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Managing roots, nitrogen and fungicides to improve yield and quality of wheat

by

P J Gregory, M J Gooding, K E Ford, M P Clarke
and S Pepler

Crops Research Unit and the Department of Soil Science, The University of Reading,
Reading, Berkshire, RG6 6AS

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CONTENTS

Abstract

The major aim of this project was to determine whether root growth, distribution and activity late in the growing season (particularly after flowering) influence grain yield and quality of cultivars in response to fungicide and late-season nitrogen applications. Four experiments were carried out over three seasons on a free-draining sandy loam overlying sand at the Crops Research Unit of the University of Reading. These investigated the effects of cultivar, irrigation/drought, fungicide applications, and late-season nitrogen applications to soil or foliage on root growth and distribution, canopy green area duration, grain yield, grain quality, and root activity in nitrogen uptake from the soil.

When fungicides were applied, the size of root system was maintained during early grain-filling, and root length typically increased. There were significant differences between cultivars in the quantity of roots below 30 cm depth. Shamrock had the longest root system. Fungicide applications had small, but seasonally variable, effects on root growth but consistently increased green leaf area duration. Application at flag leaf emergence generally gave good control of all diseases with little benefit from a further application at ear emergence. There were significant differences between cultivars with Consort being most responsive. Fungicide applications significantly increased grain yields (through increased thousand grain weight and specific weight) and grain N content by delaying leaf senescence via disease control.

There was no relation between grain yield and post-anthesis rooting extent or distribution, but the size of the root system during the post-anthesis period was related to late season N uptake and hence to grain quality. Grain yield and N content were related to green leaf area duration after anthesis (0.17 t grain ha^{-1} and 2.67 kg N ha^{-1} for each day that the flag leaf remained green), although these benefits do not accrue indefinitely and were limited to a thermal time period less than 700 ^{o}Cd after anthesis.

It is suggested that fungicide application may delay both senescence of leaves and of the root system, leading to increased N in the grain, either through continued uptake of N into the crop, or through retention of N in the plant that would otherwise leak from the plant. Overall, the results suggest that breeding/variety selection and agronomy could be exploited to optimise late-season rooting to use N more efficiently and to improve grain N content.

1. Background and introduction

1.1 Root growth and distribution

If current improvements in winter wheat (*Triticum aestivum* L.) productivity in the United Kingdom (UK) are to be maintained, it has been claimed that a better understanding of soil-root-shoot interactions is essential (Bingham, 2001). Roots support and regulate canopy growth by providing anchorage, by channelling nutrients and water to the photosynthetic surface (Bingham, 2001) and by producing hormones (McDonald and Davies, 1996). Grain yield improvements have derived from both genetic and agronomic developments (MacLeod, 1993), but yields in the UK are still below their theoretical potential. Whilst detailed field rooting studies have been performed on older cultivars (Gregory *et al*., 1978, cv. Maris Huntsman) such studies have become increasingly unfashionable (Bingham, 2001). The work on older cultivars found that the size of the root system increased exponentially until the end of March, and then linearly until anthesis (Gregory *et al*., 1978). At anthesis, in the UK, the maximum weight of the root system was usually between 970 - 1700 kg ha^{-1} and length between 15.4 - 32.0 km m^{-2} (Gregory, 1994b). After anthesis only small quantities of dry matter were partitioned to the roots (Gregory, 1994a), and root senescence began (Ellis, 1979). The classical response of applying N-fertilizer to the soil is the localized proliferation of the surface root system (Gregory, 1994a), sometimes at the expense of rooting depth (Lucas *et al*., 2000). However, N-fertilizer has also been reported to increase the length of the entire root system (Robinson *et al*., 1994), with both the number and length of laterals (Ellis, 1979), and the degree of branching (Gregory, 1994a), increased by applied N. Under conditions of low soil mineral N, applying N-fertilizer can also increase the rate of N inflow into the roots (Robinson *et al*., 1994).

Soil water availability directly affects root and shoot growth by controlling the supply of water and nutrients to the photosynthetic surface, and by affecting soil aeration. Prolonged high soil moisture contents result in poor aeration and anaerobic conditions that reduce root growth through the production of toxic compounds, both by the root (Ellis, 1979), and within the rhizosphere (Lucas *et al*., 2000). Conversely low soil moisture contents have been reported to reduce root and shoot development (Barraclough and Weir, 1988) and to increase rooting depth (Lucas *et al*., 2000). When soil moisture is maintained at optimum levels by irrigation, a greater proportion of the root system is found in the surface layers, where most of the water is taken up (Klepper, 1991). Investigations of the root systems of modern cultivars produced under the current high input farming practices in the UK are limited. Several analyses have, however, suggested that modern,

shorter wheat cultivars are less efficient at accumulating nitrogen compared with their taller predecessors (Austin *et al*., 1977; Cosser *et al*., 1997; Foulkes *et al*. 1998).

Here we report an experiment (NI) to characterize the root development of a modern cultivar of wheat and to investigate how this is influenced by moisture and nitrogen availability.

1.2 Fungicide and nitrogen management

If roots could be managed to optimise above ground partitioning and canopy radiation interception, this may improve the effectiveness of conventional inputs. Optimizing inputs is particularly relevant late in the season when fungicides and nitrogen are applied to maintain both yield and quality.

Wheat yield has often been linearly related to the size and duration of the photosynthetic canopy after ear emergence, whether duration is influenced by climate, agronomy or genotype (Evans et al., 1975). Yield increases following fungicide use can also be related to the fungicide effects on the size and duration of the canopy (Bryson *et al*., 2000; Gooding *et al*., 2000; Dimmock and Gooding, 2002a). Green tissue is maintained by controlling known pathogens (Ruske *et al*., 2003); or, possibly, by controlling minor fungal pathogens not easily identified in the field (Bertelsen *et al*., 2001); or through direct physiological effects of the fungicide on the plant (Grossmann and Retzlaff, 1997). The extent to which canopies can be maintained, and hence their life potentially extended by fungicides will depend on water and nutrient uptake, and hence presumably also root activity. Even if the canopy can be maintained, there may be a temporal limit to the association between leaf life and grain yield. For example (Dimmock and Gooding, 2002b) found that extending the flag leaf life of cv. Consort with fungicide produced much larger yield improvements than similar extensions to the flag leaf life of cv. Hereward. When the yields of both cultivars were plotted against thermal time from anthesis (Fig. 1.1.) there appeared to be no benefit from extending flag leaf life beyond 692 ºC days (ºC d, S.E. = 11.2) post anthesis (base temperature = 0 ºC). This conclusion, however, is ambiguous, particularly because the yield response to flag leaf life of Consort never deviated from linearity, so the apparent cut-off at around 700 ºC d after anthesis may have been an artefact of other cultivar × fungicide interactions. Additionally, yield improvements may not follow light interception by green tissue if photosynthetic ability is curtailed by drought (Biscoe and Gallagher, 1978). Soil moisture deficits (SMD) would be expected to accumulate during grain filling in most seasons so the ‘break’ in Fig. 1 may reflect an effect of drought on photosynthesis, rather than sink limitation, and may therefore be related to root extent and activity.

Further work is necessary, therefore, to determine whether the cut off in yield response in Fig. 1.1 occurs more widely within cultivars, and if it does, whether it related to root performance.

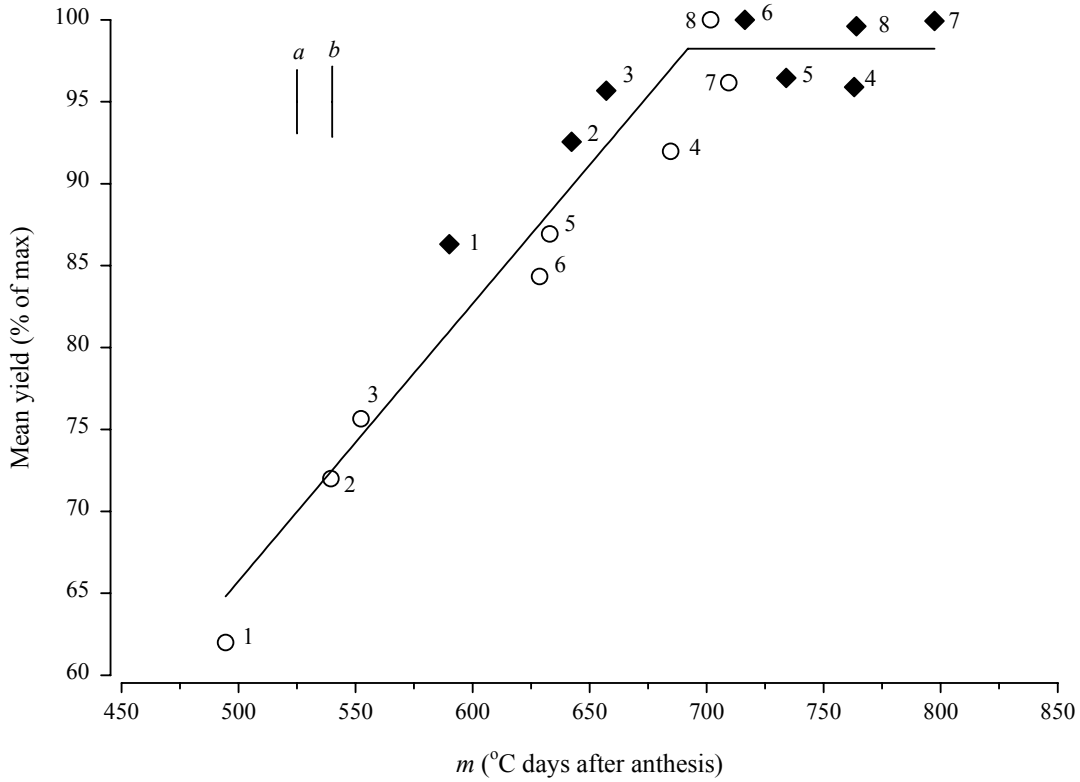

Fig. 1.1. Relationship between the thermal time to 37% green flag leaf area (Gompertz *m*) from anthesis and the mean grain yield of cultivars Consort (○) and Hereward (◆) winter wheat. Points are different fungicide treatments applied at GS 39 and again at GS 59. 1 = Untreated. Error bars are SEDs for comparing points of (a) Consort and (b) Hereward. From Pepler *et al*. (2005a).

As well as dry matter accumulation, late-season nitrogen uptake is necessary to maintain grain protein concentrations, and also to prevent premature senescence as grain nitrogen demand increases. As with yield, data from a large number of experiments (Dimmock and Gooding, 2002a; Ruske *et al.* 2003) demonstrate that accumulation of nitrogen by grain can be linearly related to canopy longevity, as it is maintained by fungicide-use and disease control. This occurs because both nitrogen uptake into the above ground biomass and net remobilisation of nitrogen from the vegetative tissues is increased when severe disease is controlled (Ruske *et al*., 2003*a*). In some circumstances, nitrogen accumulation by grain keeps pace with dry matter accumulation as canopy senescence is delayed. When this occurs, grain protein concentration is not affected by fungicide use. In other situations, fungicide use can either increase or reduce protein concentration. This variation in response depends on cultivar (Dimmock and Gooding, 2002a). This is partly due to the diseases that occur on different cultivars. For example, controlling rusts (*Puccinia* spp.) usually

increases protein concentration, whereas controlling *Septoria* spp. usually reduces protein concentration (Dimmock and Gooding, 2002a). There are, however, other differences among cultivars in their response of grain protein concentration to fungicide-use that cannot be ascribed to the species of pathogen controlled (Dimmock & Gooding, 2002a; Ruske *et al*., 2003*a*). Whether these differences relate to nitrogen uptake by roots late in the season remains to be clarified. There is also an intuitive contradiction that deserves further investigation, namely how do fungicide applications improve remobilisation of N from vegetative tissues if such treatments delay senescence beyond the end of grain filling?

Because *Septoria* pathogens are common targets for late-season fungicide applications, grain protein concentrations are often reduced by their use. It has been suggested that a late-season spray of urea solution is a cost-effective means of countering any such negative effect of fungicide on grain protein concentration (Dimmock and Gooding, 2002a). However, the recovery rates of nitrogen from such applications are often poor; appear to depend on the moisture status of the crop (Gooding and Davies, 1992); and hence may also depend on late season root activity. Here we report three experiments (F1, F2 and F3), repeated in different years, to investigate, in detail, the effects on fungicides and cultivars on rooting extent and activity, and how this relates to canopy senescence, above ground accumulation and partitioning of dry matter and nitrogen, grain quality, and response to late-season applications of nitrogen. We report those studies directly funded by the HGCA but the reader is also referred to publications involving other, closely related studies at The University of Reading conducted during the same period: Dimmock and Gooding, 2002*a*,*b*,*c*; Clarke, 2002; Ruske *et al*., 2003*a*,*b*; Ruske *et al*., 2004; Clarke *et al*., 2004; Pepler *et al.*, 2005*a*,*b*,*c*.

2. Materials and methods

2.1. Site details and general crop husbandry

Field experiments were carried out at the Crops Research Unit, University of Reading (0°54'W, 51°29'N) over three seasons (2000/01, 2001/02 and 2002/03) on a free-draining sandy loam overlying coarse red-brown sand, from the Sonning series (Kay, 1936). Stone free soil bulk density to 80cm was determined from nine soil cores cut into 10 cm sections. Cores were sampled in 2001 in a W formation from between crop rows across the experimental site. The soil bulk density at the site varied with depth (Fig. 2.1), from 1.23 g cm^{-3} in the surface layer (0-10 cm) to 1.52 g cm^{-3} in the 20-30 cm section of the soil profile and remained over 1.5 g cm^{-3} in all the soil sections sampled below 30cm.

Weather data (Table 2.1) were recorded from an automated weather station at the site. In summary, low rainfall and high solar radiation receipts in 2000/01 and 2002/03 led to higher soil moisture deficits (SMD) in the summers of 2001 and 2003 compared with the summer of 2002. The 2001/02 season had lower solar radiation receipts and temperatures than the other seasons and was comparatively wet with particularly large rainfalls in May and July.

Details of soil indices and crop management not part of the experimental treatments are shown in Table 2.2. The smallest experimental unit involved 2 x 10m plots, of which the central 1.3m x 10m strip was combine harvested.

2.2. Experimental design

2.2.1. Nitrogen x irrigation (NI) experiment

Experiment NI was only conducted in the first year. Mains water (50 and 100 mm month^{-1}) was applied to cv. Hereward via trickle irrigation piping running down alternate rows, resting on the soil surface. Ten applications, each of either 5 mm or 10 mm, were made per month, within three periods; winter water 17 January - 17 March (vegetative growth), spring water 21 March - 20 May (stem elongation) and summer water 24 May - 23 July (booting to maturity). The mean nitrate concentration of the mains irrigation water was 44.1mg litre^{-1} (Source: Thames Water), which equated to 8.9 and 17.8kg N ha^{-1} for each water rate within each 60 day period. The water also contained sulphate at a mean concentration of 28mg litre^{-1} so supplied 8.4 and 16.8kg S ha^{-1} for each water rate. The water treatments were factorially combined with two N-fertiliser treatments (0, 200 kg N ha^{-1}), applied as prilled inorganic ammonium nitrate. Fertiliser-N was split equally between two applications (2 April and 8 May), during stem extension. The experimental design consisted of four randomised blocks each containing four mainplots. Three mainplots were assigned to the three timings of water addition and the fourth to a natural rainfall control. Each mainplot was split into two plots assigned to the two rates of water (50 and 100 mm month^{-1}). Within each plot the water rate x N-fertiliser treatments were randomly allocated to subplots (2 x 10 m). These were replicated four times over the blocks except for the two N levels on the natural rainfall treatment which were replicated eight times; twice within each natural rainfall mainplot.

2.2.2. Fungicide experiments (F1-F3)

Experiment F1 was conducted in the first two years and involved two winter wheat cultivars (Consort and Hereward) and eight fungicide treatments (Table 2.3) arranged in a split-plot design with three randomised blocks divided into cultivar mainplots (20m × 8m) partitioned into fungicide treatment sub-plots (10m × 2m). Treatment 1 had no fungicide applied at or after flag leaf emergence (although all plots had received fungicide at GS 3.1, Table 2.2), then Treatment 2 also had an application at GS 39, whilst Treatments 3 to 8 involved additional applications at GS 59. The fungicides were azoxystrobin (as Amistar, Syngenta, Wittlesford, UK) and epoxiconazole (as Opus, BASF, Cheadle Hume, UK), delivered at 200-250 Pa pressure in 220 l ha^{-1} through air bubble jet nozzles (size 0.3, Billericay Farm Services) to produce a spray of medium droplet size (Matthews, 2000).

Experiment F2 was conducted in all three years and was also a split-plot design, but with six winter wheat cultivars (Claire, Consort, Hereward, Malacca, Savannah and Shamrock) as mainplots,

randomised in three blocks. In 2000/01 and 2001/02 cultivar main plots (12 x 10 m) were divided into six subplots (2 x 10m) to receive one of each of the factorial combinations of three fungicide treatments (Treatments 1, 2 and 8 in Table 2.3) and two late-season (GS 71) foliar urea treatments (either no urea or urea supplying 40 kg N ha^{-1} in 400 l ha^{-1}). In 2001/02 sub plots of Treatments 1 and 8 for cvs Consort, Hereward and Shamrock allocated to receive the foliar urea, were further divided into sub-sub-plots (5m x 2m) receiving 40 kg N ha^{-1} either sprayed as a urea solution, or as ammonium nitrate prills at GS 71. Within each of these sub-sub plots and prior to late-season N application, a ^{15}N treatment area of $1m^2$ was marked out with canes. In the foliar urea sub-sub-plots, this area was protected with a polystyrene cover whilst the unlabelled urea (40 kg N ha^{-1}) was applied to the remaining area. Care was taken to avoid fertilizer run-off when the cover was removed. A polystyrene frame was placed on the crop marking the boundary of each ^{15}N treatment area and the area within the frame sprayed with ^{15}N enriched foliar urea (40 kg N ha^{-1} double-labelled with 10 atom% ^{15}N). Similarly, in each of the ammonium nitrate sub-sub-plots, care was taken to avoid the covered ^{15}N treatment area whilst unlabelled granular ammonium nitrate (40 kg N ha^{-1}) was scattered by hand across each subplot. To aid even application, the ^{15}N enriched ammonium nitrate (40 kg N ha^{-1} double-labelled with 10 atom% ^{15}N) was dissolved in 1 litre of distilled water per treatment area and applied directly to the soil as a solution using a watering can fitted with a 12 cm dribble-bar (Readman *et al*., 2002). Cane poles were used to separate plants from each crop row and to gently hold back the foliage whilst the labelled solution was evenly applied to the soil between each row within the ^{15}N treatment area. Care was taken to keep the dribble-bar within 8 cm of the soil surface and to time the rate of application so that the 1 litre covered the whole $1m^2$ treatment area.

In 2002/03 there were no late-season nitrogen treatments so the experiment comprised three blocks, divided into six cultivar main plots (6 x 10 m), divided into three sub-plots (2 x 10m) each receiving fungicide Treatment 1, 2 or 8.

Experiment F3 was only conducted in the 2002/03 growing season. A split-split-plot factorial design was used where two irrigation treatment main plots (12m x 20m) were replicated in three randomised blocks. The irrigation treatments were either no irrigation or trickle irrigation applied twice weekly between 14th June and 18th July 2003 to theoretical field capacity based on calculations from the meteorological data. In practice this meant a total of 160 mm being applied during grain filling, in addition to rainfall. Main plots were divided into four subplots (6m x 10m). These received one of the four factorial combinations of two fungicide treatments (1 and 8; Table

2.3) and two late season nitrogen fertilizer treatments (30 kg N ha^{-1} applied at anthesis, either as a foliar urea spray in 400 l ha^{-1} or as granular ammonium nitrate prills). One m^2 of each plot received its late season nitrogen treatment as ^{15}N labelled fertilizer, as described for Experiment F2, 2001/02. The subplots were further split into three cultivar sub-subplots (2m x 10m) namely Shamrock, Hereward and Consort.

2.3. Measurements

2.3.1. Nitrogen x irrigation (NI) experiment

Total above ground growth was sampled on three occasions (21 March, 29 May and 19 July) by randomly sampling 10 plants for the first two times and 10 ear-bearing stems per plot for the final measurement. The dry weight of each sample was determined gravimetrically after oven drying at 80 ^{o}C for 48 hours. Soil moisture content was assessed with a neutron probe (Wallingford Mk 2, Didcot Instruments, Abingdon). Two 16 second counts were made at 0.1 m intervals to a depth of 1.0 m, and the volumetric moisture content calculated using a previous site calibration for the same probe.

Root growth was assessed on five occasions (19 March, 20 April, 22 May, 12 June and 12 July) by coring to a maximum depth of 1 m. These assessments corresponded to growth stages (GS), 2.2, 3.2, 4.1, 6.3 and 8.5 (Zadoks *et al*. 1974). A steel tube (7.5 cm diameter) fitted with brass sleeves to allow the core to be removed, as described by Welbank *et al*. (1974), was driven into the soil by hand (19 March), using a mechanical tractor mounted digger (20 April), and using a JCB 526 telescopic handler with a 3 m forward reach (22 May, 12 June and 12 July). This last method reduced both local soil and core compaction as the rate of penetration could be finely controlled, even though the soil was drying. Two cores were taken per plot, one within and one between each row. Cores were taken from the centre of each plot to avoid edge effects, and where a plot was repeatedly sampled a 0.5 m discard around previous sampling sites was avoided. Each core was cut into 10 cm sections and the two cores from each depth (per plot) bulked, placed in polythene bags and immediately frozen (-20 ^{o}C). Three replicate samples were taken on each sampling occasion from the same three blocks throughout the season.

Following thawing for 24 hours in cold storage (4 ^{o}C) samples were mechanically washed (Delta-T Pumped Root Washer System type RWC, Delta-T Devices Ltd., Cambridge) to remove stones, soil and large pieces of trash. Each washed sample was cleaned by hand, using tweezers to remove organic matter, seeds, foreign and dead roots. Root samples from the top 30 cm were often sub-

sampled, with between 25 - 50 % of each sample retained for analysis, depending on original root mass. Roots were stained for at least 1 hour in a methyl violet solution (0.1% in 10% ethanol, Harris and Campbell, 1989), then rinsed and placed onto an A4 glass-bottomed steel tray with approximately 1.5ml water. The roots were separated with forceps and covered with a mesh screen (Delta-T Services Ltd., Cambridge) and the water removed by blotting. The root tray was scanned against a white backing cover (Bouma *et al*., 2000, HP flatbed scanner, Delta-T Services Ltd., Cambridge) as a 'black and white drawing' with a threshold setting of 174 and a resolution of 600dpi. Root images were analysed using DOS Delta-T Scan software to calculate root length (v. 2.03, Delta-T Services Ltd., Cambridge), with the Delta-T scan generic algorithm used to correct for root intersections (Kirchhof, 1992). Dry matter content of all scanned samples was determined gravimetrically after oven drying at 80 ^{o}C for 48 hours. Where samples had been sub-sampled, multiplication factors for the image analysis results were calculated from the dry weights of the two samples.

The temporal development of the root system was investigated by assessing the natural rainfall treatment, given 200 kg N ha^{-1} on all five sampling dates. The main effect of N-fertiliser was assessed (0 and 200 kg N ha^{-1}, natural rainfall) on 12 June and again on 12 July. Effects of irrigation were assessed using the 100 mm month^{-1} treatment, given 200 kg N ha^{-1}. The effects of winter irrigation were measured on 19 March, 22 May, 12 June and 12 July; spring irrigation on 22 May, 12 June and 12 July; and summer irrigation on 12 July.

Root (length and weight) and shoot (total above ground biomass) measurements, and root : shoot ratios (RS) were examined using analysis of variance (ANOVA). For the vertical distribution of roots with soil depth, separate ANOVAs for each 10 cm section of core were performed. The FITNONLINEAR directive in Genstat (GENSTAT 5 Committee, 1993) was used to model the exponential decline of root weight density (RWD) with depth, from an equation derived for root length density (RLD; Gale and Grigal, 1987).

$$Y = 1 - \beta^{d}$$

Where Y describes the cumulative proportion of the total root system to any depth (d). This allowed the total size of the root system and exponential rate of decline (β) to be estimated for each plot. Treatment effects on β and d were then assessed by ANOVA.

A plot combine (Wintersteiger Nursery Master Elite, Inkreis, Austria) was used to harvest the central 1.3m width from each plot. Grain was cleaned and fresh yields adjusted for moisture content

by oven drying a sub-sample at 80 ^{0}C for 48 h. Dry grain samples of known weight were passed through a 'Decca' automated seed counter to determine the thousand grain weight (TGW). The specific weight of fresh grain was obtained using a chondrometer (Gooding and Davies, 1997). Blackpoint was assessed on 50 grains per plot with each grain being scored from 0-3 depending upon the severity and extent of discolouration (Lorenz 1986). The results were calculated as a percentage of the maximum score possible. Hagberg falling numbers (HFNs) were assessed to IS 3039 using a Perten Instruments Falling Number 1500 machine. Nitrogen and sulphur concentrations of the dried wholemeal flour were determined by oxidative combustion using a LECO FP-528 and a LECO SC-144DR (LECO Instruments (UK) Ltd., Cheshire), respectively. Sodium dodecyl sulphate (SDS) sedimentation volume was measured on fresh wholemeal flour using BS 4317: Part 19. Crude protein levels were obtained by multiplying the nitrogen results by 5.7 (Draper and Stewart 1980).

2.3.2. Fungicide experiments (F1-F3)

In experiments F1-F3, visual assessments of the flag leaf were made weekly from mid June until harvest. Ten leaves were selected at random from each sub plot and the percentage diseased area and green leaf area assessed by comparison with standard keys (Anon., 1976). The principal disease on the flag leaves was *Septoria tritici*, although brown rust (*Puccinia recondita*) and powdery mildew (*Erysiphe graminis*) were also present. Modified Gompertz curves (Gooding *et al*., 2000) were then fitted to the green leaf area decline over time, and *m*, the number of days after anthesis for the flag leaf to senesce to 37% green leaf area, derived for each sub plot.

Nitrogen uptake and partitioning during grain filling was assessed in Experiment F1 in 2000/01 for Treatments 1, 2, 4, 6 and 8; in Experiment F2 in 2001/02 in the sub-sub plots receiving ^{15}N labelled fertilizer; and in all plots for Experiment F3. Fifteen ear bearing stems were randomly harvested every seven to ten days. The ear-bearing stem samples were separated into five components; flag leaf laminas, penultimate leaf laminas, other leaf laminas, stems plus chaff plus leaf sheaths, and grain. The dry matter content of the components was determined gravimetrically after oven drying (80 ^{o}C for 48 h). The ears were separated into chaff and grain using a laboratory threshing machine (except for ears sampled in June which were threshed by hand). The grain samples were milled using a laboratory mill (Perten Instruments 3100, screen diameter 0.8mm), the flag leaves were ground in a disc mill (Tema, Model T100) and the remaining stem/other leaves were bulked together with the chaff and milled (Retsch, Model SM1). The N concentration and the ^{15}N

enrichment were determined by total combustion on a Roboprep C and N analyser (Europa Scientific Ltd) linked to a VG602 mass spectrometer.

Roots were assessed on Consort receiving Treatments 1, 2, 4, 6 and 8 for Experiment F1 in 2000/01; on all cultivars for Treatments 1 and 8 in the absence of late-season nitrogen in Experiment F2 in 2000/01; and on Shamrock, Consort, Hereward and Malacca for Treatments 1 and 8 in the absence of late-season nitrogen in Experiment F2 in 2001/02.

Roots were taken by extracting soil cores equally from between, and within, the crop row midway through anthesis (average GS 63, between 18 and 20 June 2001, 10 and 14 June 2002) and again four weeks later, at the soft dough stage (average GS 85, between 16 and 18 July 2001 and 8 and 12 July 2002). A steel soil corer (1 m x 75mm diameter) with removable brass sleeves was used as described for Experiment NI. The length of the core was compared to that of the extraction site to check for signs of compaction. In 2001, two soil cores per sub plot (except for sub plots receiving fungicide Treatment 1 which were cored four times) were taken during each sampling period and cut into 10cm sections, to a depth of 80cm, with those from the same plot and depth bulked together for analysis. In 2002, this was increased to eight cores per sub plot with sampling restricted to the 10-20 cm, 20-30 cm, 40-50cm and 60-70cm sections of the soil profile. Rather than freezing, as was done in Experiment NI, bulked soil core sections were stored in polythene bags at 4^{o}C for up to two weeks prior to root washing. Root washing, scanning and analysis was conducted as described for Experiment NI.

Grain was combined and assessed for quality as described for the Experiment NI, except that additionally, grain sulphur was assessed on the dried wholemeal flour using a LECO SC-144DR (LECO Instruments (UK) Ltd., Cheshire).

Appropriate plot and split-plot, factorial analyses of variance were performed using Genstat 6 (VSN International Ltd., 2002). Regression analyses were conducted to investigate relationships between green leaf area duration and grain yield and quality.

Table 2.1. Monthly mean air temperatures, rainfall, soil moisture deficit (SMD) and solar radiation receipts, Crops Research Unit, University of Reading

Month	Air temperatures (°C, mean of daily max. and min.)			Total Rainfall (mm)			Calculated SMD (mm)			Solar radiation receipts (MJ m^{-2} day^{-1}) monthly means		
	2000/ 2001	2001/ 2002	2002/ 2003	2000/ 2001	2001/ 2002	2002/ 2003	2000/ 2001	2001/ 2002	2002/ 2003	2000/ 2001	2001/ 2002	2002/ 2003
September	14.8	13.9	14.7	85	52	28	139.4	194.5	207.3	8.8	9.4	10.5
October	10.6	13.6	10.7	142	95	81	16.1	119.9	142.6	5.5	5.7	5.4
November	6.8	7.4	8.7	92	29	146	0	88.8	0	3.1	3.5	2.6
December	5.8	3.5	6.5	88	22	100	0	58.0	0.4	1.5	2.5	1.4
January	3.7	5.5	4.7	73	60	73	0	0.7	0	2.8	2.2	3.1
February	5.3	7.4	4.7	68	82	33	0	0.5	0	5.1	4.8	5.0
March	6.1	8.1	8.0	85	51	19	3.5	13.5	27.1	6.5	7.9	9.8
April	8.4	10.0	9.6	70	37	31	9.0	41.8	56.5	11.5	14.4	12.7
May	13.4	12.6	12.4	34	68	53	75.8	60.8	89.1	16.8	14.9	15.2
June	15.4	15.1	17.1	35	39	54	158.3	120.3	148.8	19.3	15.6	17.6
July	18.3	17.2	18.3	37	72	32	230.6	148.2	228.2	15.8	15.0	15.8
August	17.9	18.4	20.0	114	45	13	201.0	188.2	326.4	13.4	13.5	17.4

Table 2.2. Dates of non-experimental crop husbandry and corresponding growth stages (Zadoks *et al*., 1974).

