMDs) in the sandy loam and clay loam blocks. The trend in SMD's differed from expectation that the less water retentive sandy loam would result in higher deficits than the more water retentive clay loam. This was a consequence of relatively high summer rainfall and a higher than expected water table in the area surrounding the sandy loam block.

Table R4. Experiment A: Effects of soil type and seed rate on root and shoot growth in Consort at North Berwick, in 2000-01. Data are for GS 23. LSDs are for comparing any treatment combinations.

Soil type	Sandy loam			Clay loam			LSD
Seed rate (seeds m^{-2})	80	320	640	80	320	640	
Root length density ($cm\ cm^{-2}$) at different depths:							
0-20 cm	1.39	2.13	2.25	1.42	2.96	2.94	1.61
20-40 cm	0.84	0.54	0.94	1.05	1.24	2.23	1.09
40-60 cm	0.48	0.26	0.61	1.22	0.60	1.76	0.78
60-80 cm	0.00	0.00	0.00	0.00	0.00	0.00	n/a
Total root length ($km\ m^{-2}$)	5.41	5.85	7.61	7.38	9.61	13.87	4.61
Plant population density (plants m^{-2})	68.8	262.8	486.7	27.7	107.7	200.2	35.1
GAI	0.94	1.81	1.84	0.36	1.04	1.30	0.52

Table R5. Experiment A: Effects of soil type and seed rate on root and shoot growth, and yield components in Consort at North Berwick, in 2000-01. Data are for GS 69 and harvest. LSDs are for comparing any treatment combinations.

Soil type	Sandy loam			Clay loam			LSD
Seed rate (seeds m^{-2})	80	320	640	80	320	640	
Root length density ($cm\ cm^{-2}$) at different depths:							
0-20 cm	1.74	3.17	3.87	1.35	2.95	3.87	1.57
20-40 cm	1.82	2.92	3.15	1.29	2.75	2.54	1.26
40-60 cm	1.08	1.06	0.75	1.61	2.08	2.36	1.78
60-80 cm	0.41	0.11	0.06	1.33	1.22	1.82	1.81
Total root length ($km\ m^{-2}$)	10.11	14.51	15.65	11.14	18.00	21.18	5.31
GAI	2.70	3.24	3.75	1.93	3.15	3.44	1.26
Plant height							
Ear number (ears m^{-2})	252.2	416.9	650.1	151.8	336.5	429.6	27.6
TGW	52.6	52.4	51.5	49.3	49.9	50.3	1.82
Yield (t/ha)	6.60	8.03	8.26	3.94	6.93	7.23	0.64
Nitrogen % in canopy at GS69	1.73	1.57	1.46	2.24	1.75	1.58	0.33
Total nitrogen in canopy at GS69 ($kg\ ha^{-1}$)	94.4	104.6	100.6	76.9	105.7	100.7	10.1
Nitrogen % in grain	1.75	1.77	1.82	1.91	1.84	1.83	0.22
Total nitrogen offtake in grain ($kg\ ha^{-1}$)	115.5	142.1	150.1	75.3	127.3	132.1	14.2

Table R6. Experiment A: Soil moisture deficit (SMD) in mm of the sandy loam and clay loam blocks at North Berwick in 2000-01 (Calculated from Profile Probe, Delta-T Devices, using 0.27 $m^3 m^{-3}$ (sandy loam) and 0.35 $m^3 m^{-3}$ (clay loam) as field water capacity).

Date	Sandy loam SMD (mm)	Clay loam SMD (mm)
23 May	35	14
1 June	43	31
7 June	64	68
19 June	67	88
26 June	86	104
5 July	77	88
17 July	60	73
23 July	80	81
1 August	84	107
15 August	76	102
29 August	68	56

Experiment B: Effects of soil type, nitrogen fertiliser and seed rate on the growth of roots and shoots (SAC)

Root axes

On the clay loam, autumn applied nitrogen (at 50 kg ha^{-1}) resulted in fewer total root axes per plant at GS23 than the standard nitrogen programme, but was no difference between the two treatments on the sandy loam (Table R7). At GS23 there was no consistent effect of seed rate on the number of root axes. However at GS37 there were significantly more root axes per plant at 90 seeds m^{-2} compared to 360 seeds m^{-2} (Table R8). At the later growth stage, there was no evidence for soil type affecting the number of root axes per plant, though a combination of slightly higher plant establishment and/or nodal axes resulted in a higher number of root axes per m^2 in the clay loam compared to the sandy loam.

Root length density and total root length

At GS23 there were similar values of TRL between soil types (i.e. all between 12.7 to 14.9 km m^{-2}). However, on the sandy loam, autumn nitrogen resulted in less TRL than the standard nitrogen programme (Table R9). Autumn nitrogen resulted in a higher proportion of the TRL in the upper soil layer (0-20 cm depth) compared to the standard programme. Consequently, crops with autumn nitrogen had relatively less root at a depth of 40-60 cm.

By GS69 there was significantly higher TRL on the clay loam than the sandy loam (this is consistent with year 2000-01) (Table R10). Across all treatments TRL ranged from 12.7- 20.9 km m^{-2} on the sandy loam and from 16.8-28.1 km m^{-2} on the clay loam.

On both soil types, TRL was lowest at 90 seeds m^{-2} with delayed nitrogen, though the highest TRLs were at 360 seeds m^{-2} with autumn nitrogen (in the sandy loam) and 360 seeds m^{-2} with delayed nitrogen (in the clay loam).

The grand mean for TRLs at the two seed rates were 19.3 km m^{-2} and 24.5 km m^{-2} at 90 seeds m^{-2} and 360 seeds m^{-2}, respectively. Overall, crops at 90 seeds m^{-2} had a higher proportion of their root system at a soil depth of 60-80 cm compared to those sown at 360 seeds m^{-2}.

Table R7. Experiment B: Effects of soil type and seed rate on production of root axes per plant in Consort at North Berwick, in 2001-02. Data are for GS23-25. Note that the plants on the sandy loam were more advanced in their development than those on the clay loam. LSDs are for comparing any treatment combinations within a soil type. Table a) sandy loam at GS24/5 and Table b) clay loam at GS23.

a)

Soil type			Sandy loam				LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Seminal axes	4.3	3.9	4.6	4.5	n/a	n/a	0.51
Nodal axes	3.5	4.3	4.0	3.9	n/a	n/a	0.83
Number of main stem leaves	7.3	7.0	7.3	7.8	n/a	n/a	0.49
Number of tillers	4.8	4.6	4.9	4.9	n/a	n/a	0.33
Plant population density (plants m^{-2})	81	287	72	249	n/a	n/a	[1]
Root number m^{-2}	628	2332	621	2085	n/a	n/a	[1]

[1]Joint LSD not carried on these measurements

b)

Soil type			Clay loam				LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Seminal axes	5.4	6.0	5.8	5.8	n/a	n/a	0.55
Nodal axes	3.1	5.0	6.8	5.8	n/a	n/a	2.01
Number of main stem leaves	5.4	6.0	5.8	5.8	n/a	n/a	0.96
Number of tillers	3.6	2.8	3.1	2.5	n/a	n/a	1.30
Plant population density (plants m^{-2})	80	245	70	257	n/a	n/a	28.0
Root number m^{-2}	526	2113	753	2442	n/a	n/a	n/a

[1]Joint LSD not carried on these measurements

Table R8. Experiment B: Effects of soil type and seed rate on production of root axes per plant in Consort at North Berwick, in 2001-02. Data are for GS 37. LSDs are for comparing any treatment combinations within a soil type. Table a) sandy loam and Table b) clay loam.

a)

Soil type	Sandy loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Seminal axes	6.4	5.8	5.8	5.8	n/a	n/a	0.71
Nodal axes	25.6	17.8	23.1	19.3	n/a	n/a	8.92
Number of main stem leaves	8.4	7.4	8.3	7.8	n/a	n/a	1.07
Number of tillers	5.8	4.1	5.6	4.4	n/a	n/a	1.28
Plant population density (plants m^{-2})	74	280	75	271	n/a	n/a	[1]
Root number m^{-2}	2368	6580	2175	6775	n/a	n/a	[1]

[1]Joint LSD not carried on these measurements

b)

Soil type	Clay loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Seminal axes	6.0	5.3	6.3	6.0	n/a	n/a	0.86
Nodal axes	22.4	18.6	22.8	18.1	n/a	n/a	4.21
Number of main stem leaves	7.6	7.5	8.3	7.8	n/a	n/a	1.02
Number of tillers	5.6	4.6	5.9	4.9	n/a	n/a	1.17
Plant population density (plants m^{-2})	72	267	68	265	n/a	n/a	[1]
Root number m^{-2}	2043	6475	1972	6393	n/a	n/a	[1]

[1]Joint LSD not carried on these measurements

Table R9. Experiment B: Effects of soil type and seed rate on root and shoot growth in Consort at North Berwick, in 2001-02. Data are for GS 23. LSDs are for comparing any treatment combinations within a soil type. Table a) sandy loam and Table b) clay loam.

a)

Soil type	Sandy loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Root length density ($cm\ cm^{-2}$) at different depths:							
0-20 cm	3.21	2.98	3.08	3.01	n/a	n/a	0.81
20-40 cm	1.76	1.80	2.02	1.91	n/a	n/a	0.72
40-60 cm	1.40	1.08	2.18	2.06	n/a	n/a	0.53
60-80 cm	0.00	0.00	0.00	0.00	n/a	n/a	n/a
Total root length ($km\ m^{-2}$)	11.74	11.73	12.57	13.98	n/a	n/a	2.98
Plant population density (plants m^{-2})	77.5	288.4	71.7	266.7	73.9	274.6	41.7
GAI	0.71	1.35	0.57	0.93	0.61	0.80	0.36

b)

Soil type	Clay loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Root length density ($cm\ cm^{-2}$) at different depths:							
0-20 cm	3.23	3.30	2.59	3.14	n/a	n/a	0.55
20-40 cm	1.90	2.37	2.27	2.32	n/a	n/a	0.32
40-60 cm	1.65	1.81	1.76	2.01	n/a	n/a	0.40
60-80 cm	0.00	0.00	0.00	0.00	n/a	n/a	n/a
Total root length ($km\ m^{-2}$)	13.55	14.94	13.26	14.93	n/a	n/a	1.89
Plant population density (plants m^{-2})	76.7	250.5	75.4	259.3	64.5	260.9	28.7
GAI	0.49	1.36	0.38	1.04	0.41	1.10	0.31

Table R10. a) and b). Experiment B: Effects of soil type (sandy loam and clay loam), nitrogen fertiliser and seed rate on root and shoot growth in Consort at North Berwick, in 2001-02. Data are for GS 69. LSDs are for comparing any treatment combinations within a soil type. Table a) sandy loam and Table b) clay loam (over page).

Table R 10 a)

Soil type	Sandy loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Root length density ($cm\ cm^{-3}$) at different depths:							
0-20 cm	3.77	5.65	4.45	5.45	4.16	5.47	1.42
20-40 cm	1.57	2.54	1.36	1.74	0.98	1.92	1.79
40-60 cm	0.67	1.42	0.80	1.43	0.69	0.80	0.48
60-80 cm	0.39	0.82	0.60	0.64	0.51	0.53	0.51
Total root length ($km\ m^{-2}$)	15.80	20.86	16.42	18.52	12.68	17.45	3.87
Plant population density (plants m^{-2})	77.5	288.4	71.7	266.7	73.9	274.6	
GAI	5.85	7.31	5.79	6.93	5.21	6.45	0.80
Ear number (ears m^{-2})	477	570	448	635	470	628	28.6
TGW	47.3	48.9	49.1	48.7	49.0	49.4	1.05
Yield (t/ha)	10.0	11.20	10.11	11.21	9.88	10.79	0.52
Nitrogen % at GS69	2.11	2.02	2.16	2.15	2.27	2.26	0.22
Total nitrogen in canopy at GS69 ($kg\ ha^{-1}$)	183.8	190.8	182.0	198.1	185.5	191.0	8.12

Table R10 b)

Soil type	Clay loam						LSD
Nitrogen application	Autumn + Standard		Standard		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	
Root length density (cm cm^{-3}) at different depths:							
0-20 cm	4.46	6.75	5.13	5.32	4.06	6.75	0.97
20-40 cm	1.97	2.72	2.19	2.82	2.30	3.74	0.88
40-60 cm	1.76	1.50	2.50	1.75	1.22	2.68	1.20
60-80 cm	1.14	0.75	1.32	1.05	0.81	0.89	0.92
Total root length (km m^{-2})	18.65	23.44	22.29	21.88	16.80	28.12	4.88
Plant population density (plants m^{-2})	76.7	250.5	75.4	259.3	64.5	260.9	
GAI	4.49	5.18	4.02	5.99	3.51	4.48	0.50
Plant height							
Ear number (ears m^{-2})	390	540	357	523	390	515	24.9
TGW	45.7	46.9	46.7	47.7	47.5	47.8	1.01
Yield (t/ha)	7.96	10.02	8.22	9.74	7.96	9.46	0.43
Nitrogen % at GS69	2.17	2.09	2.21	2.16	2.31	2.22	0.27
Total nitrogen in canopy at GS69 (kg ha^{-1})	142.1	176.7	149.9	178.0	151.9	178.4	9.54

Crop growth and yield

Plant establishment was between 70-86% (Table R9). There were more plants per m^2, but not significantly so, with autumn nitrogen applied than in either the standard or delayed nitrogen treatments. There were slightly fewer plants on the clay loam compared to the sandy loam. At GS23, GAI was significantly higher with autumn nitrogen than other treatments.

By GS69, GAI was highest across all treatments, in the sandy loam compared to those in the clay loam. At both seed rates and both soil types the GS69 GAI was least in the crops with delayed nitrogen (Table R10).

The number of ears per m^2 was higher on the sandy loam compared to the clay loam. Across all nitrogen treatments, ear numbers were higher at a sowing rate of 90 seeds m^{-2} than at 360 seeds m^{-2}. There was no consistent effect of nitrogen programme on ear number.

Across all treatments, yield was higher in the sandy loam compared to those in the clay loam. Crops sown at 360 seeds m^{-2} out-yielded those sown at 90 seeds m^{-2}, and generally delayed nitrogen reduced yield compared to other nitrogen treatments.

Table R11 shows the average soil moisture deficits (SMDs) in the sandy loam and clay loam blocks. As with Experiment A, the unseasonal rainfall in the summer months resulted in a trend in SMD's different to expectation. Until mid July the SMD in the less water retentive sandy loam was, as expected, higher than that in the clay loam. However, after mid July there was a reverse of this trend.

Table R11. Experiment B: Soil moisture deficit (SMD) in mm of the sandy loam and clay loam blocks at North Berwick in 2001-02 (Calculated from Profile Probe, Delta-T Devices, using 0.28 m^3 m^{-3} and 0.34 m^3 m^{-3} as field water capacity).

Date	Sandy loam SMD (mm)	Clay loam SMD (mm)
10 June	63	50
19 June	73	58
10 July	100	79
26 July	53	40
2 August	53	28
12 August	63	33
24 August	80	52

Experiment C: Effects of nitrogen fertiliser timing and seed rate on the growth of roots and shoots in two varieties, Consort and Malacca (SAC)

Root axes

There were no differences in the number of root axes per plant between varieties, though at this early stage of development Consort had slightly more nodal roots (Table R12). The higher plant population density for Malacca tended to offset this difference in root per plant and thus the number of roots m^{-2} were similar between the two varieties.

There was no consistent effect of nitrogen timing on the number of root axes as there was evidence of an interaction this factor and seed rate and variety. The lower seed rate tended to increase the number of nodal axes relative to the higher seed rate.

Table R12. Experiment C: Effects of nitrogen timing and seed rate on production of root axes per plant in Consort and Malacca at Boghall, Midlothian, in 2002-03. Data are for GS 23. LSDs are for comparing any treatment combinations.

Variety	Consort				Malacca				LSD
Nitrogen timing	Early		Delayed		Early		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	90	360	
Seminal axes	4.88	4.38	4.88	4.38	5.13	4.75	4.75	4.88	0.37
Nodal axes	8.00	4.00	5.75	6.00	6.38	2.63	6.25	4.50	2.16
Number of main stem leaves	6.1	5.3	5.6	5.1	5.6	4	5.4	5.1	0.64
Number of tillers	4.4	3.4	4.4	3.4	4.2	2.4	4.4	3.0	0.36
Plant population density (plants m^{-2})	48	158	46	163	54	177	53	180	n/a
Root number m^{-2}	515	1324	489	1691	621	1305	583	1688	n/a

[1]Joint LSD not carried on these measurements

Root length density (RLD) and total root length (TRL)

At GS23, delayed spring nitrogen increased the proportion of total length at the soil surface (0-20 cm) and reduced the proportion of root system at 20-40 cm compared to the early spring nitrogen treatment (Table R13). However, in Malacca sown at 90 seeds m^{-2} the late nitrogen treatment had relatively little RLD at a soil depth of 0-20 cm, but relatively more at 20-40 cm. There was no consistent effect of variety at GS23, though with the exception of the crop at 90 seeds m^{-2} with early nitrogen, Consort had a relatively low TRL compared to Malacca. There was evidence that low seed rates increased the proportion of the root system below a soil depth of 20 cm, though this was less pronounced than in Experiment A.

Overall the root systems in this Experiment were smaller, with less root growth below a soil depth of 20 cm, in Experiments A and B.

As at GS23, there was further evidence that the lower seed rate increased the proportion of root system below 20 cm in the mature crop (Table R14). At GS69, Malacca with early nitrogen had a higher TRL and higher RLD in the 0-20 cm layer, compared with the other treatment combinations.

Crop growth and yield

Malacca had higher plant establishment than Consort, and generally a lower GAI than Consort at GS23 (Table R13). The lower seed rate resulted in smaller GAIs than the higher seed rate, though this was not always significant. At GS69, with the exception of Malacca grown at 360 seeds m^{-2}, the delayed nitrogen treatment resulted in GAI's than the early nitrogen treatment. Delaying nitrogen resulted in a reduction in yield that was associated with a reduction in ears m^{-2}, though TGW had compensated by as much as 2.1 g in some treatments.

Table R13. Experiment C: Effects of nitrogen timing and seed rate on root and shoot growth in Consort and Malacca at Boghall, Midlothian, in 2002-03. Data are for GS 23. LSDs are for comparing any treatment combinations.

Variety	Consort				Malacca				LSD
Nitrogen timing	Early		Delayed		Early		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	90	360	
Root length density ($cm\ cm^{-2}$) at different depths:									
0-20 cm	1.69	1.83	1.12	1.92	1.23	2.19	1.06	1.99	0.22
20-40 cm	0.62	0.54	0.36	0.47	0.41	0.74	0.52	0.64	0.42
40-60 cm	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.00	0.08
60-80 cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	n/a
Total root length (km m^{-2})	4.65	4.81	2.99	4.79	3.31	5.89	3.19	5.28	1.73
Plant population density (plants m^{-2})	51.7	188.7	50.9	196.1	60.4	210.0	57.7	220.9	n/a
GAI	0.93	1.14	0.70	0.83	0.65	0.98	0.66	1.08	0.31

[1]Joint LSD not carried on these measurements

Table R14. Experiment C: Effects of nitrogen fertiliser timing and and seed rate on root and shoot growth, and yield components in Consort and Malacca at Boghall, Midlothian in 2002-03. Data are for GS 69. LSDs are for comparing any treatment combinations.

Variety	Consort				Malacca				LSD
Nitrogen timing	Early		Delayed		Early		Delayed		
Seed rate (seeds m^{-2})	90	360	90	360	90	360	90	360	
Root length density ($cm\ cm^{-2}$) at different depths:									
0-20 cm	3.23	4.39	4.08	4.18	3.78	4.35	3.05	3.58	0.29
20-40 cm	0.91	0.92	0.80	0.84	1.22	1.12	1.09	1.27	0.31
40-60 cm	0.22	0.11	0.05	0.08	0.14	0.20	0.26	0.11	0.21
60-80 cm	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	n/a
Total root length ($km\ m^{-2}$)	8.73	10.85	9.87	10.22	10.29	11.35	8.80	9.93	2.17
Plant population density (plants m^{-2})	51.7	50.9	188.7	196.1	60.4	210.0	57.7	220.9	n/a
GAI	5.22	5.84	4.68	4.94	5.00	5.43	3.96	5.60	0.36
Ear number (ears m^{-2})	221	384	244	347	284	411	237	369	23.2
TGW	40.8	38.1	38.5	38.4	39.1	36.3	38.5	36.4	0.98
Yield (t/ha)	5.69	6.07	5.38	5.57	5.68	6.11	4.98	5.63	0.61

[1]Joint LSD not carried on these measurements

Experiment D: Effects of seed rate on the growth of roots and shoots, with implications for yield in withholding water (HAUC)

Soil pits and root counts

The soil pit characteristics are listed in Table R15 and the number of roots counted in the soil pits are listed in Table R16.

There were no significant differences between seed rates at any sampling date on the numbers of roots in the soil pits (Table R17). When the difference between seed rates was analysed separately for each depth in the soil pit there were some differences between seed rates. At GS 23, 0-15 cm depth, the two higher seed rates had twice the number of roots when compared with the lowest seed rate whereas at GS 31, 0-15 cm depth, the number of roots at the middle seed rate was very high (Table R18). At GS 23 and 69, 45-60 cm depth, the highest seed rate had more roots compared with the other two seed rates as would be expected. In general the number of roots increased with increasing depth although this was not statistically significant at most of the depths.

Table R15: Experiment D: Soil pit characteristics (Flat Nook 2001).

	Seed rate		Sampling time (growth stage)		
			GS 23	GS 31	GS 69
43	80 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	33.5	35.33	38
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand	Loamy sand
		Pit depth (cm)	60	90	105
		Rooting depth (cm)	45	75	90
48	80 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	31.33	32.66	44.33
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand	Loamy sand
		Pit depth (cm)	60	90	105
		Rooting depth (cm)	60	90	105
37	320 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	34	38	38
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand	Loamy sand
		Pit depth (cm)	60	79	105
		Rooting depth (cm)	60	79	105
42	320 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	32.66	33	41.33
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand	Loamy sand
		Pit depth (cm)	60	90	105
		Rooting depth (cm)	60	75	105
49	640 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	35.5	32.33	37.33
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Sandy clay loam	Loamy sand	Loamy sand
		Pit depth (cm)	45	90	105
		Rooting depth (cm)	45	90	105
54	640 (seeds/ m^2)	Date dug	30/4/01	31/5/01	10/7/01
		Top soil depth (cm)	36.5	37.66	38
		Soil texture: Top soil	Sandy loam	Sandy loam	Sandy loam
		Soil texture: Sub soil	Sandy clay loam	Sandy clay loam	Sandy clay loam
		Pit depth (cm)	60	90	105
		Rooting depth (cm)	60	90	105

Table R16: Experiment D: The number of roots at different depths in soil pits dug at different growth stages. (Flat Nook 2001).

Soil pit	Seed rate (seeds/m^2)	Depth (cm)	Growth stage		
			GS 23	GS 31	GS 69
43	80	0-15	46	64	156
		15-30	8	89	168
		30-45	2	90	65
		45-60	0	5	61
		60-75	-	1	61
		75-90	-	0	16
		90-105	-	-	0
48	80	0-15	57	134	120
		15-30	17	180	167
		30-45	2	95	94
		45-60	1	3	75
		60-75	-	0	106
		75-90	-	6	41
		90-105	-	-	10
37	320	0-15	105	552	107
		15-30	65	347	127
		30-45	20	138	119
		45-60	3	40	66
		60-75	-	9	44
		75-90	-	2	34
		90-105	-	-	13
42	320	0-15	101	381	137
		15-30	60	244	148
		30-45	17	55	183
		45-60	2	13	60
		60-75	-	2	49
		75-90	-	0	22
		90-105	-	-	5
49	640	0-15	96	247	273
		15-30	36	123	321
		30-45	8	105	160
		45-60	*	37	161
		60-75	-	4	156
		75-90	-	2	120
		90-105	-	-	29
54	640	0-15	119	188	403
		15-30	67	187	499
		30-45	39	168	312
		45-60	10	65	125
		60-75	-	24	123
		75-90	-	15	4
		90-105	-	-	*

Table R17. Experiment D: Soil pit root count results ([a] = $\log_{10}$ transformed data of root numbers + 1)

	GS 23	GS 31	GS 69
80 seeds m^2	16.6 (0.86)[a]	56 (1.22)[a]	81 (1.709)[a]
320 seeds m^2	46.6 (1.41)	149 (1.57)	80 (1.757)
640 seeds m^2	53.6 (1.58)	97 (1.71)	207 (2.139)
Depth 0-15cm	87.3	261.0	199.3
Depth 15-10 cm	42.2	195.0	238.3
Depth 30-45 cm	14.7	108.5	155.5
Depth 45-60 cm	4.3	27.2	91.3
Depth 60-75 cm		6.7	89.8
Depth 75-90 cm		4.2	39.5
Depth 90-105 cm			81.0
Probabilities			
Seed	(0.056)	(0.344)	(0.073)
LSD: Seed	(0.606)	(0.690)	(0.4040)

Seed rate means are the mean number of roots across all depths in the two pits at the same seed rate.

Table R18. Experiment D: Soil pit results: Analysis of each depth by ANOVA separately.

Growth stage	GS 23	GS 31	GS 69
Depth 0-15 cm			
80 seeds m^2	54.5	99	138
320 seeds m^2	103.0	467	122
640 seeds m^2	107.5	218	338
Probability	0.022*	0.040*	0.053
LSD	33.53	252.0	179.5
CV (%)	12.1	30.3	28.3
Depth 15-30 cm			
80 seeds m^2	12.5	135	168
320 seeds m^2	62.5	296	138
640 seeds m^2	51.5	155	410
Probability	0.065	0.142	0.060
LSD	42.44	197.0	232.9
CV (%)	31.6	31.7	30.7
Depth 30-45 cm			
80 seeds m^2	2.0	93	80
320 seeds m^2	18.5	97	151
640 seeds m^2	23.5	137	236
Probability	0.342	0.582	0.219
LSD	40.46	135.5	217.6
CV (%)	86.7	39.3	44.0
Depth 45-60 cm			
80 seeds m^2	0.5	4.0	68
320 seeds m^2	2.5	26.5	63
640 seeds m^2	10.0	51.0	143
Probability	0.010*	0.129	0.026*
LSD	3.042	50.60	50.79
CV (%)	16.3	58.5	17.5
Depth 60-75 cm			
80 seeds m^2	-	0.5	83.5
320 seeds m^2	-	5.5	46.5
640 seeds m^2	-	14.0	139.5
Probability	-	0.405	0.059
LSD	-	27.56	72.79
CV (%)	-	129.9	25.5
Depth 75-90 cm			
80 seeds m^2	-	3.0	29
320 seeds m^2	-	1.0	28
640 seeds m^2	-	8.5	62
Probability	-	0.505	0.748
LSD	-	18.78	155.0
CV (%)	-	141.6	123.3
Depth 90-105 cm			
80 seeds m^2	-	-	5
320 seeds m^2	-	-	9
640 seeds m^2	-	-	29
Probability	-	-	0.110
LSD	-	-	27.55
CV (%)	-	-	44.7

Root length, root length density (RLD)

Root length density summary tables are shown for GS23 (Table R31) and GS69 (Table R32).

At GS 23 sampling the length of root expressed as mm per cm depth of the soil core generally decreased as the soil depth increased. Only for the core depth of 0-20 cm did the amount of roots increased as the seed rate increased (Table R19). For all other depths no significant differences were found. For the core depths of 20-40 cm and 40-60 cm the middle seed rate has more roots compared with the high seed rate but for the depth from 60-80 cm the highest seed rate had the greater number of roots.

At GS 69 sampling for the 0-20 cm core depth the highest seed rate had significantly greater number of roots compared with the lowest seed rate (Table R20). Otherwise there were no differences between seed rates at the other core depths.

Table R19. Experiment D: Root lengths expressed as mm per cm depth of soil core (19.6 cm^3) Trial 1 GS23. Results in brackets are transformed data: ^{a} = log_{10} data and ^{b} = log_{10} (data + 1).

	Depth of core (cm)			
	20	40	60	80
Means				
80 seeds m^2	82	8.8 (0.885)^a	1.00 (0.272)^b	0.3 (0.08)^b
320 seeds m^2	160	45.8 (1.472)	4.90 (0.631)	4.5 (0.43)
640 seeds m^2	227	32.3 (1.424)	1.50 (0.317)	7.4 (0.63)
Probability	0.001***	(0.053)	(0.061)	(0.131)
LSD	63.4	(0.5168)	(0.3197)	(0.554)
Df	13	(13)	(13)	(13)
CV (%)	32.5	(32.9)	(63.0)	(117.3)

Table R20. Experiment D: Root lengths per cm depth of soil core (19.6 cm^3) Trial 1 GS 69. Transformed data in brackets: ^{a} = square root transformed.

	Depth of core (cm)			
	20	40	60	80
Means				
80 seeds m^2	473	130	125	75 (7.82)^a
320 seeds m^2	579	151	65	41 (5.41)
640 seeds m^2	703	149	103	67 (7.04)
Probability	0.012**	0.692	0.299	(0.600)
LSD	138.1	57.3	81.5	(5.236)
Df	11 (2)	11 (2)	11 (2)	(11 (2))
CV (%)	18.6	31.4	65.7	(61.0)

The figure in brackets for the degrees of freedom are the number of missing values.

Crop growth and yield

The average plant populations for trial one for each of the seed rates, 80, 320 and 640 were 46, 179 and 325 plants m^{-2} respectively and for trial two were 50, 207 and 366 plant m^{-2}.

In all cases the GAI increased as the seed rate increased (Table R21). At GS 23 the higher two seed rates were significantly different to the lowest seed rate whereas at GS 31 all were significantly different from each other. At GS 69 only the lowest seed rate was significantly different from the higher seed rate.

Table R21. Experiment D: Trial One, Green area index results (from plots 1-18).

	GS 23	GS 31	GS 69
80 seeds m^2	0.141	1.169	2.44
320 seeds m^2	0.289	1.718	2.94
640 seeds m^2	0.341	2.148	3.16
Probability	<0.001***	<0.001***	0.026*
LSD	0.0748	0.3340	0.526
CV (%)	35	23.9	22.2

In trial two at GS23 and 31, for the ambient plots, all seed rates were significantly different from each other with GAI increasing as the seed rate increased (Table R22). However at GS 69 when the plots had been irrigated there was no difference in GAI between the seed rates. The difference in the GAI between the higher two seed rates was only 0.01 with the lowest seed rate only being 0.17 lower in the GAI.

Table R22. Experiment D: Trial Two, Green area index results (GS 23 and 31 from plots 1-18 and GS 69 from the irrigated plots 37-54).

	GS 23	GS 31	GS 69
80 seeds m^2	0.172	1.496	2.77
320 seeds m^2	0.340	2.085	2.93
640 seeds m^2	0.429	2.493	2.94
Probability	<0.001***	<0.001***	0.824
LSD	0.0625	0.3991	0.629
CV (%)	23.9	23.7	26.2

The analysis of the ambient blocks only for trial one showed that the middle (320 seeds m^{-2}) and highest seed rates (640 seeds m^{-2}) had significantly greater yield, specific weight and TGW compared with the lowest seed rate (80 seeds m^{-2}) (Table R23). There was no difference between the higher two seed rates. There were no differences between seed rates for stem height, ear number and above ground dry matter.

At GS69 grain nitrogen % in combined leaf and stem material significantly increased with a reduction in seed rate. though nitrogen offtakes were not significantly different (Table 24). Grain nitrogen % was highest at the lowest seed rate, though N offtake in the grain was significantly higher at 320 seeds m^{-2} and 640 seeds m^{-2} than at 80 seeds m^{-2}.

Table R23. Experiment D: Trial One, Preharvest and grain assessment results for ambient blocks only.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	44.26	40.7	1091	5.010	75.513	45.32
320 seeds m^2	45.10	42.3	1161	6.581	76.825	46.84
640 seeds m^2	45.83	49.8	1180	6.443	77.013	47.17
Probability	0.089	0.074	0.059	<0.001***	<0.001***	<0.001***
SEM	0.489	2.89	26.7	0.1066	0.1117	0.326
LSD	1.400	8.29	76.6	0.3053	0.3198	0.934
CV (%)	4.3	26.2	9.3	7.1	0.6	2.8

Table R24. Experiment D: Trial One, Total nitrogen offtake in above-ground material at GS69 and in grain at harvest for ambient blocks only

	Nitrogen (%) in canopy at GS69	Total nitrogen offtake at GS69 (kg ha^{-1})	Nitrogen (%) in grain	Nitrogen offtake in grain (kg ha^{-1})
80 seeds m^2	2.39	106.1	2.04	102.4
320 seeds m^2	2.03	113.1	1.83	120.5
640 seeds m^2	1.86	101.5	1.92	123.5
LSD	0.24	10.9	0.21	9.8

The analysis of the plots in which water was withheld (in trial one) (Table R25) showed that yield was significantly greater for the middle and the highest seed rates compared with the lowest seed rate. There were no differences between seed rates for the other yield components. .

Table R25. Experiment D: Trial One, Preharvest and grain assessment results for plots in which water was withheld.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	44.75	35.1	1025	6.35	77.0	49.0
320 seeds m^2	45.00	41.0	1215	7.88	78.0	49.2
640 seeds m^2	45.50	48.2	1320	7.33	77.9	50.7
Probability	0.934	0.078	0.132	0.022*	0.323	0.553
LSD	6.511	11.42	324.8	0.836	1.909	4.910
CV (%)	4.5	8.7	8.6	3.7	0.8	3.1

The analysis of the whole of trial one without dividing the blocks into ambient and guttered (Table R26) showed that ear number was significantly greater for the highest seed rate (640 seeds m^2) compared with the middle and the lowest seed rate (320 & 80 seeds m^2). The higher two seed rates (640 & 320 seeds m^2) had significantly greater dry matter, yield, specific weight and TGW compared with the lowest seed rate (80 seeds m^2). There were no differences between seed rates for stem height.

Table R26. Experiment D: Trial One, Analysis of the whole trial not divided into ambient and guttered.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	44.32	40.1	1084	5.158	75.678	45.73
320 seeds m^2	45.09	42.2	1167	6.726	76.956	47.10
640 seeds m^2	45.80	49.6	1196	6.541	77.111	47.57
Probability	0.081	0.031*	0.010*	<0.001***	<0.001***	<0.001***
LSD	1.291	7.36	72.8	0.2779	0.3073	0.880
CV (%)	4.3	24.9	9.4	6.7	0.6	2.8

The analysis of the ambient blocks of trial two (Table R27) showed that the middle (320 seeds m^{-2}) and highest seed rates (640 seeds m^{-2}) had significantly greater yield, specific weight and TGW compared with the lowest seed rate (80 seeds m^{-2}). There was no difference between the higher two seed rates. Ear number increased with increasing seed rate and each seed rate was significantly different from each other.

Table R27. Experiment D: Trial Two, Preharvest and grain assessment results of the ambient blocks only.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	44.37	38.27	1091	5.368	75.617	45.48
320 seeds m^2	44.76	44.00	1185	6.688	76.217	47.05
640 seeds m^2	45.40	51.44	1209	6.837	76.533	47.28
Probability	0.336	<0.001***	0.051	<0.001***	<0.001***	<0.001***
LSD	1.404	2.124	98.7	0.3668	0.3694	0.910
CV (%)	3.7	5.7	10.2	7.0	0.6	2.3

The analysis of the irrigated blocks (in trial two) (Table R28) showed yield and specific weight the highest and middle seed rate were significantly different compared with the lowest seed rate. The TGW increased significantly with increasing seed rate. For ear number the highest seed rate was different compared with the middle and the lowest seed rate.

Table R28. Experiment D: Trial Two, Preharvest and grain assessment results of the irrigated blocks only.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	48.53	40.25	1348	5.76	74.63	45.60
320 seeds m^2	49.42	44.42	1410	7.28	76.27	47.77
640 seeds m^2	50.36	53.25	1411	7.97	76.97	49.07
Probability	0.310	<0.001***	0.472	<0.001***	<0.001***	<0.001***
LSD	2.476	5.177	124.0	0.744	1.006	1.216
CV (%)	4.0	9.0	7.2	8.5	1.1	2.1

The analysis of all of trial two without dividing into irrigated and ambient (Table R29) showed that ear number and specific weight increased significantly with increasing seed rate. The higher two seed rates (640 & 320 seeds m^2) have significantly greater dry matter, yield and TGW compared with the lowest seed rate (80 seeds m^2). There were no differences between seed rates for stem height.

Table R29. Experiment D: Trial Two, All of the trial not divided into irrigated and ambient.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg hl^{-1})	TGW (g)
80 seeds m^2	45.76	38.93	1177	5.497	75.289	45.52
320 seeds m^2	46.31	44.14	1260	6.887	76.233	47.29
640 seeds m^2	47.05	52.04	1276	7.216	76.678	47.88
Probability	0.096	<0.001***	0.022*	<0.001***	<0.001***	<0.001***
SEM	0.412	0.728	26.0	0.1203	0.1534	0.257
LSD	1.176	2.077	74.3	0.3432	0.4375	0.733
CV (%)	3.8	6.9	8.9	7.8	0.9	2.3

Table R30 (over page) shows the soil moisture deficits (SMD) in the irrigated and non-irrigated plots. The deficit was approximately 20-30 mm higher in the non-irrigated plots.

Table R30. Experiment D: The soil moisture deficit (SMD) of ambient and irrigated plots in Flat Nook 2001. (Calculated from Diviner probe data using 255mm as field water capacity.)

Date	Ambient SMD	Irrigated SMD
27/06/01	123	107
06/07/01	137	113
13/07/01	141	116
18/07/01	137	111
23/07/01	142	113
02/08/01	153	127
08/08/01	127	113
13/08/01	133	111
23/08/01	83	57

Ambient data calculated using the data from three tubes in three plots. Irrigated data calculated from one tube.

Table R31. Experiment D: Root length density (cm cm^{-3}) and crop growth, summary Table for GS23.

80 seeds m^2			320 seeds m^2			640 seeds m^2		
Total root length (km m^{-2})		0.9	Total root length (km m^{-2})		2.0	Total root length (km m^{-2})		2.5
GAI		0.141	GAI		0.289	GAI		0.341
Plant population (mean plants m^2)		51.2	Plant population (mean plants m^2)		184.5	Plant population (mean plants m^2)		324.7
Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	0.418	89.1	0-20	0.817	75.0	0-20	1.157	86.3
20-40	0.045	9.6	20-40	0.233	21.4	20-40	0.165	12.3
40-60	0.005	1.1	40-60	0.025	2.2	40-60	0.008	0.6
60-80	0.001	0.2	60-80	0.015	1.4	60-80	0.011	0.8
Total	0.469		Total	1.09		Total	1.341	

Table R32. Experiment D: Root length density (cm cm^{-3}) and crop growth, summary table for GS69.

80 seeds m^2			320 seeds m^2			640 seeds m^2		
Total root length (km m^{-2})		7.6	Total root length (km m^{-2})		7.9	Total root length (km m^{-2})		9.6
GAI		2.44	GAI		2.94	GAI		3.16
Plant population (mean plants m^2)		51.2	Plant population (mean plants m^2)		184.5	Plant population (mean plants m^2)		324.7
Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	Cm cm^{-3}	%
0-20	2.450	59.3	0-20	2.950	69.3	0-20	3.580	68.8
20-40	0.665	16.1	20-40	0.772	18.1	20-40	0.757	14.6
40-60	0.636	15.4	40-60	0.330	7.7	40-60	0.526	10.1
60-80	0.382	9.2	60-80	0.207	4.9	60-80	0.340	6.5
Total	4.133		Total	4.259		Total	5.203	

Experiment E: Effects of nitrogen fertiliser and seed rate on the growth of roots and shoots, with implications for yield in changing water supply to crops (HAUC)

Soil pits and root counts

The soil pit characteristics for the non-irrigated (ambient) plots at GS23 and GS69 are listed in Table R33 and those for the irrigated plots at GS69 in Table R34. The number of roots counted in the soil pits are listed in Table R35.

There were no differences between seed rates or nitrogen treatments at either growth stage for the number of roots in the soil pits (Table R36).

Table R33. Experiment E: Soil pit characteristics for the non-irrigated (ambient) plots at GS23 and GS69.

Plot			GS 23 Ambient	GS 69 Ambient
45	360 seeds m^2	Date dug	2/04/02	3/07/02
	Autumn +	Top soil depth (cm)	40	52
	Standard N	Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	78	105
		Rooting depth (cm)	45	95
46	90 seeds m^2	Date dug	2/04/02	3/07/02
	Autumn +	Top soil depth (cm)	38	52
	Standard N	Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	79	108
		Rooting depth (cm)	45	95
51	360 seeds m^2	Date dug	2/04/02	3/07/02
	Delayed N	Top soil depth (cm)	37	49
		Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	76	102
		Rooting depth (cm)	45	80
52	90 seeds m^2	Date dug	2/04/02	3/07/02
	Delayed N	Top soil depth (cm)	38	48
		Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	74	110
		Rooting depth (cm)	45	95
57	90 seeds m^2	Date dug	2/04/02	3/07/02
	Autumn +	Top soil depth (cm)	38	44
	Standard N	Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	78	106
		Rooting depth (cm)	45	95
58	360 seeds m^2	Date dug	2/04/02	3/07/02
	Autumn +	Top soil depth (cm)	48	57
	Standard N	Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	78	106
		Rooting depth (cm)	60	95
63	360 seeds m^2	Date dug	2/04/04	3/07/02
	Delayed N	Top soil depth (cm)	38	42
		Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	78	103
		Rooting depth (cm)	45	95
64	90 seeds m^2	Date dug	2/04/02	3/07/02
	Delayed N	Top soil depth (cm)	36	37
		Soil texture: Top soil	Loamy sand	Loamy sand
		Soil texture: Sub soil	Sand	Sand
		Pit depth (cm)	76	106
		Sandstone depth (cm)	-	98
		Rooting depth (cm)	45	75

Table R34. Experiment E: Soil pit characteristics for the irrigated plots at GS69.