	GS	2000/01 NI	2000/01 F1 & F2	2001/02 F1 & F2	2002/03 F2 & F3
Indices before seed bed preparation (MAFF, 1994)					
pH		6.7	6.7	6.9	6.9
Phosphorus		3	3	3	3
Potassium		2	2	1	1
Magnesium		2	2	1	1
Drilling date		17.10.00	10.10.00	17.10.01	10.10.02
Seed rate (seeds m^{-2})		400	400	400	400
Fertilizer (kg ha^{-1})					
Sulphur	Seed bed	16	16 kg	30 kg	30 kg
Potassium	Seed bed	33	33 kg	62 kg	62 kg
Nitrogen	3.0		100 kg	100 kg	100 kg
Nitrogen	3.2		100 kg	100 kg	100 kg
Crop protection chemicals (active ingredient ha^{-1})					
Autumn/winter herbicide	1.3-2.2	Bromoxynil 400 g loxynil 400g	Bromoxynil 400 g loxynil 400g	Isoproturon 2.5 kg	Isoproturon 2.5 kg
Spring fungicide	3.1	Epoxiconazole 63g	Epoxiconazole 63g	Epoxiconazole 63g	Epoxiconazole 63g
Spring herbicide	3.1	Metsulfuron-methyl 5.25g Thifensulfuron-methyl 51g	Metsulfuron-methyl 5.25g Thifensulfuron-methyl 51g	Fluroxypyr 200 g	Metsulfuron-methyl 5.25g Thifensulfuron-methyl 51g
	3.4	Fluroxypyr 200 g			
Summer fungicide	4.1	Azoxystrobin 250g Epoxiconazole 38g			
	6.3	Azoxystrobin 125g			
Summer insecticide	7.0	Lambda-cyhalothrin 5 g	Lambda-cyhalothrin 5 g		
Combine harvest date		1.8.01	14.8.01	14.8.01	7.8.01

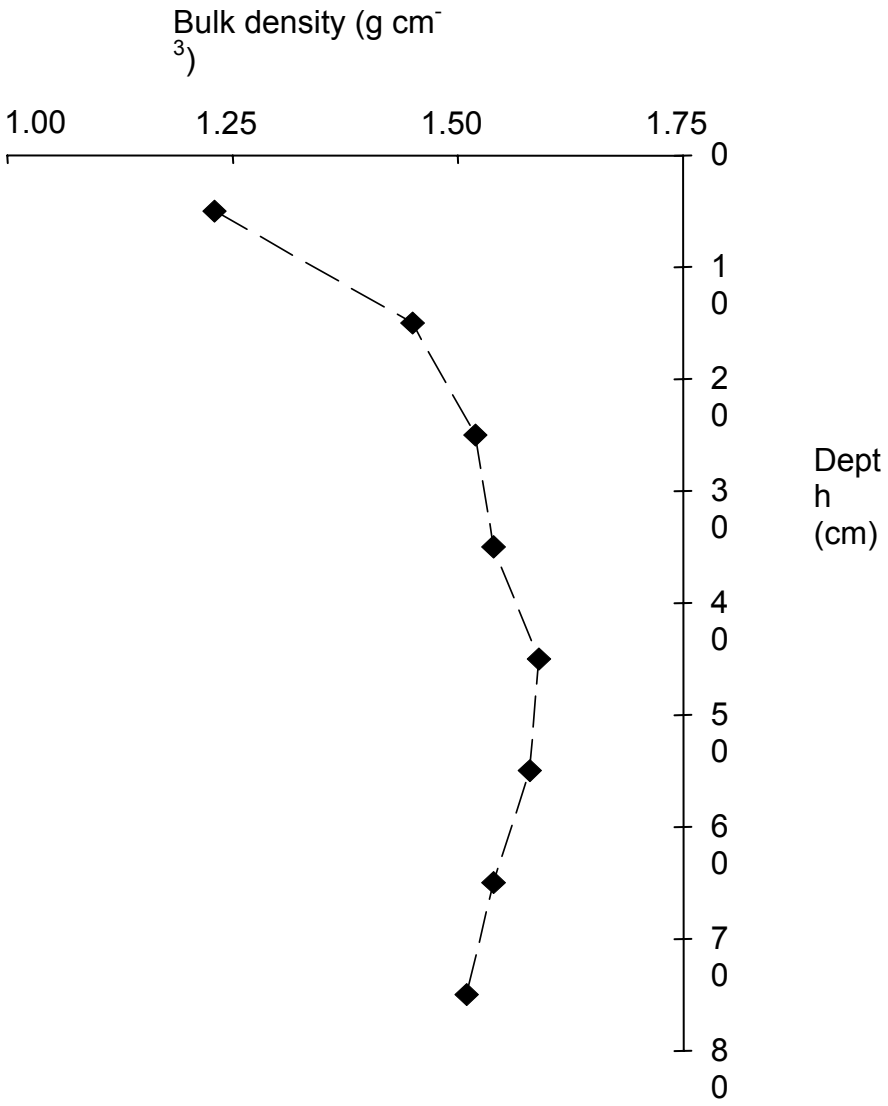

Fig. 2.1. Soil bulk density (g cm^{-3}) down the soil profile at the site

Table 2.3. Fungicide treatments for Experiments 1F and 2F (g a.i. ha^{-1}) applied at different growth stages (GS, Zadoks *et al*., 1974).

Treatment	GS 31 Epoxiconazole	GS39 Epoxiconazole/ Azoxystrobin	GS 59 Epoxiconazole/ Azoxystrobin
1	63	0/0	0/0
2	63	63/125	0/0
3	63	63/125	32/0
4	63	63/125	63/0
5	63	63/125	0/63
6	63	63/125	0/125
7	63	63/125	32/63
8	63	63/125	63/125

3. Results for nitrogen x irrigation (NI) experiment

With the exception of the first sample the root coring method enabled cores to be extracted to a depth of at least 70 cm. The field site contained spatially variable deposits of gravel that hindered progress, and prevented the extraction of some deeper cores. Despite above average rainfall in the autumn and winter, rainfall in the summer was below average, which combined with above average air temperatures, resulted in a significant soil moisture deficit by August (Table 2.2).

3.1. Temporal development of the root and shoot

Root growth during the spring was rapid (Fig. 3.1). By 2 April, a single core taken to a depth of 130 cm revealed live roots extending beneath this depth. Between 19 March and 22 May, the root system proliferated in the surface layers (0 - 40 cm, Fig. 3.1). This net growth in the surface ceased by 12 June (anthesis) with growth shifting to below 40 cm. By 12 July the surface root system was senescing whilst below 40 cm the system was still expanding. This was associated with drying of the soil, particularly in the surface layers (Fig. 3.2). This temporal shift in the vertical distribution of root growth was expressed more in root weight density (RWD) than in root length density (RLD) suggesting increases in root fineness, particularly below 40 cm. The late increase in root length below 40 cm rendered the exponential decline model (Gale & Grigal, 1987) inappropriate for the RLD data, but the model was fitted to RWD.

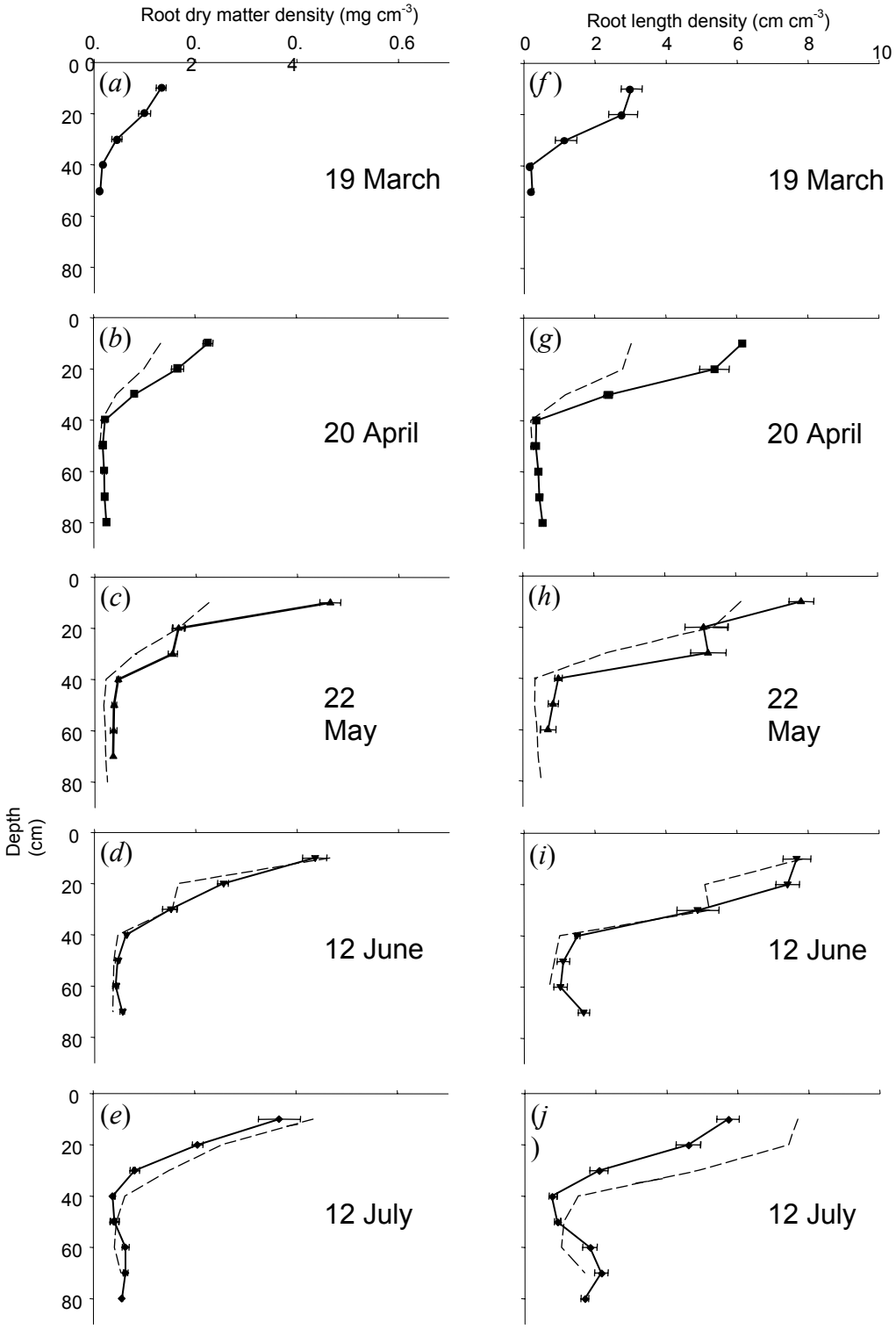

Fig. 3.1. The temporal development of the vertical distribution of the root system of winter wheat (natural rainfall, 200 kg N ha^{-1}). Dashed line is the distribution on the previous assessment date. Error bars are SEs (2, 2, 4, 6, 8 df; *a-e* & *f-j*).

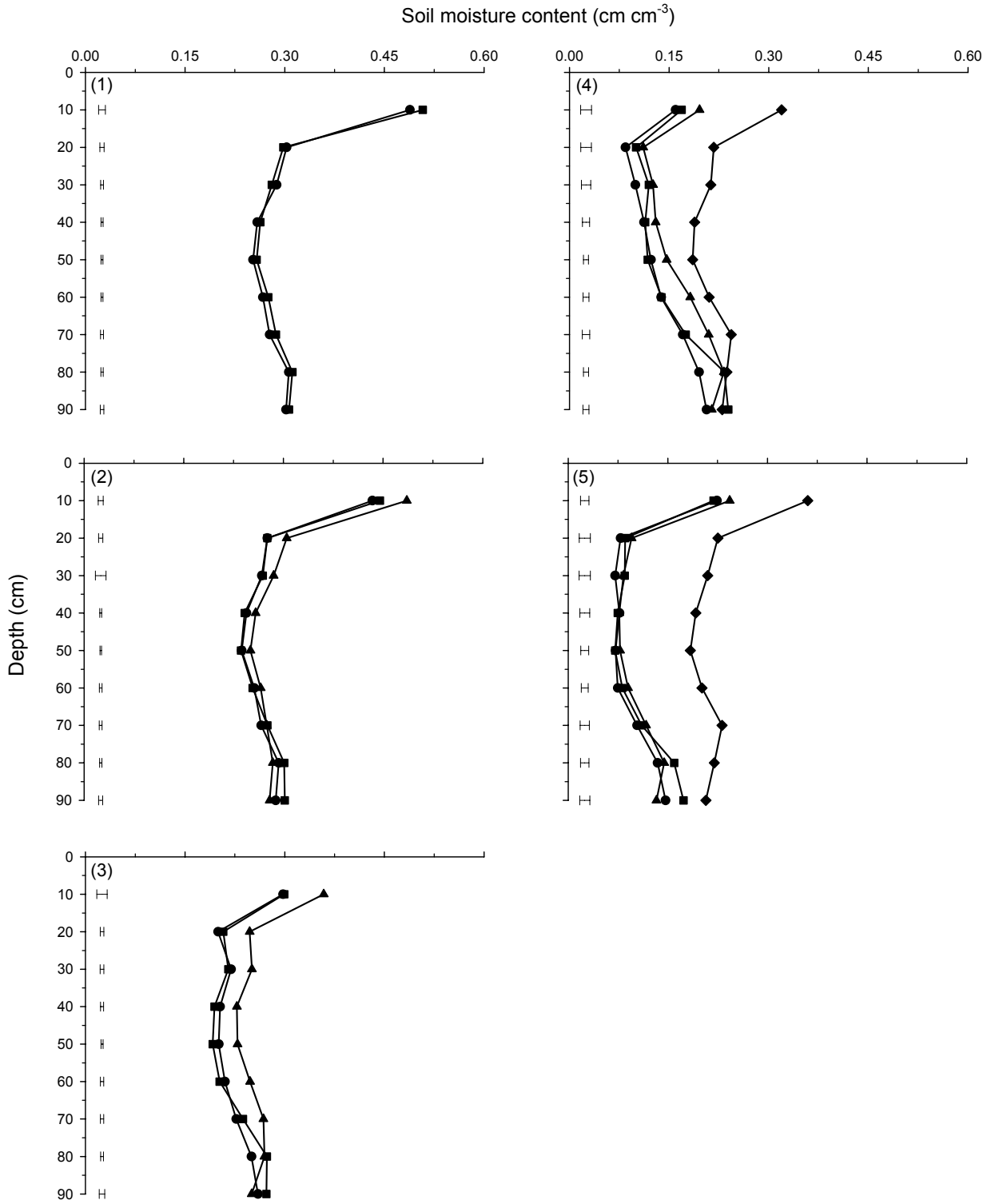

Fig. 3.2. The effect of applying additional winter [■], spring [▲] and summer [♦] irrigation (200 kg N ha^{-1}, 100 mm $month^{-1}$) on the vertical distribution of soil moisture (measured with a neutron probe). ● denotes the natural rainfall control treatment. Measurements were made on 21 March (1), 19 April (2), 22 May (3), 13 June (4) and 11 July (5). Error bars represent SEs for comparisons at each depth (Graph 1, 5 df; 2-3, 10 df; 4-5, 15 df).

The measured mass and length (Table 3.1) of the root system for the natural rainfall treatment given 200 kg N ha^{-1} was greatest on 12 June (GS 6.0), at 891 kg ha^{-1} and 25.2 km m^{-2}. In contrast, above ground dry matter production continued to increase until 12 July (Table 3.1). At the first sampling, the root system accounted for about 25 % of the total crop dry matter but this declined to just 4 % by 12 July. When the exponential decline model was used to estimate the total mass of the root system (Table 3.2) the root mass was again greatest on 12 June at 1047 kg ha^{-1} and a similar reduction in the RS ratio was predicted. The exponential decline (β) in the vertical distribution of RWD did not differ greatly throughout the season (mean -0.95), and was not significantly affected by either N-fertilizer application or irrigation treatment (Table 3.2).

Table 3.1. Effect of time, N-fertilizer and irrigation on root and shoot production, root : shoot ratio (RS), total root length and grain yield. Root mass was calculated from the extracted soil cores.

	Date of assessment	Irrigation timing / N-fertilizer (kg ha^{-1})					SE (df)
		Natural rainfall		Winter	Spring	Summer	
		0	200	200	200	200	
Root mass (kg DM ha^{-1})[a]	19 March		264	231			47.3 (2)
	20 April		507				49.4 (2)
	22 May		697	755	696		41.9 (4)
	12 June	751	891	784	622		81.9 (6)
	12 July	638	747	861	811	573	69.2 (8)
Total above ground biomass (kg DM ha^{-1})	21 March		878	822			82.8 (2)
	29 May		9290	9600	8680		351 (4)
	19 July	9750	19300	20800	25800	20300	1100 (8)
RS	March		0.33	0.30			0.062 (2)
	May		0.08	0.08	0.08		0.006 (4)
	July	0.07	0.04	0.04	0.03	0.03	0.006 (8)
Total root length (km m^{-2})	19 March		7.4	7.5			1.76 (2)
	20 April		17.4				2.76 (2)
	22 May		21.0	21.4	19.2		3.34 (4)
	12 June	19.6	25.2	21.9	18.7		2.73 (6)
	12 July	14.3	18.9	24.0	22.6	15.9	1.58 (8)
Grain yield (t DM ha^{-1})		3.39	7.83	9.60	8.63	9.30	0.168 (47)[b] 0.298 (27)[c]

[a] Calculated using a rooting depth of 50 cm assessment 1 and 70 cm thereafter.
[b] SE for comparing two N-fertilizer treatments
[c] SE for comparing different irrigation timings

Table 3.2. The effect of time, N-fertilizer and irrigation on the predicted total mass of the root system, shape of the vertical distribution of root weight density (RWD) with depth and root : shoot ratio (RS).

	Assessment	Irrigation timing / N-fertilizer (kg ha^{-1}) Natural rainfall 0	Natural rainfall 200	Winter 200	Spring 200	Summer 200	SE (df)
Predicted total root mass (kg DM ha^{-1})	19 March		322	319			67.1 (2)
	20 April		596				55.5 (2)
	22 May		916	923	834		30.8 (4)
	12 June	903	1047	1061	758		69.3 (5)
	12 July	807	883	1107	1032	812	88.7 (8)
Exponential rate of RWD decline (β)	19 March		-0.945	-0.961			0.0065 (2)
	20 April		-0.942				0.0060 (2)
	22 May		-0.938	-0.942	-0.942		0.0045 (4)
	12 June	-0.940	-0.948	-0.936	-0.943		0.0104 (5)
	12 July	-0.944	-0.951	-0.934	-0.949	-0.948	0.0068 (8)
RS	March		0.40	0.42			0.081 (2)
	May		0.10	0.10	0.10		0.005 (4)
	July	0.09	0.05	0.05	0.04	0.04	0.009 (8)

3.2.Effect of nitrogen on root and shoot growth

The application of 200 kg N ha^{-1} increased RWD and RLD below 40 cm (Fig. 3.3), particularly at the end of the season (12 July) but effects on total root mass and root length (Table 3.1) were not dramatic. This contrasts with the effect of nitrogen on the above ground biomass which was increased by an additional 9.6 t DM ha^{-1} while grain yield was increased by 4.4 t DM ha^{-1} (Table 3.1). Consequently the proportionate contribution of roots to the total mass of the plant was significantly reduced by the application of N-fertilizer (Table 3.1). The same result was found when the exponential decline model was fitted to the RLD data to derive the predicted total amount of root material (Table 3.2).

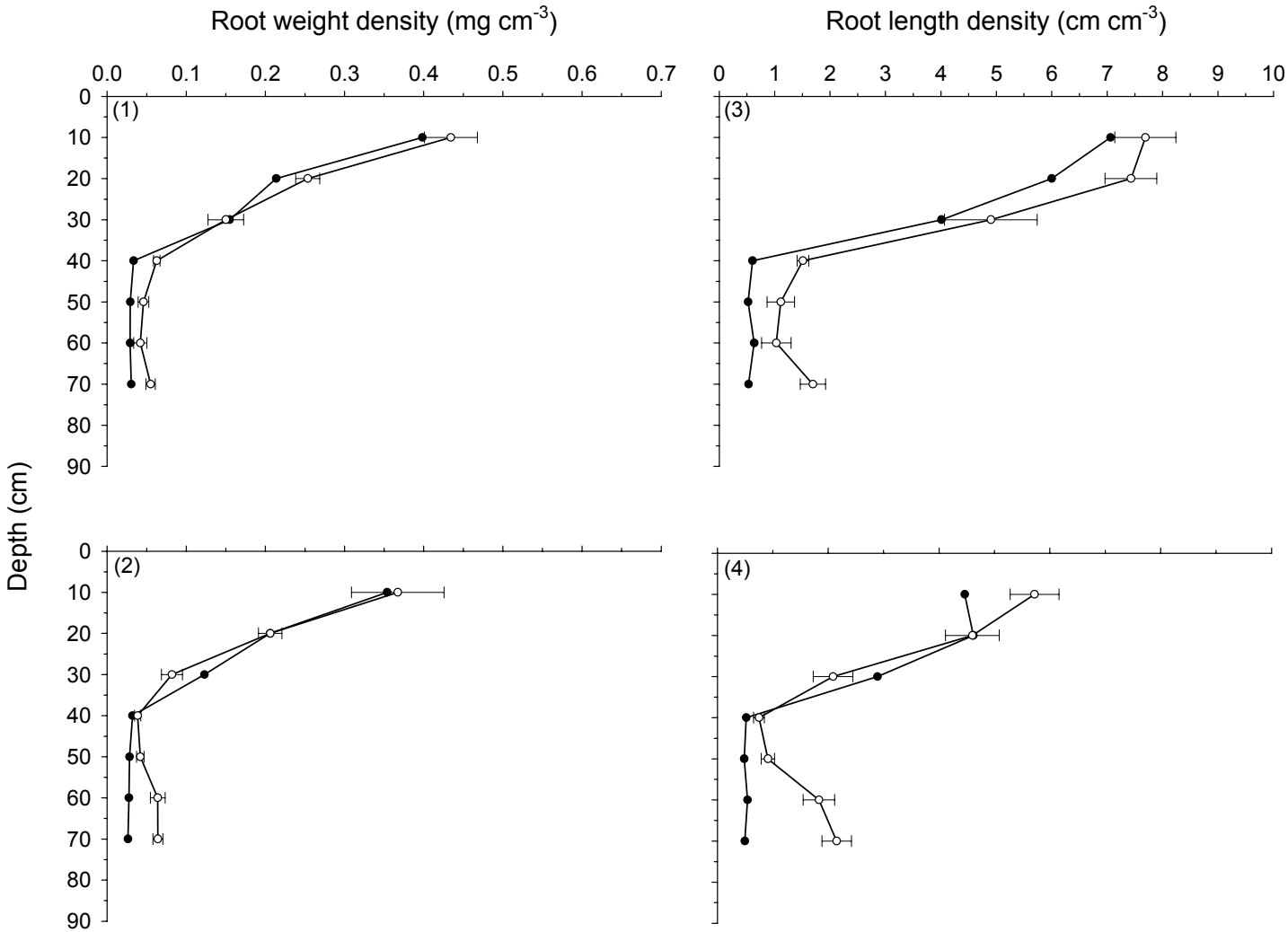

Fig. 3.3. Effect of applying 200 kg N ha^{-1} (natural rainfall) on the vertical distribution of root weight (1-2) and root length density (3-4) on two dates, 12 June (1-3) and 12 July (2-4). ● and ○ denote treatments where N-fertilizer was withheld and applied. Error bars are SEs (6 & 8 df; graphs 1,3 & 2,4).

3.3.Effect of irrigation on root and shoot growth

Winter irrigation significantly reduced the length and weight of the root system below 30 cm at the end of the season, i.e. long after irrigation had ceased (Fig. 3.4). In the surface layers however, the effect was quite different and the senescence of the roots above the plough layer seen in the control plots between the June and July assessments was not evident in plots previously receiving winter irrigation. Winter irrigation increased root length and weight on 12 July (Table 3.1 and 3.2), but the RS ratio did not differ from the natural rainfall control throughout the season. Despite this, grain yields were increased by 1.8 t DM ha^{-1} with winter irrigation (Table 3.1).

Spring irrigation maintained soil moisture (Fig. 3.2) throughout the spring and summer, delaying the accumulation of a significant soil moisture deficit. The total size of the root system, particularly in the surface layers was reduced on 12 June (Fig. 3.5 and Table 3.1). However, between 12 June and 12 July, throughout grain filling, there was an increase in both RWD and RLD following spring irrigation (Fig. 3.5). This delayed growth was evident from the examination of the total mass and length of the root system on each date (Table 3.1 and 3.2), with the greatest mass and length occurring on 12 July. Spring irrigation significantly increased the growth of the shoot (Table 3.1), and grain yield (+ 0.8 t DM ha^{-1}). The result was an apparent reduction in RS ratio (Table 3.1 and 3.2).

Summer irrigation maintained soil moisture throughout the profile (Fig. 3.2) during grain filling, and reduced the size of the root system over all depths (Fig. 3.6) while grain yield was increased by 1.5 t DM ha^{-1} (Table 3.1). Both total root mass and length, measured on 12 July were reduced, which resulted in an apparent reduction in the RS ratio (Table 3.1 and 3.2).

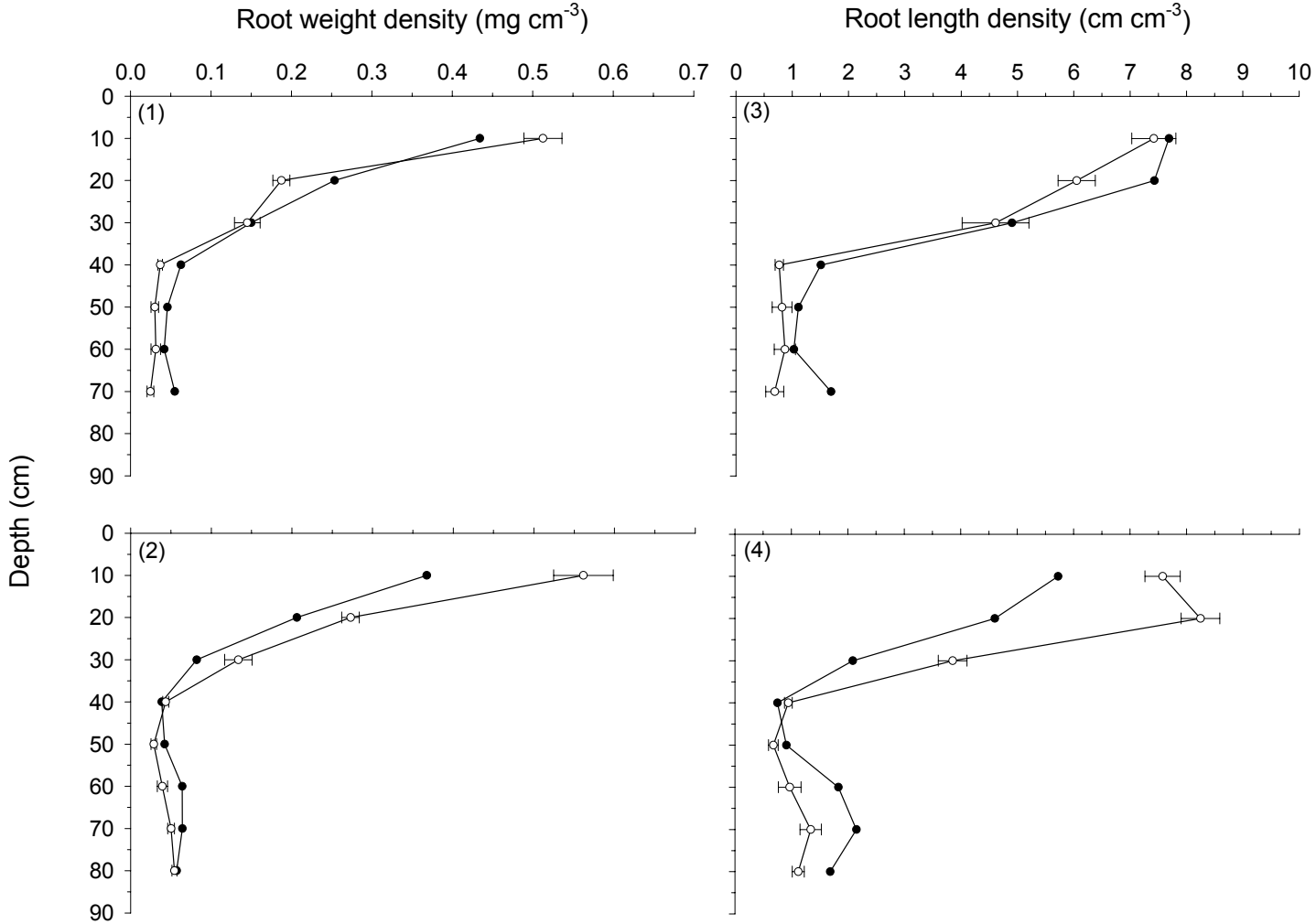

Fig. 3.4 The effect of applying additional winter irrigation (100 mm month^{-1}) on the vertical distribution of root weight (1-2) and root length density (3-4) on two dates, 12 June (1-3) and 12 July (2-4). ● and ○ denote natural rainfall and winter irrigation treatments. Error bars are SEs (6 & 8 df; graphs 1,3 & 2,4).

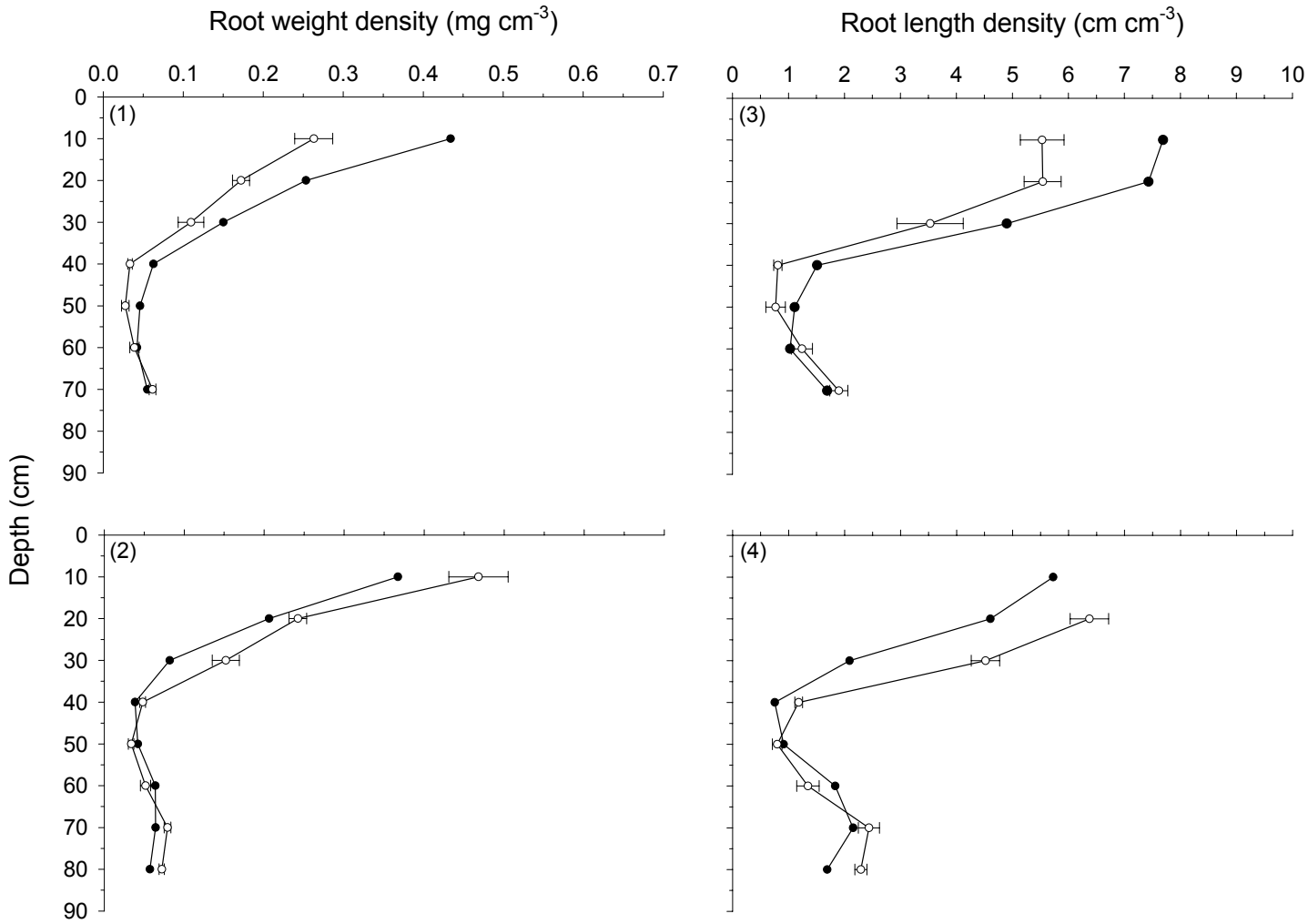

Fig. 3.5 The effect of applying additional spring irrigation (100 mm month^{-1}) on the vertical distribution of root weight (1-2) and root length density (3-4) on two dates, 12 June (1-3) and 12 July (2-4). ● and ○ denote natural rainfall and spring irrigation treatments. Error bars are SEs (6 & 8 df; graphs 1,3 & 2,4).

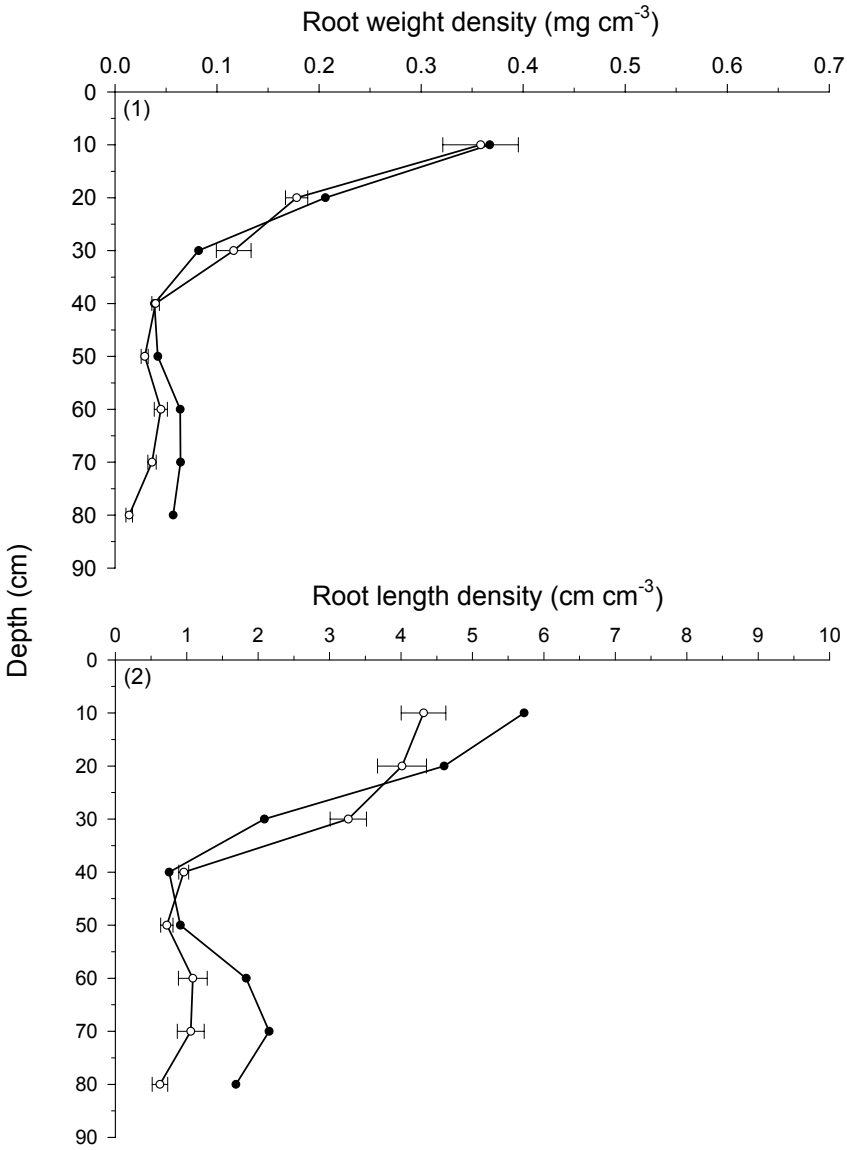

Fig. 3.6 The effect of applying additional summer irrigation (100 mm month^{-1}) on the vertical distribution of root weight (1) and root length density (2), 12 July. ● and ○ denote natural rainfall and summer irrigation treatments. Error bars are SEs (8 df).

3.4.Effects on grain yield and quality

There were no interactions with rate of water so data are presented as means of the 50 and 100mm month^{-1} treatments (Table 3.3). Irrigation at all times increased grain yield, particularly when nitrogen was also applied. Yield improvements by winter and spring irrigation derived from effects on grain population whilst summer irrigation also increased thousand grain weight. When nitrogen had been applied, irrigating in the spring reduced thousand grain weight. Specific weight was increased by applying nitrogen and reduced by irrigating in spring. The Hagberg falling number was reduced by applying nitrogen. Applying nitrogen fertilizer significantly increased grain protein concentration and grain nitrogen yield. Winter and, and particularly spring irrigation tended to reduce grain protein concentration. Summer irrigation increased protein concentration, particularly when nitrogen had been withheld. The total yield of nitrogen in the grain at harvest was increased by irrigation, mostly when nitrogen had also been applied. Summer water resulted in the largest increase in nitrogen yield, followed by winter, then spring irrigation. SDS-sedimentation volume was increased with nitrogen fertilizer. Sediment volume was increased by all irrigation treatments when nitrogen had also been applied, but only by summer irrigation when nitrogen had been withheld. When no nitrogen had been applied blackpoint was reduced by spring irrigation. Nitrogen application reduced blackpoint severity.

Table 3.3. The effect of irrigation and its interaction with nitrogen fertilizer on grain yield, grain weight, grain population, sample impurity, specific weight, Hagberg falling number and blackpoint severity in 2000/01.

Nitrogen fertilizer (kg ha^{-1})	Irrigation timing[a]	Grain yield (t DM ha^{-1})	1000 grain weight (g)	Grain population (10^3 m^{-2})	Specific weight (kg hl^{-1})	Hagberg falling number (s)	Protein concentration (% DM)	SDS sed. volume (ml)	Black-point (%)	Grain N yield (kg ha^{-1})
0	-	3.39	44.7	7.5	81.5	268	7.85	46.9	12.5	47
0	Winter	3.66	45.9	7.7	81.2	268	7.65	45.9	12.9	48
0	Spring	4.05	45.5	9.0	81.1	256	7.44	44.4	7.9	53
0	Summer	3.79	46.8	8.1	82.8	278	8.76	62.2	13.9	57
200	-	7.83	50.1	15.6	84.2	245	12.40	66.0	6.2	171
200	Winter	9.41	49.5	19.0	83.4	268	12.15	75.9	5.8	201
200	Spring	8.77	46.3	19.3	82.5	254	12.05	77.5	6.0	183
200	Summer	9.35	52.1	17.9	83.8	239	12.84	77.0	6.9	210
SE (df)										
Comparison between timings :		0.257 (16)	0.58 (16)	0.36 (20)	0.34 (37)	7.6 (30)	0.167 (29)	2.90 (16)	1.12 (32)	6.3 (22)
Same timing :		0.170 (47)	0.37 (48)	0.26 (47)	0.31 (49)	6.5 (48)	0.142 (48)	1.76 (48)	0.99 (46)	4.9 (48)

[a] Winter = 17 January to 17 March; Spring = 21 March to 20 May; Summer = 24 May to 23 July

4. Discussion of nitrogen x irrigation (NI) experiment

4.1. Temporal development of the root and shoot

The temporal pattern of the root development in the rainfed plots was broadly consistent with previous work (Gregory *et al*., 1978) showing rapid growth during spring to a maximum occurring at anthesis. The mass at anthesis was low compared to previously published data (Gregory, 1994b) but while total mass was reduced between anthesis and the end of grain filling, net root senescence was confined to the surface layers.

The RS values in early spring (March) were comparable to those reported by Gregory *et al*. (1978). During early growth up to 50 % of assimilated dry matter was transferred below ground (Gregory *et al*., 1997). The linear phase of root growth occurs earlier than that of shoot growth (Barraclough, 1984). However, termination of linear growth for the roots also occurs earlier than shoots. This combined with a shift in resource allocation to the above ground shoot arising from the application of N-fertilizer, reduced the RS ratio rapidly in the spring to 0.08. By mid May, Gregory *et al*. (1978) reported a RS ratio of 0.09. The RS ratio continued to decrease, albeit more slowly during the summer, as dry matter was partitioned and accumulated above ground during grain filling. The final RS ratio found in this investigation was smaller than the 0.07 measured by Gregory *et al*. (1978). This may have arisen due to shallower sampling; at 80 cm the system was still extending during grain filling.

The exponential decline of RWD with depth (Gale & Grigal, 1987) did not vary between assessments, consistent with the recent re-analysis of RLD data presented by Gregory *et al.* (1978; Anon., 2001).

4.2. Nitrogen fertilizer

Considering the large increase in above ground dry matter production by the addition of N-fertilizer (+ 98 %, 19 July), the effect of fertilizer on root mass (12 July) was much smaller (+ 17.1 %), consistent with N-fertilizer studies in barley (Welbank *et al*., 1974). In high yielding cultivars of winter wheat the size of the root system (RLD) is far greater than is needed for uptake of mobile nutrients and water (Gregory, 1994a; Lucas *et al*., 2000). Based on "single root models" values of RLD as low as 0.1 - 1.0 cm cm^{-3} are thought to be sufficient to exploit the relatively mobile soil nitrate ion (van Noordwijk, 1983). These models however, do not account for either the

heterogeneity of the soil environment or changing rates of ion uptake depending on root location and age. Nitrogen fertilizer increased total root length by 32.2 % (12 July), presumably by also increasing root fineness. This however, was restricted to depths greater than 40 cm rather than the more frequently cited localized surface proliferation, (Gregory, 1994a). Rainfall throughout the spring was above average, so some N may have leached to deeper parts of the profile encouraging proliferation there. Alternatively N-fertilizer may have initially stimulated the extension of the entire root system (Robinson *et al*., 1994), but the rapid accumulation of a soil moisture deficit at the surface during grain filling may have resulted in the plant's allocation of resources shifting to deeper and wetter parts of the profile. N-fertilizer reduced the RS ratio by relieving the N limitation on canopy expansion, subsequently increasing resource capture and the assimilation and partitioning of dry matter to the above ground components; this is consistent with previous studies (Welbank *et al*., 1974).

4.3. Irrigation timing

The reduced root growth and activity below 40 cm with winter irrigation (12 June - 12 July) suggests either, a shift in the functional balance in favour of shoot growth arising from an enhanced supply of soil resources (Brouwer, 1962), or a damaged root system. Natural rainfall in the autumn and winter was exceptionally high, supplying additional irrigation kept the soil near saturation for most of the winter period, preventing net drainage. The field site was also located on a flood plain, with a high water table. Transient waterlogging during this period may have damaged the root system due to poor aeration resulting in anaerobic conditions (Ellis, 1979; Lucas *et al*., 2000). However, the rate of surface root senescence in the summer (12 June - 12 July) was reduced. Winter irrigation significantly increased the size of the grain sink, so that the demand for soil resources to maintain assimilate supply throughout grain filling was higher. If the root system at depth were damaged, perhaps more resources were channelled to the surface layers to support growth.

Applying additional spring irrigation also initially reduced the size of the root system (12 June). High soil moisture contents, as discussed, may be responsible for the reduced spring root growth although both greater drainage and higher rates of evapotranspiration are likely to have prevented severe root damage. Spring irrigation may have shifted the functional balance (Brouwer, 1962) in favour of shoot production by increasing the supply of soil resources (nutrients and water). The effects of spring irrigation on soil moisture were still detectable in the summer, throughout grain filling. The soil moisture deficit was reduced, increasing the availability of soil N, from both enhanced mineralization and possibly also the nitrate contained in the irrigation water (see below).

This enhanced supply of soil resources may have promoted the continued surface extension of the root system throughout grain filling (Klepper, 1991). Subsequently, late season resource capture was improved, and a greater proportion of the assimilate was allocated to the above ground sinks. The relative effect of spring irrigation on above ground dry matter partitioning and yield, compared to the effect on the root system was large. This suggests that above ground growth was not significantly limited by the size of the root system.

Supplying additional summer irrigation negated the accumulation of a significant soil moisture deficit, maintaining supplies of both water and, presumably also N throughout grain filling (Table 2.8). In contrast to expectation, the rate of root senescence was increased throughout the profile, despite prolonging canopy life (Fig. 2.5). Regardless of rooting depth if water is readily available in the surface layers this tends to be preferentially extracted (Gregory, 1994b). In accordance with the functional balance hypothesis (Brouwer, 1962) the increased supply of soil resources (water and nutrients) resulted in an apparent shift in the partitioning and redistribution of assimilate to the above ground components, even at the end of the season.

Overall the rooting characteristics of Hereward did not appear to differ significantly from previous investigations with older cultivars. Given suitable conditions, winter wheat grown on sandy soils in the UK can achieve high yields with only small amounts of assimilate partitioned below ground. However, N-fertilizer and the timing of soil water availability can modify the distribution of roots, both with depth and time. The timing of water availability affected both the size and the sign of effects on root mass and length.

4.4. Grain yield and quality

The increase in yield following the application of about 200kg N ha^{-1}, associated with increased grain numbers, rather than grain size, is well documented (Gooding and Davies, 1997). What is less easy to explain is the increase in yield following irrigation in the winter, during high-rainfall periods. The concentration of nitrogen and sulphur in the mains water used for irrigation water was considerably higher than that in rainwater for this region in these years (Source: National Air Quality Information Archive). It is difficult, however, to allocate the yield benefit following winter irrigation to the increased nutrient supply. Nitrogen supplied whilst irrigating was small compared to crop demand, and the interaction between winter irrigation and nitrogen fertilizer was synergistic, rather than substitutive. When nitrogen fertilizer was not applied there was no effect of winter irrigation on the yield of nitrogen in the grain. Sulphur in the irrigation water may have accounted

for a large proportion of crop demand and the drainage and organic matter characteristics of the soil may have contributed to the likelihood of sulphur deficiency (McGrath and Zhao, 1995). However, significant quantities of sulphur were applied to the seed bed (Table 2.2), and more sulphur would have been deposited as sulphate or sulphur dioxide during the growing season (estimated at 10kg S ha^{-1} yr^{-1} for this site in this year. Source: National Air Quality Information Archive). Nonetheless, both nitrate and sulphate ions would be highly mobile in this soil, and susceptible to leaching. The irrigation regime, comprising frequent application of small amounts of nutrient in solution might be a particularly effective delivery system.

While nutritional effects of irrigation cannot be discounted entirely there are other physical effects of winter irrigation that may have been important. Firstly, we confirmed (Clarke, 2002) that winter water reduced the diurnal temperature range of the soil (Loomis and Connor, 1992), possibly reducing the frequency and severity of cold temperature stress. Secondly, despite the lack of a calculated soil moisture deficit during winter, the neutron-probe measurements (Clarke, 2002) demonstrated that winter irrigation buffered any effects of drainage during the drier periods, an effect still observed in early April.

Part of the yield increases from spring and summer irrigation may also have derived from nutritional effects. However, in both cases, the maintenance of soil moisture levels may also have been important. The neutron-probe measurements demonstrated that spring irrigation reduced the rate of soil drying during spring such that an effect on soil moisture was still evident in June. Summer irrigation largely negated a significant soil moisture deficit during grain filling. These results are consistent with other experiments in the UK showing that irrigation by trickle lines to alleviate drought after anthesis increases yield mostly through increases in thousand grain weight, and that this effect interacts positively with nitrogen fertilizer applied in the spring (Pushman and Bingham, 1976).

The reduction in Hagberg falling number following nitrogen application, contrasts with the positive effects of nitrogen on Hagberg falling number at this site in other years (Clarke, 2002; Ruske *et al*., 2003*b*; Kindred *et al*., 2005), and previous experiments elsewhere in the UK (Gooding *et al*., 1986*a*; Kettlewell, 1999). However, this experiment was also slightly unusual in finding that nitrogen increased grain size (Clarke *et al*., 2004) and there is often a negative association between grain size and Hagberg falling number (Evers *et al*., 1995), possibly due to effects mediated through grain cavity size (Greenwell *et al*., 2001; Kindred *et al*., 2004).

The increase in grain protein concentration following nitrogen application was consistent with expectations (Gooding and Davies, 1997). The reduction in grain protein concentration by winter and spring irrigation again suggests that nitrogen in the mains water was not an important component of the irrigation treatment effects. Rather, these reductions in protein concentration are consistent with analysis of protein concentration over time in the HGCA surveys of cereal quality (Smith and Gooding, 1999) showing winter and spring rainfall to be associated with reduced protein concentration in the national crop. Similar effects of early rainfall have been reported in New South Wales Australia (Taylor and Gilmour, 1971; Verrell and O'Brian, 1996) and Canada (Hopkins, 1968). Each study speculates on the likely mechanisms for this effect. Early rainfall may: i) encourage excessive vegetative proliferation restricting the availability of N for redistribution; ii) increase leaching and other forms of N loss (Powlson *et al*., 1992); and iii) augment late season soil moisture reserves prolonging green leaf life during grain filling, favouring grain carbohydrate accumulation.

The increase in grain protein concentration by the summer irrigation, contrasts with the effects of earlier rainfall and irrigation, yet is still consistent with what has been found in other surveys of UK wheat (Farrand, 1972; Smith and Gooding, 1996). When late season rainfall or irrigation has been associated with increased grain protein concentrations, it is probably a result of increased N-mineralization and/or improved crop uptake.

5. Results of fungicide (F1-F3) experiments

5.1. 2000/01

5.1.1. Experiment F1

5.1.1.1. Green leaf area and foliar disease

The area of *Septoria tritici* on the flag leaves developed slowly (Table 5.1). The area on Consort was reduced by the fungicide applied at flag leaf emergence, but no fungicide application to Hereward or any at ear emergence to Consort significantly reduced the area of the disease. The area of brown rust on Consort developed rapidly between the last two assessment dates, and eventually covered a larger area of the flag leaf than did *S. tritici* on this cultivar. Fungicide applied at flag leaf emergence was sufficient to reduce the area of brown rust to trace levels.

The green leaf area duration of the flag leaf (Fig 5.1*a*, *b*; Table 5.2), particularly that of Consort, was increased by fungicide application at flag leaf emergence (Table 5.2). The additional sprays at ear emergence had only small and inconsistent effects on the life of the flag leaf. For example, the senescence of Consort flag leaves, as defined by the time to reach flag 37% green leaf area (modified Gompertz *m*) was delayed by 9 days by Treatment 2, but only by a further 1 day by sprays at ear emergence (average of treatments 3-8; S.E. = 0.46), just exceeding 700 ºCd after anthesis. For Hereward, the fungicide application at flag leaf emergence was sufficient to delay senescence beyond 700 ºCd while additional sprays at ear emergence failed to delay flag leaf senescence further.

5.1.1.2. Nitrogen uptake and partitioning

Nitrogen in the above ground tissues and significance levels for all treatments assessed are presented in Tables 5.3 to 5.9. The effects of fungicide Treatments 1 and 8, with putative responses over time are also presented in Figure 5.1*c*-*n*. The amount of nitrogen in the flag leaves declined, approximately linearly, during flag leaf senescence (Fig. 5.1*c*,*d*). By the last two measurements, fungicide treated flag leaves contained significantly less nitrogen than untreated leaves. This effect was most pronounced for Consort as indicated by significant cultivar x fungicide interactions on both dates (Table 5.3). Similar effects were evident on nitrogen concentration in the flag leaves (Fig. 5.2), i.e. completely senesced leaves contained higher amounts and concentrations of nitrogen if they had been diseased, compared to if they had previously received fungicide. It was also evident that leaves scored as 50% green contained only very little more nitrogen than leaves which were completely senesced (Fig. 5.2).

On the leaf below the flag leaf, fungicide treatment initially increased the nitrogen content for Consort (Table 5.4; Fig. 5.1*e*,*f*), but not for Hereward. By the last sampling, however, fungicide treated leaves of Consort contained significantly less nitrogen than untreated leaves. Again, there was little effect of fungicide on the nitrogen content in the penultimate leaves of Hereward. There was little effect of fungicide on the nitrogen content of the leaves below the top two leaves until the last two measurements, when again, fungicide treatment reduced the nitrogen contents of Consort leaves, but not of Hereward leaves (Table 5.5; Fig. 5.1*g*,*h*).

Nitrogen in the stem and chaff declined approximately exponentially (Fig. 5.1*i*,*j*) during crop senescence but fungicide had no consistent effect (Table 5.6). Grain filling with nitrogen was extended by fungicide use on Consort but not on Hereward, such that by the last assessment, fungicide applied at flag leaf and ear emergence had increased grain nitrogen quantity by 11 mg/ear in Consort, but by only 4 mg/ear in Hereward (Table 5.7; Fig. 5.1.*k*,*l*). Total N in the above ground, ear-bearing shoots increased linearly during grain filling, and at a faster rate in Consort receiving fungicide at both timings (Table 5.8; Fig. 5.1*m*,*o*)

If it is assumed that all nitrogen disappearing from the vegetative parts of the shoot, and all nitrogen taken up during grain filling contributes to grain nitrogen, it can be calculated that, during the period of assessment, flag leaves, penultimate leaves, stem and chaff, and uptake, contributed 8%, 6%, 5%, 36% and 45% of the nitrogen found in the grain at the end of grain filling. Fungicide treatment did not significantly affect these proportions. Net remobilisation from the vegetative tissues during the sampling period and nitrogen harvest index at the last sampling (grain N/total above ground N) appeared to be increased by fungicide use on Consort (Table 5.9) but this was not statistically significant.

5.1.1.3. Root extent and distribution

Roots proliferated in the top 30cm of soil, i.e. the approximate plough layer, averaging over 4 cm/cm^3. Between 30 and 80 cm, however, root length density averaged only 0.7 cm/cm^3, but with no obvious decline down through the profile from 30 to 80 cm.

The individual fungicide treatment means are shown for Consort in Tables 5.10 to 5.13. Fig. 5.3 compares the untreated mean (Treatment 1) with the average of all the fungicide treatments measured (Treatments 2, 4, 6 & 8). There was no evidence of a significant decline in root extent

between anthesis and the soft dough stage. Indeed, over all depths and fungicide treatments, root length density appeared to increase from 1.9 to 2.2 cm/cm^3 between the two assessments (compare Table 5.10 with 5.11). Root dry matter density did, however, decline slightly from an average of 0.11 mg/cm^3 to 0.09 mg/cm^3.

By anthesis (Table 5.10; Fig. 5.3*a*), fungicide treatment had already significantly reduced the root length density in profiles within and below the plough layer. This effect had largely disappeared by the soft dough stage (Table 5.11; Fig. 5.3*b*) although a suppressive effect of fungicide was still evident at the 70-80cm depth. Significant fungicide effects were less prevalent on root dry matter density (Tables 5.12 and 5.13) but a slight suppressive effect was again evident at 60 – 70 cm at anthesis (Table 5.12).

5.1.1.4. Combine harvested grain yield and quality

Grain yield of Consort was increased by 0.8 t by fungicide applied at flag leaf emergence, and then by an additional 0.9 t DM by further fungicide applications at ear emergence (mean of treatments 3-8; Table 5.14). There was little effect of fungicide on the grain yield of Hereward. A similar result was found for the yield of nitrogen in the grain. The flag leaf spray increased nitrogen yield of Consort by 15 kg N ha^{-1} with additional fungicide applications at ear emergence increasing nitrogen yield by an average of a further 18 kg N ha^{-1}. Fungicide had little effect on the yield of nitrogen in the grain of Hereward.

It was possible to fit 'broken-stick' models to the responses of grain yield, N yield and S yield to the longevity of flag leaf life (Fig. 5.4). However, although limits to responses were estimated to be around 700 ºCd there was wide scatter around the fitted line and parameter estimation was reliant on the inclusion of the data for Treatment 1 on Consort.

Fungicide simultaneously increased yield and reduced root length density below the plough layer so there were negative associations between yields and root length densities (Fig. 5.5)

The effects of fungicide on nitrogen yield of Consort were greater than those on grain yield such that nitrogen concentration was increased by application. Thus fungicide applied at flag leaf emergence increased protein concentration from 11.5 to 11.7% DM (Table 5.14) and additional sprays at ear emergence increased concentration from 11.7% to an average of 11.85%. Again, there was no effect of fungicide on Hereward.

The increased grain yield achieved by fungicide application at flag leaf emergence to Consort was entirely accounted for by an increased thousand grain weight (Table 5.10). The improved grain filling was also consistent with the fungicide effects on grain specific weight. The effects of the ear emergence sprays on yield, however, were not reflected in grain weight nor specific weight and are, thus, less easy to explain. The implication is that grain numbers were increased by these late treatments, possibly through effects on floret abortion rates or survival of late tillers. Hagberg falling numbers were not significantly affected by any of the fungicide treatments although there was a trend for most sprays to reduce Hagberg falling number. There was no significant effect of fungicide on S or N:S ratio. SDS-sedimentation volumes were higher for Hereward than for Consort, but were not significantly affected by fungicide. Blackpoint severity was increased by fungicide applied at flag leaf emergence, but not consistently affected by the additional ear sprays.

Table 5.1. The effect of cultivar and fungicide treatments on the area of disease symptoms on the flag leaves of winter wheat. Experiment F1; 2001.

Cultivar	Treatment No.	Time of assessment (date in 2001 and days after anthesis)							
		Septoria tritici				Brown rust			
		21.06 3	27.06 9	04.07 16	11.07 23	21.06 3	27.06 9	04.07 16	11.07 23
Consort	1	0.1	0.9	1.6	4.4	0.0	0.0	1.2	8.3
	2	0.0	0.8	1.0	2.0	0.0	0.0	0.2	0.1
	3	0.0	0.8	0.9	2.6	0.0	0.0	0.1	0.0
	4	0.0	0.9	0.8	2.0	0.0	0.0	0.1	0.1
	5	0.0	0.8	1.0	2.4	0.0	0.0	0.1	0.0
	6	0.0	0.9	0.9	2.4	0.0	0.0	0.3	0.1
	7	0.0	1.2	1.1	2.0	0.0	0.0	0.3	0.0
	8	0.0	1.0	0.9	2.2	0.0	0.0	0.1	0.0
Hereward	1	0.1	0.4	1.0	2.2	0.0	0.0	0.6	1.0
	2	0.0	0.9	0.7	1.6	0.0	0.0	0.0	0.0
	3	0.0	0.8	0.9	2.0	0.0	0.0	0.1	0.0
	4	0.1	0.6	0.8	2.1	0.0	0.0	0.3	0.0
	5	0.0	0.8	0.8	1.8	0.0	0.0	0.2	0.0
	6	0.1	0.8	0.8	2.1	0.0	0.0	0.1	0.0
	7	0.1	0.3	0.5	1.6	0.0	0.0	0.1	0.0
	8	0.3	0.7	1.3	2.4	0.0	0.0	0.1	0.0
SE[a] (28 df)			0.17	0.24	0.25				
Significance of effects[b]									
Cultivar			-	-	-				
Fungicide			-	-	***				
Cv x Fung.			-	-	**				

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.2. The effect of cultivar and fungicide treatments on the green leaf area of wheat flag leaves and the time taken to reach 37% green leaf area (Gompertz *m*). Experiment F1; 2001.