Plot			GS 69
68	360 seeds m^2	Date dug	3/07/02
	Autumn +	Top soil depth (cm)	37
	Standard N	Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	94
		Sandstone depth (cm)	87
		Rooting depth (cm)	75
71	90 seeds m^2	Date dug	3/07/02
	Autumn +	Top soil depth (cm)	47
	Standard N	Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	100
		Sandstone depth (cm)	100
		Rooting depth (cm)	75
56	360 seeds m^2	Date dug	3/07/02
	Delayed N	Top soil depth (cm)	41
		Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	99
		Sandstone depth (cm)	100
		Rooting depth (cm)	80
59	90 seeds m^2	Date dug	3/07/02
	Delayed N	Top soil depth (cm)	50
		Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	98
		Sandstone depth (cm)	98
		Rooting depth (cm)	80
60	360 seeds m^2	Date dug	3/07/02
	Autumn +	Top soil depth (cm)	37
	Standard N	Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	96
		Sandstone depth (cm)	-
		Rooting depth (cm)	80
55	90 seeds m^2	Date dug	3/07/02
	Autumn +	Top soil depth (cm)	38
	Standard N	Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	104
		Sandstone depth (cm)	-
		Rooting depth (cm)	80
72	360 seeds m^2	Date dug	3/07/02
	Delayed N	Top soil depth (cm)	37
		Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	84
		Sandstone depth (cm)	84
		Rooting depth (cm)	75
67	90 seeds m^2	Date dug	3/07/02
	Delayed N	Top soil depth (cm)	35
		Soil texture: Top soil	Loamy sand
		Soil texture: Sub soil	Sand
		Pit depth (cm)	92
		Sandstone depth (cm)	78
		Rooting depth (cm)	75

Table R35. Experiment E: The root number at different depths in soil pits from non-irrigated (ambient) plots at GS23 and GS69 and irrigated plots at GS69.

Plot	Treatment	Depth (cm)	GS 23 Ambient	GS 69 Ambient	Plot	Treatment	GS 69 Irrigated
45	360 seeds m^2	0-15	194	289	68	360 seeds m^2	310
	Autumn +	15-30	180	510		Autumn &	421
	Standard N	30-45	31	327		Standard N	166
		45-60	0	67			37
		60-75	-	23			3
		75-80	-	54			0
		80-95	-	59			-
46	90 seeds m^2	0-15	127	270	71	90 seeds m^2	242
	Autumn +	15-30	89	628		Autumn &	301
	Standard N	30-45	5	491		Standard N	56
		45-60	0	66			26
		60-75	-	29			13
		75-80	-	106			0
		80-95	-	7			-
51	360 seeds m^2	0-15	192	325	56	360 seeds m^2	231
	Delayed N	15-30	171	564		Delayed N	284
		30-45	37	331			83
		45-60	0	103			75
		60-75	-	123			77
		75-80	-	61			20
		80-95	-	0			-
52	90 seeds m^2	0-15	107	330	59	90 seeds m^2	153
	Delayed N	15-30	75	317		Delayed N	122
		30-45	13	209			59
		45-60	0	63			179
		60-75	-	104			29
		75-80	-	54			2
		80-95	-	14			-
57	90 seeds m^2	0-15	115	288	60	360 seeds m^2	367
	Autumn +	15-30	22	349		Autumn &	432
	Standard N	30-45	9	324		Standard N	158
		45-60	0	238			14
		60-75	-	224			40
		75-80	-	55			10
		80-95	-	26			-
58	360 seeds m^2	0-15	241	314	55	90 seeds m^2	233
	Autumn +	15-30	114	433		Autumn &	328
	Standard N	30-45	46	387		Standard N	113
		45-60	3	258			22
		60-75	-	144			23
		75-80	-	105			15
		80-95	-	27			-
63	360 seeds m^2	0-15	305	182	72	360 seeds m^2	345
	Delayed N	15-30	108	499		Delayed N	282
		30-45	43	553			60
		45-60	0	108			37
		60-75	-	55			3
		75-80	-	56			-
		80-95	-	9			-
64	90 seeds m^2	0-15	142	437	67	90 seeds m^2	341
	Delayed N	15-30	62	836		Delayed N	276
		30-45	29	534			57
		45-60	0	25			64
		60-75	-	4			3
		75-80	-	0			0
		80-95	-	0			-

Table R36. Experiment E: Soil pit root data at GS23 and GS69. For non-irrigated at GS23 and irrigated at GS69 [a] = $\log_{10}$ transformed data of root numbers + 1. For GS69 non-irrigated at GS69 [b] = square root transformed data.

Means	GS 23	GS 69 Ambient	GS 69 Irrigated
Autumn N + Standard N	86 (1.43)[a]	218 (13.4)[b]	139 (1.70)[a]
Delayed N	95 (1.47)	221 (12.3)	116 (1.68)
90 seeds m^2	59 (1.29)	226 (12.6)	111 (1.65)
360 seeds m^2	121 (1.61)	213 (13.0)	144 (1.73)
Probabilities			
Nitrogen	(0.890)	(0.599)	(0.912)
Seed	(0.346)	(0.854)	(0.719)
Nitrogen * Seed	(0.745)	(0.873)	(0.901)
SEM's			
Nitrogen	(0.237)	(1.47)	(0.167)
Seed	(0.237)	(1.47)	(0.167)
Nitrogen * Seed	(0.335)	(2.08)	(0.236)
LSD's			
Nitrogen	(0.688)	(4.17)	(0.475)
Seed	(0.688)	(4.17)	(0.475)
Nitrogen * Seed	(0.973)	(5.90)	(0.672)
Degrees of freedom	(27)	(51)	(43)
CV (%)	(65.4)	(60.7)	(48.3)

There were some significant differences when each depth in the soil pit was analysed separately (Table R39) although these should be treated with caution as there were only three degrees of freedom. For the pits dug at GS23 the 360 seed rate had a greater number of roots compared with the 90 seed rate for the 0-15 cm, 15-30 cm and 30-45 cm depths. For the pits dug in the irrigated block at GS69, the autumn + standard N treatment had significantly greater number of roots compared with the delayed N treatment at a soil depth of 15-30 cm. However although statistically not significant, the delayed N treatment had a greater number of roots compared with the autumn + standard N treatment in the GS69 ambient pit at the 15-30 cm depth.

Table R37. Experiment E: Soil pit results dug at GS23 and GS69 (ambient and irrigated). Analysis of each depth separately by ANOVA. Transformations are given in brackets above the depth if carried out. (Note that Table R37 is on two pages).

Growth stage	GS 23	GS 69 Ambient	GS 69 Irrigated
Depth 0-15 cm	(log_{10})		(Square root)
Autumn N + Standard N	198 (2.279)	290	288 (16.90)
Delayed N	218 (2.304)	319	268 (16.15)
90 seeds m^2	145 (2.159)	331	242 (15.41)
360 seeds m^2	271 (2.423)	278	313 (17.63)
Probabilities: ***Seed***	(0.008**)	0.380	(0.202)
Nitrogen	(0.596)	0.627	(0.623)
Seed*Nitrogen	(0.542)	0.241	(0.620)
LSD's: Seed & Nitrogen	(0.1330)	166.5	(1.335)
Seed*Nitrogen	(0.1881)	235.4	(6.131)
CV (%)	(2.6)	24.3	(11.7)
Degrees of freedom	(3)	3	(3)
Depth 15-30 cm			
Autumn N + Standard N	116.0	480	371
Delayed N	125.5	629	241
90 seeds m^2	72.5	608	257
360 seeds m^2	169.0	502	355
Probabilities: ***Seed***	0.006**	0.377	0.072
Nitrogen	0.548	0.242	0.037*
Seed*Nitrogen	0.510	0.449	0.723
LSD's: Seed & Nitrogen	44.81	325.8	114.5
Seed*Nitrogen	63.37	460.7	162.0
CV (%)	16.5	26.1	16.6
Degrees of freedom	3	3	3
Depth 30-45 cm			(Log_{10})
Autumn N + Standard N	27.0	382	123.2 (2.055)
Delayed N	35.2	407	64.7 (1.806)
90 seeds m^2	17.8	390	71.2 (1.832)
360 seeds m^2	44.5	400	116.7 (2.029)
Probabilities: ***Seed***	0.016*	0.932	(0.1311)
Nitrogen	0.222	0.834	(0.080)
Seed*Nitrogen	0.184	0.612	(0.326)
LSD's: Seed & Nitrogen	17.11	341.3	(0.3039)
Seed*Nitrogen	24.19	482.6	(0.4298)
CV (%)	24.4	38.4	(7.0)
Degrees of freedom	3	3	(3)
Depth 45-60 cm		(Log_{10})	(Square root)
Autumn N + Standard N	0.75	157 (2.11)	25 (4.90)
Delayed N	0	75 (1.81)	89 (9.03)
90 seeds m^2	0	98 (1.85)	73 (7.79)
360 seeds m^2	0.75	134 (2.07)	41 (6.14)
Probabilities: ***Seed***	0.391	(0.415)	(0.205)
Nitrogen	0.391	(0.297	(0.027)
Seed*Nitrogen	0.391	(0.456)	(0.202)
LSD's: Seed & Nitrogen	2.387	(0.752)	(3.257)
Seed*Nitrogen	3.375	(1.063)	(4.606)
CV (%)	282.8	(17.0)	(20.8)
Degrees of freedom	3	(3)	(3)
Depth 60-75 cm		(Square root)	(Log_{10})
Autumn N + Standard N		105 (9.3)	20 (1.14)

Delayed N	72 (7.7)	28 (1.08)
90 seeds m^2	90 (8.1)	17 (1.10)
360 seeds m^2	86 (8.8)	31 (1.11)
Probabilities: *Seed*	(0.882)	(0.991)
Nitrogen	(0.731)	(0.920)
Seed*Nitrogen	(0.604)	(0.747)
LSD's: Seed & Nitrogen	(13.58)	(1.843)
Seed*Nitrogen	(19.20)	(2.606)
CV (%)	(71.1)	(74.0)
Degrees of freedom	(3)	(3)
Depth 75-80 cm		(1/root numbers)
Autumn N + Standard N	80	6.2 (0.54)
Delayed N	43	5.5 (0.60)
90 seeds m^2	54	4.2 (0.60)
360 seeds m^2	69	7.5 (0.53)
Probabilities: *Seed*	0.579	(0.906)
Nitrogen	0.227	(0.917)
Seed*Nitrogen	0.556	(0.886)
LSD's: Seed & Nitrogen	78.3	(1.603)
Seed*Nitrogen	110.8	(2.267)
CV (%)	56.7	(125.7)
Degrees of freedom	3	(3)
Depth 80-95 cm	(Log_{10})	
Autumn N + Standard N	29.8 (1.39)	
Delayed N	5.7 (0.54)	
90 seeds m^2	11.8 (0.88)	
360 seeds m^2	23.8 (1.06)	
Probabilities: *Seed*	(0.735)	
Nitrogen	(0.177)	
Seed*Nitrogen	(0.618)	
LSD's: Seed & Nitrogen	(1.529)	
Seed*Nitrogen	(2.163)	
CV (%)	(70.3)	
Degrees of freedom	(3)	

Root length and root length density (RLD)

Root length density summary Tables are shown for GS23 (Tables R50), GS69 non-irrigated (Table R51) and GS69 irrigated (Table R52).

At GS23 there were no significant differences between root length for the different nitrogen treatments (Table R38). There were no significant differences between treatments for the ambient plots at GS69 (Table R39). The delayed N treatment had significantly less root length at the 20 cm core depth compared with the other two N treatments in the irrigated plots at GS69 sampling (Table R40). There were no other differences with core depths (Table 40).

Table R38. Experiment E: Root lengths per cm depth of soil core (19.6 cm^3) at GS23. For the 360 seeds m^2 seed rate. Results in brackets are the transformed results: ^{a} = square root transformed.

	Depth of core (cm)		
	20	40	60
Means			
Autumn + Standard N	476	80.7	1.95 (1.38)^a
Standard N	379	45.4	0.71 (0.69)
Delayed N	486	93.8	2.79 (1.34)
Probability	0.510	0.139	(0.609)
SEM	33.5	13.64	(0.515)
LSD	131.5	53.56	(2.021)
Df	4	4	(4)
CV (%)	13.0	32.2	(78.6)

Table R39. Experiment E: Root lengths per cm depth of soil core (19.6 cm^3) at GS69 in the non-irrigated plots. For the 360 seeds m^2 seed rate. Results in brackets are the transformed results: ^{a} = natural log transformed; ^{b} = log_{10} transformed; ^{c} = square root transformed.

	Ambient plots			
	Depth of core (cm)			
	20	40	60	80
Means				
A + S N	364.0 (5.896)^a	172 (2.232)^b	57.1 (7.40)^c	72 (8.31)^c
Standard N	301.7 (5.705)	152 (2.176)	64.2 (7.95)	49(6.96)
Delayed N	317.5 (5.756)	157 (2.185)	66.1 (7.92)	75 (8.03)
Probability	(0.130)	(0.777)	(0.929)	(0.835)
SEM	(0.0474)	(0.0574)	(1.123)	(1.639)
LSD	(0.2134)	(0.2254)	(4.410)	(6.436)
Df	(3 (1)*)	(4)	(4)	(4)
CV (%)	(1.4)	(4.5)	(25.1)	(36.6)

Abbreviations: A + S N = Autumn + Standard N treatment; * missing value.

Table R40. Experiment E: Root lengths per cm depth of soil core (19.6 cm^3) at GS69 in the irrigated plots. For the 360 seeds m^2 seed rate. Results in brackets are the transformed results: [a] = log_{10} transformed; [b] = natural log transformed.

	Irrigated plots			
	Depth of core (cm)			
	20	40	60	80
Means				
A + S N	465 (2.665)[a]	172 (5.141)[b]	83	26.9 (1.424)[a]
Standard N	456 (2.653)	168 (5.087)	77	36.4 (1.493)
Delayed N	292 (2.464)	126 (4.827)	64	55.5 (1.685)
Probability	(0.006)**	(0.270)	0.772	(0.521)
SEM	(0.0229)	(0.1235)	18.3	(0.1541)
LSD	(0.0897)	(0.4849)	72.0	(0.6052)
Df	(4)	(4)	4	(4)
CV (%)	(1.5)	(4.3)	42.4	(17.4)

Abbreviations: A + S N = Autumn + Standard N treatment.

Crop growth and yield

The average plant populations were 77 plants m^2 (90 seeds m^2 rate) and 269 plants m^2 (360 seeds m^2 rate). There were no differences in GAI between nitrogen treatments at either GS23 or GS69 sampling (Table R41).

Table R41. Experiment E: Green area index results at GS 23 and for ambient and irrigated plots at GS 69. For the 360 seeds m^2 seed rate.

Means	GS 23	GS 69 Ambient	GS 69 Irrigated
Autumn N + Standard N	0.409	3.65	5.60
Standard N	0.308	4.43	5.00
Delayed N	0.303	4.04	4.87
Probability	0.121	0.061	0.180
SEM	0.0390	0.218	0.286
LSD	0.1144	0.638	0.839
Df	22	22	22
CV (%)	34.4	16.1	16.7

The analysis across the whole trial without taking into account the ambient, irrigated and guttered plots (Table R42), showed no differences for yield. Stem height, ear number, TGW and specific weight were all significantly greater for the 360 seed rate compared with the 90 seed rate. In general stem height, ear number, TGW and specific weight decreased from the autumn + standard N treatment to the standard N treatment to the delayed N treatment. All N treatments were significantly different to each other for stem height and ear number. For the TGW the autumn + standard N treatment was significantly greater to the standard N and delayed N treatments. For the specific weight the delayed N treatment was significantly lower compared with the autumn + standard N and standard N treatments.

Table R42. Experiment E: Preharvest and grain assessment results for the whole trial: Analysis of differences between seed rates and nitrogen treatments across all blocks.

Means	Stem height (cm)	Ear number (nos/m^2)	Yield (t/ha @ 15%mc)	TGW (g)	Specific weight (kg/hl)
Autumn + Standard N	67.60	41.83	6.68	41.35	74.19
Standard N	66.47	39.71	6.72	40.40	73.65
Delayed N	65.17	37.50	6.20	39.90	72.23
90 seeds m^2	65.55	35.94	6.42	39.41	71.81
360 seeds m^2	67.28	43.42	6.65	41.70	74.90
Probabilities					
Nitrogen	<0.001***	<0.001***	0.069	0.016*	<0.001***
Seed	<0.001***	<0.001***	0.248	<0.001***	<0.001***
Nitrogen x seed	0.304	0.048*	0.918	0.376	0.275
SEM's					
Nitrogen	0.397	0.728	0.174	0.350	0.318
Seed	0.324	0.594	0.142	0.285	0.260
Nitrogen x seed	0.561	1.029	0.247	0.494	0.450
LSD's					
Nitrogen	1.125	2.062	0.494	0.991	0.901
Seed	0.918	1.684	0.404	0.809	0.736
Nitrogen x seed	1.591	2.917	0.699	1.401	1.274
Degrees of freedom	55	55	55	55	55
CV (%)	2.9	9.0	13.1	4.2	2.1

There was a significant interaction between nitrogen treatment and seed rate for ear number (Table R43). The reduction in ear number from delaying N occurred only at 360 seeds m^2.

Table R43. Experiment E: Preharvest and grain assessment results for the whole trial: Interaction between nitrogen treatment and seed rate for ear number.

	90 seeds m^2	360 seeds m^2
Autumn + Standard N	36.92	46.75
Standard N	35.75	43.67
Delayed N	35.17	39.83
LSD: Nitrogen x seed	2.917	

The analysis of the ambient blocks only showed there were no significant differences for stem height, yield and TGW (Table R44). The 360 seed rate had significantly greater specific weight and ear number compared with the 90 seed rate. The autumn + standard N treatment had greater specific weight compared with both the standard and delayed N treatment.

Table R44. Experiment E: Preharvest and grain assessment results for ambient blocks only: Analysis of differences between seed rates and nitrogen treatments for blocks 2, 6, 9 and 12.

Means	Stem height (cm)	Ear number (nos/m^2)	Yield (t/ha @ 15%mc)	TGW (g)	Specific weight (kg/hl)
Autumn + Standard N	67.30	40.50	6.02	43.06	75.98
Standard N	65.32	40.50	6.17	42.65	74.65
Delayed N	66.01	36.62	5.68	41.55	74.51
90 seeds m^2	65.52	34.25	6.15	41.87	74.27
360 seeds m^2	66.91	44.17	5.75	42.97	75.83
Probabilities					
Nitrogen	0.091	0.153	0.674	0.291	0.018*
Seed	0.061	<0.001***	0.394	0.179	0.002**
Nitrogen x seed	0.077	0.277	0.999	0.845	0.913
SEM's					
Nitrogen	0.596	1.531	0.393	0.673	0.351
Seed	0.786	1.250	0.321	0.550	0.286
Nitrogen x seed	0.843	2.166	0.556	0.952	0.496
LSD's					
Nitrogen	1.796	4.616	1.185	2.029	1.057
Seed	1.466	3.769	0.967	1.657	0.863
Nitrogen x seed	2.540	6.529	1.675	2.869	1.495
Degrees of freedom	15	15	15	15	15
CV (%)	2.5	11.0	18.7	4.5	1.3

The analysis of the irrigated blocks only showed the 360 seed rate had significantly greater stem height, ear number, TGW and specific weight compared with the 90 seed rate (Table R45). The autumn + standard N treatment was greater for stem height and specific weight compared with the delayed N treatment as was the standard N treatment compared with the delayed N treatment. The TGW was significantly greater for the autumn + standard N treatment compared with the delayed and the standard N treatment. There was no significant differences for yield.

Table R45. Experiment E: Preharvest and grain assessment results for irrigated blocks only: Analysis of differences between seed rates and nitrogen treatments for blocks 7, 8, 10 and 11.

Means	Stem height (cm)	Ear number (nos/m^2)	Yield (t/ha @ 15%mc)	TGW (g)	Specific weight (kg/hl)
Autumn + Standard N	68.49	39.75	7.10	40.26	72.08
Standard N	67.33	37.12	7.01	38.57	71.64
Delayed N	65.31	37.50	6.60	38.18	69.20
90 seeds m^2	66.28	35.25	6.92	37.85	69.08
360 seeds m^2	67.81	41.00	6.88	40.16	72.87
Probabilities					
Nitrogen	0.005**	0.148	0.450	0.034*	0.018*
Seed	0.037*	<0.001***	0.908	0.002**	<0.001***
Nitrogen x seed	0.112	0.016*	0.565	0.257	0.288
SEM's					
Nitrogen	0.579	0.962	0.289	0.537	0.670
Seed	0.473	0.786	0.236	0.438	0.547
Nitrogen x seed	0.819	1.361	0.409	0.759	0.947
LSD's					
Nitrogen	1.746	2.901	0.871	1.619	2.019
Seed	1.426	2.368	0.711	1.322	1.648
Nitrogen x seed	2.470	4.102	1.232	2.289	2.855
Degrees of freedom	15	15	15	15	15
CV (%)	2.4	7.1	11.8	3.9	2.7

At GS69 grain nitrogen % and total nitrogen offtake in above-ground growth (combined leaf and stem material) in non-irrigated plots was significantly higher in the standard or delayed nitrogen treatment than in the autumn + standard nitrogen treatment. (Table R46) In the irrigated plots, the standard nitrogen treatment had the lowest grain nitrogen % and total nitrogen offtake.

Table R46. Experiment E: Total nitrogen in canopy at GS69 for ambient and irrigated blocks.

	Ambient Nitrogen (%) in canopy at GS69	Ambient Total nitrogen offtake at GS69 (kg ha^{-1})	Irrigated Nitrogen (%) in grain	Irrigated Nitrogen offtake in grain (kg ha^{-1})
Autumn and standard N	1.96	98.5	2.13	132.6
Standard N	2.34	121.3	1.97	117.8
Delayed N	2.45	121.6	2.24	123.5
LSD	0.34	8.7	0.30	7.5

There was a significant interaction between nitrogen treatment and seed rate for ear number (Table R47). For both the autumn + standard N treatment and the standard N treatment the 360 seed rate had greater ear number compared with the 90 seed rate, but not for the delayed N treatment.

Table R47. Experiment E: Preharvest and grain assessment results for irrigated blocks only: Interaction between N treatment and seed rate for ear number.

	Seed rate (seeds m^2)	
N treatment	90	360
Autumn + Standard N	34.75	44.75
Standard N	34.00	40.25
Delayed N	37.00	38.00
LSD: Nitrogen x seed	4.102	

The analysis of guttered plots only showed the autumn + standard N treatment had greater ear number and specific weight compared with the delayed N treatment (Table R48). There were no differences between the N treatments for stem height, yield and TGW.

Table R48. Experiment E: Preharvest and grain assessment results for plots in which water was withheld. Analysis of differences between seed rates and nitrogen treatments for plots 2, 6, 8, 13, 20, 25, 31 and 32.

Means	Stem height (cm)	Ear number (nos/m^2)	Yield (t/ha @ 15%mc)	TGW (g)	Specific weight (kg/hl)
Autumn + Standard N	67.48	48.25	7.348	42.56	76.80
Delayed N	65.23	41.25	6.805	41.82	74.85
Probabilities					
Nitrogen	0.251	0.039*	0.062	0.394	0.034*
SEM's					
Nitrogen	1.121	1.307	0.1320	0.532	0.371
LSD's					
Nitrogen	5.046	5.883	0.5939	2.393	1.671
Degrees of freedom	3	3	3	3	3
CV (%)	3.4	5.8	3.7	2.5	1.0

Irrigation and withholding water experiment

When the amount of water removed by the gutters on a plot is compared with the amount of rainfall in a 24 hour period it shows that the gutters only removed a relatively small proportion of the rainfall. On average the gutters collected 22% of the rainfall on a plot (Table R49).

Table R49. Experiment E: Rainfall and collected gutter water at Flat Nook, 2002.

Date	Gutter water (litres/plot)	Rainfall (litres/m^2)	Rainfall (litres/plot (17.5m^2))	% of rain collected per plot
24/05/02	10.75			
25/05/02	17.6875			
26/05/02	29.125			
27/05/02	13.0625			
28/05/02	12.9375			
29/05/02	2.125			
30/05/02	11.875			
03/06/02	39.9375	6.604	115.57	35
05/06/02	31.0625	5.842	102.235	30
06/06/02	72.9375	12.446	217.805	33
07/06/02	6.25	1.27	22.225	28
08/06/02	24.5625	3.81	66.675	37
09/06/02	12.25	2.794	48.895	25
10/06/02	2.5	1.27	22.225	11
13/06/02	15.25	3.556	62.23	25
14/06/02	4.125	1.016	17.78	23
15/06/02	5.625	1.778	31.115	18
16/06/02	2.1875	0.762	13.335	16
21/06/02	1.0625	0.508	8.89	12
27/06/02	0.0625	0	0	0
30/06/02	4.75	1.778	31.115	15
01/07/02	12.5625	4.064	71.12	18
02/07/02	7.6875	2.794	48.895	16
03/07/02	8.9375	2.286	40.005	22
04/07/02	15	2.794	48.895	31
05/07/02	104.125	17.79	311.325	33
08/07/02	10.25	2.286	40.005	26
09/07/02	20.3125	3.556	62.23	33
10/07/02	12.8125	3.302	57.785	22
11/07/02	0.5	0.508	8.89	6
19/07/02	17.25	3.302	57.785	30
20/07/02	28.3125	4.826	84.455	34
21/07/02	0.0625	0	0	0
23/07/02	4.1875	1.778	31.115	13

Table R50. Experiment E: Root length density (cm cm^{-3}) and crop growth, summary Table for GS23 in 2002.

Autumn + Standard N application			**Standard N application**			Delayed N application		
Total root length (km m^{-2})		5.3	**Total root length (km m^{-2})**		4.0	**Total root length (km m^{-2})**		5.5
GAI		0.409	**GAI**		0.308	**GAI**		0.303
Plant population (mean plants m^2)		371.3	**Plant population (mean plants m^2)**		264.7	**Plant population (mean plants m^2)**		260.3
Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	2.427	85.2	0-20	1.929	89.2	0-20	2.476	83.4
20-40	0.411	14.4	20-40	0.231	10.6	20-40	0.477	16.1
40-60	0.010	0.4	40-60	0.004	0.2	40-60	0.014	0.5
Total	2.848		Total	2.164		Total	2.967	

Table R51. Experiment E: Root length density (cm cm^{-3}) and crop growth in non-irrigated plots at GS69 in 2002.

Autumn + Standard N application			**Standard N application**			Delayed N application		
Total root length (km m^{-2})		6.3	**Total root length (km m^{-2})**		6.2	**Total root length (km m^{-2})**		5.8
GAI		3.65	**GAI**		4.43	**GAI**		4.04
Plant population (mean plants m^2)		371.3	**Plant population (mean plants m^2)**		264.7	**Plant population (mean plants m^2)**		260.3
Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	1.855	54.7	0-20	1.537	53.2	0-20	1.618	51.69
20-40	0.876	25.8	20-40	0.775	26.8	20-40	0.800	25.5
40-60	0.291	8.6	40-60	0.327	11.3	40-60	0.337	10.7
60-80	0.367	10.8	60-80	0.250	8.7	60-80	0.382	12.2
Total	3.389			2.889			3.137	

Table R52. Experiment E: Root length density (cm cm^{-3}) and crop growth in irrigated plots at GS69 in 2002.

Autumn + Standard N application			**Standard N application**			Delayed N application		
Total root length (km m^{-2})		7.0	**Total root length (km m^{-2})**		6.9	**Total root length (km m^{-2})**		5.1
GAI		5.60	**GAI**		5.00	**GAI**		4.87
Plant population (mean plants m^2)		266.3	**Plant population (mean plants m^2)**		252.7	**Plant population (mean plants m^2)**		258.3
Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	2.4	63.2	0-20	2.3	60.5	0-20	1.5	55.6
20-40	0.9	23.7	20-40	0.9	23.7	20-40	0.6	22.2
40-60	0.4	10.5	40-60	0.4	10.5	40-60	0.3	11.1
60-80	0.1	2.6	60-80	0.2	5.3	60-80	0.3	11.1
Total	3.8		Total	3.8		Total	2.7	

Experiment F: Effects of nitrogen fertiliser timing on the growth of roots and shoots in two varieties, Consort and Malacca, with implications for yield in adjusting seed rate and changing water supply (HAUC)

Soil pits and root counts

The soil pit characteristics for plots at GS23 and GS 69 are listed in Table R53. The number of roots counted in the soil pits are listed in Table R54.

At GS 23 (Table R55) and GS 69 (Table R56) sampling there were no differences between varieties, nitrogen treatments or seed rates for the number of roots in the soil pits.

When each depth was analysed separately by ANOVA at GS69 (Table R57) there were some significant differences between treatments at soil depths of 45-60 cm and 75-80 cm depths but these differences should be treated with caution since the residual degrees of freedom in the ANOVA is only one. For example, at a soil depth of 45-60 cm the 90 seed m^{-2} treatment had a higher root number compared with the 360 seed m^{-2} treatment and Malacca had greater root number compared with Consort.

Table R53. Experiment F: Soil pit characteristics for plots at GS23 and GS69.

Plot			GS 23	GS 69
1	Malacca	Date dug	April 2 2003	July 16 2003
	360 seeds m^2	Top soil depth (cm)	48	36
	Late N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand
		Pit depth (cm)	75	95
		Rooting depth (cm)	60	95
2	Malacca	Date dug	April 2 2003	July 16 2003
	90 seeds m^2	Top soil depth (cm)	43	32
	Late N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand
		Pit depth (cm)	75	95
		Rooting depth (cm)	45	95
6	Consort	Date dug	April 2 2003	July 16 2003
	360 seeds m^2	Top soil depth (cm)	42	41
	Early N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand
		Pit depth (cm)	75	95
		Rooting depth (cm)	45	95
7	Consort	Date dug	April 2 2003	July 16 2003
	90 seeds m^2	Top soil depth (cm)	43	43
	Early N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Loamy sand
		Pit depth (cm)	75	95
		Rooting depth (cm)	45	95
34	Consort	Date dug	April 2 2003	Juy 16 2003
	360 seeds m^2	Top soil depth (cm)	42	45
	Late N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Sandstone
		Pit depth (cm)	75	95
		Rooting depth (cm)	60	95
35	Consort	Date dug	April 2 2003	July 16 2003
	90 seeds m^2	Top soil depth (cm)	37	43
	Late N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Sandstone
		Pit depth (cm)	75	95
		Rooting depth (cm)	30	75
38	Malacca	Date dug	April 2 2003	July 16 2003
	90 seeds m^2	Top soil depth (cm)	42	40
	Early N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Sandstone
		Pit depth (cm)	75	95
		Rooting depth (cm)	45	95
39	Malacca	Date dug	April 2 2003	July 16 2003
	360 seeds m^2	Top soil depth (cm)	40	38
	Early N	Soil texture: Top soil	Sandy loam	Sandy loam
		Soil texture: Sub soil	Loamy sand	Sandstone
		Pit depth (cm)	75	95
		Rooting depth (cm)	75	80

Table R54. Experiment F: The number of roots at different depths in soil pits at different growth stages.

Plot	Treatment	Depth (cm)	GS 23	GS 69
1	Malacca	0-15	47	208
	360 seeds m^2	15-30	73	144
	Late N	30-45	23	56
		45-60	3	43
		60-75	0	57
		75-80	-	22
		80-95	-	1
2	Malacca	0-15	46	263
	90 seeds m^2	15-30	60	200
	Late N	30-45	22	55
		45-60	5	38
		60-75	0	17
		75-80	-	13
		80-95	-	7
6	Consort	0-15	96	378
	360 seeds m^2	15-30	48	197
	Early N	30-45	14	54
		45-60	0	28
		60-75	0	17
		75-80	-	17
		80-95	-	12
7	Consort	0-15	49	272
	90 seeds m^2	15-30	60	218
	Early N	30-45	22	107
		45-60	5	55
		60-75	0	10
		75-80	-	8
		80-95	-	2
34	Consort	0-15	75	215
	360 seeds m^2	15-30	32	134
	Late N	30-45	0	94
		45-60	1	25
		60-75	0	28
		75-80	-	16
		80-95	-	1
35	Consort	0-15	50	266
	90 seeds m^2	15-30	15	216
	Late N	30-45	0	43
		45-60	0	16
		60-75	0	5
		75-80	-	0
		80-95	-	0
38	Malacca	0-15	41	182
	90 seeds m^2	15-30	28	157
	Early N	30-45	7	70
		45-60	0	42
		60-75	0	5
		75-80	-	5
		80-95	-	3
39	Malacca	0-15	127	184
	360 seeds m^2	15-30	39	137
	Early N	30-45	4	17
		45-60	4	15
		60-75	1	12
		75-80	-	1
		80-95	-	0

Table R55. Experiment F: Soil pit root data: GS23 sampling. Data analysed using a Kruskal-Wallis one way ANOVA

	Variety	Seed	Nitrogen
Value of H	0.001646	0.9748	0.9483
Adjusted H for ties	0.001720	1.018	0.9908
Sample size of each group	20	20	20
Mean rank: Group 1	Consort: 20.43	90 seeds m^2: 18.68	Early N: 22.30
Mean rank: Group 2	Malacca: 20.57	360 seeds m^2: 22.32	Late N: 18.70
Degrees of freedom	1	1	1
Chi square p value	0.967	0.313	0.320

Table R56. Experiment F: Soil pit root data: GS 69 sampling

([a] = $\log_{10}$ transformed data of root numbers + 1).

	GS69
Means	
Early N	79
Late N	78
90 seeds m^2	81
360 seeds m^2	75
Consort	87
Malacca	70
Probabilities	
Nitrogen	(0.882)[a]
Seed	(0.826)
Variety	(0.866)
Nitrogen x Seed	(0.526)
Nitrogen x Variety	(0.167)
Variety x Seed	(0.371)
Variety x Seed x Nitrogen	(0.999)
SEM's	
Nitrogen	(0.1396)
Seed	(0.1396)
Variety	(0.1396)
Nitrogen x Seed	(0.1974)
Nitrogen x Variety	(0.1974)
Variety x Seed	(0.1974)
Variety x Seed x Nitrogen	(0.2791)
LSD's	
Nitrogen	(0.3969)
Seed	(0.3969)
Variety	(0.3969)
Nitrogen x Seed	(0.5612)
Nitrogen x Variety	(0.5612)
Variety x Seed	(0.5612)
Variety x Seed x Nitrogen	(0.7937)
Degrees of freedom	(48)
CV (%)	(49.8)

Table R57. Experiment F: Soil pit results at GS 69 sampling: Analysis of each depth separately by ANOVA

Depth	0-15 cm	15-30 cm	30-45 cm
Transformation	(Recipricol: 1/ rootno)	(Square root)	
Early N	254 (0.00431)	177.2 (13.26)	55.0
Late N	238 (0.00426)	173.5 (12.10)	62.0
90 seeds m^2	246 (0.00418)	197.8 (14.03)	61.8
360 seeds m^2	246 (0.00438)	153.0 (12.33)	55.2
Consort	283 (0.00368)	191.2 (13.77)	74.5
Malacca	209 (0.00488)	159.5 (12.59)	42.5
Probabilities: *Nitrogen*	(0.833)	(0.667)	0.781
Seed	(0.520)	(0.100)	0.795
Variety	(0.112)	(0.143)	0.348
Nitrogen x Seed	(0.178)	(0.180)	0.344
Nitrogen x Variety	(0.122)	(0.151)	0.508
Seed x Variety	(0.426)	(0.562)	0.825
LSD's: Single factors	(0.002724)	(3.415)	247.77
Two way interactions	(0.003853)	(4.830)	350.40
Depth	**45-60 cm**	**60-75 cm**	**75-80 cm**
Tranformation	(Log $_{10}$)	(Log_{10})	(Square root (rootnos +1)
Early N	35.00 (1.4967)	11.0 (1.002)	7.75 (2.777)
Late N	30.50 (1.4538)	26.8 (1.283)	12.75 (3.415)
90 seeds m^2	37.75 (1.5369	9.2 (0.907)	6.50 (2.548)
360 seeds m^2	27.75 (1.4137	28.5 (1.378)	14.00 (3.644)
Consort	31.00 (1.4474	15.0 (1.094)	10.25 (3.091)
Malacca	34.50 (1.5031	22.8 (1.191)	10.25 (3.100)
Probabilities: *Nitrogen*	(0.051)	(0.204)	(0.052)
Seed	(0.018*)	(0.124)	(0.030*)
Variety	(0.039*)	(0.487)	(0.893)
Nitrogen x Seed	(0.009**)	(0.326)	(0.033*)
Nitrogen x Variety	(0.009**)	(0.179)	(0.020*)
Seed x Variety	(0.030*)	(0.877)	(0.031*)
LSD's: Single factors	(0.04389)	(1.1833)	(0.6639)
Two way interactions	(0.06208)	(1.6735)	(0.9388)
Depth	**80-95 cm**		
Transformation	(Log_{10})		
Early N	4.25 (0.548)		
Late N	2.25 (0.376)		
90 seeds m^2	3.00 (0.496)		
360 seeds m^2	3.50 (0.429)		
Consort	3.75 (0.473)		
Malacca	2.75 (0.452)		
Probabilities: *Nitrogen*	(0.289)		
Seed	(0.573)		
Variety	(0.841)		
Nitrogen x Seed	(0.500)		
Nitrogen x Variety	(0.112)		
Seed x Variety	(0.099)		
LSD's: Single factors	(1.0667)		
Two way interactions	(1.5085)		

For the interaction of seed rate and nitrogen timing (Table R58), the early N treatment at the 90 seed rate had greater root number however at the late N treatment the 360 seed rate had more roots. For the interaction of nitrogen and variety (Table R58), early N treated Consort had more roots compared with late N treated whereas for Malacca the reverse was the case. For the interaction of seed rate and variety (Table R58), Malacca had more roots at 90 seeds m^{-2} compared with Consort, whereas there was no difference between varieties at 360 seeds m^{-2}.

Table R58. Experiment F: Interactions for soil pit root numbers at GS 69 at the 45-60 cm depth. Data is the log_{10} transformed data.

Nitrogen x Seed	90 seeds m^2	360 seeds m^2
Early N treatment	1.6818	1.3116
Late N treatment	1.3920	1.5157
LSD	0.06208	
Nitrogen x Variety	**Consort**	**Malacca**
Early N treatment	1.5938	1.3997
Late N treatment	1.3010	1.6066
LSD	0.06208	
Seed x Variety	**Consort**	**Malacca**
90 seeds m^2	1.4722	1.6015
360 seeds m^2	1.4225	1.4048
LSD	0.06208	

At the 75-80 cm depth the 360 seed rate had more roots in the soil pit compared with the 90 seed rate. For the interaction of nitrogen and seed rate (Table R59), the 360 seed rate at the late N treatment had greater root number compared with the early N treatment whereas at the 90 seed rate there was no difference between N treatments. For the interaction of seed rate and variety (Table R59), the number of roots increased with increasing seed rate for Consort but for Malacca there was no difference between seed rates. For the interaction of nitrogen and variety (Table R59), root number was greater for Consort in the early N treatment compared with the late N treatment whereas for Malacca the reverse was the case.

Table R59. Experiment F: The interactions for soil pits at GS 69 at the 75-80 cm depth. Data is the square root transformed data.

Nitrogen x Seed	90 seeds m^2	360 seeds m^2
Early N treatment	2.725	2.828
Late N treatment	2.371	4.459
LSD	0.9388	
Seed x Variety	**Consort**	**Malacca**
90 seeds m^2	2.000	3.096
360 seeds m^2	4.183	3.105
LSD	0.9388	
Nitrogen x Variety	**Consort**	**Malacca**
Early N treatment	3.621	1.932
Late N treatment	2.562	4.269
LSD	0.9388	

Root length and root length density (RLD)

Root length density summary Tables are shown for GS23 (Table R67) and GS69 (Table R68).

There were no significant differences between N treatments and variety for root length at GS 23 sampling (Table R60) or at GS 69 sampling (Table R61).

Table R60. Experiment F: Root lengths per cm depth of soil core (19.6 cm^3) at GS23. Transformations are in brackets: ^{a} = log_{10} transformed.

	Depth of core (cm)		
	20	40	60
Means			
Early N	110.4	65.5	25.9 (1.399)^a
Late N	113.4	59.3	17.0 (1.215)
Consort	129.6	74.2	19.3 (1.253)
Malacca	94.2	50.6	23.6 (1.360)
Probabilities: Nitrogen	0.849	0.681	(0.056)
Variety	0.060	0.152	(0.216)
Nitrogen x Variety	0.535	0.946	(0.634)
SEM's: Nitrogen	10.82	10.16	(0.0549)
Variety	10.82	10.16	(0.0549)
Nitrogen x Variety	15.30	14.37	(0.0777)
LSD's: Nitrogen	37.43	35.17	(0.1901)
Variety	37.43	35.17	(0.1901)
Nitrogen x Variety	52.93	49.74	(0.2688)
Df	6	6	(6)
CV (%)	23.7	39.9	(10.3)

Table R61. Experiment F: Root lengths per cm depth of soil core (19.6 cm^3)

at GS69. Transformations are given in brackets: [a] = $\log_{10}$ transformed data and [b] = (1/mean40) transformed.

	Depth of core (cm)			
	20	40	60	80
Means				
Early N	166 (2.198)[a]	85.4 (0.01178)[b]	87.9	4.40
Late N	149 (2.170)	100.6 (0.01048)	103.2	5.16
Consort	173 (2.227)	100.2 (0.01045)	101.3	5.07
Malacca	143 (2.141)	85.8 (0.01181)	89.9	4.49
Probabilities: Nitrogen	(0.700)	(0.302)	0.127	0.127
Variety	(0.263)	(0.282)	0.234	0.234
Nitrogen x Variety	(0.486)	(0.401)	0.228	0.228
SEM's: Nitrogen	(0.0490)	(0.000812)	6.11	0.306
Variety	(0.0490)	(0.000812)	6.11	0.306
Nitrogen x Variety	(0.0692)	(0.001149)	8.64	0.432
LSD's: Nitrogen	(0.1694)	(0.002811)	21.15	1.057
Variety	(0.1694)	(0.002811)	21.15	1.057
Nitrogen x Variety	(0.2396)	(0.003975)	29.91	1.496
Df	(6)	(6)	6	6
CV (%)	(5.5)	(17.9)	15.7	15.7

Crop growth and yield

The average plant populations were 74 seeds m^2 for the 90 seeds m^2 sowing rate and 237 seeds m^2 for the 360 seeds m^2 sowing rate. At GS23 sampling Consort had a significantly greater green area index compared with Malacca but by GS 69 there were no differences between the varieties (Table R62). There were no differences in green area index between nitrogen treatments at GS 23 or 69 sampling.