Cultivar	Treatment No.	Time of assessment (date in 2001 and days after anthesis)								Gompertz *m* (days)	Gompertz *m* (^{o}Cd)
		21.06 3	27.06 9	04.07 16	11.07 23	18.07 30	25.07 37	01.08 44	08.08 51		
Consort	1	97.2	97.8	95.0	83.2	28.0	0.0	0.0	0.0	29.1	541
	2	96.8	97.9	96.4	95.9	85.4	46.6	3.8	0.0	38.0	694
	3	97.3	97.9	96.8	95.5	84.4	42.8	7.0	5.2	37.9	693
	4	97.7	97.6	96.9	95.8	86.0	45.7	20.5	9.7	40.3	742
	5	97.3	97.9	96.5	95.4	79.0	38.7	6.3	1.6	37.3	682
	6	97.5	97.7	96.7	95.5	80.2	46.5	14.3	4.2	39.2	724
	7	96.9	97.4	96.2	95.8	83.0	50.6	12.5	8.0	39.6	732
	8	97.4	97.6	96.6	95.9	85.0	46.9	13.4	9.0	39.1	725
Hereward	1	97.3	98.2	96.5	94.7	82.8	28.1	2.7	0.0	36.3	666
	2	97.5	97.6	97.2	96.3	75.7	45.1	21.2	4.8	39.9	741
	3	97.3	97.9	96.9	96.0	81.4	39.5	17.0	7.5	38.9	716
	4	97.1	97.9	96.7	95.7	81.4	42.4	20.5	14.8	39.9	743
	5	97.1	97.6	96.6	96.0	84.5	42.2	21.4	9.2	39.3	724
	6	97.4	97.9	97.0	95.9	71.9	39.7	17.7	7.3	38.1	699
	7	97.4	98.0	97.1	96.4	88.2	44.2	16.9	10.2	39.4	732
	8	97.1	97.9	96.1	95.6	79.8	31.1	12.0	6.5	37.1	678
SE[a] (28 df)		0.21	0.14	0.27	1.03	3.89				1.15	49.1
Significance of effects[b]											
Cultivar		-	-	-	*	-				-	-
Fungicide		-	-	**	***	***				***	***
Cv x Fung.		-	*	*	***	***				*	*

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

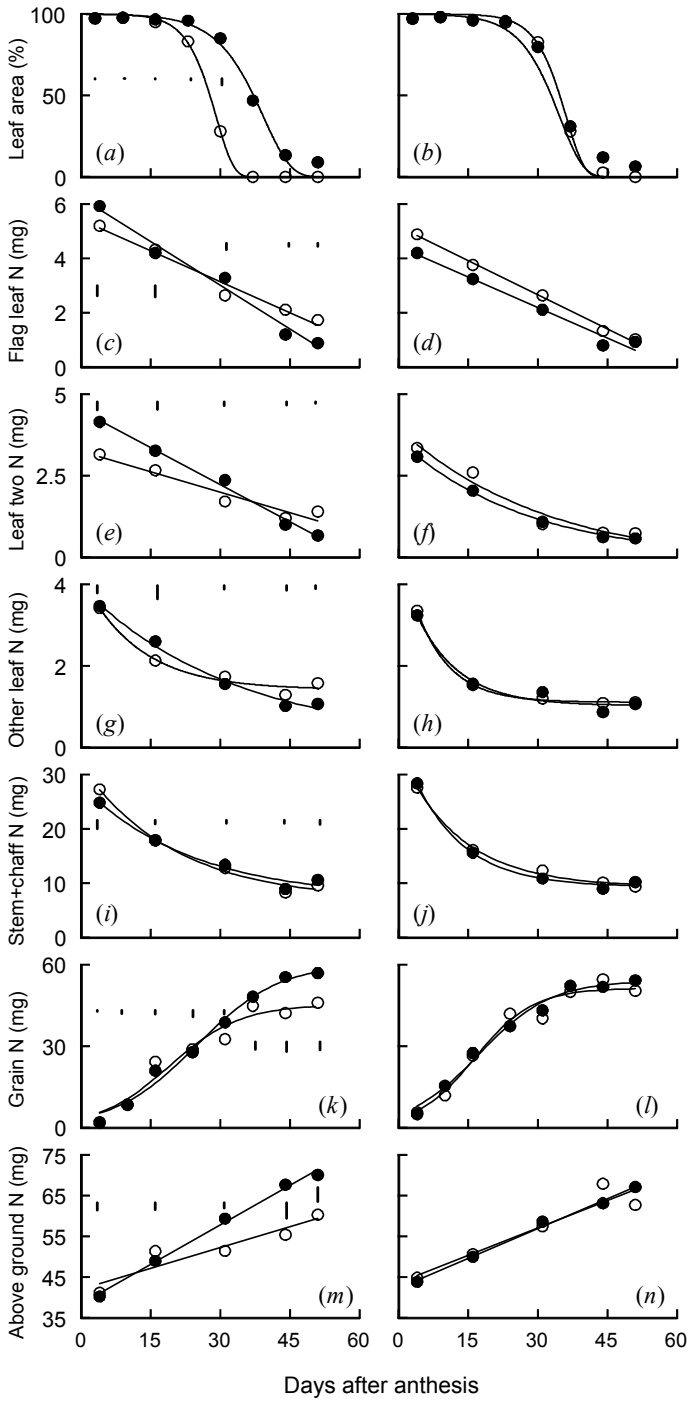

Fig. 5.1. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on green leaf area of the flag leaf and amounts of nitrogen per ear bearing stem in different above ground components in 2001. Left and right columns of graphs correspond to cvs Consort and Hereward respectively. Fitted curves are modified Gompertz (*a*,*b*), linear (*c*-*e*,*m*,*n*), exponential (*f*-*j*), and logistic (*k*,*l*). Vertical bars in Consort graphs are S.E. (28 D.F. for *a* and *b*; 16 D.F for *c*-*m*) for comparing points within a variety. Experiment F1; 2001.

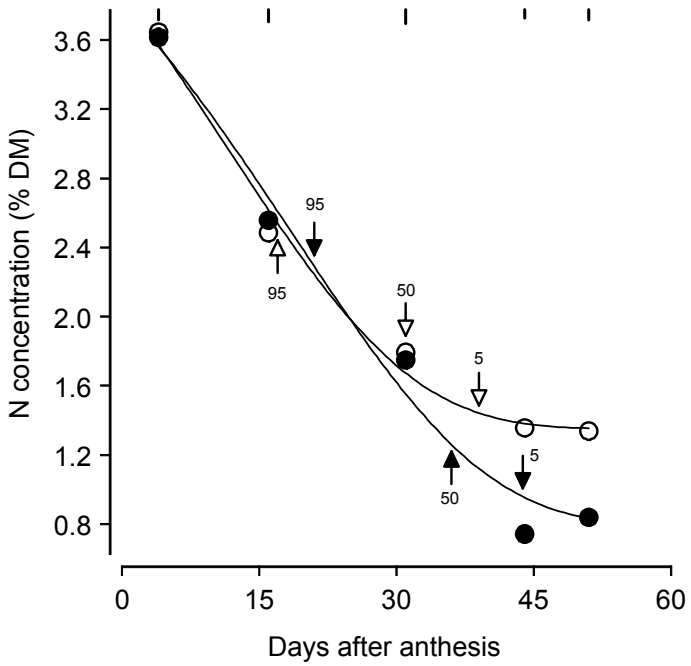

Fig. 5.2. The effect of fungicide treatment (○ = untreated; ● = 63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on nitrogen concentration in the flag leaves. Arrows (Δ = untreated; ▲= with fungicide) and numerals denote the timings for different green areas (%) of the flag leaf; mean of two cultivars Vertical bars are S.E. (16 D.F.). Fitted lines are Gompertz. Experiment F1; 2001.

Table 5.3. The effect of cultivar and fungicide treatment on the nitrogen content of flag leaf laminas (mg leaf^{-1}) of ear bearing stems of wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)				
		22.06 4	04.06 16	19.07 31	01.08 44	08.08 51
Consort	1	5.2	4.3	2.6	2.1	1.7
	2	5.0	4.4	2.9	1.2	1.0
	4	5.2	5.2	3.5	1.2	0.8
	6	4.2	3.9	3.2	1.0	1.0
	8	5.9	4.2	3.3	1.2	0.9
Hereward	1	4.9	3.8	2.6	1.3	1.0
	2	4.6	3.1	2.1	1.3	0.9
	4	4.3	4.6	2.6	1.2	1.0
	6	4.3	3.2	2.3	1.0	0.7
	8	4.2	3.2	2.1	0.8	0.9
SE[a] (16 df)		0.37	0.41	0.24	0.12	0.11
Significance of effects[b]						
Cultivar		*	-	-	-	-
Fungicide		-	**	-	***	***
Cv x Fung.		-	-	-	*	**

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.4. The effect of cultivar and fungicide treatment on the nitrogen content of penultimate leaf laminas (mg leaf^{-1}) of ear bearing stems of wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)				
		22.06 4	04.06 16	19.07 31	01.08 44	08.08 51
Consort	1	3.2	2.7	1.7	1.2	1.4
	2	3.5	3.1	2.1	1.0	0.7
	4	3.8	3.6	2.4	0.8	0.6
	6	3.1	2.8	2.2	0.8	0.7
	8	4.2	3.3	2.4	1.0	0.7
Hereward	1	3.4	2.6	1.0	0.8	0.7
	2	3.3	2.0	1.0	0.7	0.5
	4	3.2	2.4	1.2	0.7	0.5
	6	3.6	2.2	1.1	0.6	0.5
	8	3.1	2.0	1.1	0.6	0.6
SE[a] (16 df)		0.26	0.24	0.13	0.11	0.05
Significance of effects[b]						
Cultivar		-	-	-	-	-
Fungicide		-	-	*	-	***
Cv x Fung.		*	-	-	-	***

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.5. The effect of cultivar and fungicide treatment on the nitrogen content of leaf laminas below the top two leaves (mg stem^{-1}) of ear bearing stems of wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)				
		22.06 4	04.06 16	19.07 31	01.08 44	08.08 51
Consort	1	3.4	2.1	1.7	1.3	1.6
	2	3.2	2.0	1.4	0.9	1.1
	4	3.4	2.4	1.5	1.2	1.0
	6	2.8	2.0	1.6	0.9	1.1
	8	3.5	2.6	1.6	1.0	1.1
Hereward	1	3.4	1.5	1.2	1.1	1.1
	2	3.4	1.5	1.3	1.0	1.0
	4	3.2	1.3	1.5	0.9	1.2
	6	3.8	2.3	1.4	1.1	1.1
	8	3.2	1.6	1.4	0.9	1.1
SE[a] (16 df)		0.19	0.33	0.10	0.08	0.08
Significance of effects[b]						
Cultivar		-	-	-	-	-
Fungicide		-	-	-	*	*
Cv x Fung.		*	-	-	-	*

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.6. The effect of cultivar and fungicide treatment on the nitrogen content of leaf stem, leaf sheaths and chaff (mg stem^{-1}) of ear bearing stems of wheat. Experiment F1; 2001.

Cultivar	Tr. No..	Time of assessment (date in 2001 and days after anthesis)				
		22.06 4	04.06 16	19.07 31	01.08 44	08.08 51
Consort	1	27.3	17.9	12.8	8.3	9.6
	2	25.6	17.3	12.8	9.9	9.5
	4	27.0	18.8	14.2	10.2	11.1
	6	27.4	18.2	13.5	8.9	9.7
	8	24.8	17.9	13.4	9.0	10.6
Hereward	1	27.6	16.1	12.4	10.1	9.4
	2	26.9	14.9	13.0	9.1	10.1
	4	27.6	15.2	14.0	10.3	11.8
	6	29.8	14.6	12.8	9.9	9.5
	8	28.4	15.6	10.9	9.0	10.2
SE[a] (16 df)		1.63	0.77	0.59	0.67	0.81
Significance of effects[b]						
Cultivar		-	-	-	-	-
Fungicide		-	-	*	-	-
Cv x Fung.		-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.7. The effect of cultivar and fungicide treatment on the nitrogen content of grain (mg ear^{-1}) of ear bearing stems of wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)							
		22.06 4	28.06 10	04.06 16	12.07 24	19.07 31	25.07 37	01.08 44	08.08 51
Consort	1	2.1	8.4	24.3	28.9	32.6	44.9	42.5	46.0
	2	1.8	9.4	23.0	30.6	38.0	49.2	49.2	49.2
	4	1.7	9.1	21.4	28.6	39.3	47.2	56.6	45.4
	6	2.0	9.3	24.1	31.9	39.9	47.9	51.2	52.6
	8	1.8	8.5	21.0	27.8	38.8	48.3	55.5	56.9
Hereward	1	5.6	11.9	26.6	42.0	40.3	50.0	54.6	50.4
	2	5.3	14.6	25.3	39.8	49.6	57.0	55.5	49.5
	4	4.7	15.6	25.0	35.7	45.1	51.1	52.4	62.3
	6	4.4	16.2	23.5	40.6	46.8	51.4	49.2	53.0
	8	5.0	15.5	27.5	37.4	43.2	52.3	51.9	54.3
SE[a] (16 df)		0.45	1.24	1.46	2.40	1.49	2.67	3.63	2.97
Significance of effects[b]									
Cultivar		***	*	*	*	**	-	-	-
Fungicide		-	-	-		***	-	-	-
Cv x Fung.		-	-	-		-	-	-	*

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.8. The effects of cultivar and fungicide treatment on the total nitrogen content (mg stem^{-1}) per ear-bearing shoot of wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)				
		22.06 4	04.06 16	19.07 31	01.08 44	08.08 51
Consort	1	41.2	51.4	51.5	55.4	60.3
	2	39.2	49.8	57.2	62.3	61.4
	4	41.2	51.3	60.9	70.0	58.9
	6	39.5	51.0	60.4	62.9	65.0
	8	40.3	49.0	59.4	67.7	70.1
Hereward	1	44.8	50.6	57.5	67.9	62.7
	2	43.5	46.7	67.0	67.7	62.0
	4	43.0	48.5	64.5	65.6	76.8
	6	45.9	45.7	64.5	61.8	64.8
	8	43.9	50.0	58.6	63.1	67.1
SE[a] (16 df)		1.90	1.80	1.41	3.97	3.38
Significance of effects[b]						
Cultivar		-	-	**	-	-
Fungicide		-	-	***	-	-
Cv x Fung.		-	-	*	-	*

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.9. The effect of cultivar and fungicide treatment on the remobilisation of nitrogen from vegetative tissues during grain filling, and on nitrogen harvest index at the end of grain filling of wheat. Experiment F1; 2001.

Cultivar	Treatment No.	Remobilization from vegetative tissues (%)	Nitrogen harvest index (%)
Consort	1	63.3	76.3
	2	67.1	80.0
	4	65.7	77.3
	6	66.9	80.9
	8	65.8	81.3
Hereward	1	68.8	80.5
	2	67.0	79.7
	4	62.0	81.1
	6	71.3	81.7
	8	67.2	80.9
SE[a] (16 df)		2.64	1.16
Significance of effects[b]			
Cultivar		-	-
Fungicide		-	-
Cv x Fung.		-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.10. The effect of fungicide treatment on root length density (cm cm^{-3}) during anthesis of Consort winter wheat. Experiment F1; 2001.

Depth	Fungicide treatment number					S.E.[a] for Tr. 1	S.E.[a] for Tr. 2-8	Significance of effects[b]
						8 DF	8 DF	
	1	2	4	6	8	6 reps	3 reps	
0-10	4.1	3.7	3.5	4.0	3.7	0.74	1.05	-
10-20	7.4	4.4	4.4	4.3	5.2	1.55	1.09	- (*)[c]
20-30	1.9	2.5	2.4	6.9	2.4	1.44	1.02	-
30-40	0.8	0.8	0.7	0.8	0.4	0.24	0.17	-
40-50	1.0	0.5	0.4	0.3	0.4	0.18	0.13	* (***)[c]
50-60	1.0	0.6	0.9	0.3	0.4	0.20	0.14	- (*)[c]
60-70	0.9	0.6	0.8	0.3	0.7	0.25	0.18	-
70-80	1.2	1.0	0.1	1.0	1.5			

[a]SE = Standard error of means within a variety; [b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively; [c]significance when treatments 2, 4, 6 & 8 are grouped and contrasted with treatment 1

Table 5.11. The effect of fungicide treatment on root length density (cm cm^{-3}) at the soft dough stage of Consort winter wheat. Experiment F1; 2001.

Depth	Fungicide treatment number					S.E.[a]	Significance of effects[b]
						8 DF	
	1	2	4	6	8	6 reps	
0-10	4.2	4.1	3.1	4.4	3.3	0.61	-
10-20	4.6	5.4	4.8	6.8	6.1	1.24	-
20-30	3.9	4.1	5.6	6.0	4.2	0.77	-
30-40	0.8	0.7	1.1	1.0	0.9	0.22	-
40-50	0.6	0.5	0.4	0.6	0.6	0.14	-
50-60	0.8	0.6	0.6	0.6	0.9	0.19	-
60-70	1.0	0.9	0.7	0.8	0.9	0.22	-
70-80	1.5	1.0	0.8	0.5	0.7	0.17	* (**)[c]

[a]SE = Standard error of means within a variety; [b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively; [c]Significance when treatments 2,4,6 & 8 are grouped and contrasted with treatment 1

Table 5.12. The effect of fungicide treatment on root dry matter density (mg cm^{-3}) during anthesis of Consort winter wheat. Experiment F1; 2001.

Depth	Fungicide treatment number					S.E.[a] for Tr. 1	S.E.[a] for Tr. 2-8	Significance of effects[b]
						8 DF	8 DF	
	1	2	4	6	8	6 reps	3 reps	
0-10	0.27	0.27	0.27	0.33	0.27	0.066	0.047	-
10-20	0.19	0.23	0.20	0.21	0.23	0.028	0.020	-
20-30	0.14	0.13	0.12	0.18	0.12	0.024	0.017	-
30-40	0.04	0.06	0.04	0.06	0.15	0.055	0.039	-
40-50	0.05	0.04	0.03	0.03	0.03	0.010	0.007	-
50-60	0.06	0.05	0.05	0.03	0.03	0.009	0.006	- (*)[c]
60-70	0.05	0.05	0.04	0.03	0.04	0.010	0.007	-
70-80	0.07	0.06	0.03	0.06	0.07			

[a]SE = Standard error of means within a variety; [b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively; [c]Significance when treatments 2,4,6 & 8 are grouped and contrasted with treatment 1

Table 5.13. The effect of fungicide treatment on root dry matter density (mg cm^{-3}) at the soft dough stage of Consort winter wheat. Experiment F1; 2001.

Depth	Fungicide treatment number					S.E.[a]	Significance of effects[b]
						8 DF	
	1	2	4	6	8	6 reps	
0-10	0.14	0.13	0.13	0.18	0.13	0.022	-
10-20	0.16	0.19	0.16	0.24	0.20	0.043	-
20-30	0.14	0.16	0.19	0.21	0.15	0.029	-
30-40	0.04	0.04	0.05	0.05	0.05	0.007	-
40-50	0.03	0.03	0.02	0.03	0.04	0.006	-
50-60	0.03	0.04	0.03	0.03	0.04	0.009	-
60-70	0.04	0.05	0.03	0.04	0.05	0.010	-
70-80	0.05	0.05	0.04	0.03	0.03	0.007	-

[a]SE = Standard error of means within a variety; [b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

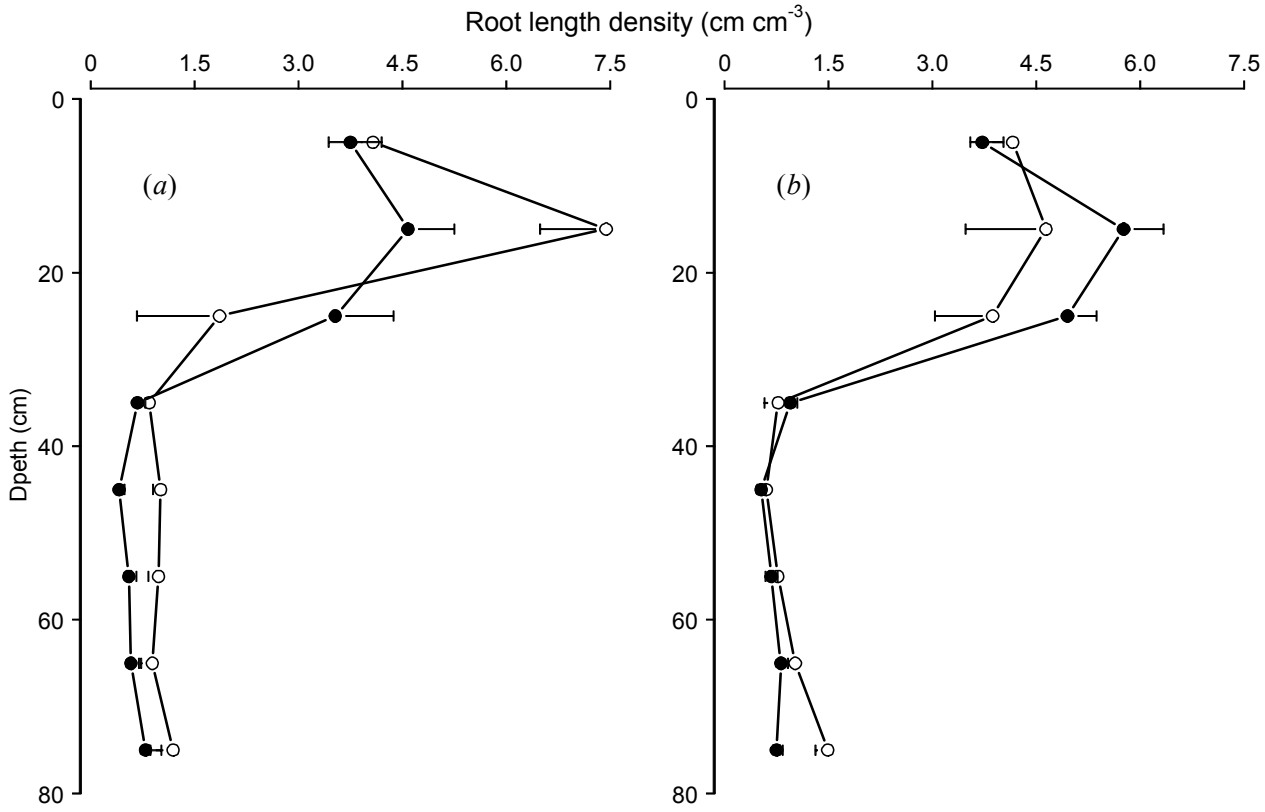

Fig. 5.4. The effect of fungicide treatment (○ = untreated; ● = mean of treatments 2,4,6 & 8) on root length density in Consort winter wheat at (a) anthesis, and (b) the soft dough stage. Error bars are S.E. (7 DF). Experiment F1; 2001.

Table 5.14. The effect of cultivar and fungicide treatment on the yield and quality of winter wheat. Experiment F1; 2001.

Cultivar	Tr. No.	Grain yield t ha^{-1} @ 85% DM	1000 grain weight g	Specific weight kg hl^{-1}	Hagberg falling number s	Protein content % DM	Sulphur content % DM	N:S ratio	SDS-sedim. volume ml	Black-point Ang. trans. score	Yield of grain N kg ha^{-1}
Consort	1	9.9	48.8	75.2	272	11.5	0.138	14.7	41.3	6.9	170
	2	10.7	54.3	77.5	243	11.7	0.136	15.1	41.3	12.4	185
	3	11.5	54.5	77.1	253	11.8	0.139	14.8	41.7	10.8	203
	4	11.6	53.7	77.9	253	12.1	0.136	15.7	41.7	14.8	210
	5	11.8	55.0	78.1	265	11.7	0.143	14.5	43.0	17.7	206
	6	10.9	54.0	78.1	236	11.7	0.134	15.4	38.3	9.6	190
	7	11.9	55.5	77.8	245	11.8	0.144	14.4	43.7	9.7	209
	8	11.3	54.8	78.5	234	12.0	0.141	15.1	43.3	10.8	202
Hereward	1	10.4	50.0	79.4	276	12.8	0.146	15.4	58.7	13.4	199
	2	10.1	52.6	79.3	264	12.9	0.138	16.5	54.0	16.8	195
	3	10.5	52.3	79.1	271	12.8	0.143	15.8	55.7	17.0	199
	4	10.5	52.7	79.7	259	12.7	0.146	15.4	56.3	21.7	199
	5	10.8	51.5	79.4	268	12.8	0.140	16.1	56.7	15.5	206
	6	10.2	51.3	79.2	277	12.8	0.140	16.2	56.0	9.5	196
	7	10.8	53.3	79.3	242	12.8	0.143	15.8	55.7	13.9	205
	8	10.2	51.8	79.9	258	12.6	0.140	15.8	57.7	18.1	191
SE[a] (28 df)		0.21	0.77	0.30	14.5	0.14	0.0024	0.28	1.17	2.21	5.1
Significance of effects[b]											
Cultivar		-	-	**	-	-	-	-	*	-	-
Fungicide		***	***	***	-	-	-	-	-	**	***
Cv x Fung.		**	- (**)[c]	***	-	- (*)[c]	-	-	-	-	**

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively
[c]Significance when treatments 3-8 are grouped and contrasted with treatments 1 and 2

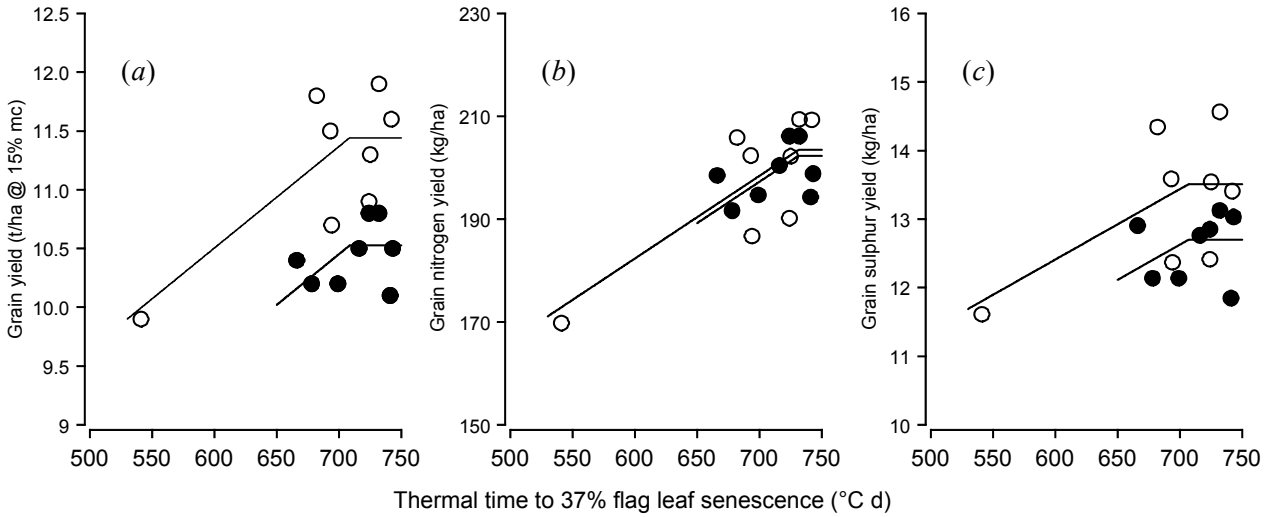

Fig. 5.4. The relationship between maintaining green area of the flag leaf with fungicides and grain mass, nitrogen and sulphur yields. ○ = Consort, ● = Hereward. The breaks for (*a*) mass yield, (*b*) nitrogen yield, and (*c*) sulphur yields are fitted at 709 (S.E.=26.6), 730 (S.E. = 31.6), and 707 ^{o}C d (S.E. = 42.0) respectively. Responses to the break are 0.0086 t/ha/^{o}Cd (S.E. = 0.00287), 0.161 kg N/ha/^{o}Cd (S.E. = 0.0447), and 0.0103 kg S/ha/^{o}Cd (S.E. = 0.0054). Experiment F1; 2001.

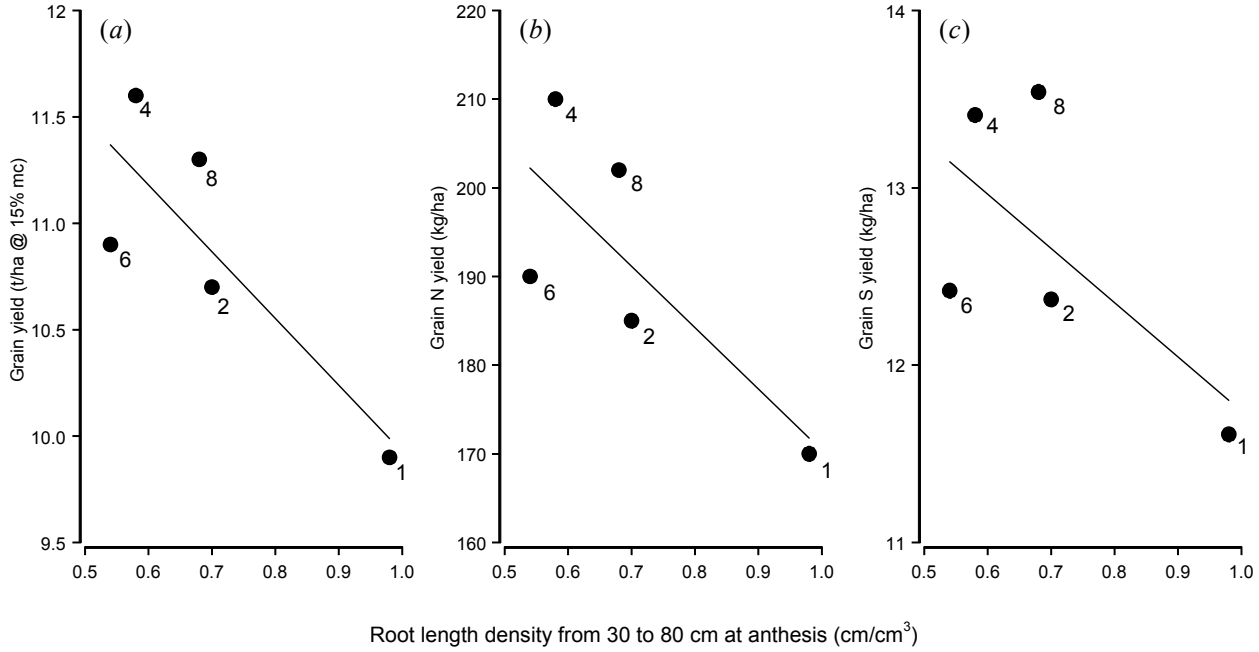

Fig. 5.5. The associations between root length density below the plough layer and yield of (a) grain, correlation coefficient (*r*) = -0.83; (b) nitrogen in the grain, *r* = -0.77; and (c) sulphur in the grain, *r* = -0.66. Points and numerals denote fungicide treatment means (see Table 2.3). Experiment F1; 2001.

5.1.2. Experiment F2

5.1.2.1. Green leaf area and foliar disease

Table 5.15 shows the effects of cultivar, fungicide and urea treatments on green leaf area. The results for fungicide Treatments 1 & 8 on each of the cultivars for plots not receiving urea (i.e. for direct comparison with the root analyses) are shown in Fig. 5.6. *S. tritici* was the principal disease on the flag leaves, particularly those of Savannah and Malacca (Table 5.15). The disease was reduced by fungicide applied at flag leaf emergence but there was no additional benefit from spraying again at ear emergence. Significant amounts of brown rust developed on the flag leaves of untreated Shamrock and, as in Experiment F1, also of Consort. Again, application of fungicide at flag leaf emergence was sufficient to reduce the area of brown rust to trace levels. The effect of the application of fungicide at flag leaf emergence on green leaf area duration varied greatly with cultivar (Table 5.16; Fig. 5.6). Senescence (time to 37% green leaf area; Gompertz *m*) of the flag leaves of Shamrock, Savannah, and Consort was delayed by more than six days, compared to a delay of less than two days for Claire. There was little effect of the additional fungicide at ear emergence on the senescence of any cultivar.

5.1.2.2. Root extent and distribution

During anthesis Hereward and Savannah had comparatively high root length densities in the top 10 cm of soil, particularly when compared with Malacca (Table 5.17). Below the plough layer, the highest root length densities were achieved by Shamrock, an affect that was statistically significant at 60-70 cm. At this time, during anthesis, Shamrock was the only cultivar to have regularly more roots than 1 cm/cm^3 below the plough layer. In contrast, Savannah had less than 1 cm roots/cm^3 throughout the 30-80cm profile. As in Experiment F1 root length density tended to increase between anthesis (average = 1.97 cm/cm^3; Table 5.17) and the soft dough stage (average = 2.82 cm/cm^3; Table 5.18) but, again as in Experiment F1, this was not evident in the dry matter data (0.105 and 0.108 mg/cm^3 for GS 64 and 85 respectively; Tables 5.19 and 5.20). By the soft dough stage the highest root densities in the plough layer were recorded for Shamrock and Savannah (Table 5.18; Fig. 5.7*a*). Below the plough layer Shamrock and Savannah maintained their respective higher and lower root length densities observed in the previous assessment. Similar effects of cultivar and depth were detected on root dry matter (Table 5.20; Fig.

5.7*b*). Fungicide reduced root length and dry matter at 10-20 cm and also root dry matter between 60 and 70 cm (Table 5.20).

5.1.2.3. Combine harvested grain yield and quality

Consistent with effects on senescence (Gompertz *m*), thousand grain weight of Consort and Savannah were the most responsive to the fungicide applied at flag leaf emergence (Table 5.21). There were no significant cultivar × fungicide interactions on either yield or specific weight which were both increased by fungicide application at flag leaf emergence. Hagberg falling number was reduced, and blackpoint increased by the same fungicide treatment, but in all cases the effect of the additional spray at ear emergence was small. There was a significant interaction between fungicide and cultivar on grain protein concentration. Fungicide treatment increased the protein concentration of Shamrock, but had the opposite effect on Savannah. There were no significant effects of fungicide on the protein concentrations of the other cultivars. There was no significant effect of fungicide on sulphur concentration, N:S ratio or SDS-sedimentation volume. Fungicide applied at flag leaf emergence increased the yield of nitrogen in the grain by average of 11 kg N ha^{-1}. The additional spray at ear emergence gave a further increase of 5 kg N ha^{-1}.

There was no association between the grain yield of a cultivar when disease had been controlled (Treatment 8), nor its grain yield response to fungicide (Treatment 8 – Treatment 1), and rooting characteristics on either date of assessment or at any depth (Figs 5.8*a-d*-5.11*a-d*). In contrast, the ability of a cultivar to yield large quantities of N in the grain when disease had been controlled, and also a cultivars grain N response to fungicide application appeared to be positively associated with root dry matter densities below the plough layer (Fig. 5.9*g*, Fig. 5.11*g*). In consequence, the grain protein concentration response of a cultivar to fungicide was significantly associated with rooting extent below the plough layer (Fig. 5.10*o*, Fig 5.11*o*). i.e. The respective positive and negative grain protein responses to fungicide of Shamrock and Savannah could be explained on the basis of their rooting characteristics at depth. Grain sulphur yields (Fig. 5.8*i*,*j*, Fig. 5.9*i*,*k*) and concentrations (Figs 5.8-5.11) were also positively associated with rooting extent.

The application of foliar urea increased grain protein and sulphur concentrations (Table 5.21). The effect on grain protein was proportionately larger on protein than on sulphur such that N:S ratio also rose. Urea increased SDS sedimentation volume and blackpoint severity. The application of 40 kg N ha^{-1} as foliar urea only increased the yield of nitrogen in the grain by 9 kg N ha^{-1}.

Table 5.15. The effect of cultivar, fungicide and foliar urea treatments on the area of disease symptoms on the flag leaves of winter wheat. Experiment F2; 2001.

Cultivar	Treatment No.	Time of assessment (date in 2001 and days after anthesis)							
		Septoria tritici				Brown rust			
		21.06 3	27.06 9	04.07 16	11.07 23	21.06 3	27.06 9	04.07 16	11.07 23
Shamrock	1	0.0	0.5	0.7	2.9	0.0	0.1	1.6	6.6
	2	0.0	0.4	0.6	1.8	0.0	0.0	0.1	0.1
	8	0.0	0.8	0.9	2.5	0.0	0.1	0.1	0.0
Claire	1	0.0	1.4	2.5	2.1	0.0	0.0	0.0	0.0
	2	0.0	1.2	1.5	1.5	0.0	0.1	0.1	0.0
	8	0.1	0.8	1.2	1.4	0.0	0.0	0.0	0.0
Consort	1	0.1	1.8	2.4	3.8	0.0	0.0	0.5	5.3
	2	0.1	1.3	1.8	1.8	0.0	0.0	0.1	0.1
	8	0.0	1.0	1.6	1.9	0.0	0.0	0.0	0.0
Hereward	1	0.2	1.4	1.6	3.4	0.0	0.0	0.1	0.8
	2	0.1	1.2	0.8	2.5	0.0	0.0	0.0	0.0
	8	0.0	0.6	0.8	2.7	0.0	0.0	0.0	0.0
Savannah	1	0.1	2.3	3.2	9.3	0.0	0.0	0.0	0.0
	2	0.1	0.8	0.9	3.0	0.0	0.0	0.0	0.0
	8	0.1	0.9	1.6	3.0	0.0	0.0	0.0	0.0
Malacca	1	0.0	2.1	2.6	7.3	0.0	0.0	0.0	0.3
	2	0.1	1.5	2.1	3.6	0.0	0.0	0.0	0.1
	8	0.1	1.2	1.6	6.1	0.0	0.0	0.0	0.0
SE[a] (60 df)			0.25	0.23	0.73				
Urea treatment means									
No urea		0.0	0.9	1.3	2.7	0.0	0.0	0.2	0.9
With urea		0.1	1.4	1.9	4.0	0.0	0.0	0.1	0.6
SE (60 df)			0.08	0.08	0.24				
Significance of effects[b]									
Cultivar			*	*	-				
Fungicide			***	***	***				
Urea			***	***	***				
Cv.F			-	**	***				
Cv.U			-	-	-				
F.U			-	-	-				
Cv.F.U			-	-	-				

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.16. The effect of cultivar, fungicide and foliar urea treatments on the green leaf area of wheat flag leaves and the time taken to reach 37% green leaf area (Gompertz *m*). Experiment F2; 2001.

Cultivar	Tr. No.	Time of assessment (date in 2001 and days after anthesis)								Gompertz *m* (days)
		21.06 3	27.06 9	04.07 16	11.07 23	18.07 30	25.07 37	01.08 44	08.08 51	
Shamrock	1	98.3	97.4	95.6	87.7	46.2	6.8	0.0	0.0	31.3
	2	98.2	97.7	96.8	96.0	85.9	55.5	13.3	0.0	40.0
	8	98.1	97.0	95.9	95.4	87.2	63.3	20.3	7.1	41.5
Claire	1	97.4	97.0	94.7	95.6	64.0	16.1	0.8	0.0	34.0
	2	97.3	96.7	95.9	96.2	73.0	23.2	5.2	0.0	35.6
	8	96.9	97.3	95.7	96.1	80.4	27.8	7.6	0.0	36.2
Consort	1	97.4	96.8	94.3	87.7	48.3	3.7	0.0	0.0	31.2
	2	97.3	96.9	95.4	95.3	80.4	51.4	6.5	0.0	38.9
	8	97.3	97.1	95.6	94.8	80.9	49.0	18.1	3.6	39.4
Hereward	1	97.6	97.3	95.7	93.5	74.6	22.3	2.4	0.0	35.3
	2	96.9	97.5	96.8	95.4	84.2	57.3	19.3	1.7	40.8
	8	97.3	97.5	96.1	95.1	81.1	55.1	19.9	5.0	40.8
Savannah	1	97.2	96.5	94.2	88.3	45.5	3.8	0.0	0.0	31.1
	2	96.4	97.4	96.3	94.8	81.2	39.1	8.5	0.0	37.7
	8	96.7	97.2	95.3	94.6	80.3	47.0	15.2	0.0	39.3
Malacca	1	97.4	96.6	94.3	89.1	38.7	11.5	0.0	0.0	30.7
	2	97.6	96.8	95.2	93.9	61.8	23.1	6.7	0.0	34.1
	8	97.5	96.9	95.4	91.0	54.7	32.9	7.8	0.5	34.7
SE[a] (60 df)		0.21	0.25	0.34	0.84	4.79	3.49			0.64
Urea treatment means										
No urea		97.4	97.4	96.1	93.9	67.7	31.3	7.59	0.94	35.9
With urea		97.4	96.7	94.9	92.8	71.0	34.3	9.23	1.04	36.6
SE (60 df)		0.07	0.08	0.11	0.28	1.60	1.16			0.21
Significance of effects[b]										
Cultivar		***	*	-	-	-	*	-	-	**
Fungicide		-	-	***	***	***	***	-	-	***
Urea		-	***	***	**	-	-	-	-	*
Cv.F		-	-	-	***	**	-	-	-	***
Cv.U		-	-	-	*	-	-	-	-	-
F.U		-	-	-	-	-	-	-	-	-
Cv.F.U		-	-	-	-	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

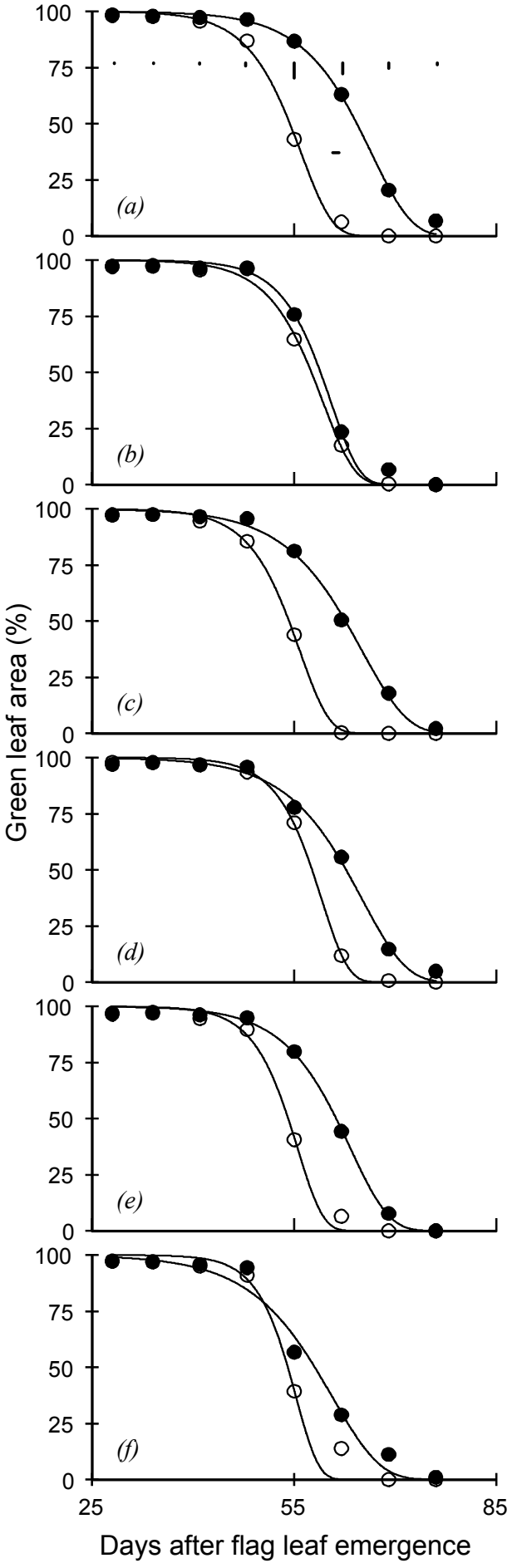

Fig. 5.6. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on green leaf area of the flag leaf. Cultivars are *a*, Shamrock; *b*, Claire; *c*, Consort; *d*, Hereward; *e*, Savannah; *f*, Malacca. Fitted curves are modified gompertz. Vertical bars in Shamrock graphs are S.E. (60 D.F) for comparing points within a variety. Horizontal bar is for comparing time to 37% green leaf area (Gompertz *m*). Experiment F2; 2001.

Table 5.17. The effect of fungicide treatment and cultivar on root length density (cm cm^{-3}) during anthesis of winter wheat. Experiment F2; 2001.

Cultivar	Tr. No.	Depth (cm)							
		0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Shamrock	1	3.2	4.4	3.2	1.3	1.1	1.5	1.7	1.1
	8	3.9	5.3	2.8	1.1	0.9	1.4	1.7	1.9
Claire	1	4.6	3.4	2.4	1.0	1.1	1.1	0.3	1.0
	8	4.5	4.3	2.7	0.9	0.7	1.2	1.0	1.1
Consort	1	3.4	4.2	3.0	1.0	0.9	0.6	0.8	0.7
	8	3.1	4.2	2.5	0.8	0.7	0.9	0.8	0.8
Hereward	1	6.1	5.7	2.3	1.0	0.8	0.9	0.9	0.7
	8	5.2	5.9	2.9	1.0	0.9	0.9	0.9	0.7
Savannah	1	5.1	4.4	2.5	0.6	0.8	0.6	0.6	1.5
	8	3.4	5.1	2.8	0.4	0.7	0.7	0.4	0.6
Malacca	1	2.7	3.0	2.0	0.9	0.9	0.8	1.0	1.0
	8	3.6	4.0	1.9	0.7	0.6	0.5	0.7	1.4
SE[a] (12 df)		1.02	0.83	0.62	0.18	0.20	0.20	0.27	
Significance of effects[b]									
Cultivar		*	-	-	-	-	-	*	
Fungicide		-	-	-	-	-	-	-	
Cv.F		-	-	-	-	-	-	-	

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.18. The effect of fungicide treatment and cultivar on root length density (cm cm^{-3}) at the soft dough stage of winter wheat. Experiment F2; 2001.

Cultivar	Tr. No.	Depth (cm)							
		0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Shamrock	1	4.7	7.2	6.2	1.6	2.1	1.9	2.0	2.5
	8	7.1	6.7	7.6	1.4	1.7	1.9	1.9	1.8
Claire	1	4.8	6.1	4.5	1.2	1.4	2.0	1.8	1.0
	8	4.6	2.4	7.2	1.9	1.1	1.8	1.5	0.8
Consort	1	3.6	7.1	7.6	1.3	0.8	0.9	1.3	1.0
	8	3.8	5.9	4.1	0.9	0.7	0.9	0.9	1.4
Hereward	1	3.1	5.1	5.5	0.9	0.8	1.5	1.4	1.0
	8	4.5	5.4	5.8	1.5	0.9	1.2	1.3	1.0
Savannah	1	8.0	8.7	6.9	1.2	0.8	0.9	1.0	0.9
	8	5.3	8.2	3.5	0.6	0.3	0.5	0.8	1.0
Malacca	1	3.7	4.8	3.7	1.7	1.3	1.9	1.2	0.4
	8	3.8	3.7	4.4	1.1	1.0	1.4	1.4	1.2
SE[a] (12 df)		0.95	0.85	0.77	0.29	0.32	0.37	0.25	0.51
Significance of effects[b]									
Cultivar		**	**	-	-	*	*	-	-
Fungicide		-	*	-	-	-	-	-	-
Cv.F		-	-	**	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.19. The effect of fungicide treatment and cultivar on root dry matter density (mg cm^{-3}) at the soft dough stage of winter wheat. Experiment F2; 2001.

Cultivar	Tr. No.	Depth (cm)							
		0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Shamrock	1	0.24	0.20	0.13	0.08	0.07	0.08	0.09	0.05
	8	0.25	0.23	0.12	0.06	0.05	0.07	0.08	0.11
Claire	1	0.26	0.16	0.10	0.07	0.06	0.06	0.03	0.06
	8	0.27	0.20	0.14	0.06	0.04	0.06	0.05	0.06
Consort	1	0.20	0.20	0.14	0.06	0.05	0.04	0.05	0.05
	8	0.24	0.18	0.12	0.06	0.05	0.06	0.05	0.05
Hereward	1	0.31	0.20	0.10	0.05	0.05	0.05	0.05	0.03
	8	0.25	0.27	0.11	0.08	0.06	0.06	0.05	0.04
Savannah	1	0.28	0.18	0.12	0.04	0.05	0.03	0.03	0.10
	8	0.29	0.23	0.13	0.03	0.04	0.04	0.03	0.04
Malacca	1	0.20	0.14	0.08	0.07	0.06	0.05	0.05	0.06
	8	0.25	0.19	0.10	0.04	0.04	0.04	0.04	0.08
SE[a] (12 df)		0.051	0.034	0.022	0.011	0.013	0.012	0.013	
Significance of effects[b]									
Cultivar		-	-	-	-	-	-	-	-
Fungicide		-	-	-	-	-	-	-	-
Cv.F		-	-	-	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.20. The effect of fungicide treatment and cultivar on root dry matter density (mg cm^{-3}) at the soft dough stage of winter wheat. Experiment F2; 2001.

Cultivar	Tr. No.	Depth (cm)							
		0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Shamrock	1	0.24	0.22	0.20	0.06	0.06	0.07	0.07	0.10
	8	0.23	0.22	0.21	0.05	0.07	0.08	0.07	0.07
Claire	1	0.25	0.22	0.20	0.06	0.05	0.09	0.06	0.05
	8	0.21	0.09	0.28	0.10	0.05	0.07	0.06	0.02
Consort	1	0.16	0.26	0.16	0.07	0.04	0.04	0.06	0.04
	8	0.19	0.22	0.13	0.04	0.03	0.04	0.05	0.08
Hereward	1	0.15	0.19	0.19	0.04	0.03	0.07	0.06	0.04
	8	0.21	0.19	0.20	0.07	0.04	0.05	0.05	0.04
Savannah	1	0.32	0.27	0.21	0.06	0.04	0.03	0.04	0.04
	8	0.22	0.28	0.14	0.03	0.02	0.02	0.04	0.03
Malacca	1	0.19	0.20	0.12	0.08	0.06	0.07	0.05	0.01
	8	0.18	0.15	0.16	0.06	0.05	0.06	0.05	0.04
SE[a] (12 df)		0.036	0.021	0.024	0.011	0.008	0.014	0.004	
Significance of effects[b]									
Cultivar		-	*	-	-	*	-	*	
Fungicide		-	*	-	-	-	-	*	
Cv.F		-	-	-	*	-	-	-	

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

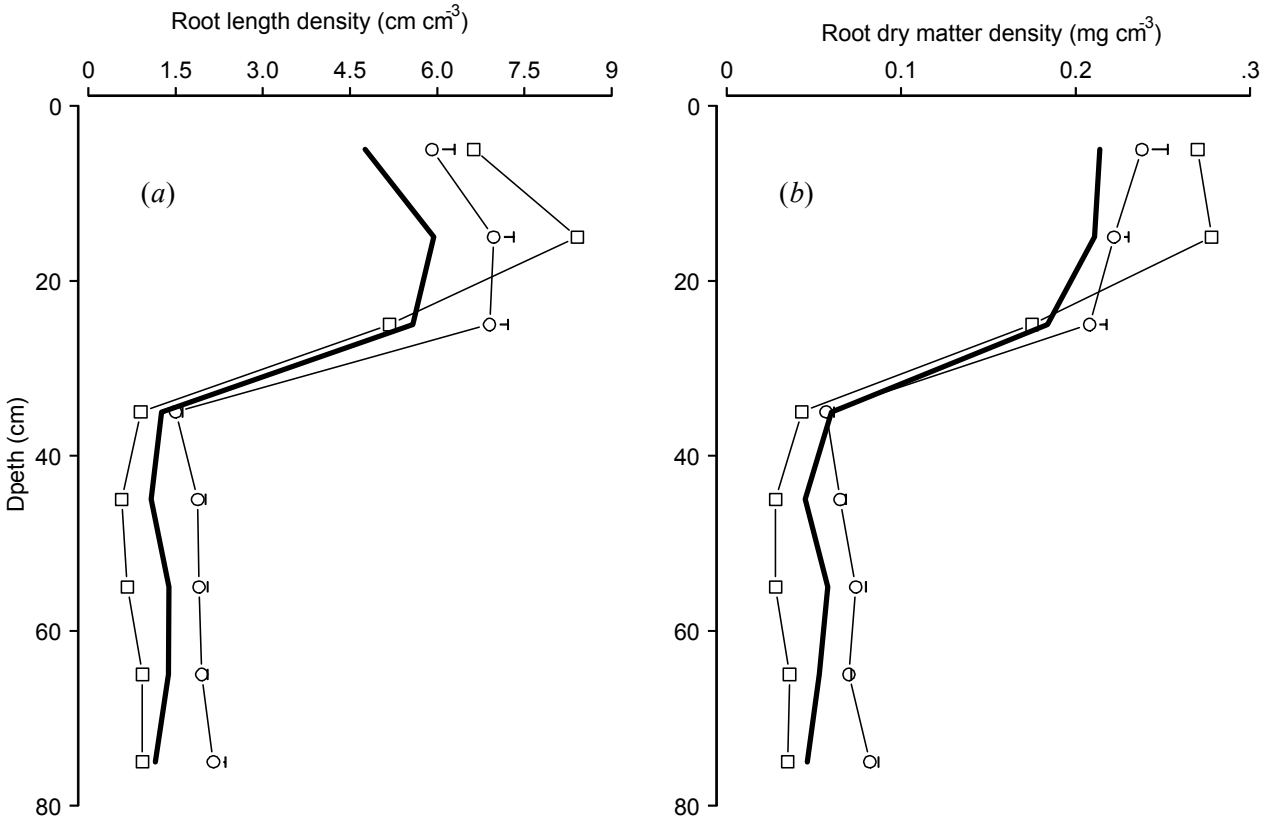

Fig. 5.7. The effect of winter wheat cultivar on root distribution at the soft dough stage; Points are means of with and without fungicide for Shamrock (○) and Savannah (□). Heavy line is the grand mean for six cultivars, including the two presented. Error bars are S.E. of cultivar means (10 DF). Experiment F2; 2001.

Table 5.21. The effect of cultivar and fungicide treatment on the yield and quality of winter wheat. Experiment F2; 2001.

Cultivar	Tr. No.	Grain yield t ha^{-1} @ 85% DM	1000 grain weight g	Specific weight kg hl^{-1}	Hagberg falling number s	Protein content % DM	Sulphur content % DM	N:S ratio	SDS-sedim. volume Ml	Black-point Ang. trans. score	Yield of grain N kg ha^{-1}
Shamrock	1	10.6	46.5	77.8	288	12.1	0.156	13.6	61.8	16.4	191
	2	11.3	48.1	78.2	255	12.1	0.158	13.4	60.3	21.1	205
	8	11.6	49.1	78.9	281	12.6	0.160	13.9	61.8	16.8	218
Claire	1	11.1	46.4	74.6	261	11.4	0.141	14.2	38.7	11.2	189
	2	11.9	48.8	75.5	257	11.4	0.142	14.1	40.2	10.7	202
	8	11.7	47.9	77.6	263	11.3	0.137	14.7	39.2	11.3	198
Consort	1	10.6	49.3	75.9	279	12.0	0.141	15.1	41.7	8.2	189
	2	11.6	54.6	77.8	243	11.8	0.138	15.1	42.2	10.8	204
	8	11.9	52.9	78.0	253	12.0	0.141	15.1	43.3	11.9	214
Hereward	1	10.8	49.5	78.6	259	12.9	0.155	14.5	59.8	14.4	206
	2	11.3	51.9	78.8	263	12.8	0.154	14.6	60.2	18.5	217
	8	11.2	51.0	79.1	243	13.0	0.154	14.8	61.2	16.3	218
Savannah	1	11.1	51.9	75.5	253	11.4	0.141	14.2	35.2	12.2	188
	2	11.8	55.2	76.2	248	11.0	0.138	14.0	33.2	13.8	194
	8	11.9	57.8	76.5	244	11.0	0.137	14.1	33.3	17.0	195
Malacca	1	10.0	45.3	74.3	389	12.1	0.140	15.2	55.3	6.1	181
	2	10.3	46.5	75.4	378	12.2	0.141	15.2	56.2	6.2	186
	8	10.9	48.7	76.6	362	11.9	0.140	14.9	56.7	6.8	194
SE[a] (60 df)		0.18	0.67	0.50	9.2	0.12	0.0016	0.19	0.97	1.56	3.8
Urea treatment means											
No urea		11.2	50.1	76.8	283	11.7	0.144	14.3	48.4	11.5	195
With urea		11.2	50.0	77.0	275	12.2	0.147	14.7	49.4	14.0	204
SE (60 df)		0.061	0.22	0.17	3.1	0.04	0.0005	0.08	0.32	0.52	1.3
Significance of effects[b]											
Cultivar		*	***	***	***	***	**	-	***	***	*
Fungicide		***	***	***	*	-	-	-	-	*	***
Urea		-	-	-	-	***	***	***	*	***	***
Cv.F		-	**	-	-	*	-	-	-	-	-
Cv.U		-	-	-	-	-	-	-	-	-	-
F.U		-	-	-	-	-	-	-	-	-	-
Cv.F.U		-	-	-	-	-	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

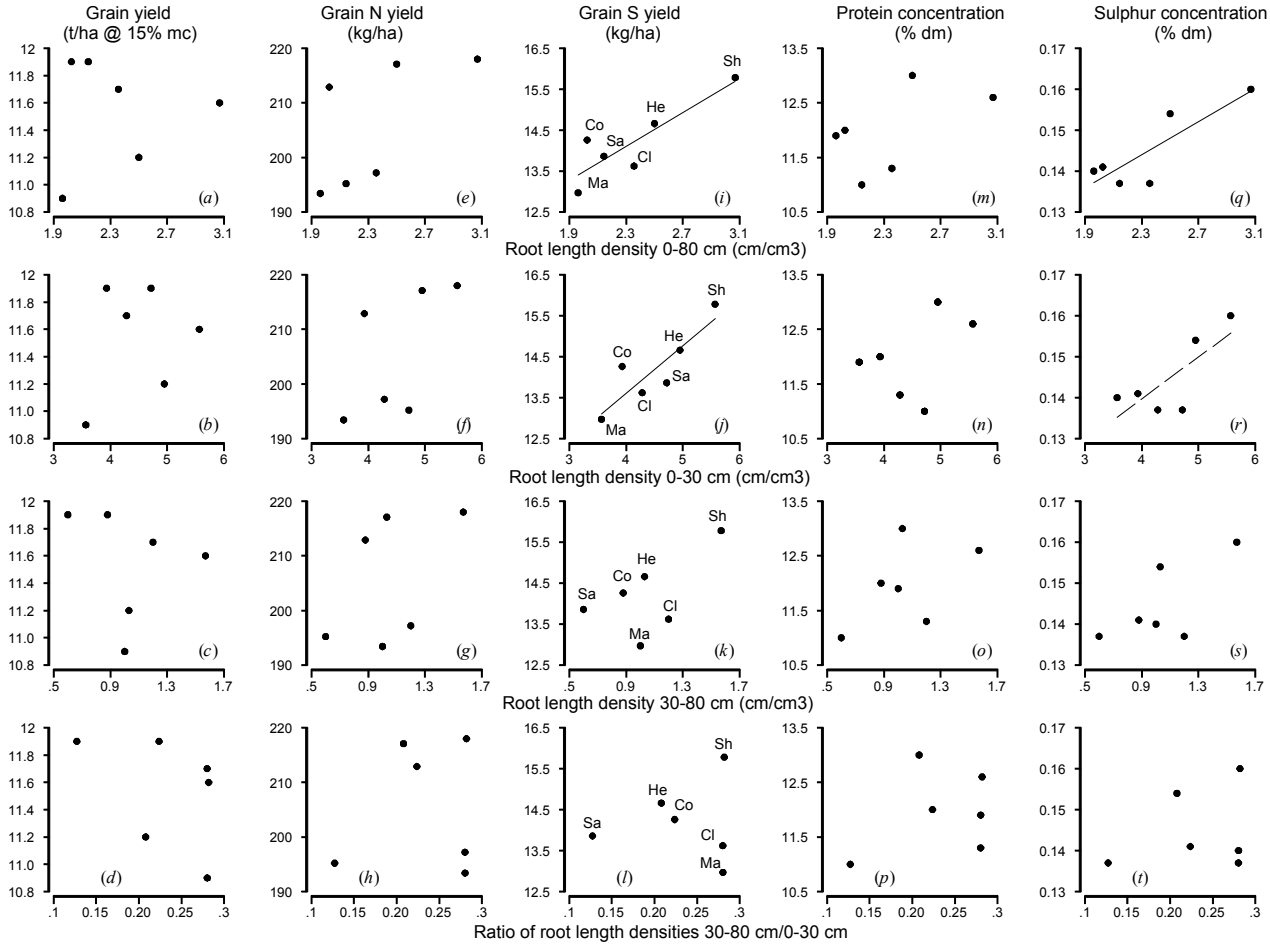

Fig. 5.8. Associations between grain yield, nitrogen and sulphur and root length densities over different depths for cultivars receiving fungicide Treatment 8 (see Table 2.3). Root length densities are the mean of assessments made at anthesis and the soft dough stage. Solid lines are fitted where correlation coefficient (r) > 0.81 (i.e. P<0.05) and dashed lines fitted where r > 0.73 (i.e. P<0.1). Cultivars in grain S yield graphs are denoted: Sh = Shamrock, Cl = Claire, Co = Consort, He = Hereward, Sa = Savannah, Ma = Malacca. Experiment F2; 2001.

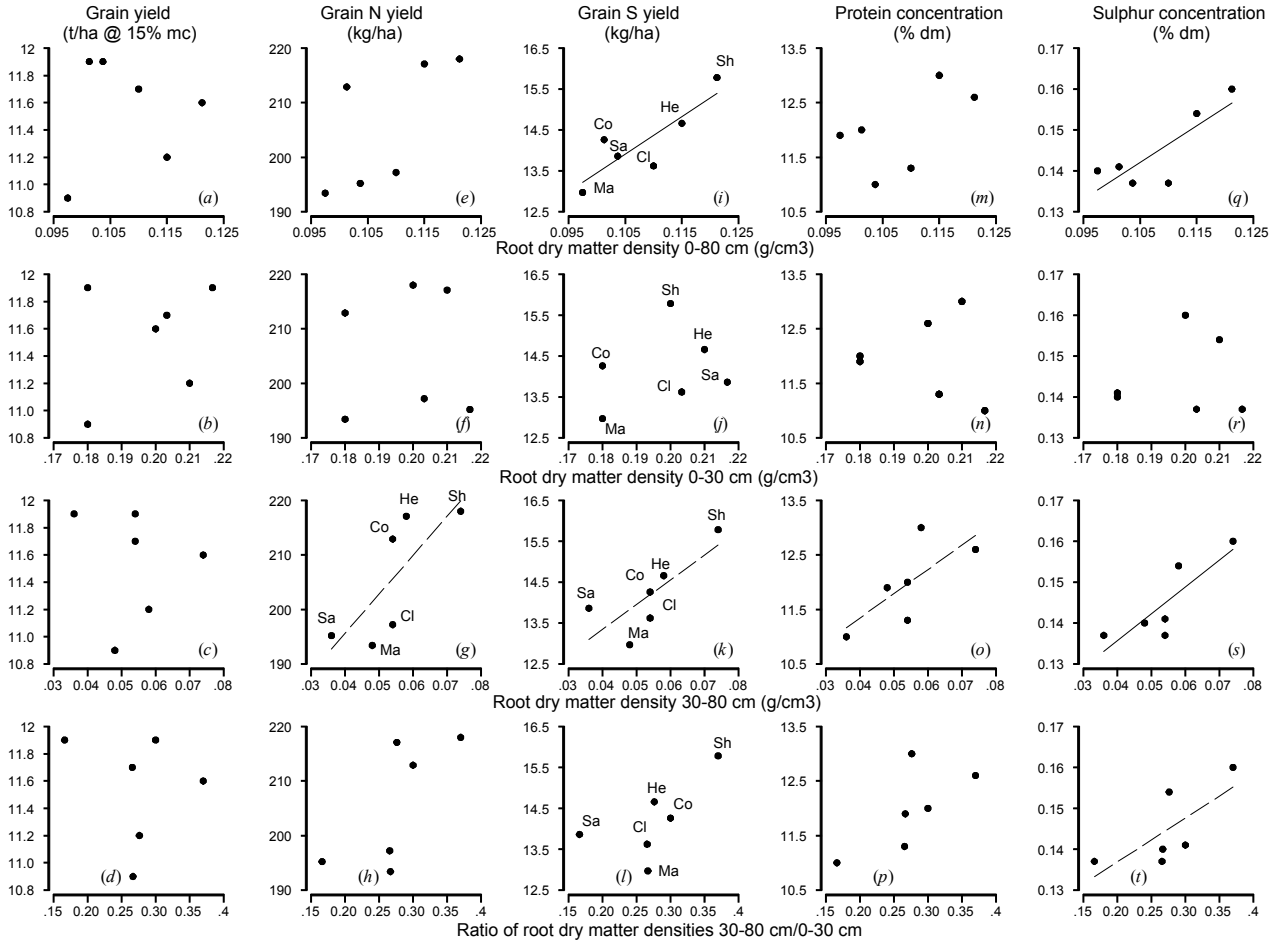

Fig. 5.9. Associations between grain yield, nitrogen and sulphur and root dry matter densities at anthesis over different depths for cultivars receiving fungicide Treatment 8 (see Table 2.3). Solid lines are fitted where correlation coefficient (r) > 0.81 (i.e. P<0.05) and dashed lines fitted where r > 0.73 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Cl = Claire, Co = Consort, He = Hereward, Sa = Savannah, Ma = Malacca. Experiment F2; 2001.