The analysis across the three harvested blocks (Table R63) showed that the stem height for the early N treatment was significantly taller compared with the late N treatment. The 360 seed rate had a greater number of ears and yield compared with the 90 seed rate. There was a significant interaction between seed rate and variety for yield (Table R64). Consort had a significantly greater yield compared with Malacca at the 90 seed rate whereas there was no difference between the two varieties at the 360 seed rate. Consort had a heavier specific weight compared with Malacca. There were no differences between above-ground dry matter and TGW.

Table R62. Experiment F: GAI at GS23 and GS69.

Means	GS 23	GS 69
Early N	0.502	3.53
Late N	0.453	3.08
Consort	0.604	3.29
Malacca	0.351	3.32
Probabilities		
Nitrogen	0.395	0.092
Variety	<0.001***	0.883
Nitrogen x variety	0.122	0.502
SEM's		
Nitrogen	0.0400	0.179
Variety	0.0400	0.179
Nitrogen x variety	0.0566	0.254
LSD's		
Nitrogen	0.1156	0.518
Variety	0.1156	0.518
Nitrogen x variety	0.1635	0.733
Degrees of freedom	30	30
CV (%)	35.6	23.0

However, the data in the three blocks analysed in Table R63 were under three different conditions, ambient, irrigated and sheltered. To determine if the different conditions in the blocks affected the ANOVA results when analysed as if the blocks were under the same conditions, the block probability was calculated for each variable (Table R65) after the analysis. This showed that the environmental conditions of the blocks were affecting the yield and TGW (Table R65).

Therefore an ANOVA was done for each of the three blocks separately for these two variables. The results of this data (Table R66) should be treated with caution since the degrees of freedom is only one. In the ambient and irrigated blocks yield was significantly greater for the 360 seed rate compared with the 90 seed rate but not for the sheltered block (Table R66). In the ambient and sheltered blocks there were no differences for TGW. However, in the irrigated block TGW was significantly greater for Malacca compared with Consort and for the 90 seed rate compared with the 360 seed rate.

Table R63. Experiment F: Preharvest and grain assessment results: Analysis of the differences between nitrogen treatments, variety and seed rates across the three harvested blocks.

Means	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg/hl)	TGW (g)
Early N	68.17	44.02	1184	6.342	72.50	42.01
Late N	65.60	43.00	1305	6.282	72.45	42.46
90 seeds m^2	66.24	37.06	1247	5.763	72.08	42.21
360 seeds m^2	67.53	49.96	1242	6.861	72.87	42.26
Consort	66.96	43.25	1335	6.427	73.13	42.08
Malacca	66.80	43.77	1154	6.197	71.82	42.39
Probabilities						
Nitrogen	0.007**	(0.641)	0.286	0.700	0.926	0.581
Seed	0.134	(<0.001***)	0.963	<0.001***	0.159	0.949
Variety	0.853	(0.851)	0.118	0.160	0.025*	0.705
Nitrogen x Seed	0.434	(0.150)	0.477	0.366	0.599	0.931
Nitrogen x Variety	0.329	(0.478)	0.236	0.739	0.557	0.705
Variety x Seed	0.627	(0.219)	0.891	0.045*	0.478	0.557
Var x Seed x Nitrogen	0.803	(0.680)	0.940	0.895	0.926	0.481
SEM's						
Nitrogen	0.573	(0.0916)	76.8	0.1092	0.372	0.567
Seed	0.573	(0.0916)	76.8	0.1092	0.372	0.567
Variety	0.573	(0.0916)	76.8	0.1092	0.372	0.567
Nitrogen x Seed	0.811	(0.1295)	108.6	0.1544	0.526	0.801
Nitrogen x Variety	0.811	(0.1295)	108.6	0.1544	0.526	0.801
Variety x Seed	0.811	(0.1295)	108.6	0.1544	0.526	0.801
Var x Seed x Nitrogen	1.147	(0.1831)	153.5	0.2184	0.744	1.133
LSD's						
Nitrogen	1.739	(0.2777)	232.8	0.3312	1.129	1.719
Seed	1.739	(0.2777)	232.8	0.3312	1.129	1.719
Variety	1.739	(0.2777)	232.8	0.3312	1.129	1.719
Nitrogen x Seed	2.460	(0.3928)	329.3	0.4685	1.597	2.431
Nitrogen x Variety	2.460	(0.3928)	329.3	0.4685	1.597	2.431
Variety x Seed	2.460	(0.3928)	329.3	0.4685	1.597	2.431
Var x Seed x Nitrogen	3.479	(0.5555)	465.7	0.6625	2.258	3.438
Degrees of freedom	14	(14)	14	14	14	14
CV (%)	3.0	(4.8)	21.4	6.0	1.8	4.6

Table R64. Experiment F: The interaction between seed rate and variety for yield.

Seed rate	Consort	Malacca
90 seeds m^2	6.048	5.478
360 seeds m^2	6.805	6.917
LSD	0.4685	

Table R65. Experiment F: The influence of the three different environmental conditions (ambient, irrigated and sheltered) as the three blocks in ANOVA on the preharvest and grain assessment results.

	Stem height (cm)	Ear number (mean per 0.1 m^2)	Above ground dry matter (g m^2)	Yield (t ha^{-1})	Specific weight (kg/hl)	TGW (g)
Block variance ratio	0.89	1.98	2.310	66.51	2.550	12.63
Block probability	0.4327	0.1749	0.1358	<0.001***	0.1137	<0.001***
Block CV (%)	1.0	10.2	11.5	17.3	1.0	5.8

Table R66. Experiment F: Yield and TGW results analysed separately for each of the blocks under different environmental conditions. Transformations in brackets: [a] = square root. These results contain no 3 way interaction and the degrees of freedom are very low.

	Yield (t ha^{-1})			TGW (g)		
	Ambient	Irrigated	Sheltered	Ambient	Irrigated	Sheltered
Means	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
Early N	6.735 (2.5904)[a]	7.388	4.905	43.43 (6.590)	44.375	38.23
Late N	6.465 (2.5379)	7.072	5.308	42.41 (6.511)	44.207	40.77
90 seeds m^2	5.883 (2.4234)	6.658	4.750	42.20 (6.495)	44.520	39.91
360 seeds m^2	7.318 (2.7049)	7.803	5.463	43.63 (6.606)	44.063	39.09
Consort	6.865 (2.6173)	7.178	5.238	42.62 (6.528)	43.048	40.57
Malacca	6.335 (2.5110)	7.283	4.975	43.21 (6.573)	45.535	38.43
Probabilities						
Nitrogen	(0.170)	0.149	0.113	(0.321)	0.085	0.272
Seed	(0.032)*	0.042*	0.065	(0.239)	0.031*	0.607
Variety	(0.086)	0.395	0.172	(0.487)	0.006**	0.315
N x Seed	(0.389)	0.179	0.168	(0.271)	0.144	0.447
N x Variety	(0.178)	0.442	0.229	(0.506)	0.027*	0.577
Var x Seed	(0.143)	0.147	0.112	(0.989)	0.011*	0.936
SEM's						
Factors	(0.01015)	0.0530	0.0513	(0.0308)	0.0159	0.818
Interactions	(0.01436)	0.0750	0.0725	(0.0436)	0.0225	1.158
LSD's						
Factors	(0.18242)	0.9530	0.9212	(0.5543)	0.2859	14.707
Interactions	(0.25798)	1.3477	1.3028	(0.7839)	0.4043	20.799
Df	(1)	1	1	(1)	1	1

Table R67. Experiment F: Root length density (cm cm^{-3}) and crop growth at GS23 in 2003.

Consort			Malacca			Early Nitrogen			Late Nitrogen		
Total root length (km m^{-2})		2.1	Total root length (km m^{-2})		1.6	Total root length (km m^{-2})		1.9	Total root length (km m^{-2})		1.8
GAI		**0.604**	**GAI**		0.351	**GAI**		**0.502**	***GAI***		0.453
Plant population (mean plants m^2)		299.8	Plant population (mean plants m^2)		184.5	Plant population (mean plants m^2)		235.7	Plant population (mean plants m^2)		251.2
Layer (cm)	cm cm^{-3}	%	Layer (cm)	Cm cm^{-3}	%	Layer (cm)	Cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	0.660	58.1	0-20	0.480	55.9	0-20	0.562	54.7	0-20	0.578	59.8
20-40	0.378	33.2	20-40	0.258	33.1	20-40	0.334	32.5	20-40	0.302	31.3
40-60	0.098	8.6	40-60	0.120	14.0	40-60	0.132	12.8	40-60	0.087	8.9
60-80			60-80			60-80			60-80		
Total	1.137		Total	0.858		Total	1.028		Total	0.967	

Table R68. Experiment F: Root length density (cm cm^{-3}) and crop growth at GS69 in 2003.

Consort			***Malacca***			***Early Nitrogen***			Late Nitrogen		
Total root length (km m^{-2})		3.5	Total root length (km m^{-2})		3.0	Total root length (km m^{-2})		3.2	Total root length (km m^{-2})		3.3
GAI		**3.29**	**GAI**		3.32	**GAI**		**3.53**	***GAI***		3.08
Plant population (mean plants m^2)		299.8	Plant population (mean plants m^2)		184.5	Plant population (mean plants m^2)		235.7	Plant population (mean plants m^2)		251.2
Layer (cm)	cm cm^{-3}	%	Layer (cm)	Cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%	Layer (cm)	cm cm^{-3}	%
0-20	0.881	46.5	0-20	0.727	44.4	0-20	0.847	48.2	0-20	0.761	42.8
20-40	0.511	26.9	20-40	0.437	26.7	20-40	0.435	24.8	20-40	0.513	28.8
40-60	0.285	15.0	40-60	0.276	16.8	40-60	0.280	15.9	40-60	0.281	15.8
60-80	0.219	11.6	60-80	0.198	12.1	60-80	0.194	11.1	60-80	0.223	12.6
Total	1.897		Total	1.638		Total	1.756		Total	1.778	

Experiments G: Effects of plant population density on the growth of roots and shoots (University of Edinburgh)

General comment for Experiments G, H and I

Note that the GAI in the root tube experiments is not directly comparable with the figures collected in the field because the leaves occupied more than the surface area of the circular tubes. However the ratio of root length to green area is comparable.

The number of primary axes increased to about 25 by growth stage 31, i.e. approximately 2500 m^{-2}. The main activity after that was in the degree of proliferation. By anthesis the cortex of some of the main axes had collapsed in the upper part of the profile although the lower parts of the roots were still healthy and functioning and the vascular connections with the stem must have been intact. The proportion of tertiary axes was generally rather low and, as expected, root hairs appeared to be absent.

Experiment G

In this experiment, PPDs were varied by using two diameters of tubes and by varying the number of plants (1, 2, 3) in the smaller diameter tube. The root systems in each pot could not easily be separated.

The total root length declined with PPD at least where PPD is less than 200. The two higher PPDs appeared to have deeper rooting and at depths shallower than 0.60 m the root length density was greater for the two lowest PPDs. Although the PPDs varied by a factor of 6 the ratio of root length to green area declined by only 25%. The limiting environment resulted in a shallower rooting depth, a lower RLD but rather little effect on GAI. The two environments represented an extreme contrast greater than would be likely to occur in the field. The only caveat is that considerable nitrogen was mineralised from the organic matter in the soil mix.

Note that the very large values of GAI were for plants that had not been vernalised. Also the foliage occupied more space than the cross sectional area of the pots. These figures for GAI are therefore not comparable with those in the field. On the other hand the ratio of root length to GA should be comparable.

Table R68. Experiment G: The influence of (a) plant population density and (b) limiting and non-limiting soil moisture on root length density (cm cm^{-3}), rooting depth, total root length and GAI in variety consort.

	(a)				(b)	
	PPD (m^{-2})				Environment	
	50	106	212	319	limiting	non-limiting
Replicates	10	10	10	10	20	20
Root length density (cm cm^{-3})						
0-20 cm	3.72	3.42	2.66	2.16	2.85	1.05
20-40 cm	3.02	3.59	2.54	2.16	2.49	2.04
40-60 cm	3.60	3.12	1.93	1.41	1.66	1.68
60-80 cm	3.14	1.69	2.21	2.79	2.19	1.68
80-100 cm	2.88	1.65	1.71	2.14	1.75	2.65
100-120 cm	1.55	0.96	1.02	1.13	1.26	1.22
120-140 cm	0.30	0.04	0.08	0.16	0.07	0.00
140-160 cm	0.00	0.01	0.02	0.02	0.00	0.00
Rooting depth (m)	1.23	1.32	1.33	1.27	1.24	1.33
Total root length (km m^{-2})	36.43	28.96	24.36	25.12	24.55	32.48
GAI	33.7	31.3	34.0	33.9	32.7	33.8
Rl/GA	1.08	0.92	0.72	0.74	0.75	0.96

Experiment H: Effects of nitrogen timing and limiting or non-limiting soil moisture on root and shoot growth (University of Edinburgh)

Before GS55, There were large differences in TRL and the distribution of RLD between different nitrogen timings and drought *versus* non-drought conditions, though these . Early (spring) nitrogen supply (N1) resulted in more root growth above 80 cm by growth stage 33, whilst delaying the main application resulted in less root growth in the plough layer at this stage. Although differences were small by anthesis. After GS33, there were effects of drought on root depth. By GS33, TRL and RLD at all depths were higher in the droughted (W0) than non-droughted (W1) treatments. By GS55, these strong effects were not apparent.

Table R69. Experiment H: The influence of nitrogen timing on root length density (cm cm^{-3}), rooting depth, total root length and GAI in variety consort.

	N1,2,3	N1	N2	N3	N1	N2	N3	N1	N2	N3
GS	11	24	24	24	33	33	33	55+	55+	55+
Replicates	5	2	2	2	2	2	2	6	6	6
0-20 cm	0.06	8.79	8.05	13.95	5.03	6.50	1.89	2.18	4.28	1.30
20-40 cm	0.00	0.24	1.79	1.74	9.77	6.50	8.28	3.57	3.73	3.86
40-60 cm		0.00	0.00	0.00	13.44	11.96	11.93	4.05	4.84	5.84
60-80 cm					13.07	9.23	11.34	5.86	6.01	5.35
80-100 cm					8.98	8.48	10.24	5.19	5.92	4.98
100-120 cm					5.37	12.73	9.00	5.51	5.82	5.90
120-140 cm					1.59	3.50	3.59	2.38	1.94	2.71
140-160 cm					0.00	0.00	2.63	0.00	0.00	0.00
Rooting depth	0.14	0.41	0.50	0.47	1.26	1.31	1.35	1.29	1.29	1.36
Total root length	0.12	18.04	19.69	40.61	114.51	118.63	117.80	57.49	65.10	59.91
GAI	0.03	0.36	0.35	0.42	15.05	15.88	16.23	14.53	17.52	18.18
Rl/GA	4.04	49.69	56.63	97.35	7.61	7.47	7.26	3.96	3.72	3.29

Table R70. Experiment H: The influence of limiting (drought) and non-limiting watering on root length density (cm cm^{-3}), rooting depth, total root length and GAI in variety consort.

	W0,1	W0	W1	W0	W1	W0	W1
GS	11	24	24	33	33	55+	55+
Replicates	5	3	3	3	3	9	9
0-20 cm	0.06	9.81	13.79	7.28	1.95	2.00	3.18
20-40 cm	0.00	1.20	1.31	8.87	7.50	3.60	3.85
40-60 cm		0.00	0.00	14.29	10.59	5.25	4.57
60-80 cm				15.03	7.38	5.84	5.65
80-100 cm				9.80	8.67	5.19	5.54
100-120 cm				9.80	7.46	5.38	6.10
120-140 cm				4.90	0.89	1.71	2.98
140-160 cm				1.75	0.00	0.00	0.00
Rooting depth	0.14	0.42	0.49	1.35	1.26	1.32	1.31
Total root length	0.12	22.02	30.21	145.07	88.90	57.94	63.72
GAI	0.03	0.39	0.36	17.29	14.15	16.62	16.87
Rl/GA	4.041667	56.31	83.7	8.3904	6.28	3.485	3.778

Experiment I: Root and shoot growth in two varieties, Consort and Malacca (University of Edinburgh)

There appeared to be no agronomically significant differences between the two varieties although Consort seemed to have a slightly higher total root length with a suggestion of greater root length density between 0.6 and 1.2 m. The ratio of root length to green area was relatively constant over the whole range of growth stages. The high value for Malacca in the later GSs is due to a low GAI, perhaps associated with premature leaf senescence. Although all the tubes were watered, the amount added was less than the actual rate of evapotranspiration and a larger deficit than planned ha built up by the end of the experiment.

Table R70. Experiment I: Root length density (cm cm^{-3}), rooting depth, total root length and GAI in varieties Consort and Malacca.

Variety	Consort	Malacca	Consort	Malacca	Consort	Malacca	Consort	Malacca	Consort	Malacca
GS	12	12	21	21	26	28	33	32	50+	50+
replicates	3	3	3	3	3	3	3	3	9	9
0-20 cm	0.06	0.04	0.40	0.09	1.04	0.86	1.41	2.05	1.31	1.34
20-40 cm					0.28	0.23	1.89	1.44	1.43	1.23
40-60 cm					0.03	0.06	2.01	1.78	1.34	1.71
60-80 cm					0.01	0.02	1.70	1.64	2.18	1.62
80-100 cm							1.48	1.89	2.51	1.96
100-120 cm							1.78	1.15	2.87	2.08
120-140 cm							0.27	0.17	0.44	0.70
140-160 cm										0.00
Rooting depth (m)	0.12	0.12	0.14	0.15	0.65	0.81	1.35	1.38	1.36	1.36
Total root length(km m^{-2})	0.11	0.08	0.79	0.17	2.71	2.36	21.10	20.25	24.25	21.27
GAI	0.0	0.0	0.1	0.1	1.5	1.3	13.8	13.3	10.4	4.2
Rl/GA (km m^{-2})	2.58	1.92	9.91	1.31	1.82	1.76	1.53	1.52	2.33	5.10

DISCUSSION

1. General crop and root system responses

Our experimental programme resulted in widely contrasting root systems and leaf canopies across a range of agronomic treatments soil conditions. Crops were not always sown at the original target dates of September or early October (because of unsuitable weather and soil conditions at our preferred trial locations). However, this provided an opportunity to examine more fully the root-shoot relations of crops with small to medium sized canopies, and very small to large root systems, in limiting environments.

Furthermore conditions such as poor soil structure tend to show most in late-sown autumn or spring-sown crops where root systems are less extensive, where the shorter period of growth and greater overlap of shoot and root growth reduce the range of plant responses to alleviate poor soil conditions. Thus our study covers a wide range of agronomic and environmental conditions on which to base our understanding of managing root systems.

Hoad et al. (2001) showed that the total root length of winter wheat grown on UK soils typically ranged between 12 km m^{-2} and 32 km m^{-2} at high yielding sites in the UK. Our field-grown crops had total lengths at the upper end of this range, but also well below this range. Likewise the range of root length densities (RLD) (cm cm^{-3}) was wide; from typical values of above 3-5 cm cm^{-3} in the plough layer to less than 1 cm cm^{-3} below soil depths of 40 cm, or under very poor rooting in the plough layer.

With emphasis on soil conditions that might encourage shallow rooting, most of our soil coring in the field trials was to a maximum depth of 80 cm, below which there was negligible root growth, as confirmed by soil coring (Experiments A to F) and root counts in soil pits (Experiments D, E and F). However in the controlled environment studies (Experiments G to I) we extended this depth to 160 cm. This is important considering that individual roots of cereal crops have been recorded as reaching a depth of over 2 m (e.g. Kirby & Rackham 1971; Hoad et al. 2001).

Our results are consistent with earlier reports that roots are distributed unevenly with the bulk of their length in the surface layers (e.g. Welbank & Williams 1968; Welbank et al. 1974; Gregory et al. 1978; Barraclough 1984; Madsen 1985). Growth occurs sequentially down the profile and this often leads to an exponential decrease in root length density with depth

(Barraclough 1984; Barraclough & Leigh 1984; Haberle et al. 1996). Thus the vertical distribution of the root system changes throughout the season. At anthesis i.e. GS69 we recorded a wider range of root system distributions (down the soil profile) compared to most other studies: emphasising that a wheat root system typically has 50-70 % of its total root length in the top 20-30 cm, another 20-25 % within the next 30 cm and less than 1-2 % below 100 cm.

The following discussion is put into context of other research on agronomic and environmental influences on systems and their impacts on whole plant growth. This is accompanied by further integration of results from across our experiments to gain some general conclusions about treatment effects on root growth and relationships between roots and shoots. Covering a range of situations (soil, climate and agronomy) experienced by farmers resulted in confounding factors such as different rates of crop establishment and plant population densities and differential growth and development between seasons. However the controlled environment studies were used to interpret these complex situations and the integration of results across experiments is an important step in developing our understanding of root systems and their potential management.