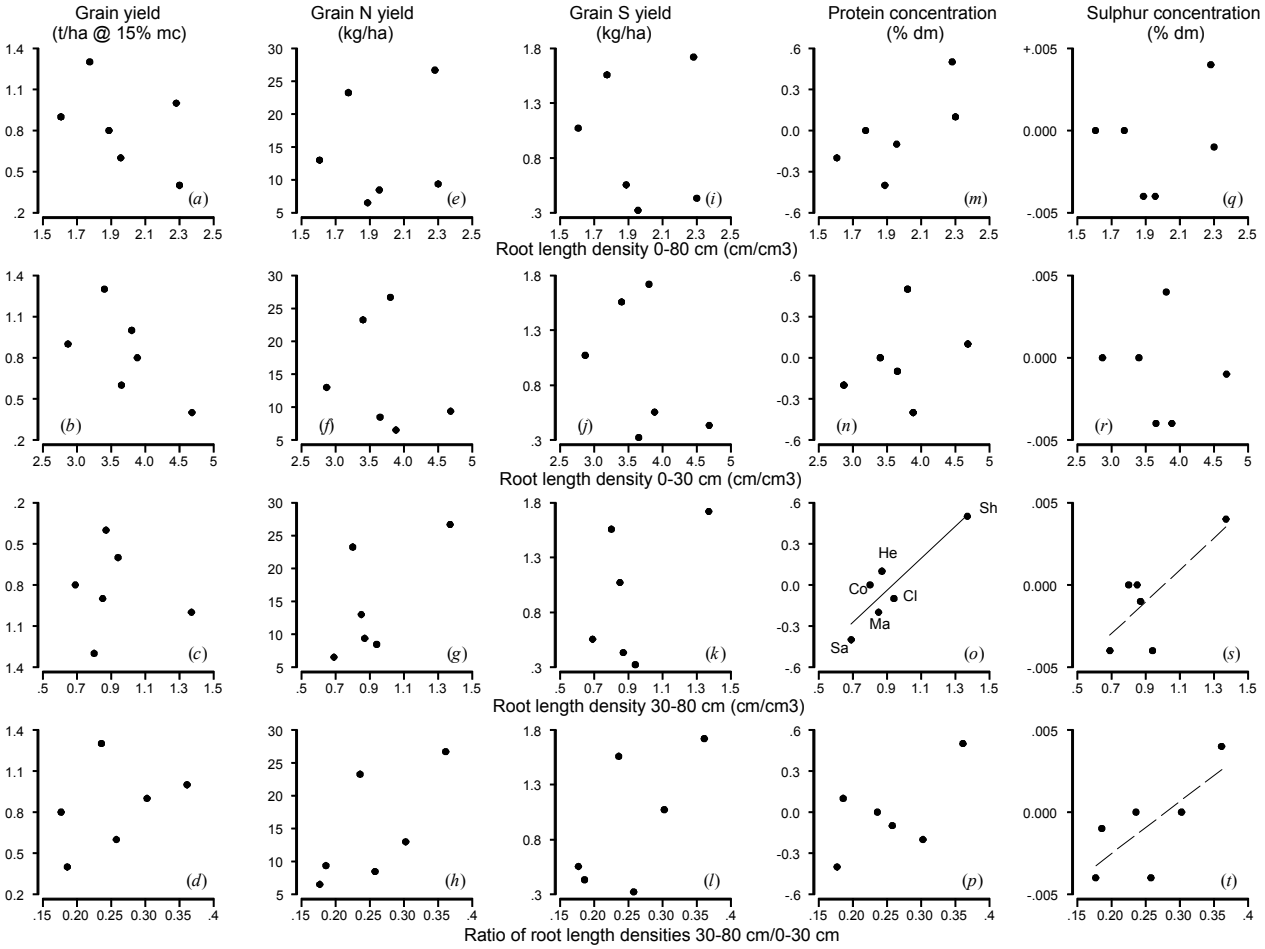

Fig. 5.10. Associations between grain yield, nitrogen and sulphur responses to fungicide (Treatment 8 – Treatment 1; see Table 2.3) and root length densities at anthesis over different depths for cultivars (mean of Treatments 1 & 8). Solid lines are fitted where correlation coefficient (r) > 0.81 (i.e. P<0.05) and dashed lines fitted where r > 0.73 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Cl = Claire, Co = Consort, He = Hereward, Sa = Savannah, Ma = Malacca. Experiment F2; 2001.

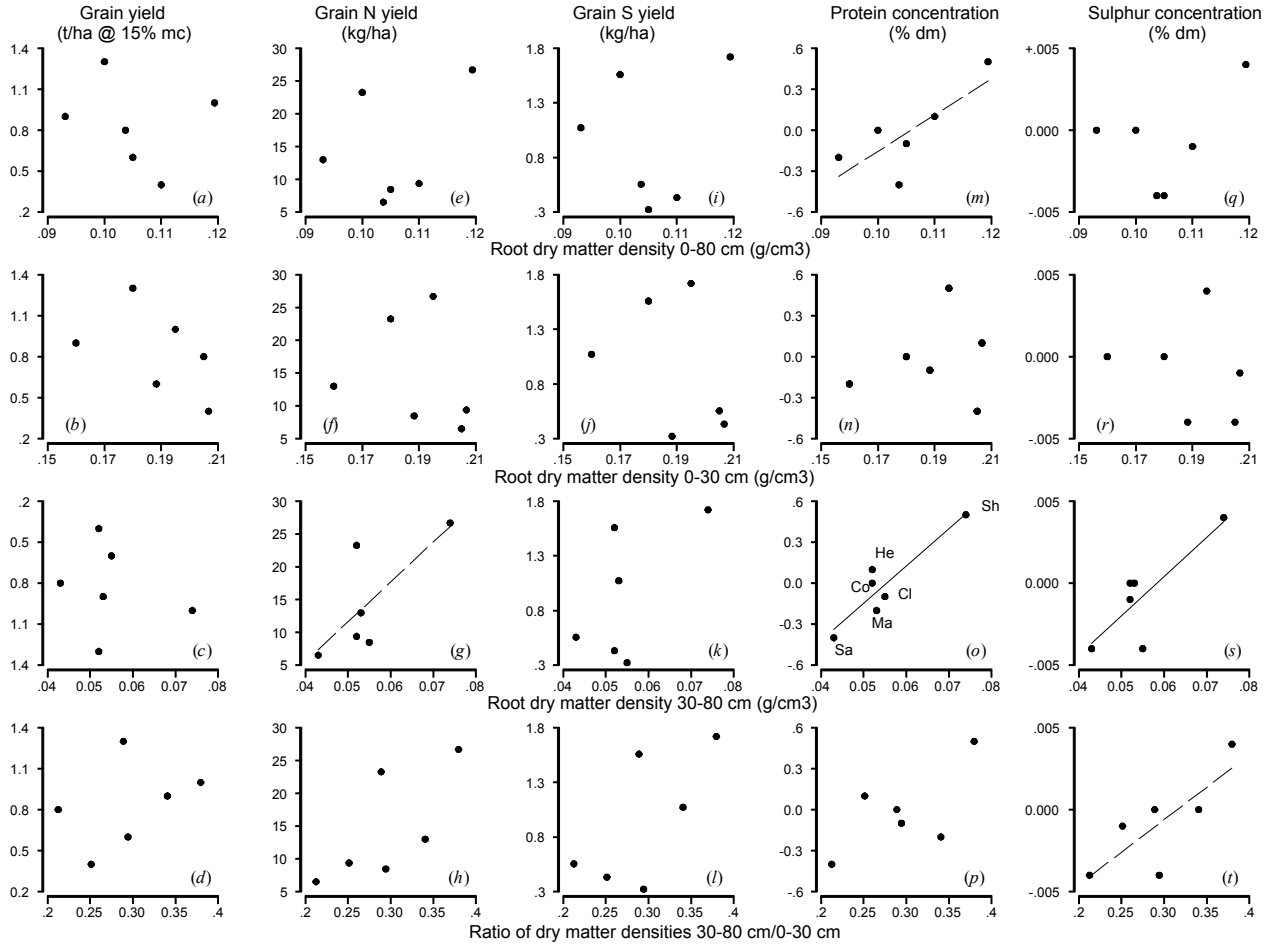

Fig. 5.11. Associations between grain yield, nitrogen and sulphur responses to fungicide (Treatment 8 – Treatment 1; see Table 2.3) and root dry matter densities at anthesis over different depths for cultivars (mean of Treatments 1 & 8). Solid lines are fitted where correlation coefficient (r) > 0.81 (i.e. P<0.05) and dashed lines fitted where r > 0.73 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Cl = Claire, Co = Consort, He = Hereward, Sa = Savannah, Ma = Malacca. Experiment F2; 2001.

5.2. 2002

5.2.1. Experiment F1

5.2.1.1. Green leaf area and foliar disease

Septoria tritici was the principal disease on the flag leaf, reaching higher levels than recorded in the previous year (Table 5.22). Untreated Consort again suffered more from brown rust than did Hereward but, in contrast to 2001, brown rust symptoms were much less severe than those of *S. tritici*. The fungicide reduced the areas of *S. tritici* and maintained flag leaf green area. Consort was more responsive to fungicide treatment than Hereward with regards to effects on time to senescence (Table 5.23). In contrast to the previous year, fungicide applications at ear emergence maintained the life of the flag leaf for longer than could be achieved with just the flag leaf spray, and in most cases beyond 700 ºCd.

5.2.1.2. Combine harvested grain yield and quality

Consort gave higher grain yields than Hereward, but Hereward had higher average thousand grain weights and specific weights (Table 5.24). Commensurate with effects of the flag leaf spray on green leaf area duration Consort was more responsive to application than Hereward with regards to grain yield, thousand grain weight and grain specific weight (Table 5.24). Benefits of the ear sprays on yield were, however, very limited, even on Consort, with little or no yield response evident from extending flag leaf life beyond 700 ºCd (Fig. 5.12*a*). A similar limit to yield response was fitted to the Hereward data although there did appear to be some yield benefit from fungicide Treatment 6 not accounted for by the plateau after 700 ºCd (Table 5.24; Fig. 5.12*a*). Hereward had higher Hagberg falling numbers than Consort, but falling numbers were lowered by fungicide treatment on both cultivars. Fungicide treatment reduced the grain protein concentration, sulphur concentration and SDS-sedimentation volume of Concert but not of Hereward. There was no effect of fungicide on N:S ratio or blackpoint. Fungicide applied at flag leaf emergence increased the yield of nitrogen in the grain by 39 and 12 kg N ha^{-1} for Consort and Hereward respectively (Table 5.24). There was no further benefit to applying fungicide again at ear emergence for yields of grain nitrogen or sulphur yield of Consort (Table 5.24, Fig. 5.12*b*,*c*), although there was a small (+6 kg N ha^{-1} for the average of Treatments 3-8) on Hereward.

Table 5.22. The effect of cultivar and fungicide treatments on the area of disease symptoms on the flag leaves of winter wheat. Experiment F1; 2002.

Cultivar	Treatment No.	Time of assessment (date in 2002 and days after anthesis)					
		Septoria tritici			Brown rust		
		19.06 16	26.06. 23	04.07 31	19.06 16	26.06. 23	04.07 31
Consort	1	1.4	3.0	15.6	0.0	0.0	1.7
	2	0.6	0.9	2.9	0.0	0.0	0.0
	3	0.9	0.9	3.5	0.0	0.0	0.0
	4	0.3	0.2	2.0	0.0	0.0	0.0
	5	0.6	0.7	2.0	0.0	0.0	0.0
	6	0.9	0.2	2.0	0.0	0.0	0.0
	7	0.6	0.5	2.3	0.0	0.0	0.0
	8	0.6	1.2	2.6	0.0	0.0	0.0
Hereward	1	0.4	2.5	11.2	0.0	0.0	0.2
	2	0.1	0.2	2.9	0.0	0.0	0.0
	3	0.2	0.1	2.4	0.0	0.0	0.0
	4	0.4	0.0	1.8	0.0	0.0	0.0
	5	0.1	0.1	1.9	0.0	0.0	0.0
	6	0.1	0.1	1.6	0.0	0.0	0.0
	7	0.5	0.1	1.7	0.0	0.0	0.0
	8	0.1	0.1	1.1	0.0	0.0	1.7
SE[a] (28 df)		0.24	0.31	0.68			
Significance of effects[b]							
Cultivar		-	**	-			
Fungicide		-	***	-			
Cv x Fung.		-	-	-			

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.23. The effect of cultivar and fungicide treatments on the green leaf area of wheat flag leaves and the time taken to reach 37% green leaf area (Gompertz *m*). Experiment F1; 2002.

Cultivar	Treatment No.	Time of assessment (date in 2001 and days after anthesis)						Gompertz *m* (days)	Gompertz *m* (°C d)
		17.06 14	26.6 23	04.07 31	12.07 39	19.07 46	26.07 53		
Consort	1	96.5	94.5	78.3	30.7	0.0	0.0	38.1	578
	2	97.2	97.1	95.0	87.0	34.4	1.7	46.1	718
	3	97.2	96.3	94.1	89.8	19.6	1.2	44.7	695
	4	97.3	96.9	96.0	94.0	45.3	16.5	48.0	759
	5	97.2	97.0	96.0	90.5	38.3	14.3	47.1	738
	6	97.0	97.4	96.0	93.6	35.4	26.0	48.2	753
	7	97.3	96.9	95.6	92.0	34.5	21.0	47.6	744
	8	97.0	96.9	95.5	92.9	46.0	17.5	48.5	759
Hereward	1	97.8	95.7	86.3	59.3	7.0	0.0	41.7	639
	2	98.2	97.5	95.0	90.4	20.3	8.0	44.8	696
	3	97.8	97.2	95.7	95.3	37.2	14.0	47.6	743
	4	97.7	97.8	96.4	93.3	35.6	10.2	46.6	727
	5	97.8	97.6	96.2	92.9	37.3	16.2	47.1	735
	6	98.1	97.1	96.3	94.7	29.9	23.3	46.8	742
	7	97.7	97.6	96.6	94.9	41.2	23.0	48.9	768
	8	98.2	97.6	96.6	95.2	28.5	17.2	46.9	732
SE[a] (28 df)		0.28	0.38	0.78	3.04			0.79	13.2
Significance of effects[b]									
Cultivar		-	-	*	-			-	-
Fungicide		-	***	***	***			***	***
Cv x Fung.		-	-	***	***			**	**

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.24. The effect of cultivar and fungicide treatment on the yield and quality of winter wheat. Experiment F1; 2002.

Cultivar	Tr. No.	Grain yield t ha^{-1} @ 85% DM	1000 grain weight g	Specific weight kg hl^{-1}	Hagberg falling number s	Protein content % DM	Sulphur content % DM	N:S ratio	SDS-sedim. volume ml	Black-point Ang. trans. score	Yield of grain N kg ha^{-1}
Consort	1	7.8	39.1	72.4	314	11.8	0.144	14.3	60.7	7.3	137
	2	10.7	47.4	76.9	273	11.0	0.139	13.9	52.3	5.3	176
	3	10.8	47.9	76.7	272	11.1	0.140	13.9	58.0	9.2	178
	4	10.8	49.6	77.0	255	11.0	0.136	14.2	56.0	8.2	177
	5	10.8	50.4	76.6	233	11.1	0.137	14.2	56.0	3.1	178
	6	10.9	50.5	76.9	258	10.6	0.139	13.3	50.3	3.8	173
	7	10.9	49.0	77.1	246	10.9	0.136	14.1	54.7	8.2	176
	8	10.8	49.5	77.0	254	11.0	0.140	13.8	55.7	7.0	177
Hereward	1	9.1	46.7	77.9	339	12.3	0.142	15.1	82.3	21.7	167
	2	9.9	49.1	78.5	314	12.1	0.143	15.0	83.3	21.4	179
	3	10.0	50.0	78.5	331	12.3	0.145	14.9	83.7	20.9	183
	4	10.1	50.2	79.1	329	12.1	0.144	14.8	81.7	22.4	182
	5	10.2	49.0	79.0	310	12.2	0.145	14.8	80.0	19.7	187
	6	10.5	50.7	78.8	283	12.2	0.142	15.1	82.0	22.6	191
	7	10.1	50.4	78.6	277	12.3	0.146	14.8	83.3	21.6	186
	8	10.1	51.3	79.1	292	12.0	0.141	14.9	77.0	19.8	180
SE[a] (28 df)		0.24	0.51	0.26	16.3	0.17	0.0018	0.19	1.76	2.18	5.5
Significance of effects[b]											
Cultivar		*	*	*	**	**	-	*	**	**	-
Fungicide		***	***	***	**	*	-	-	*	-	**
Cv x Fung.		**	***	***	-	-(*)[c]	*	-	*	-	- (**)[c]

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively
[c]Significance when treatments 3-8 are grouped and contrasted with treatments 1 and 2

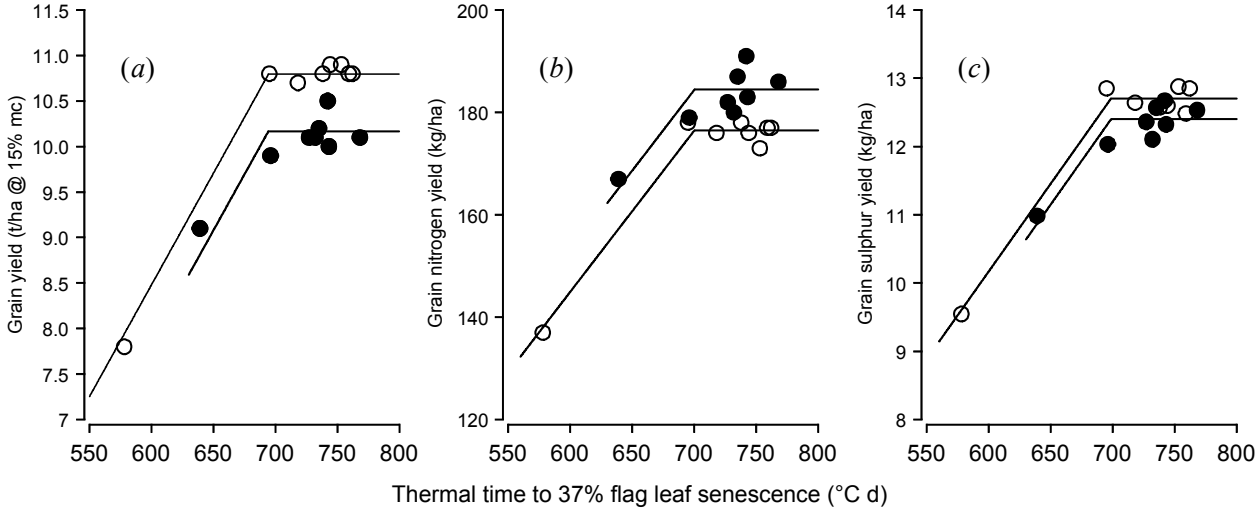

Fig. 5.12. The relationship between maintaining green area of the flag leaf with fungicides and grain mass, nitrogen and sulphur yields. ○ = Consort, ● = Hereward. The breaks for (*a*) mass yield, (*b*) nitrogen yield, and (*c*) sulphur yields are fitted at 694 (S.E.=15.9), 700 (S.E. = 7.9), and 698 ^{o}Cd (S.E. = 6.1) respectively. Responses to the break are 0.0246 t/ha/^{o}Cd (S.E. = 0.00428), 0.315 kg N/ha/^{o}Cd (S.E. = 0.0339), and 0.0257 kg S/ha/^{o}Cd (S.E. = 0.00215).

5.2.2. Experiment F2

5.2.2.1. Green leaf area and foliar disease

As in Experiment F1 for this year (2002), *S. tritici* was the principal disease of the flag leaf and reached high levels, particularly on untreated Consort, Savannah and Malacca (Table 5.25). Shamrock appeared to be the least susceptible cultivar to *S. tritici* but was the only cultivar to have brown rust on the flag leaves and also suffered most from powdery mildew. Fungicide applied at flag leaf emergence gave good control of all diseases but there was little additional benefit from the further application at ear emergence.

Flag leaf life was extended by fungicide application at flag leaf emergence. Senescence was then further delayed by the additional spray at ear emergence (Table 5.26). The greatest benefit of fungicide maintaining green leaf area was for Consort and Savannah, and the least for Hereward (Fig. 5.13).

5.2.2.2. Nitrogen uptake and partitioning

Fungicide significantly (P<0.05) increased the amount of nitrogen in the flag leaves (Fig. 5.14*a-c*) and the leaf below it (Fig. 5.14*d-f*) during the first two measurements for all three cultivars assessed, namely Shamrock, Consort and Hereward. The nitrogen content of leaves below the top two leaves (Fig. 5.14*g-h*) was also significantly increased by fungicide application in the first sampling. Thereafter, the nitrogen content declined rapidly in all fungicide-treated leaves such that by the end of grain filling there was significantly less nitrogen in the top two leaves when fungicide had been applied. A similar effect was detected for nitrogen concentration in the flag leaves (Fig. 5.15). As was the case for Consort in the previous year, senesced leaves that had not been sprayed, contained appreciably more nitrogen than senesced leaves that had received fungicide application. Again, the concentration of nitrogen in leaves scoring as 50% green approached the concentrations seen in totally senesced leaves (Fig. 5.15). The amount of nitrogen in the stem and chaff was also significantly reduced by fungicide by the last sampling (Fig. 5.14*j-l*). Nitrogen in the grain was progressively increased by previous fungicide application, particularly for Consort (Fig. 5.14*n*; P = 0.043 for the interaction on the last measurement). Total nitrogen uptake into the above ground parts of the plant increased throughout the sampling period, particularly when fungicide had been applied (Fig. 5.14*p-r*).

By the final measurement, fungicide had increased nitrogen harvest index from 0.71 to 0.76 (S.E. = 0.014) in Shamrock, from 0.70 to 0.82 in Consort, and from 0.75 to 0.78 in Hereward. The apparent remobilisation of N from non-grain, above ground tissues to the grain between the first and last samplings was increased by fungicide in all three cultivars from an average of 0.55 to 0.64 (S.E. = 0.013). On average, the relative contributions from different sources to grain nitrogen at the end of grain filling were 7%, 6%, 8%, 42% and 37% from flag leaves, penultimate leaves, stem and chaff, and uptake into above ground ear bearing shoots.

The ^{15}N analyses showed that nitrogen from the late season fertilizer was present in the non-grain parts of all cultivars by the second sampling (Fig. 5.15). Unsurprisingly, initial values in the foliage were higher for the foliar-applied urea compared with the ammonium nitrate applied to the soil. In these early stages there were large interactions with cultivar. For example, the flag leaves of Consort contained more N from urea than Shamrock (Fig. 5.16*a-c*), but this situation was reversed on the penultimate leaves (Fig. 5.16*d-f*). Even in the flag leaves, however, urea-derived N was never more than 10% of the total N and, in the stems and chaff, urea-derived N never contributed more than 5% of total N.

Urea derived-N was rapidly partitioned to the grain. Even as early as the second sampling, 67% of the urea-N in or on the above ground parts was already in the grain (Fig. 5.15*j*). Uptake of ammonium nitrate-N was lower and less rapidly portioned to the grain, so that by the second sampling less than half of the ammonium nitrate-N that was in the plant was in the grain. Movement of urea-N out of the leaves and into the grain continued throughout grain filling but even at the end of the assessment period, in senesced plants, there was still more urea-N left in the foliage than ammonium nitrate-N (Figs 5.16 and 5.17).

Fungicide treatment had similar effects on the nitrogen derived from the late-season fertilizer as it did for the total N analyses. Initially, fungicide treatment increased the amount of nitrogen from foliar urea in the top two leaves (Fig. 5.16*b*,*d*). Thereafter, however, urea-derived N declined exponentially such that by the end of grain filling leaves previously treated with fungicide contained less urea-derived N than diseased leaves. Fungicide effects were different when nitrogen had been applied to the soil. Fungicide initially increased ammonium nitrate-derived N in all leaves (Fig. 5.16*a*,*c*,*e*) and although the subsequent decline was more rapid in fungicide treated plots, amounts never fell below those seen in untreated plots (Fig. 5.16).

When averaged over the two fertilizer treatments for the last sampling, fungicide increased grain N derived from late-season fertilizer from 2.53 mg/stem (S.E. = 0.354, 18 D.F.) to 3.37 in Shamrock, from 2.33 to 4.43 in Consort, and from 3.18 to 3.48 in Hereward. The equivalent values for late-season fertilizer-derived N in the above ground crop were 3.39 mg/stem (S.E. = 0.383, 16 D.F.) and 3.97 for Shamrock, 2.86 and 4.93 for Consort, and 3.69 and 3.97 for Hereward.

5.2.2.3. Root extent and distribution

At anthesis there was no significant effect of cultivar on the root length and dry matter densities (Table 5.27) but fungicide increased root length density in the 10-20cm layer. This fungicide effect persisted to the soft dough stage (Table 5.28) when it was also significant for root dry matter. By this time there was also a significant effect of cultivar on length and dry matter densities in lower parts of the soil profile (Table 5.28) where, as in 2002, Shamrock had more root material than the other cultivars.

As in the previous year, there was no evidence of significant root senescence between GS 64 and GS 85. The root length density averaged over all varieties and depths increased from 2.7 to 3.0 cm/cm^3, while the average root dry matter density declined slightly from 0.110 to 0.109 mg/cm^3.

5.2.2.4. Combine harvested grain yield and quality

Fungicide increased the grain yield, thousand grain weight and specific weight, particularly for Claire, Consort and Savannah (Table 5.29). Fungicide reduced Hagberg falling number of all cultivars. Fungicide increased grain protein concentration of Shamrock but reduced it for all other cultivars. There was no effect of fungicide on grain sulphur concentration so N:S ratio tended to decline with fungicide-use. SDS-sedimentation volume was reduced, and blackpoint severity increased by fungicide. Fungicide increased the yield of nitrogen in the grain, particularly for Claire, Consort and Savannah.

Grain yield of cultivars in relatively disease free conditions (i.e. having received Treatment 8) was negatively associated with root length densities in the plough layer (Fig. 5.18*a*,*b*), whereas the reverse appeared to be true for grain protein concentration (Fig. 5.18*m*,*n*).

The response of cultivars to fungicide (i.e. the difference between Treatments 1 and 8) for grain yield (Fig. 5.19*a*) and grain sulphur yield (Fig. 5.19*i*,*j*) also appeared to be negatively associated

with root length densities. As in 2001, however, the ability of Shamrock to increase its protein concentration in response to fungicide application was positively associated with rooting extent below the plough layer (Fig. 5.20*o*,*p*).

The foliar urea application reduced thousand grain weight and specific weight but increased grain protein concentration, SDS-sedimentation volume and yield of nitrogen. The increase in protein concentration was not matched by increases in sulphur so urea increased the N:S ratio (Table 5.29).

Table 5.25. The effect of cultivar, fungicide and foliar urea treatments on the area of disease symptoms on the flag leaves of winter wheat. Experiment F2; 2002.

Cultivar	Tr. No.	Time of assessment (date in 2002and days after anthesis)								
		Septoria tritici			Brown rust			Powdery mildew		
		19.06 16	26.06 23	04.07 31	19.06 16	26.06 23	04.07 31	19.06 16	26.06 23	04.07 31
Shamrock	1	0.3	0.8	5.8	0.0	0.6	1.5	1.6	0.8	1.8
	2	0.1	0.4	0.8	0.0	0.0	0.0	0.4	0.1	0.4
	8	0.1	0.6	0.7	0.0	0.0	0.0	0.2	0.2	0.2
Claire	1	0.4	2.2	10.9	0.0	0.0	0.0	0.0	0.1	0.4
	2	0.2	0.8	1.4	0.0	0.0	0.0	0.1	0.0	0.0
	8	0.4	0.5	0.9	0.0	0.0	0.0	0.1	0.0	0.0
Consort	1	1.2	3.7	18.1	0.0	0.0	0.0	0.0	0.1	0.0
	2	0.6	0.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.5	0.5	1.4	0.0	0.0	0.0	0.0	0.0	0.0
Hereward	1	0.4	1.8	8.8	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.3	0.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.3	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Savannah	1	1.1	3.3	16.5	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.4	0.6	2.2	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.7	0.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Malacca	1	0.8	3.4	16.9	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.7	1.1	4.1	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.8	0.9	1.7	0.0	0.0	0.0	0.0	0.0	0.0
SE[a] (60 df)		0.10	0.27	1.23						
Urea treatment means										
No urea		0.5	1.2	5.5	0.0	0.0	0.1	0.1	0.1	0.1
With urea		0.5	1.3	5.0	0.0	0.1	0.1	0.2	0.1	0.2
SE (60 df)		0.06	0.09	0.41						
Significance of effects[b]										
Cultivar		***	**	***						
Fungicide		***	***	***						
Urea		-	-	-						
Cv.F		*	***	***						
Cv.U		-	-	-						
F.U		-	-	-						
Cv.F.U		-	-	-						

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.26. The effect of cultivar, fungicide and foliar urea treatments on the green leaf area of wheat flag leaves and the time taken to reach 37% green leaf area (Gompertz *m*). Experiment F2; 2002.