2. Influence of seed rate (plant population density) on root growth

Adjusting seed rate has a large influence on the size of the root system, as it does on the size and structure of the leaf canopy. Our field and controlled environment studies also showed potentially large, though less consistent, effects of seed rate and plant population density on root system distribution down the soil profile. Table D1 summarises some of the key responses across the Experiments A to F. It is evident that in a soil in which root growth is generally less restricted (e.g. Experiments A and D), the proportion of the total root system at soil depths below 40 cm can significantly increase at reduced seed rate compared to moderate or high seed rate. However, where total growth (i.e. root length) is very low (Experiment F) or if there is evidence of restricted root growth below the plough layer (e.g. Experiment C), then the effect on reducing seed rate on root distribution is much reduced or absent.

Although it is not clear as to how a lower plant population might increase the proportion of the root system at depth. Out hypothesis to test is that increased intra-plant competition caused by more tillering and the number of nodal root axes initiated increased the requirement for roots to reach depth.

Table D1. Summary of main root and shoot measurements as influenced by seed rate across the field experiments A to G.

Variable	Units	Experiments A and D			Experiments B and C		Experiments E and F
		80 seeds	320 seeds	640 seeds	90 seeds	360 seeds	360 seeds
Yield	t/ha	5.2	7.2	7.3	7.6	8.6	6.6
Ear population	per m2	270	391	526	352	492	429
GAI at GS 69	m-2 / m-2	2.4	3.1	3.5	4.8	5.8	4.1
Total Root Length at GS 69	km m-2	9.6	13.5	15.5	13.5	17.3	5.0
Root Length Density 0-20 cm	% at 0-20 cm	39.3	48.6	51.7	62.8	64.1	53.9
RLD 20-40	% at 20-40 cm	25.1	29.6	26.4	21.3	21.9	23.1
RLD 40-60	% at 40-60 cm	21.9	15.2	14.0	10.3	9.5	13.0
RLD 60-80	% at 60-80 cm	13.7	6.6	7.9	5.7	4.4	10.0
Sum of % above	Sum of above	100	100	100	100	100	100
Plant population density	per m2	49	185	335	66	242	255
Total Root Length / GAI	km m-2	4.2	4.3	4.5	3.0	3.0	1.2
Total Root Length / Plant	m per plant	231	88	56	202	70	20
Total Root Length / Ear	m per ear	44.0	35.7	30.9	39.3	34.6	11.8
Total Root Length / t of yield	km per t	2.0	1.9	2.1	1.8	2.0	0.8

In our experiments the reduction is seed rate affected ear number relatively more than it did GAI and total root length (TRL). This is a consequence of sowing all treatments at the same date. Thus, a TRL per ear much above 30 m ear^{-1} would appear to be excessive. Furthermore, a TRL per ear of well below 30 m ear^{-1} is evident in poorly rooted or poor yielding crops. TRL per unit of GAI is quite conservative across the seed rates, whereas TRL per ear increases with a reduction in seed rate. Interestingly, TRL per tonne of yield is remarkably constant at about 2 km m^{-2} t^{-1}, except when rooting is very poor and/or yield is low.

The following Figures illustrate some of the more local effects of adjusting seed rate on root distribution. Across all plots in Experiment A, Figure D1 shows how plant population density modified root growth down the soil profile at two growth stages. In this season (2000-01) crops were late sown and establishment was low. Consequently, the sizes of the root systems were relatively low, with total root lengths between 11 to 16.5 km m^{-2} at anthesis. The root length density in the plough layer at the lowest plant population of 47 plants m^{-2} was extremely low i.e. less than 2 cm cm^{-3}. However, below a soil depth of 40 cm, the amount of roots was equal to, or greater than, that at the higher plant populations. Furthermore, the amount of root growth between tillering and anthesis at depths below 40 cm was significantly greater at the lowest plant population density than at the highest plant population density.

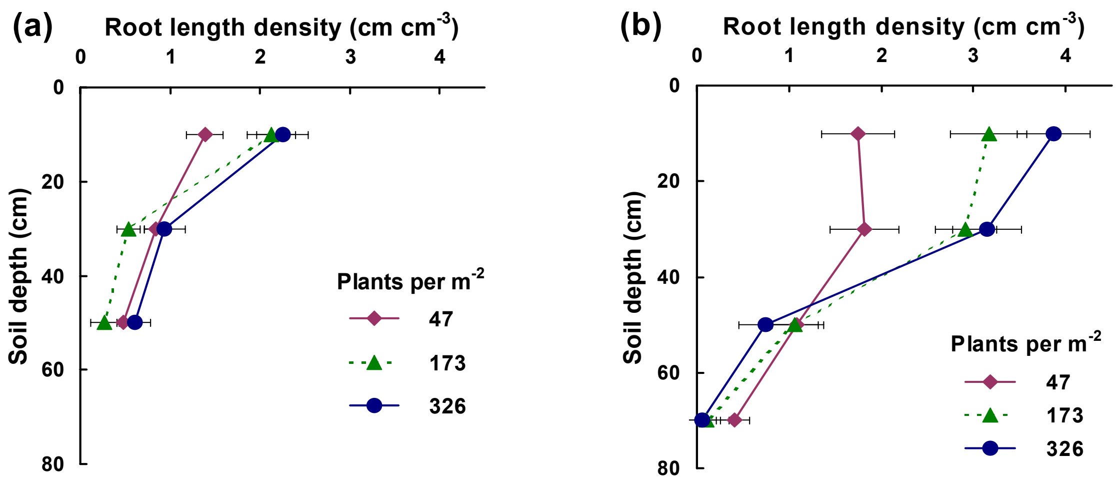


Figure D1. The effect of seed rate, expressed as plant population density, on root length density in Consort at (a) tillering and (b) anthesis in East Lothian, 2000/01. Crops were sown on 1 November at seed rates of 80, 320 and 640 seeds m^{-2}

By contrast, Experiment B in 2001-02 was sown under much improved sowing conditions and a near optimal sowing date and with good establishment. On average, this resulted in larger roots systems compared to 20001/01: with total root lengths at anthesis ranging from 16.5 to 26 km m^{-2}. Figure D2 indicates that with the exception of rooting at a depth of 60-80 cm (at anthesis) root length density at 75 plants m^{-2} was less than that at 295 plants m^{-2}. However, the proportion of the total root system below the plough layer was greatest the lower plant population. Indeed the amount of root growth below 40 cm, between tillering and anthesis, was the same at both at both plant population densities.

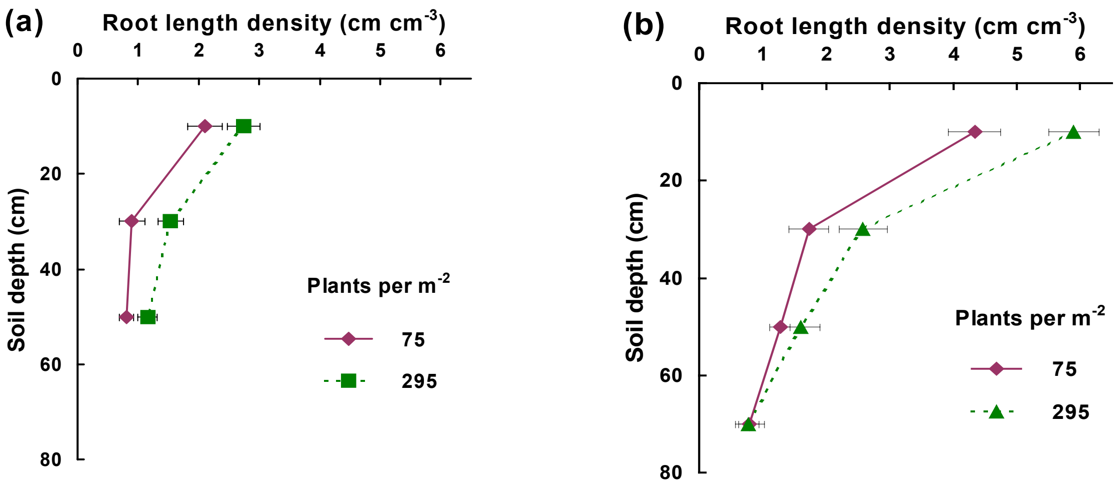


Figure D2. The effect of seed rate, expressed as plant population density, on root length density in Consort at (a) tillering and (b) anthesis in East Lothian, 2001/02. Crops were sown on 24 September at seed rates of 90 and 360 seeds m^{-2}.

Thus at higher plant population densities roots tend to be increasingly concentrated in the upper part of the soil profile (as earlier reported by Kirby and Rackham 1971), which is not beneficial if water or nutrients are required from depth. A further point to note from earlier work is that increasing seeding rate decreases the diameter and strength of the nodal (or crown) roots which are important determinants of lodging susceptibility (Easson et al. 1995) and high planting density increases the risk of infection from disease (Colbach et al. 1997).

Although we indicate that reduced seed rates can improve root systems by increasing root length density and/or the proportion of the total root system below the plough layer, the results are not consistent across all sites and years. The lack of consistency in root distribution pattern across treatments could be a consequence of differential root penetration down the soil profile. We suggest that this could off set the benefits of improved root distribution, unless earlier sowing could alleviate problems of soil compression or compaction. There is evidence that unimpeded roots in surface soil layers grow faster than normal, thus compensating for the relatively slow growth of impeded roots (Unger & Kaspar 1994).

It has been suggested that a RLD of less than 1 cm cm^{-3} (as might occur beneath a compacted soil layer) can limit nitrate uptake. Barraclough et al. (1989) demonstrated that uptake of water below 0.60 m was linearly related to root length density and that a value of 1 cm cm^{-3} was required to extract all potentially available water and the nutrients dissolved in it.

Other research has indicated that sowing date is important in improving the growth of roots at depth, especially in soils that are structurally weak or are likely to have a penetration barrier to root growth. Sowing dates within a trail (i.e. sites x season combination) was not a factor in our work. Thus it was expected that at any of our trials reduced seed rate would result in a yield reduction compared to other treatments. However, any potential benefits of *seed-rate enhancement* for root system growth, and improved root distribution, should be considered in relation to sowing date. That is the direct yield benefits of reduced seed rates are gained from earlier sowing, as report elsewhere (e.g. Spink et al. 2001)

Our own findings are complementary to advice on reducing seed rates at earlier sowing dates. It is known that the time of sowing has a large impact on total root length. Thus, wheat sown in September tends to have more root length in spring and summer than wheat sown in October (Barraclough 1984) even though the root masses are similar. Rooting depth is affected by date of sowing in a similar way to root length, with September sown crops having a deeper root system than those sown in October (Barraclough 1984).

Sowing date depends on the accessibility of the soil. Rooting depth of winter crops is generally increased by early drilling. However, drilling may be delayed by surface wetness (Cannell et al 1978) because of the risk of compacting surface soils. If sowing is too early there is also a danger of poor establishment and crops may suffer damage if there is a wet or cold spell. In practice, drilling may be delayed by surface wetness (Cannell et al. 1978) because of the risk of compacting surface soils. If sowing is too late (or too early) there is also a risk of poor establishment leading to a lower than planned plant population density and crops may suffer damage if there is a wet or cold spell.

3. Influence of nitrogen fertiliser and soil moisture on root growth

In our field trails the effects of nitrogen fertiliser on the growth and distribution of roots were generally small or inconsistent, though delaying nitrogen resulted in a yield penalty that was associated with smaller root systems and leaf canopies. Some previous research has indicated strong responses of root systems to soil nitrogen availability and applications of nitrogen fertiliser. For example, the work of Welbank et al. (1974) and Barraclough et al. (1989) showed that high nitrogen availability increased root length relative to treatments with lower nitrogen availability, though low nitrogen levels tend to increase the root to shoot weight ratio.

It was expected that the delayed N supply would decrease the amount of rooting in the plough layer compared to the early (autumn) N supply; this was evident in Experiment E and to some extent in Experiment B, though responses appeared to depend on soil type. There was a significant difference in the amount of root below the plough layer between the early N and delayed N treatments in the clay loam soil, but not in the sandy loam. However, by removing as much of the inherent variability in soils and climate as possible, our controlled environment studies indicated large differences in root growth and distribution between nitrogen timing and drought *versus* non-drought conditions.

Furthermore, in the field experiments there was less impact of experimental manipulation of water availability on whole crop growth than expected, though for equivalent sized root systems a non-irrigated treatment resulted in a significant yield penalty (Experiment D).

Figure D3 summarises some of our data for root length density at different depths in two soil types (across all plots Experiment B). A typical standard nitrogen programme of 50 kg N ha^{-1} in early spring, followed by 110 kg N ha^{-1} split as two equal doses at GS31-32 was compared with a delayed spring application (160 kg N ha^{-1} split as two equal doses at GS31-32), and a very early nitrogen supply (an additional 50 kg N ha^{-1} applied in the autumn).

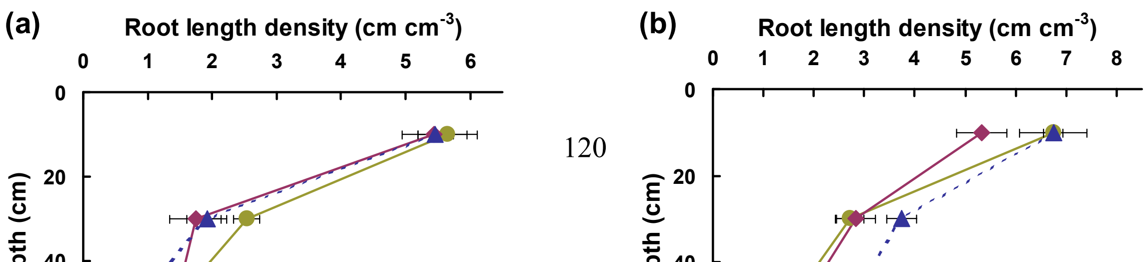


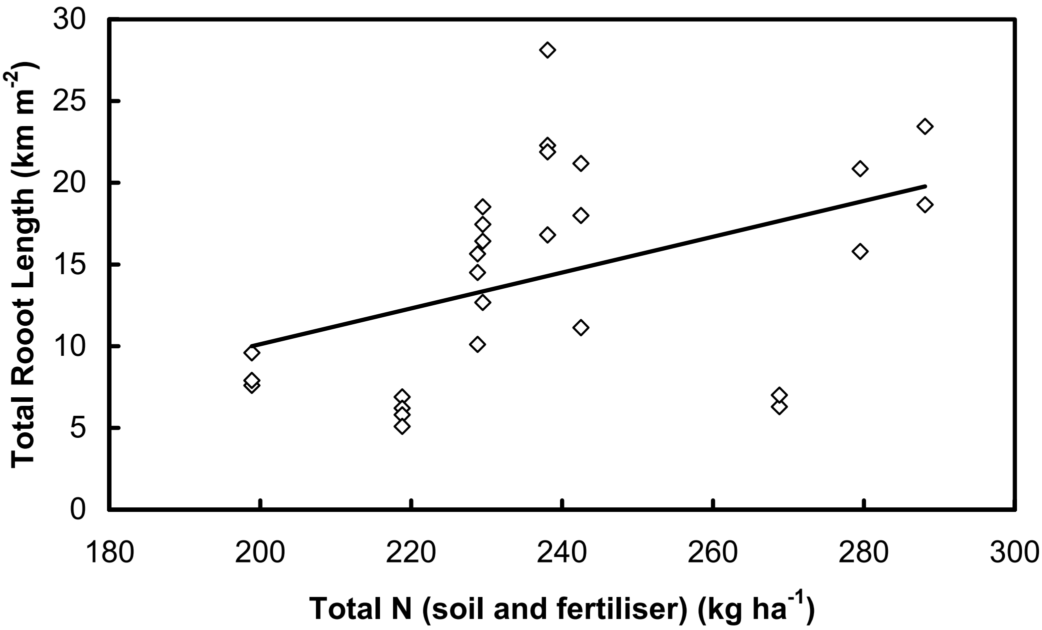
Figure D3. The effect of nitrogen fertiliser on the root length density in Consort at GS65 on (a) a sandy loam soil and (b) a clay loam soil in East Lothian, 2002. Crops were sown on 24 September at a seed rate of 360 seeds m^{-2}: establishment was approximately 80%.

The following figures summarise the overall crop responses to nitrogen, across our field trials. Total root length was weakly associated with the total amount of fertiliser available as either spring soil nitrogen or applied fertiliser nitrogen: increasing from an average of 10 km m^{-2} at a total N supply of 200 kg ha^{-1} to 18 km m^{-2} at 290 kg N ha^{-1} (Figure D4).

Nitrogen in above-ground growth (leaves + stems) at GS69 was weakly correlated with TRL and increased by approximately over 3.5 kg ha^{-1} offtake per km m^{-2} increment in TRL., between a range of TRL from 5 to 25 km m^{-2} (Figure D5).

By contrast to the weak relationships in Figures D4 and D5, across widely contrasting soil and climatic conditions, root length density in the upper soil layer (0-20 cm) recorded at GS69 was positively correlated with N offtake, though below 20 cm no trend was apparent (Figures D6 and D7).

The responses of GAI and yield to nitrogen offtake, across our site x season combinations, were as expected strongly related to nitrogen offtake (Figures D8 and D9).



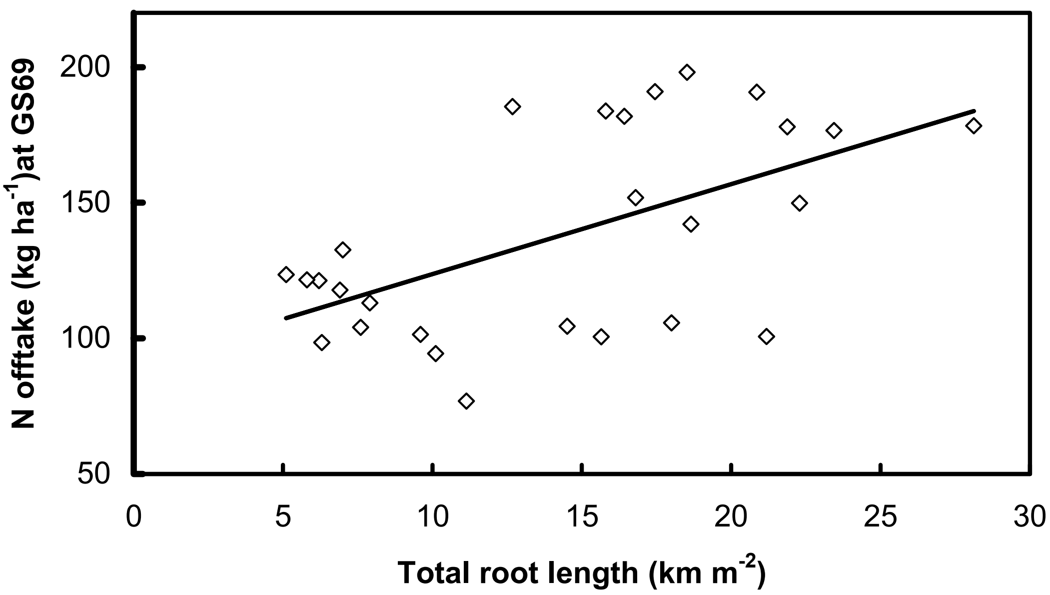
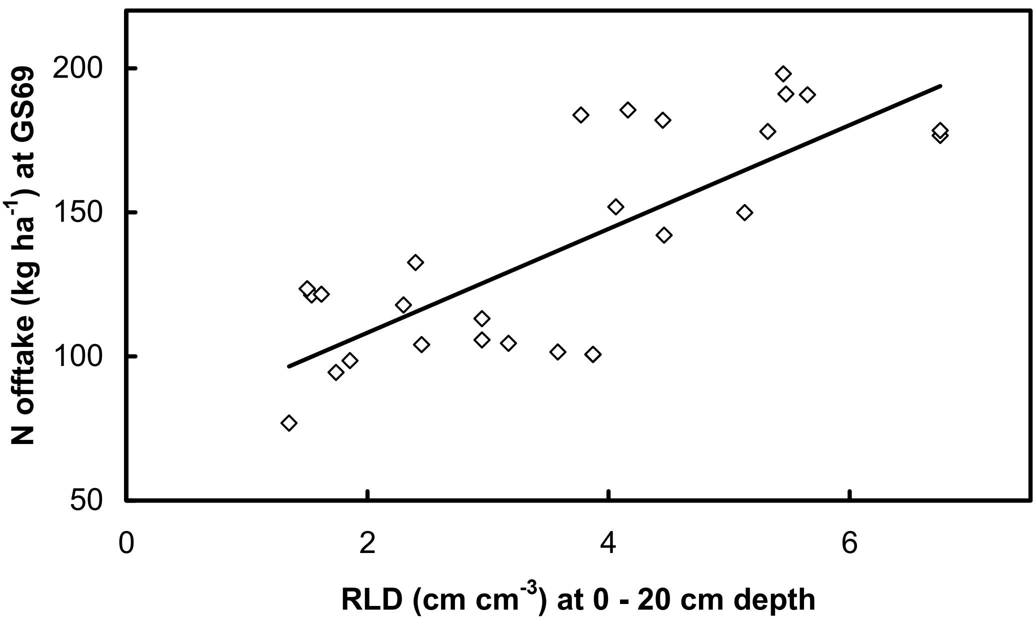


Figure D4. The change in total root length (km m^{-2}) at GS69 with increasing nitrogen supply (kg ha^{-1}) as the sum of spring soil N and applied fertiliser N (kg ha^{-1}). Data are from Experiments B, C, E and F. The slope of the regression is 0.110 x and $r^2 = 0.19$.

Figure D5. The change in above-ground nitrogen offtake (kg ha^{-1}) at GS69 with increasing total root length (km m^{-2}), also at GS69. Data are from Experiments B, C, E and F. The slope of the regression is 3.316 x and $r^2 = 0.33$.



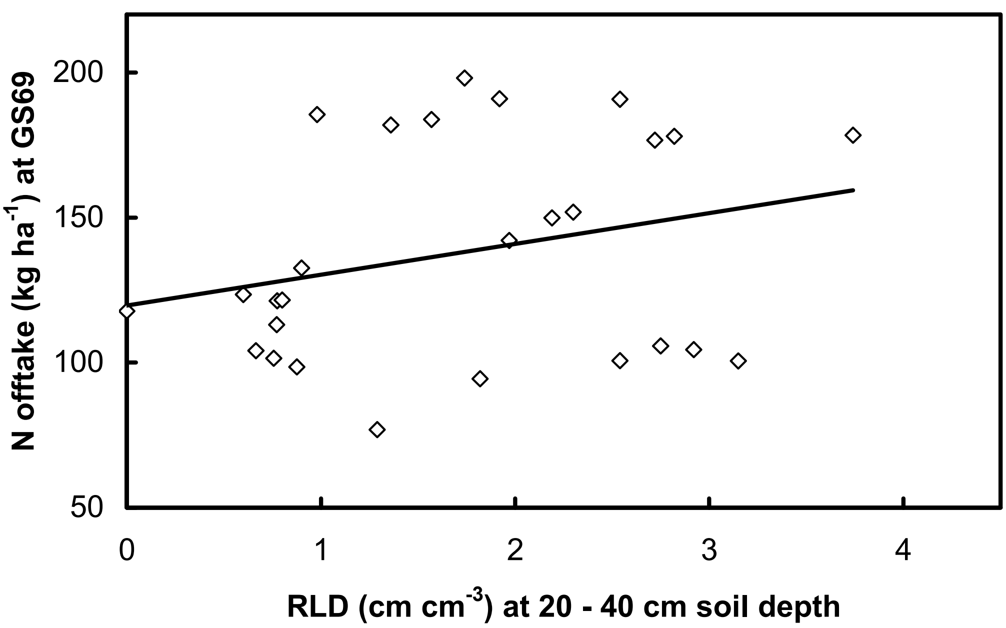
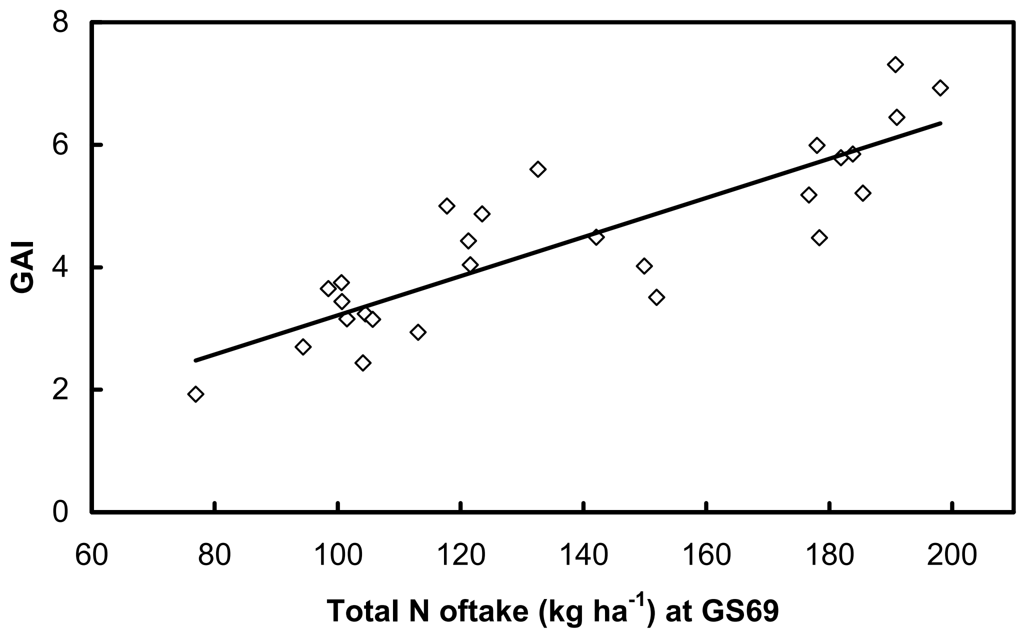


Figure D6. The change in above-ground nitrogen offtake (kg ha^{-1}) measured at GS69 with increasing root length density (RLD) (cm cm^{-1}) at a soil depth of 0 – 20 cm, also at GS69. Data are from Experiments B, C, E and F. The slope of the regression is 18.0 x and r^2 = 0.60.

Figure D7. The change in above-ground nitrogen offtake (kg ha^{-1}) measured at GS69 with increasing root length density (RLD) (cm cm^{-1}) at a soil depth of 20 – 40 cm, also at GS69. Data are from Experiments B, C, E and F. The slope of the regression is 10.6 x and r^2 = 0.07.



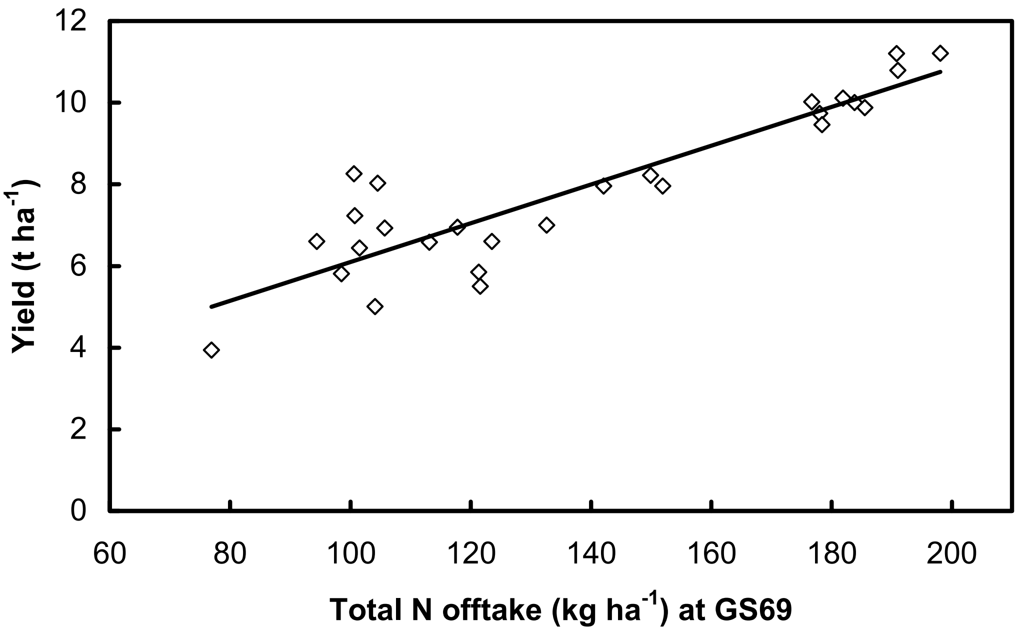


Figure D8. The change in GAI at GS69 with nitrogen offtake (kg ha^{-1}), measured at GS69. Data are from Experiments B, C, E and F. The slope of the regression is 0.048 x and r^2 = 0.81.

Figure D9. The change in yield with nitrogen offtake (kg ha^{-1}) measured at GS69. Data are from Experiments B, C, E and F. The slope of the regression is 0.032 x and r^2 = 0.74.

From our results, and those of others, we suggest that unless levels of soil nitrogen are relatively low there are limited options for using fertiliser practice to modify root structure in a precise manner. Applications of nitrogen fertiliser could alleviate some soil problems. For example, Barraclough & Weir (1988) suggested that as long as water is not limiting, the adverse effects of compaction on above-ground growth and yield could be eliminated by top dressing with nitrogen fertiliser. However, care is needed to avoid increasing the risk of nitrate leaching.

4. Influence of variety choice on root growth

This project examined a comparison of two genotypes, Consort and Malacca, in the final year. There did not appear to be agronomically significant differences in rooting between these two varieties. In the field, differences in root growth and distribution between Consort and Malacca were relatively small, and tests of these and other varieties under a wide range of climatic and soil conditions might be required for significant differences to be identified. Under more controlled conditions, Consort had a higher total root length and a suggestion of higher root length density than Malacca at soil depths of 60 to 100 cm (Experiment I).

Other work on a wider choice of genotypes, in both wheat and barley, suggest that there are significant differences between them in their root characteristics (Atkinson 1990; Wahbi and Gregory 1995; Stoppler et al. 1991; Kujira et al. 1994; Gregory 1994; Marschener 1998). There is evidence for considerable variation in root growth and root physiological responses across soil conditions between old and new cereal cultivars (Haberle 1993; Haberle et al. 1995; Wahbi & Gregory 1995; Stoppler et al. 1991), though the relative yield ranking of old and new varieties is not always associated with soil conditions (Feil and Geisler 1988). Future selection of varieties which are less prone to resource limitations, especially water, may be important in maximising crop yield in extreme environments (Gregory 1994).

Even in modern wheat varieties there is evidence for significant variation in rooting behaviour. Recent HGCA funded research (Project No. 2422) at the University of Reading (Ford et al. 2002) demonstrated how UK Recommended List varieties (Claire, Consort, Hereward, Malacca, Shamrock and Savannah) differed in their root length density in the plough layer (0-30 cm) and at depth (31-80 cm). In one experiment, there was almost a two-fold difference in root length density in the plough layer between Savannah and Malacca, but the most significant result is the high value of root length density at depth for Shamrock. A variety with this type of rooting pattern may have value in situations characterised by late season drought.

Genotypic differences in root morphology have mainly been linked to differences in yield under unfavourable growing conditions. For example, Leon & Schwarz (1992) found that above-ground growth and yield were affected by differences in the root systems of oats and barley when the plants were grown in drought or with very low N availability. It is encouraging that even in modern UK varieties, there is evidence of significant genotype differences in root growth that may be of benefit to water or nutrient capture at depth.

Although beyond the scope of our project, physiological characteristics of roots may also vary between varieties and can be important in determining the outcome of processes such as nutrient acquisition (Marschener 1998). At the whole plant level there can be differences in the efficiency of water use which relate to allocation of resources between the root and shoot (van den Boogaard et al. 1997) and to the rate of photosynthesis per unit of leaf nitrogen (van den Boogaard et al. 1996). There is evidence for genotypic differences in N absorption per unit of root length (Greef & Kullmann 1992) which result in differences in N uptake.

5. The wheat root system in relation to shoot growth and yield

This is one of the few studies to include both root and shoot growth across a wide range of conditions in both field and controlled environment experiments. Direct effects of changes in root characteristics and yield are difficult to establish because of the ways in which these changes operate through the more direct effect of the leaf canopy on yield. However, by comparing root and canopy growth across different sites, in this case based on yield potential from low to high yielding trials, in Experiments A to F, some general points can be made. Table D2, below, describes how gross changes occur in wheat of both high and low yield.

Table D2. Summary of root characteristics in relation to canopy growth and yield at low yielding and high yielding sites. The data are means from across Experiments A to F.

Mean grain yield	5.4 t ha^{-1}	10.4 t ha^{-1}
Plant population density (plants m^{-2})	138	203
GAI	4.2	6.2
Increase in GAI (dGAI) between GS23 and GS69	3.6	5.2
Ear population density (Ears m^{-1})	325	532
Total root length (km m^{-1})	8.6	19.5
Root length density (cm cm^{-3}) in upper soil layer (0-20 cm)	2.8	5.2
Root length density (cm cm^{-3}) at depth of 60-80 cm	0.3	0.7
Proportion of root system (%) in upper soil layer (0-20 cm)	63	56
Proportion of root system (%) at depth of 60-80 cm	6	8
Increase in total root length between (dTRL) GS23 and GS69	4.3	6.2
Change in dGAI/dTRL between GS23 and GS69	1.3	1.2
TRL per ear	31	37
TRL per t of yield	1.6	1.9

Of most interest is the relationship between the root system and leaf canopy. Figure D10 suggests that root-shoot relationships differ between sites of varying yield potential. At low to moderate yielding sites, total root size may remain similar (i.e. small) across a wide range of canopy sizes. As the average age site yield increases there is evidence for a greater inter-play or trade-off between root and shoot growth, such that at a similar yield could be achieved by increments in either the root system or the leaf canopy. This may not be the situation at the lower yielding sites. Thus there could be a negative correlation between root system size and leaf canopy size within a group of similar yield sites. Across all sites the general trend is for yield to be associated with increases in both total root length and GAI, though this can be a rather weak correlation (Figure D11). The latter is indicated for early (GS23) and late growth (GS69).

By contrast, the correlation between total root length and yield is much stronger, even when taking a measure of root growth at GS23 (Figure D12). This is consistent with work by Leon & Schwang (1992) who evaluated differences in total root length between genotypes of oats and barley and found that yield stability was correlated with root system length. Other work on winter wheat indicated that total root length was positively correlated with grain yield (Barraclough 1984) although similarly yielding crops could have different sized root systems.

The link between GAI and root growth appeared stronger when considering root length density, especially at GS69, but only in the plough layer (0-20 cm soil depth) (Figure D13). Thus there was a similar level of correlation between root length density and yield (Figure D14). Therefore, in relatively shallow rooting crops or shallow soils there appears to be a strong association between RLD and yield. Although RLD at depth was less related to yield, this may not be the case in deeper soils or deep soils prone to drought, in which rooting below the plough layer is important for maintaining high yields.

Our results are consistent with the view of a functional balance between root and shoots as described by Brouwer (1962) that varies according to site conditions and that root systems of different sizes can support the similar leaf canopies and yield. Changes in environmental conditions or agronomy may be accompanied by a shift in allocation between the root and shoot. For example, in our study soil type and seed rate modified the TRL-GAI relationship. Although TRL per unit of GAI was quite conservative across much of our work on seed rates, this ratio can change considerably between sites and seasons. Furthermore, our results suggest that the amount of change in either total root length or GAI during stem extension will positively correlate with site yield potential.

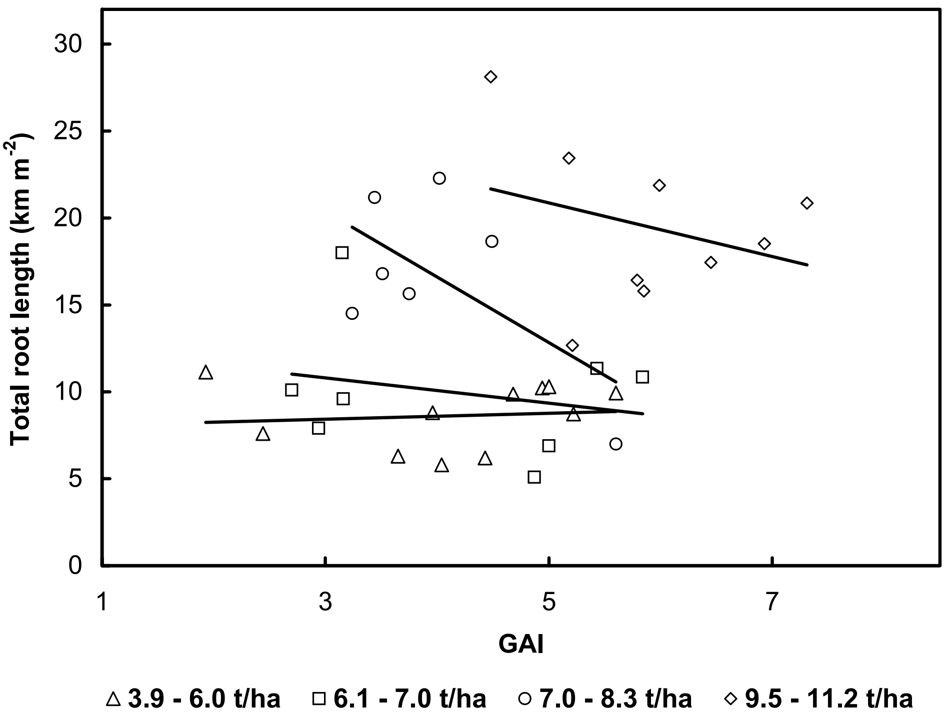
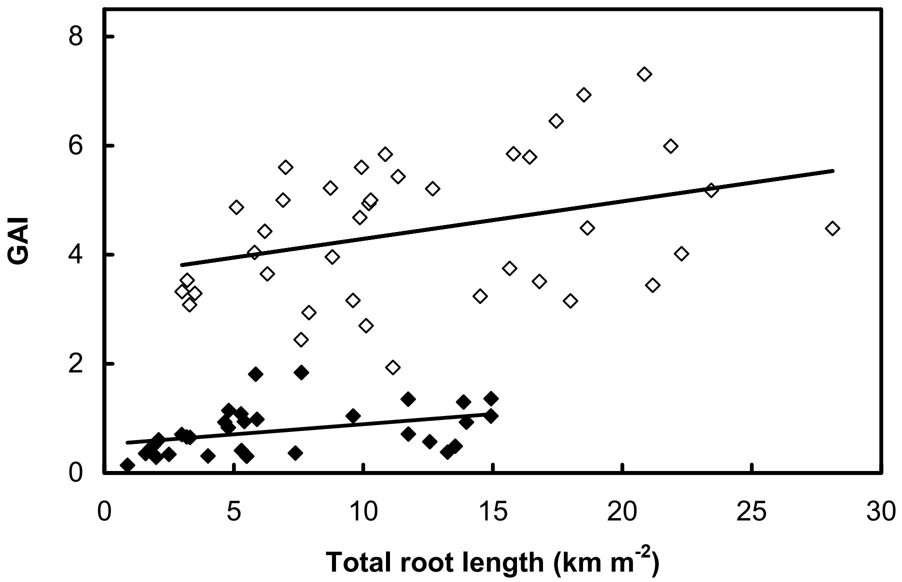


Figure D10. Relationship between GAI and total root length (RLD) (km m^{-2}) as grouped by several yield classes: very low to low (3.9 – 6.0 t ha^{-1}), low to average (6.1 – 7.0 t ha^{-1}), average (7.0 – 8.3 t ha^{-1}) and high (9.5 – 11.2 t ha^{-1}). Data are from Experiments A to F.



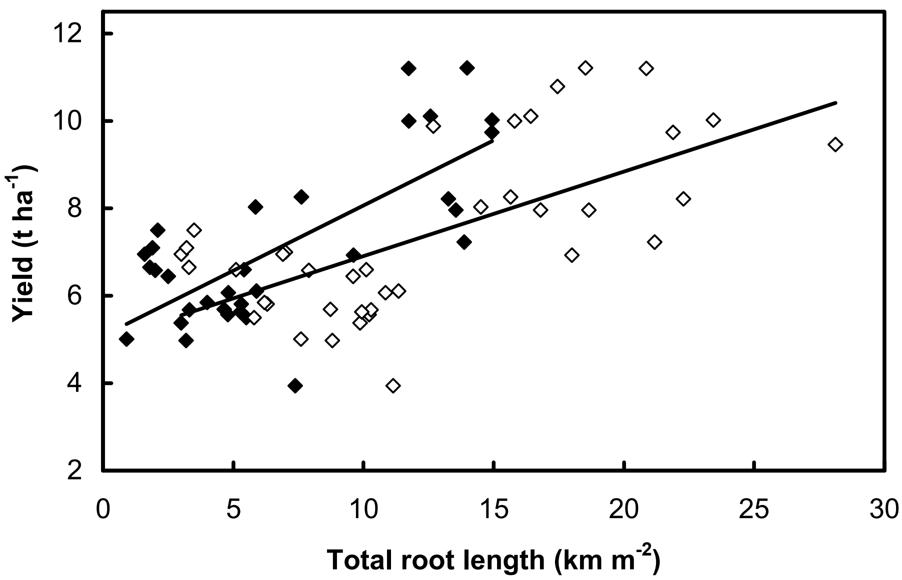
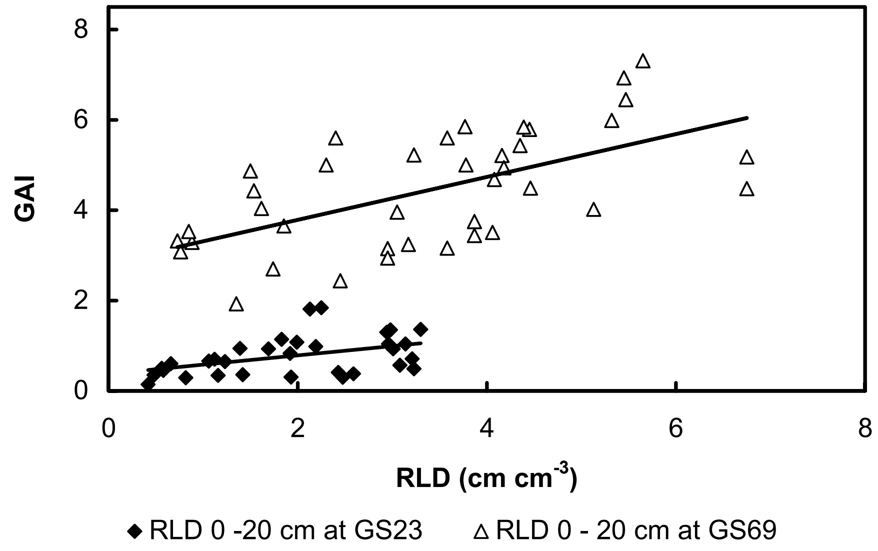


Figure D11. Relationship between GAI and total root length (km m^{-2}) measured at GS23 (closed symbols) and GS69 (open symbols). Data are from experiments A to F. The slope of the regression at GS23 is 0.037 x and r^{-2} = 0.25; and at GS69 the slope = 0.069 and r^{-2} = 0.12.