Cultivar	Tr. No.	Time of assessment (date in 2002 and days after anthesis)					Gompertz *m* (days)
		26.6	04.07	12.07	19.07	26.07	
		23	31	39	46	53	
Shamrock	1	96.3	88.5	53.7	0.0	1.2	40.4
	2	97.7	96.7	94.3	54.2	18.6	49.5
	8	97.6	96.8	96.8	81.3	36.8	53.0
Claire	1	96.2	85.6	37.2	0.0	0.0	39.1
	2	97.5	96.2	81.6	33.5	8.3	46.0
	8	97.7	97.0	94.7	58.7	37.3	52.4
Consort	1	94.7	77.5	21.7	0.0	0.0	37.0
	2	97.3	95.6	85.2	23.3	1.9	44.8
	8	97.5	96.0	93.0	77.9	43.2	54.8
Hereward	1	96.5	89.0	46.3	17.3	0.0	41.6
	2	98.0	93.9	91.5	49.1	13.3	48.4
	8	97.9	97.0	90.6	77.8	32.5	52.6
Savannah	1	95.0	80.2	12.3	0.0	0.0	36.3
	2	97.2	96.0	81.7	25.3	0.0	44.9
	8	97.5	96.9	94.2	74.2	24.9	51.6
Malacca	1	94.9	78.4	21.1	0.0	0.0	37.2
	2	96.8	93.8	86.0	22.0	2.9	44.6
	8	97.2	96.0	89.7	46.9	23.6	49.5
SE[a] (60 df)		0.31	1.58	5.35			0.81
Urea treatment means							
No urea		96.9	91.8	70.9	36.1	13.4	45.8
With urea		96.8	91.7	70.3	35.2	13.7	45.7
SE (60 df)		0.10	0.53	1.78			0.27
Significance of effects[b]							
Cultivar		**	-	*			**
Fungicide		***	***	***			***
Urea		-	-	-			-
Cv.F		-	**	*			**
Cv.U		-	-	-			-
F.U		-	-	-			-
Cv.F.U		-	-	-			-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

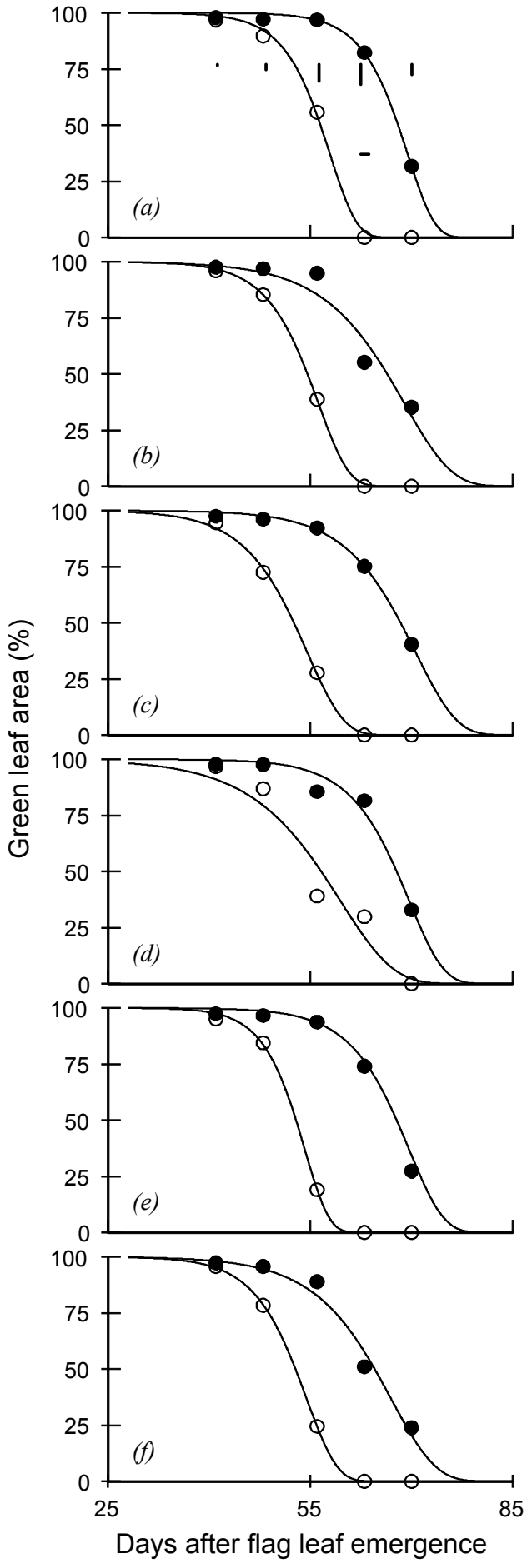

Fig. 5.13. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on green leaf area of the flag leaf. Cultivars are *a*, Shamrock; *b*, Claire; *c*, Consort; *d*, Hereward; *e*, Savannah; *f*, Malacca. Fitted curves are modified gompertz. Vertical bars in Shamrock graphs are S.E. (60 D.F) for comparing points within a variety. Horizontal bar is for comparing time to 37% green leaf area (Gompertz *m*). Experiment F2; 2002.

Table 5.27. The effect of fungicide treatment and cultivar on root length and dry matter densities at anthesis of winter wheat. Experiment F2; 2002.

Cultivar	Tr. No.	Root length density (cm cm^{-3}) Depth (cm)				Root dry matter density (mg cm^{-3}) Depth (cm)			
		10-20	20-30	40-50	60-70	10-20	20-30	40-50	60-70
Shamrock	1	4.4	3.4	0.6	1.0	0.186	0.153	0.039	0.052
	8	7.0	5.2	0.6	0.7	0.262	0.184	0.037	0.037
Consort	1	3.7	3.9	0.4	0.4	0.218	0.150	0.023	0.027
	8	4.8	2.7	0.4	0.6	0.174	0.126	0.027	0.035
Hereward	1	7.1	3.9	0.3	0.3	0.240	0.129	0.023	0.020
	8	8.3	5.1	0.2	0.5	0.338	0.189	0.017	0.025
Malacca	1	5.3	3.0	0.6	0.4	0.190	0.135	0.031	0.029
	8	5.9	3.5	0.7	0.3	0.242	0.151	0.040	0.020
SE[a] (8 df)		0.68	0.56	0.31	0.10	0.034	0.026	0.015	0.006
Significance of effects[b]									
Cultivar		-	-	-	-	-	-	-	-
Fungicide		*	-	-	-	-	-	-	-
Cv.F		-	-	-	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.28. The effect of fungicide treatment and cultivar on root length and dry matter densities at the soft dough stage of winter wheat. Experiment F2; 2002.

Cultivar	Tr. No.	Root length density (cm cm^{-3}) Depth (cm)				Root dry matter density (mg cm^{-3}) Depth (cm)			
		10-20	20-30	40-50	60-70	10-20	20-30	40-50	60-70
Shamrock	1	7.4	4.7	0.9	1.3	0.267	0.175	0.036	0.051
	8	7.6	3.6	0.3	1.2	0.282	0.129	0.021	0.056
Consort	1	6.0	3.7	0.3	0.5	0.195	0.134	0.021	0.028
	8	6.2	3.5	0.3	0.5	0.233	0.154	0.018	0.027
Hereward	1	7.2	4.1	0.2	0.3	0.222	0.141	0.014	0.017
	8	9.6	5.4	0.3	0.4	0.295	0.184	0.018	0.021
Malacca	1	4.7	4.5	0.1	0.3	0.175	0.159	0.010	0.017
	8	6.5	3.8	0.2	0.4	0.219	0.133	0.015	0.019
SE[a] (8 df)		0.72	0.53	0.13	0.13	0.015	0.025	0.005	0.004
Significance of effects[b]									
Cultivar		-	-	*	*	-	-	*	*
Fungicide		*	-	-	-	**	-	-	-
Cv.F		-	-	-	-	-	-	-	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

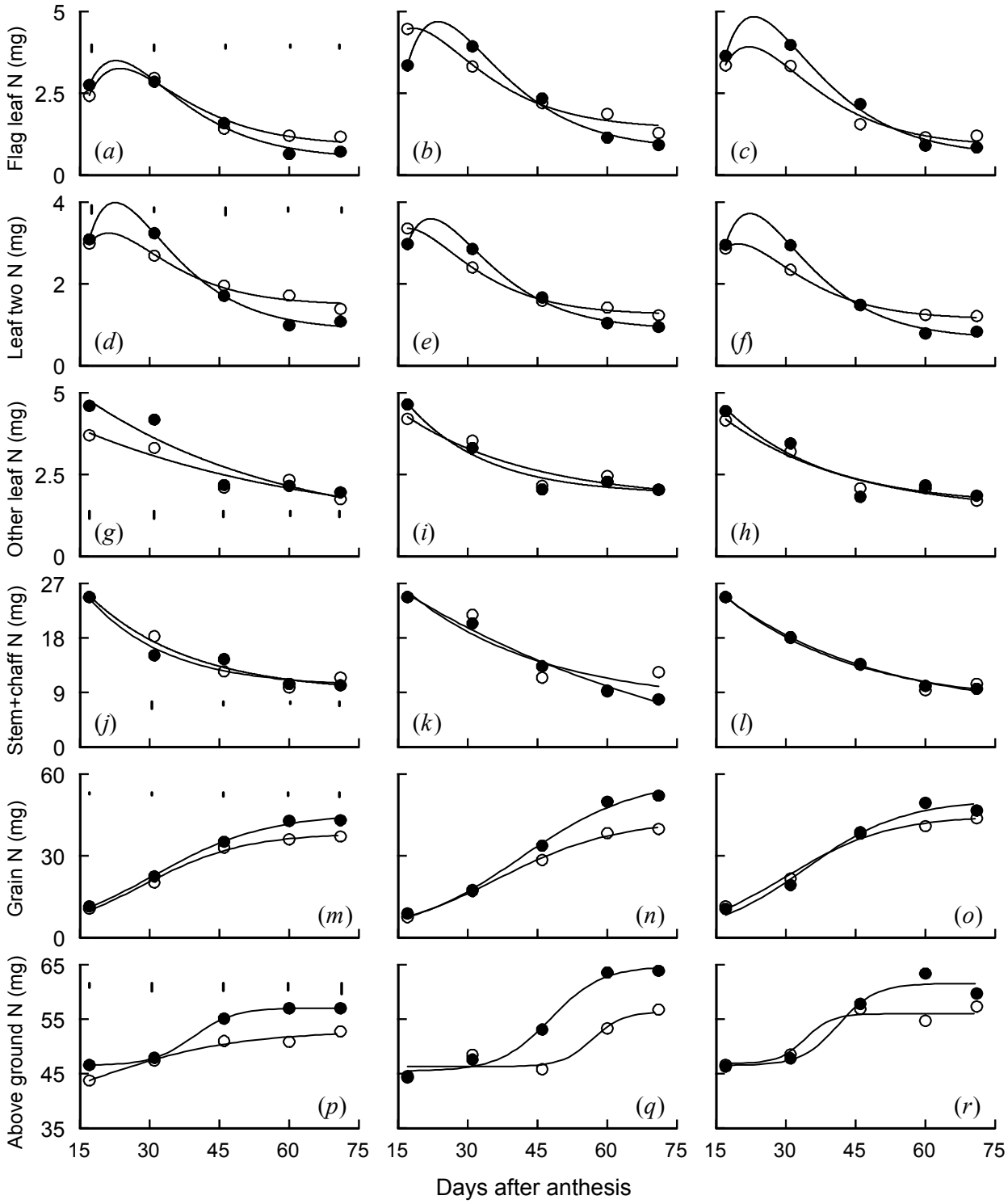

Fig. 5.14. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on amounts of nitrogen per ear bearing stem in different above ground components. Left, middle and right columns of graphs correspond to cvs Shamrock, Consort and Hereward respectively. Fitted curves are critical exponential (*a-f*), exponential (*g-l*), and logistic (*m-r*). Points are means of different late-season nitrogen treatments. Vertical bars in Shamrock graphs are S.E. (18 D.F.) for comparing points within a variety. Experiment F2; 2002.

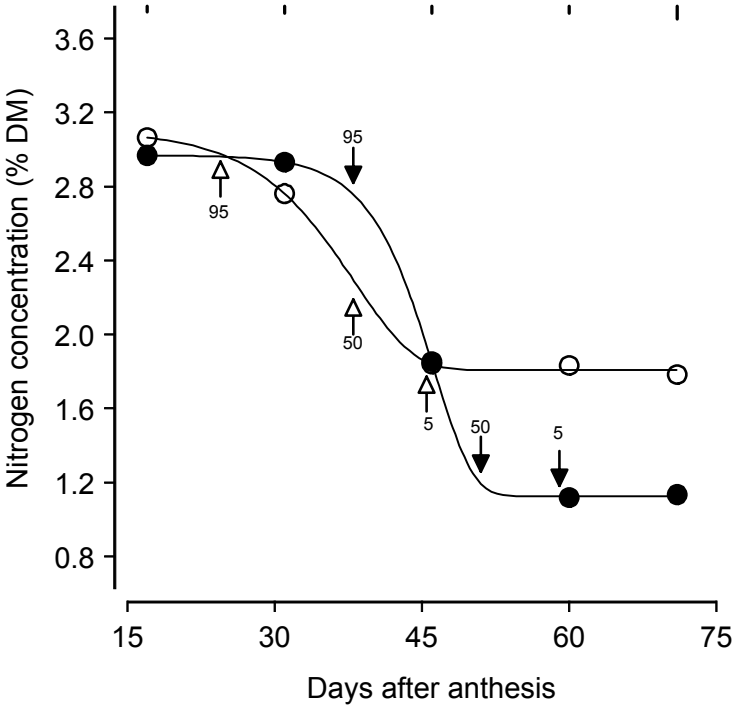

Fig. 5.15. The effect of fungicide treatment (○ = untreated; ● = 63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on nitrogen concentration in the flag leaves. Arrows (Δ = untreated; ▲= with fungicide) and numerals denote the timings for different green areas (%) of the flag leaf; mean of three cultivars. Vertical bars are S.E. (16 D.F.). Fitted lines are Gompertz. Experiment F2; 2002.

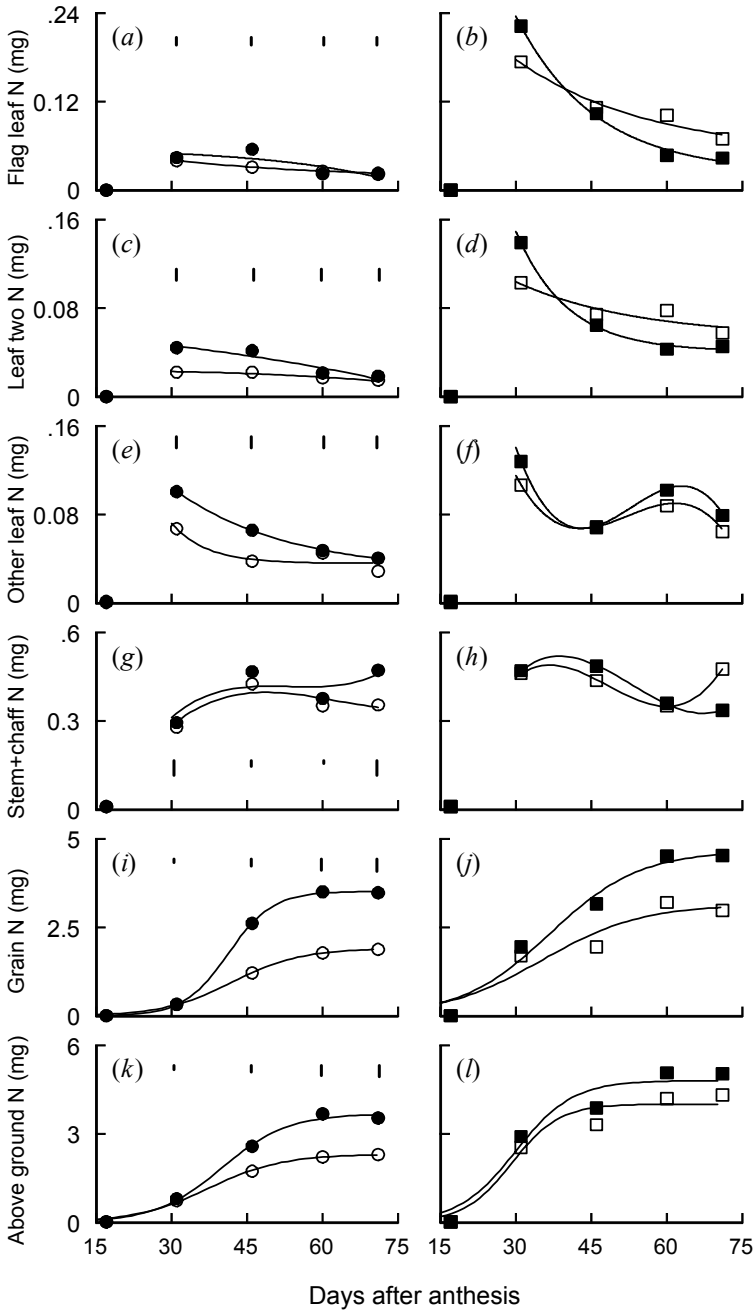

Fig. 5.16. The effect of fungicide treatment (solid symbols, 63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on the amounts of nitrogen per ear bearing stem derived from ammonium nitrate prills (circles, left column of graphs) or urea solution (squares, right column of graphs) labelled with ^{15}N, in different above ground components of winter wheat in 2002 (mean of three cultivars). Vertical bars are S.E. (30 D.F. for *a* and *b*; 18 D.F for *c*-*n*). Fitted lines are exponential (*a*-*e*), cubic (*f*-*h*) and logistic (*i*-*l*; constant omitted). Experiment F2; 2002.
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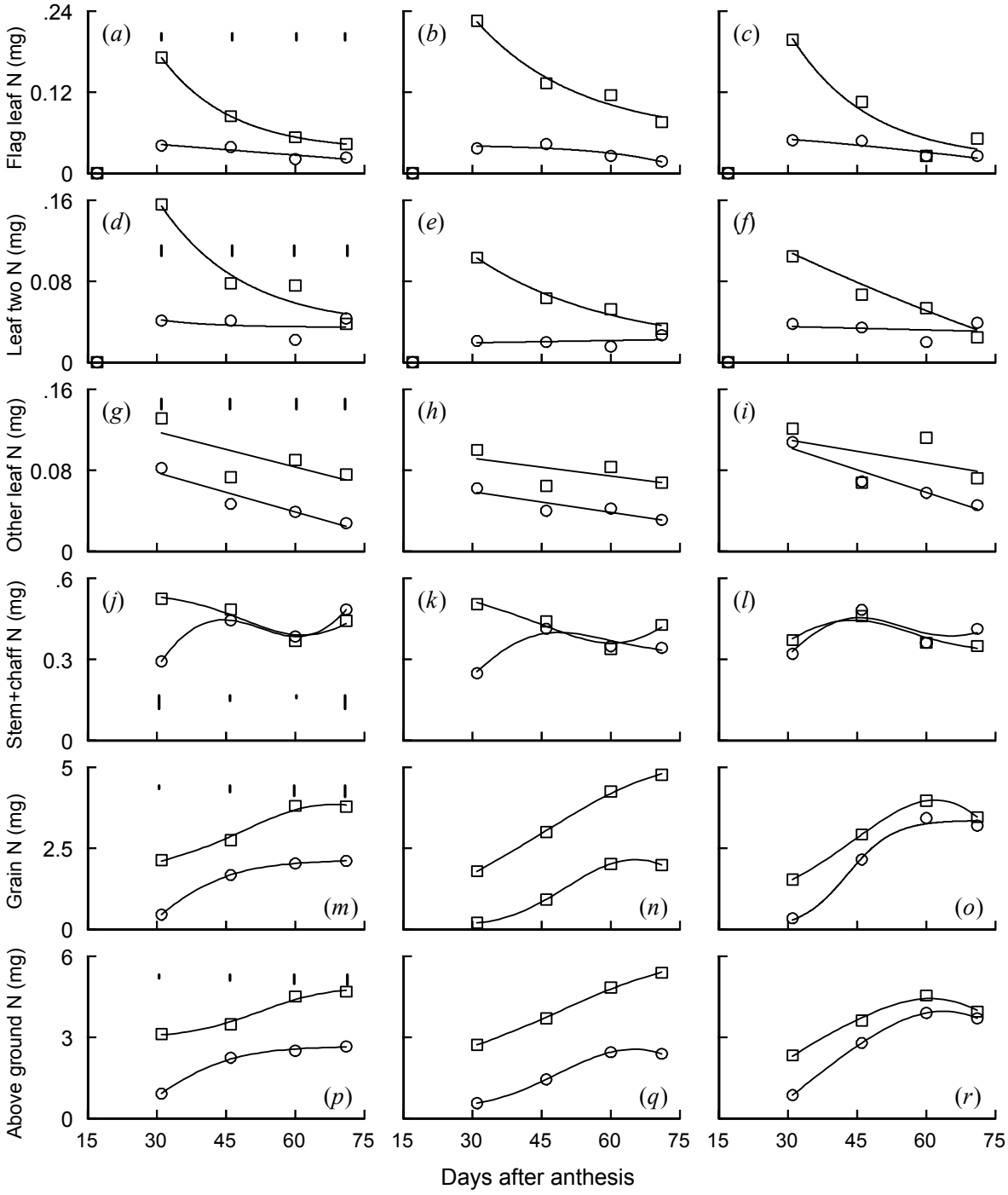

Fig. 5.17. The effect of winter wheat cultivar on accumulation of N from a foliar urea spray (□) or ammonium nitrate prills (○) labelled with ^{15}N. Quantities are per ear bearing stem in different above ground components. Left, middle and right columns of graphs correspond to cvs Shamrock, Consort and Hereward respectively. Points are means of different fungicide treatments. Vertical bars in Shamrock graphs are S.E. (12 D.F.) for comparing points within a variety. Experiment F2; 2002.

Table 5.29. The effect of cultivar and fungicide treatment on the yield and quality of winter wheat. Experiment F2; 2002.

Cultivar	Tr. No.	Grain yield t ha^{-1} @ 85% DM	1000 grain weight g	Specific weight kg hl^{-1}	Hagberg falling number s	Protein content % DM	Sulphur content % DM	N:S ratio	SDS-sedim. volume ml	Black-point Ang. trans. score	Yield of grain N kg ha^{-1}
Fungicide x cultivar means in the absence of urea											
Shamrock	1	8.9	43.4	76.3	321	11.7	0.141	14.5	77.0	18.5	155
	2	10.0	45.5	76.6	268	12.0	0.141	15.1	75.3	20.9	178
	8	10.4	47.4	78.3	250	12.1	0.142	15.0	75.0	16.3	188
Claire	1	8.9	39.2	71.8	325	11.6	0.137	14.9	50.7	5.2	154
	2	10.7	45.2	74.4	303	11.0	0.135	14.4	49.0	8.0	176
	8	11.9	48.4	76.5	277	10.9	0.140	13.7	48.7	10.8	192
Consort	1	8.4	40.7	73.0	272	11.3	0.149	13.3	59.0	4.3	142
	2	11.3	47.0	76.2	245	11.2	0.149	13.2	57.0	7.3	189
	8	11.8	51.3	77.0	245	10.9	0.150	12.8	56.7	6.5	192
Hereward	1	9.3	45.4	78.0	356	12.4	0.154	14.1	82.7	21.0	171
	2	10.2	48.3	78.1	300	12.2	0.151	14.2	80.0	23.6	185
	8	10.6	48.9	79.1	331	12.1	0.150	14.2	78.3	17.2	192
Savannah	1	9.4	43.8	74.1	322	10.6	0.150	12.5	45.8	7.6	149
	2	11.7	51.2	76.3	296	10.3	0.150	12.0	44.3	9.9	180
	8	12.4	53.2	77.4	280	10.2	0.150	12.0	43.2	8.8	188
Malacca	1	9.1	41.1	72.5	387	12.3	0.142	15.5	75.8	2.3	168
	2	11.1	48.6	75.9	379	11.8	0.140	15.0	78.2	6.9	196
	8	11.2	47.9	76.7	370	11.8	0.144	14.6	76.7	10.0	196
SE[a] (24 df)		0.17	0.89	0.29	12.2	0.11	0.0017	0.20	0.89	1.80	2.8
Urea treatment means[c]											
No urea		9.9	46.2	77.0	296	11.7	0.148	14.0	71.4	14.0	173
With urea		9.8	45.0	76.4	294	12.5	0.147	15.0	74.2	11.8	182
SE (18 df)		0.07	0.36	0.16	7.2	0.06	0.0011	0.13	0.67	0.87	1.5
Significance of effects[b]											
Cultivar		*	*	***	***	***	-	*	***	***	-
Fungicide		***	***	***	***	***	-	**	**	*	***
Urea[c]		-	*	*	-	***	-	***	**	-	***
Cv.F.		***	**	***	-	**	-	-	-	-	***
Cv.U[c]		-	-	-	-	-	-	-	-	-	-
U.F[c]		-	-	*	-	-	-	-	-	-	-
Cv.U.F[c]		-	-	-	-	-	-	-	-	-	-

[a] SE = Standard error of means within a variety
[b] -, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively
[c] Only from comparisons made on Shamrock, Consort and Hereward

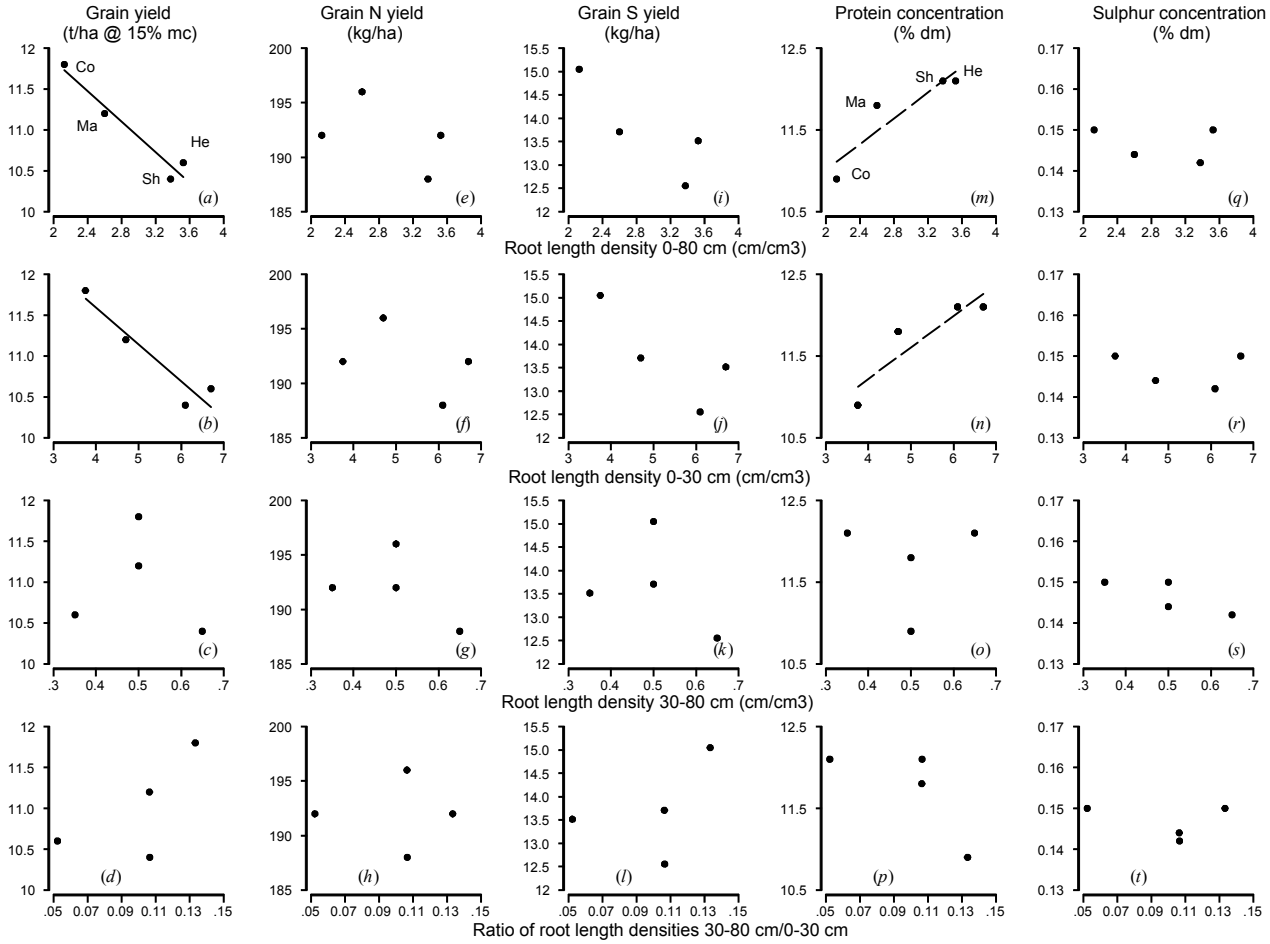

Fig. 5.18. Associations between grain yield, nitrogen and sulphur and root length densities over different depths at anthesis for cultivars receiving fungicide treatment 8 (see Table 2.3). Solid lines are fitted where correlation coefficient (r) > 0.95 (i.e. P<0.05) and dashed lines fitted where r > 0.9 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Co = Consort, He = Hereward, Ma = Malacca. Experiment F2; 2002.

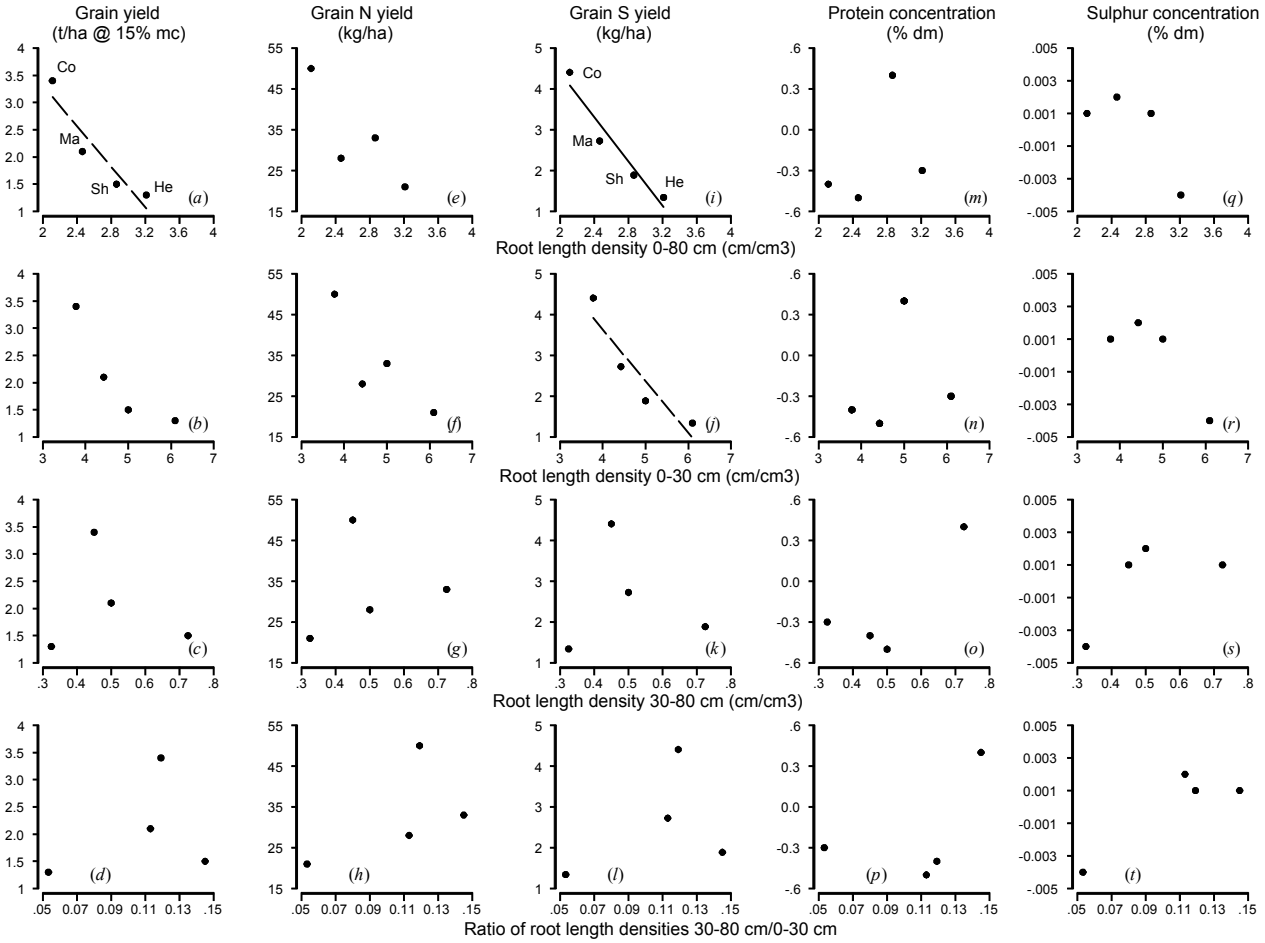

Fig. 5.19. Associations between grain yield, nitrogen and sulphur responses to fungicide (Treatment 8 – Treatment 1; see Table 2.3) and root length densities at anthesis over different depths for cultivars (mean of Treatments 1 & 8). Solid lines are fitted where correlation coefficient (r) > 0.95 (i.e. P<0.05) and dashed lines fitted where r > 0.9 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Co = Consort, He = Hereward, Ma = Malacca. Experiment F2; 2002.