Figure D12. Relationship between grain yield (t ha^{-1}) and total root length (km m^{-2}) measured at GS23 (closed symbols) and GS69 (open symbols). Data are from experiments A to F. The slope of the regression at GS23 is 0.298 x and r^{-2} = 0.52; and at GS69 the slope = 0.194 and r^{-2} = 0.43.



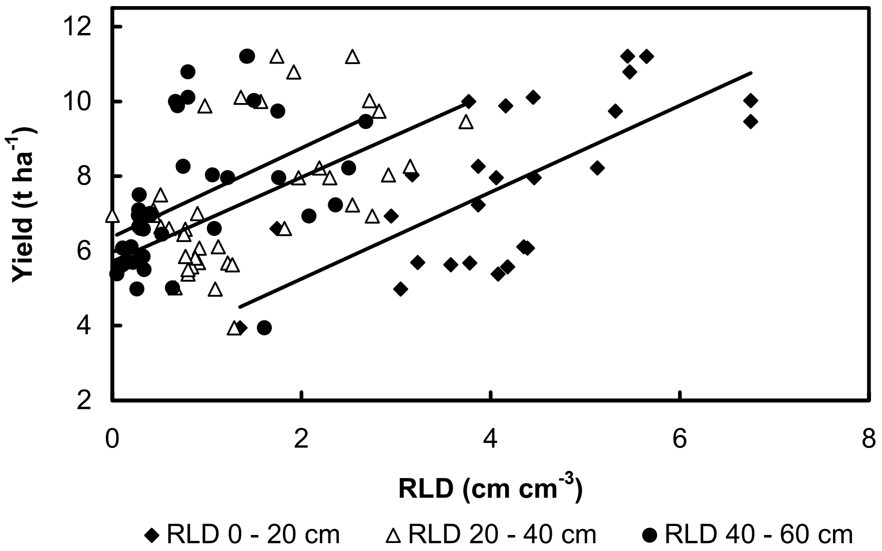


Figure D13. Relationship between grain yield (t ha^{-1}) and root length density (cm cm^{-1}) at a soil depth of 0 – 20 cm measured at GS23 (closed symbols) and GS69 (open symbols). Data are from experiments A to F. The slope of the regression at GS23 is 0.207 x and r^{-2} = 0.2; and at GS69 the slope = 0.471 and r^{-2} = 0.36.

Figure D14. Relationship between grain yield (t ha^{-1}) and root length density (cm cm^{-1}) at soil depths of 0 – 20 cm (closed diamond), 20 – 40 cm (open triangle) and 40 – 60 cm (close circle) at GS69. Data are from experiments A to C. The slope of the regressions are 0 – 20 cm slope = 1.16 x and r^{-2} = 0.48; 20 – 40 cm slope = 1.13 and r^{-2} = 0.29; 40 – 60 cm slope = 1.19 and r^2 = 0.22.

6. Measuring root systems and implications for crop and soil management

Our aim was to investigate how simple measures of root growth could be:

(3) related to the actual values of root length or root length density estimated from the more time consuming and expensive research methods

(4) developed for growers and agronomists as measures on root and / or soil and crop health that would be useful in crop management in the current season remedial action for crop and soil in following seasons.

With a positive relationship between root growth and yield, though not always independent from leaf canopy growth, it was important to establish if simple measures of root growth could be used by farmers and agronomists to take action the current season, though more likely in future seasons, to alleviate situations of poor crop growth.

The following Figures (D 15 to D20) illustrate some of the relationships between relatively simple root measurements of root counts down the face of a soil pit profile (Experiments D to F) and number of root axes (Experiments A to C) and root length density and yield.

There was a good correlation between root counts at the face of a soil pit and the actual RLD measured at GS23 (Figures D15 and D16), though the correlation between the two was weaker at GS69 (Figure D17).

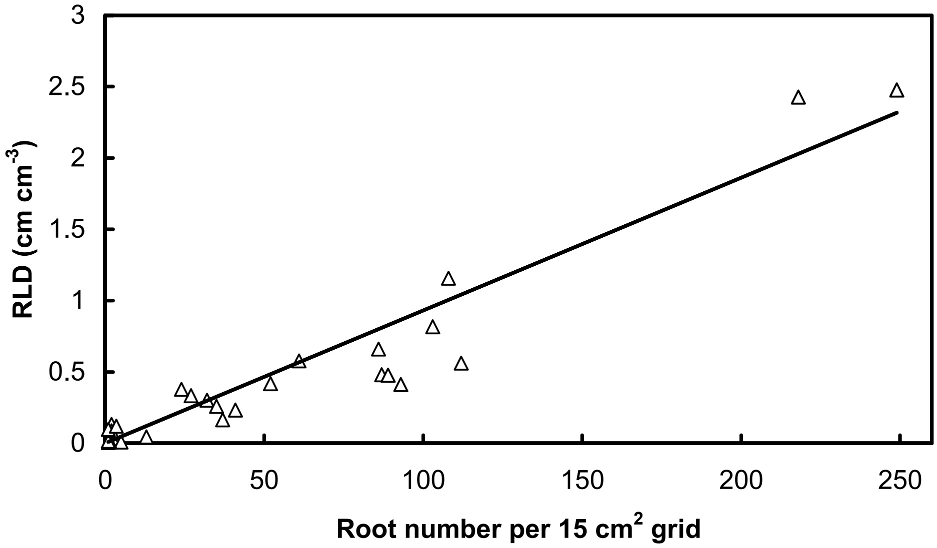
The number of root axes per plant was poorly correlated with total root length or RLD: as expected this measure needs to take into account the change in plant population density. Knowing the PPD means that the number of root axes per m^2 be estimated. Although this measure is potentially easier than making root counts at various depths down a soil pit, the correlation between the number of root axes per m^2 and RLD at GS23 is weaker than for root counts along the face of a soil pit and RLD at the same growth stage: compare Figures D18 and D15 or D16).

The number of root axes per m^2 has a moderate correlation with yield (Figure D19), whereas the actual RLD from Experiments A to C has a strong correlation with yield (this is a stronger correlation that for RLD at GS69 across Experiments A to G (Figure D13). The fact that RLD at GS23 was positively correlated with yield (Figure D20) and appears to be relatively robust across different soil types and seasons, suggests that a simple measure of RLD would be helpful to advise on crop and soil condition. These measures need to be refined and tested across other sites - most likely through Knowledge Transfer initiatives and training days.

Visual assessments can be used to identify key features of the soil to examine in more detail (e.g. Ball and Douglas 2002). The relatively simple methods we have describe herein could help to better quantify existing scoring systems for root abundance and soil condition. For example, quantifying visual assessments by adding thresholds to terms such as common, few or sparse by linking to soil structural scores (e.g. Ball and Douglas 2000) or visual keys (e.g. Batey 2000). This would have the advantage of being simpler than some of the more detailed, though highly valuable, visual assessments of soil profiles (e.g. Hodgson 1976). If proven to be robust across other sites and seasons then a measure that is correlated with RLD would be a better semi-quantitative measure of, at least the upper, root system.

This should assist in quantifying soil fertility and physical condition. It would also give a way of quantifying change over time in both soil problems and soil improvement. These root measurement done in early spring may have limited scope to alter management in the same season. If a low root count (i.e. RLD) below the plough layer indicated severe compaction, then the amelioration of the condition could only be eliminated by the application of top dressings of nitrogen fertiliser if water was not limiting. Thus this is a short-term measure, for a condition that has been identified in the current season to be remedied for the following year.

In the longer term, the appropriate root measurements and soil inspection can help to understand risks of soil compaction adversely affecting crop growth and yield at a particular site. In vulnerable soils the strategy should be to reduce the impact of poor rooting by efficient application of nutrients, and by managing soils through the use of tillage and by growing deep rooted crops in rotation. These practices help to improve root distribution and increase the rooting depth. Because compaction reduces the ability of winter wheat to cope with water shortages in the spring and summer, the detrimental effects of soil compaction may be reduced by earlier autumn sowing dates which have a greater chance of avoiding summer droughts.



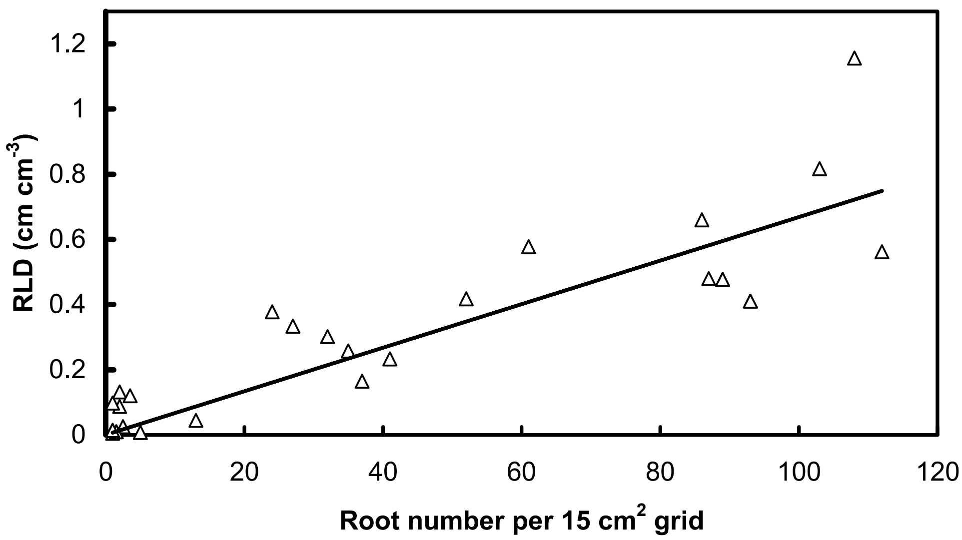


Figure D15. Relationship between root length density (RLD) (cm cm^{-1}) and roots counted within 15 cm square grids placed at depths down the exposed face of soil pits. Data are from all soil depths measured at GS23 in Experiments D, E and F. The slope of the regression is 0.009 and $r^2 = 0.92$.

Figure D16. As above, but with the two highest RLDs and root counts removed. The slope of the regression is 0.007 and $r^2 = 0.76$

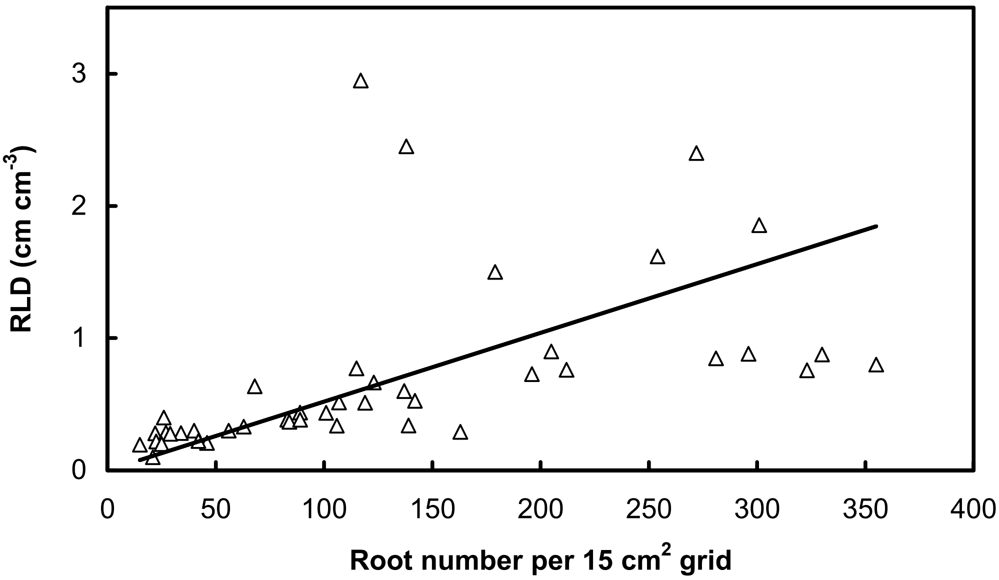
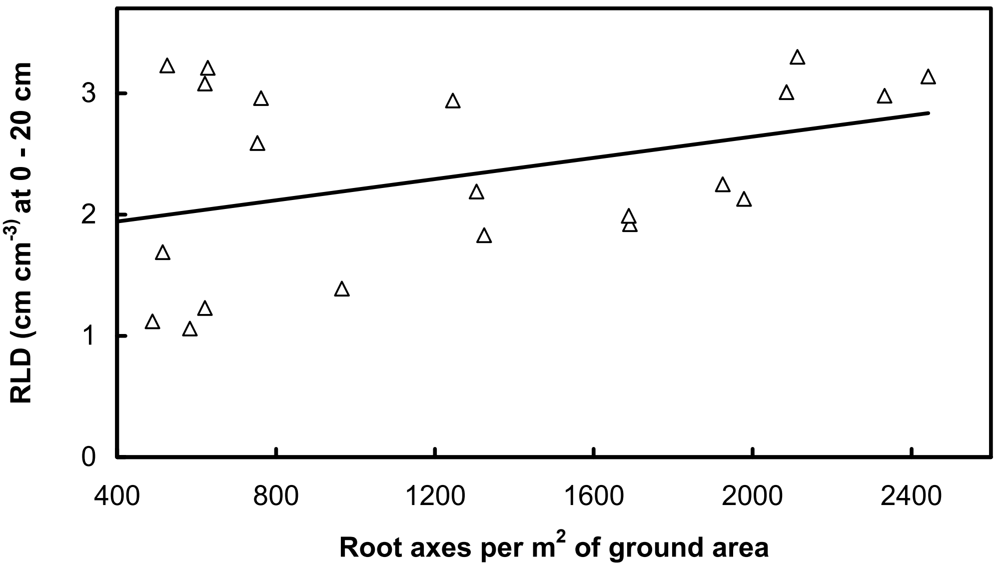


Figure D17. Relationship between root length density (RLD) (cm cm^{-1}) and roots counted within 15 cm square grids placed at depths down the exposed face of soil pits. Data are from all soil depths measured at GS69 in Experiments D, E and F. The slope of the regression is 0.005 and $r^2 = 0.31$



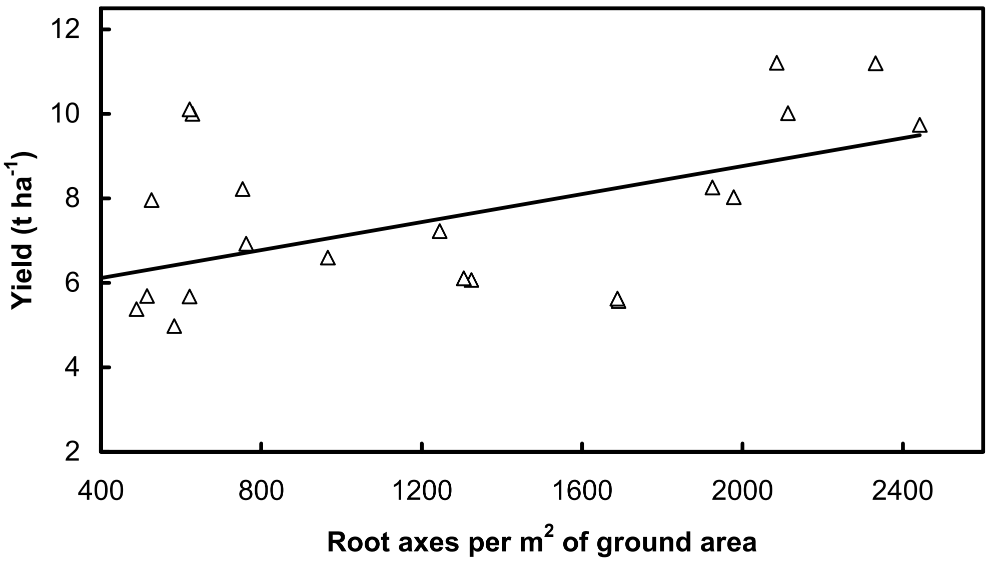


Figure D18. Relationship between root length density (RLD) (cm cm^{-1}) at a soil depth of 0 – 20 cm and the number of root axes per m^2 of ground estimated from counts on individual plants carefully dug up from trail plots. Data are from root measurements at GS23 in Experiments A, B and C. The slope of the regression is 0.0004 and $r^2 = 0.16$.

Figure D19. Relationship between yield (t ha^{-1}) and the number of root axes per m^2 of ground estimated from counts on individual plants carefully dug up from trail plots. Data are from root measurements at GS23 in Experiments A, B and C. The slope of the regression is 0.0017 and $r^2 = 0.29$.

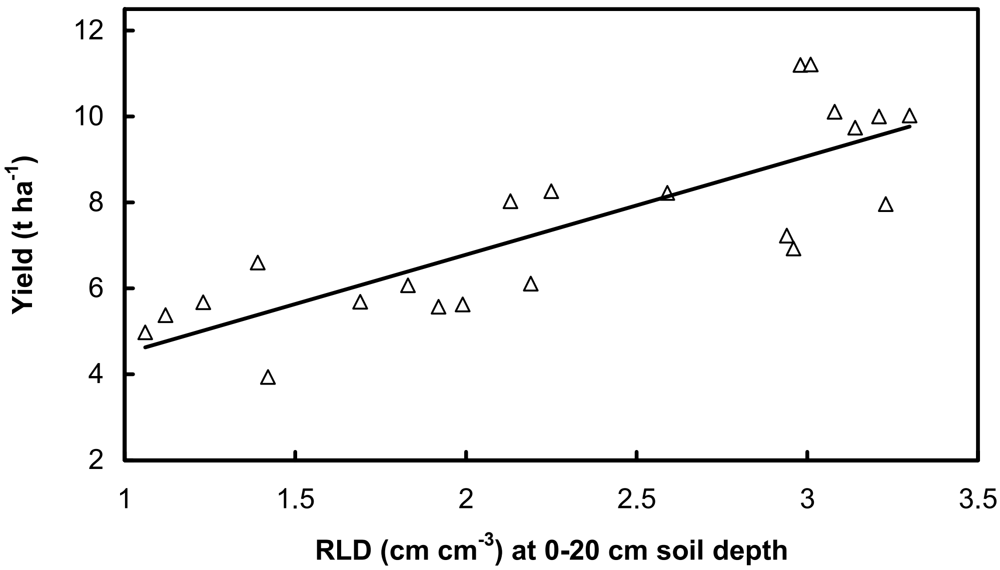


Figure D20. Relationship between yield (t ha^{-1}) and root length density (RLD) (cm cm^{-1}) at a soil depth of 0 – 20 cm. Data are from root measurements in Experiments A, B and C. The slope of the regression is 2.29 and r^2 = 0.68.

7. Concluding remarks

The key messages from the agronomic treatments in this study are:

(4) Adjusting seed rate (and hence plant population density) has a large and significant affect on the size of the root system. There is also a potentially large, though less consistent, effect of improving root distribution by reducing seed rate. However, this must be considered in relation to sowing so as not to compromise on leaf canopy size and ear population density.
(5) Adjusting the nitrogen fertiliser programme within a reasonable range about current practice does not have any consistent in-season benefits for root growth and yield, though there is limited evidence for site-specific benefits in root growth.
(6) Variety choice may offer limited scope for agronomically important variations in total root size or root distribution. Nevertheless, research in this project and from elsewhere suggests that some rooting characteristics could be targeted in crop improvement programmes.

Crops which do not invest enough in roots growth may be at risk of yield loss, even under UK conditions. This may occur, for example, when whole plant growth or allocation to roots is insufficient is restricted by soil physical condition and especially if this is later followed by a dry spring or summer. There is no firm evidence to suggest that too much root growth may result in lower shoot growth and crop yield, though there is evidence of a trade-off between GAI and total root length at some high yielding sites. This is evidence of a dynamic feedback between the root and shoot systems.

Our data showing the wide variation in root system size and distribution, often associated with leaf canopies of similar size mean that the concept of root limitation is difficult to quantify. Because there may be differences in the relative resource availability between sites, a root system which can supply the shoot adequately in one place may be limiting in another.

Our results support the view that it is not the absolute size of the root system which determines a limitation to leaf canopy growth because a root system which is usually adequate may become limiting with a change in soil conditions e.g. drought. Limitations occur when there is either a penetration barrier to root depth or poor root growth in the plough layer and immediately below.

Shallow or poor root development can prevent the crop from accessing large volumes of the subsoil until too late in the growing season thus precluding the exploitation of water and nutrients in the deep soil layers. Shallow rooting systems, characteristic of compacted soils, result in a reduction in nutrient and water uptake to the detriment of yield. Even if the soil is uncompacted, continuous wetness during the early stages of growth can encourage shallow rooting which can exacerbate the effect of dry weather later.

To a limited extent the risks of soil compaction adversely affecting crop growth and yield could be reduced by efficient application of nutrients. However managing soils through the use of appropriate cultivations and by good rotational practice such as growing deep-rooted crops in the rotation and with careful consideration of sowing date should help to improve root distribution and increase the rooting depth.

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