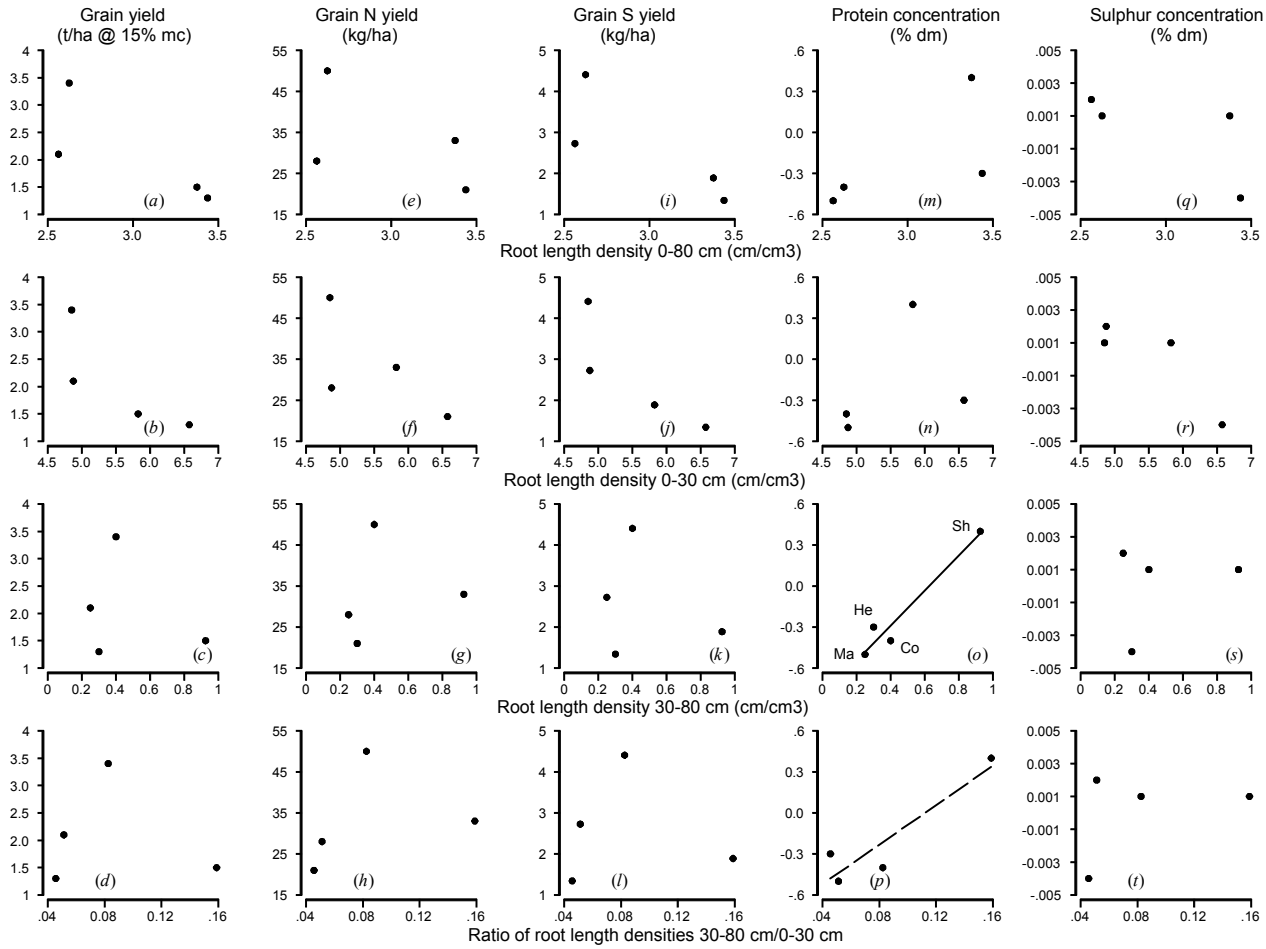

Fig. 5.20. Associations between grain yield, nitrogen and sulphur responses to fungicide (Treatment 8 – Treatment 1; see Table 2.3) and root length densities at the soft dough stage over different depths for cultivars (mean of Treatments 1 & 8). Solid lines are fitted where correlation coefficient (r) > 0.95 (i.e. P<0.05) and dashed lines fitted where r > 0.9 (i.e. P<0.1). Cultivars are denoted: Sh = Shamrock, Co = Consort, He = Hereward, Ma = Malacca. Experiment F2; 2002.

5.3. 2003

5.3.1. Experiment F2

5.3.1.1. Green leaf area and foliar disease

As in 2002, *S. tritici* was again the principal foliar disease (Table 5.30), and this developed particularly on Consort, Savannah and Malacca when fungicide was not applied. Brown rust remained below 1% of the flag leaf area for all cultivars and treatments. Powdery mildew was never seen on the flag leaves.

Green leaf area duration of the flag leaves was extended by fungicide use, particularly on Consort and Savannah (Table 5.31). The application of the additional fungicide at ear emergence failed to extend flag leaf life beyond what was achieved with just the spray at flag leaf emergence.

5.3.1.2. Combine harvested grain yield and quality

Grain yield was increased by the fungicide applied at flag leaf emergence, particularly the yields of Consort and Savannah (Table 5.32). Fungicide also increased thousand grain weight, specific weight (particularly on Consort and Malacca) and yield of nitrogen (particularly Consort and Savannah). Fungicide had no significant effect on grain nitrogen and sulphur concentrations but, nonetheless, tended to improve (i.e. reduce) N:S ratios.

Table 5.30. The effect of cultivar, fungicide and foliar urea treatments on the area of disease symptoms on the flag leaves of winter wheat. Experiment F2; 2003

Cultivar	Treatment No.	Time of assessment (date in 2003 and days after anthesis)					
		Septoria tritici			Brown rust		
		18.06 9	27.06 18	04.07 25	18.06 9	27.06 18	04.07 25
Shamrock	1	0.7	3.0	3.1	0.0	0.0	0.0
	2	0.1	0.4	0.8	0.0	0.0	0.0
	8	0.3	0.2	0.5	0.0	0.0	0.0
Claire	1	1.0	1.2	3.6	0.0	0.0	0.0
	2	0.1	0.5	1.8	0.0	0.0	0.0
	8	0.2	0.6	0.5	0.0	0.0	0.0
Consort	1	1.7	3.9	7.7	0.0	0.0	0.8
	2	0.6	0.7	2.1	0.0	0.0	0.2
	8	0.4	0.6	0.9	0.0	0.0	0.0
Hereward	1	1.0	2.2	4.8	0.0	0.0	0.6
	2	0.4	0.4	1.5	0.0	0.0	0.0
	8	0.2	0.3	0.9	0.0	0.0	0.0
Savannah	1	1.5	3.3	11.6	0.0	0.0	0.0
	2	0.3	1.0	1.2	0.0	0.0	0.0
	8	0.1	0.5	0.6	0.0	0.0	0.0
Malacca	1	2.5	3.0	7.4	0.0	0.0	0.9
	2	0.7	1.0	3.1	0.0	0.0	0.1
	8	0.4	0.9	2.0	0.0	0.0	0.0
SE[a] (24 df)			0.29	1.35			
Significance of effects[b]							
Cultivar			**	-			
Fungicide			***	***			
Cv.F			**	-			

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.31. The effect of cultivar, fungicide and foliar urea treatments on the green leaf area of wheat flag leaves, the time taken to reach 37% green leaf area (Gompertz *m*) and the Gompertz rate (*k*) of green leaf area decline. Experiment F2; 2003.

Cultivar	Tr. No.	Time of assessment (date in 2003 and days after anthesis)					Gompertz *m* (days)	Gompertz *k*
		18.06 9	27.06 18	04.07 25	11.07 32	18.073 39		
Shamrock	1	98.4	95.8	94.8	48.5	4.0	33.0	-0.36
	2	99.2	98.4	97.2	95.0	22.2	38.1	-0.48
	8	99.0	98.7	97.6	93.8	20.1	38.0	-0.46
Claire	1	97.9	97.1	94.2	42.9	1.2	32.4	-0.39
	2	98.4	98.2	96.8	92.3	12.5	37.4	-0.46
	8	98.1	97.8	97.3	91.9	9.8	37.2	-0.48
Consort	1	97.3	94.4	90.1	29.2	1.7	31.6	-0.33
	2	97.8	97.7	96.3	93.7	26.1	38.3	-0.42
	8	97.8	97.9	97.3	95.2	34.6	38.9	-0.43
Hereward	1	97.6	96.5	93.0	59.3	6.7	34.8	-0.24
	2	98.6	98.4	97.0	94.3	14.0	37.6	-0.50
	8	98.5	98.4	96.6	93.9	23.0	38.1	-0.44
Savannah	1	97.1	95.1	85.0	32.5	2.2	31.9	-0.33
	2	98.3	97.5	97.2	93.8	19.2	37.9	-0.46
	8	98.3	98.1	97.4	94.9	23.8	38.3	-0.47
Malacca	1	96.1	95.3	90.4	25.9	0.0	31.2	-0.37
	2	97.7	97.7	95.5	92.2	13.3	37.4	-0.46
	8	97.7	97.6	96.0	91.6	10.2	37.2	-0.47
SE[a] (60 df)		0.23	0.30	1.63	4.59		0.32	0.028
Significance of effects[b]								
Cultivar		**	***	-	*		-	-
Fungicide		***	***	***	***		***	***
Cv.F		-	*	-	*		***	-

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

Table 5.32. The effect of cultivar and fungicide treatment on the yield and quality of winter wheat. Experiment F2; 2003.

Cultivar	Tr. No.	Grain yield t ha^{-1} @ 85% DM	1000 grain weight g	Specific weight kg hl^{-1}	Hagberg falling number s	Protein content % DM	Sulphur content % DM	N:S ratio	SDS-sedim. volume ml	Yield of grain N kg ha^{-1}
Shamrock	1	8.2	39.7	76.6	218	12.9	0.167	13.6	77.7	159
	2	8.7	40.5	77.7	200	13.0	0.169	13.5	77.3	169
	8	8.9	41.9	78.3	189	13.1	0.168	13.7	74.0	174
Claire	1	9.3	40.7	74.6	263	11.8	0.149	13.9	45.0	164
	2	9.9	43.1	75.5	260	12.0	0.151	13.9	45.3	176
	8	9.9	42.4	76.2	258	12.1	0.154	13.8	44.7	180
Consort	1	7.4	38.7	73.7	241	12.7	0.158	14.1	56.3	141
	2	9.3	44.7	76.3	203	12.4	0.157	13.9	52.7	172
	8	8.8	43.1	77.2	190	12.6	0.158	14.0	52.0	166
Hereward	1	8.1	40.9	76.3	248	13.7	0.169	14.3	72.0	165
	2	8.7	43.2	77.6	246	13.6	0.167	14.3	72.3	177
	8	8.6	42.6	78.4	243	13.7	0.167	14.3	75.0	174
Savannah	1	7.7	43.8	75.6	282	11.8	0.156	13.2	42.0	135
	2	9.0	46.5	75.9	261	11.4	0.153	13.0	38.3	153
	8	9.1	47.7	76.7	260	11.4	0.154	13.0	37.7	155
Malacca	1	8.3	41.8	73.5	341	13.2	0.157	14.7	67.3	163
	2	9.1	45.5	75.9	298	12.9	0.158	14.4	69.3	175
	8	9.2	45.1	77.0	348	12.9	0.158	14.3	66.0	178
SE[a] (24 df)		0.14	1.23	0.32	12.1	0.10	0.0011	0.10	1.25	2.85
Significance of effects[b]										
Cultivar		*	*	***	***	***	***	***	***	**
Fungicide		***	**	***	*	-	-	**	-	***
Cv.F.		**	-	*	-	-	-	-	-	*

[a]SE = Standard error of means within a variety
[b]-, *, **, *** = Probability (P) >0.05, <0.05, <0.01 and <0.001 respectively

5.3.2. Experiment F3

5.3.2.1. Green leaf area and foliar disease

As in the neighbouring Experiment F2, *S. tritici* was again the principal foliar disease (data not presented), and this developed particularly on Consort.

Green leaf area duration of the flag leaves was extended by irrigation and also by fungicide use, particularly on Consort (Table 5.33).

5.3.2.2. Nitrogen uptake and partitioning

Nitrogen in the flag leaves was initially greater for the plots receiving their late-season nitrogen as a foliar urea spray, compared to ammonium nitrate prills (Fig. 5.21). This effect, however, rapidly disappeared as the quantity of nitrogen in the flag leaves declined. The mass of nitrogen in the flag leaves was increased by irrigation. Total nitrogen in the above ground biomass, and in the grain usually appeared to be greater in plots receiving late-season nitrogen as ammonium nitrate, compared with urea; an effect that was statistically significant on the second assessment date.

Recovery of N from the ^{15}N labelled fertilizer in the flag leaves was initially greater when the nitrogen was applied as foliar urea spray (Fig. 5.22). However, ^{15}N from late-season fertilizer in the flag leaf declined exponentially and differences between the two nitrogen sources had disappeared by the second sampling. Foliar urea-derived N was greater than ammonium nitrate derived N in the grain and the above ground biomass for the first sampling (Fig. 5.22) but this situation rapidly reversed. The benefit of ammonium nitrate prills over the foliar urea spray appeared to be greater when irrigation was applied but the nitrogen x irrigation interaction was not significant on any individual date.

By the time the flag leaves had senesced, the total N-mass in the flag leaves (Fig. 5.23) was reduced by previous fungicide application, particularly for Consort ($P<0.01$ for the fungicide x cultivar interaction at the last two samplings). Conversely, by the end of grain filling, fungicide increased the amount of nitrogen in the grain, again particularly in Consort ($P<0.05$ for the interaction). Fungicide also reduced the amount of nitrogen derived from the late-season fertilizer (Fig. 5.24) remaining in the flag leaves. With regards the grain and above ground biomass, fungicide and cultivar effects on late-season fertilizer N appeared to be similar to the effects on total N (Fig. 5.24), i.e. there was greater recovery in Consort when fungicide was applied.

5.3.2.3. Combine harvested grain yield and quality

Fungicide increased both grain yield and grain nitrogen yield to the same extent such that protein concentration was not significantly affected by application (Table 5.33). Fungicide reduced the Hagberg falling number of Consort and Hereward, but not of Shamrock. Fungicide also significantly reduced SDS-sedimentation volume of Consort. Irrigation appeared to increase grain yield but, overall, there was little or no effect of irrigation, or form of late-season nitrogen fertilizer on grain yield or quality.

Table 5.33. The effect of cultivar, fungicide treatment, irrigation and source of late-season nitrogen on the time for the flag leaf green area to decline to 37% (Gompertz *m*), grain yield and quality of winter wheat. Experiment F3, 2003.

Cultivar	Fung-icide	Irrig-ation	Late-season N[c]	Gompertz *m* (days)	Grain yield t ha^{-1} @ 85% DM	Hagberg falling numbers	Protein content % DM	SDS-sedim. volume ml	Yield of grain N kg ha^{-1}
Fungicide x cultivar means									
Shamrock	1			35.1	7.5	205	12.8	81.9	143
	8			38.1	8.0	206	12.7	79.8	152
Consort	1			31.4	7.2	241	12.4	67.4	133
	8			39.8	7.7	185	12.6	62.3	144
Hereward	1			34.1	7.3	263	13.6	79.1	148
	8			37.6	8.1	235	13.7	77.6	167
SE[a] (32 min. df)				0.55	0.16	8.0	0.29	0.78	4.1
Irrigation x late season N means									
		None	AN	35.0	7.5	234	12.9	74.7	145
		Yes	AN	37.8	7.6	217	13.1	73.4	149
		None	U	34.2	7.6	238	12.4	74.5	141
		Yes	U	37.1	7.8	200	13.5	76.1	156
SE[a] (12 df)				0.47	0.17	4.8	0.33	0.83	3.7
Significance of effects[b]									
Irrigation (I)				*	-	-	-	-	-
Fungicide (F)				***	***	***	-	**	**
Nitrogen (N)				-	-	-	-	-	-
I.F				-	-	-	-	-	-
I.N				-	-	-	-	-	-
F.N				-	-	*	-	-	-
I.F.N				-	-	*	-	-	-
Cultivar (Cv)				-	-	***	***	***	***
I.Cv				-	-	-	-	-	-
F.Cv				***	-	*	-	**	-
N.Cv				-	-	-	-	-	-
I.F.Cv				-	-	-	-	-	-
I.N.Cv				-	-	-	-	-	-
F.N.Cv				-	-	-	-	-	-
I.F.N.Cv				-	-	-	-	-	-

[a]SE = Standard error of fungicide means within a variety or nitrogen means within an irrigation treatment
[b]-, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively
[c]30 kg N ha^{-1} applied after anthesis as either ammonium nitrate granules (AN) or as a spray applied to the foliage in 300 l ha^{-1}.

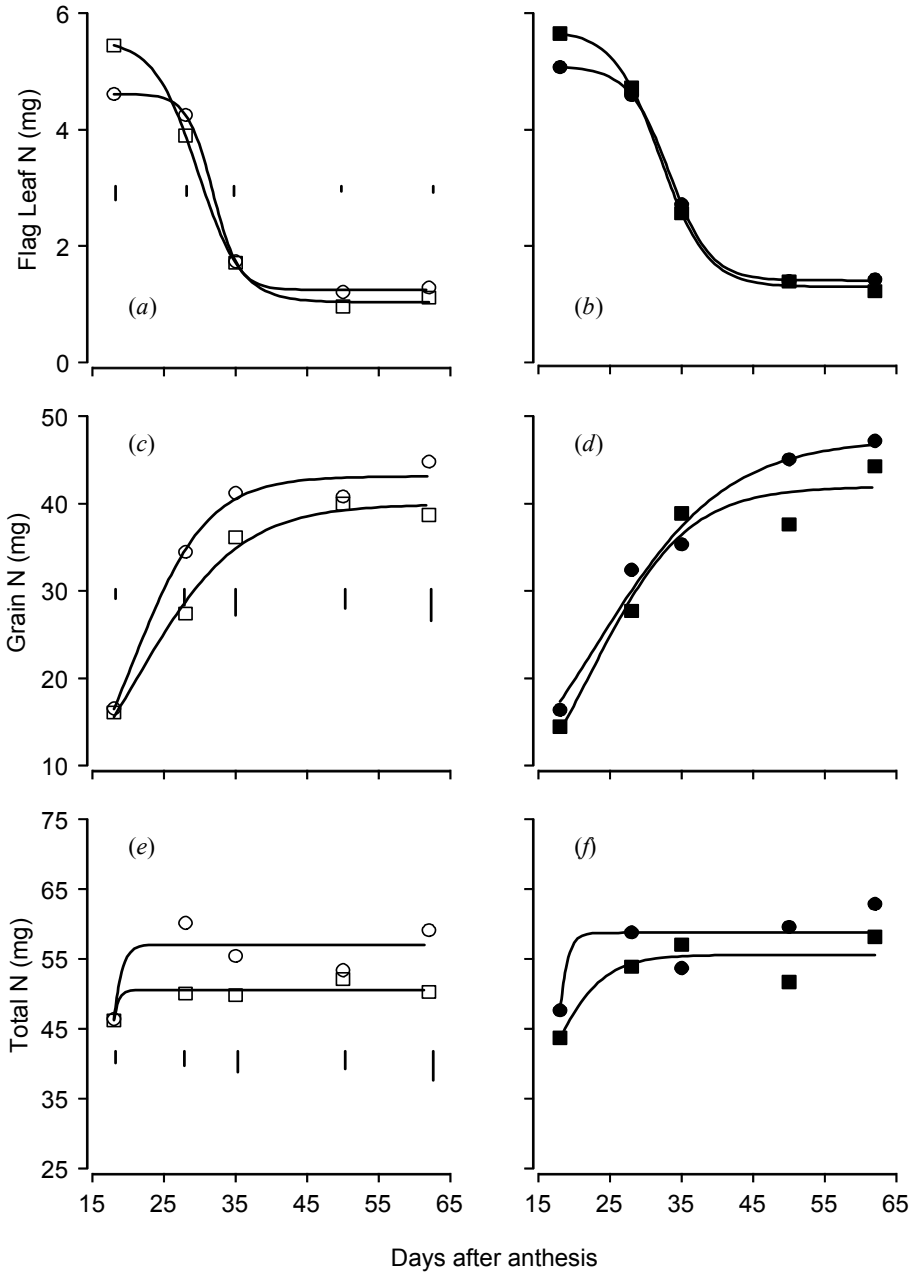

Fig. 5.21. The effect of late-season irrigation (solid symbols) and source of late-season nitrogen fertilizer (30 kg N ha^{-1} applied as either ammonium nitrate prills (circles) or as a spray of urea solution (squares) on the amounts of nitrogen per ear bearing stem in different above ground components of winter wheat in 2003 (mean of three cultivars and two fungicide treatments). Vertical bars are S.E. (12 D.F.) for comparing nitrogen treatments within an irrigation treatment. Fitted lines are logistic (constant omitted for grain N). Experiment F3; 2003.

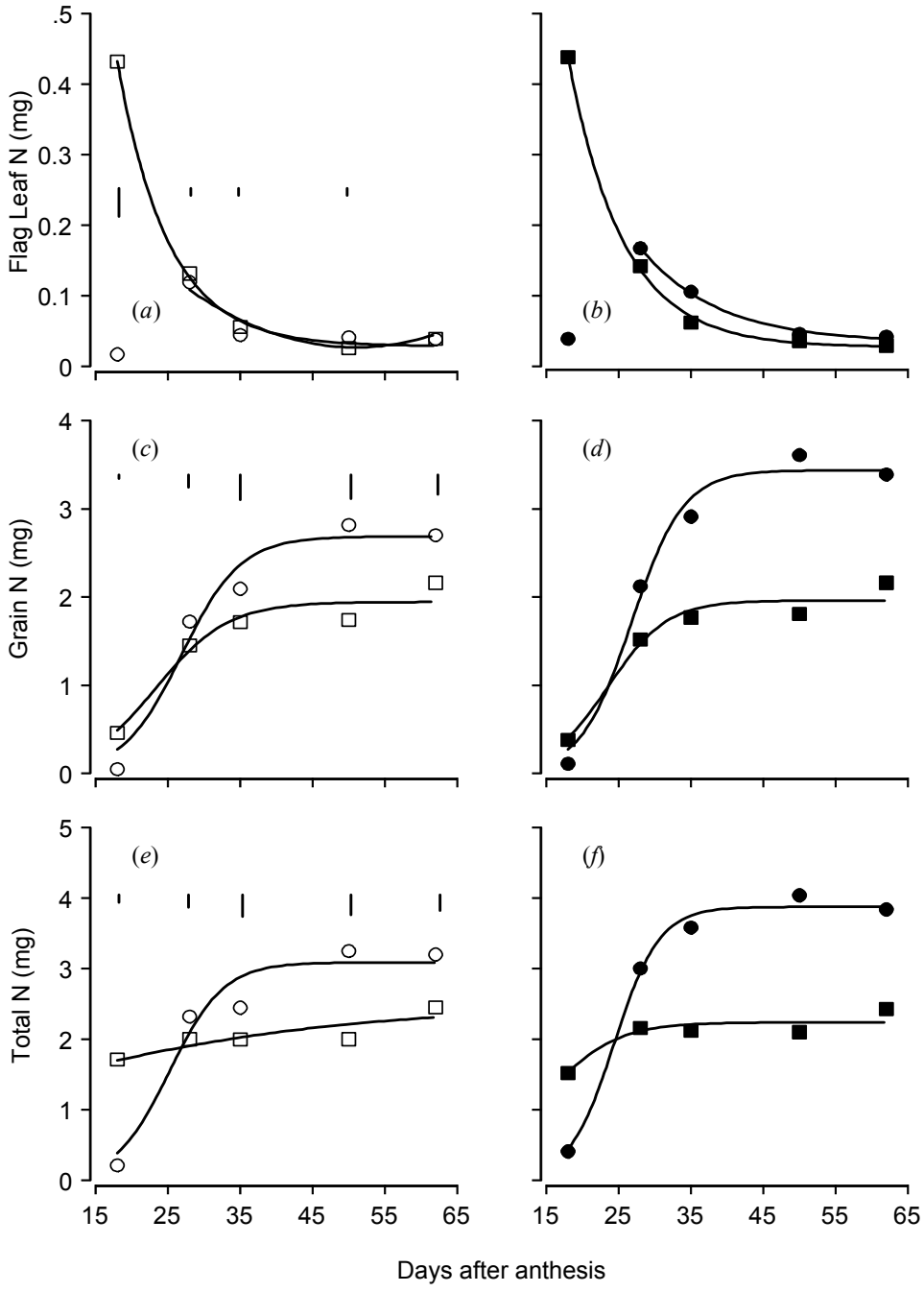

Fig. 5.22. The effect of late-season irrigation (solid symbols) on recovery of nitrogen from different sources of late-season nitrogen fertilizer (30 kg N ha^{-1} applied as either ammonium nitrate prills (circles) or as a spray of urea solution (squares)) labelled with ^{15}N, in different above ground components of winter wheat stems in 2003 (mean of three cultivars and two fungicide treatments). Vertical bars are S.E. (12 D.F.) for comparing nitrogen treatments within an irrigation treatment. Fitted lines are exponential (*a,c*) and logistic (*d-f*; constant omitted for grain N). Experiment F3; 2003.

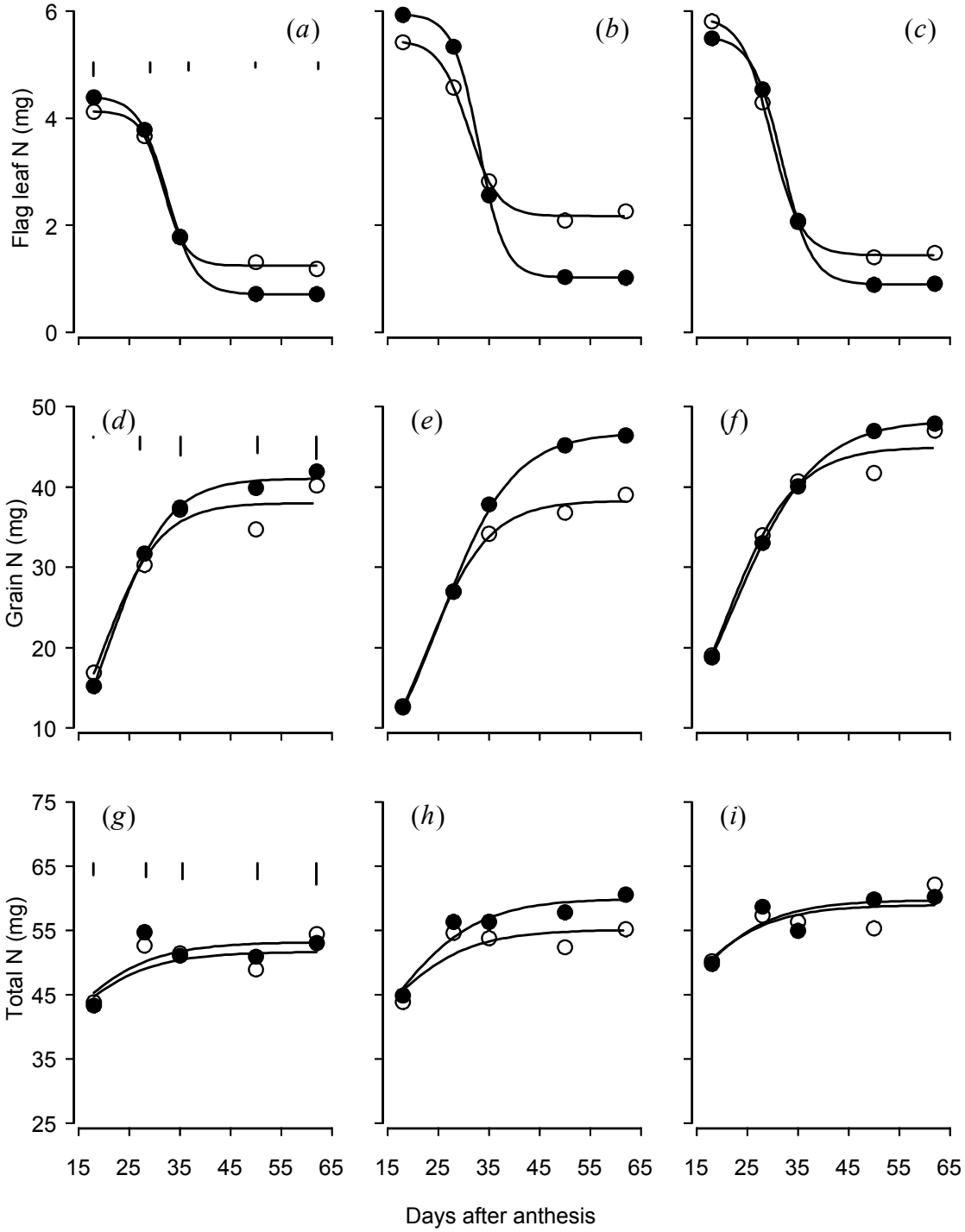

Fig. 5.23. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on amounts of nitrogen per ear bearing stem in different above ground components. Left, middle and right columns of graphs correspond to cvs Shamrock, Consort and Hereward respectively. Fitted curves are logistic (constant omitted for *d-f*). Points are means of different late-season nitrogen and irrigation treatments. Vertical bars in Shamrock graphs are S.E. (min. D.F. is 32) for comparing points within a variety. Experiment F3; 2003.

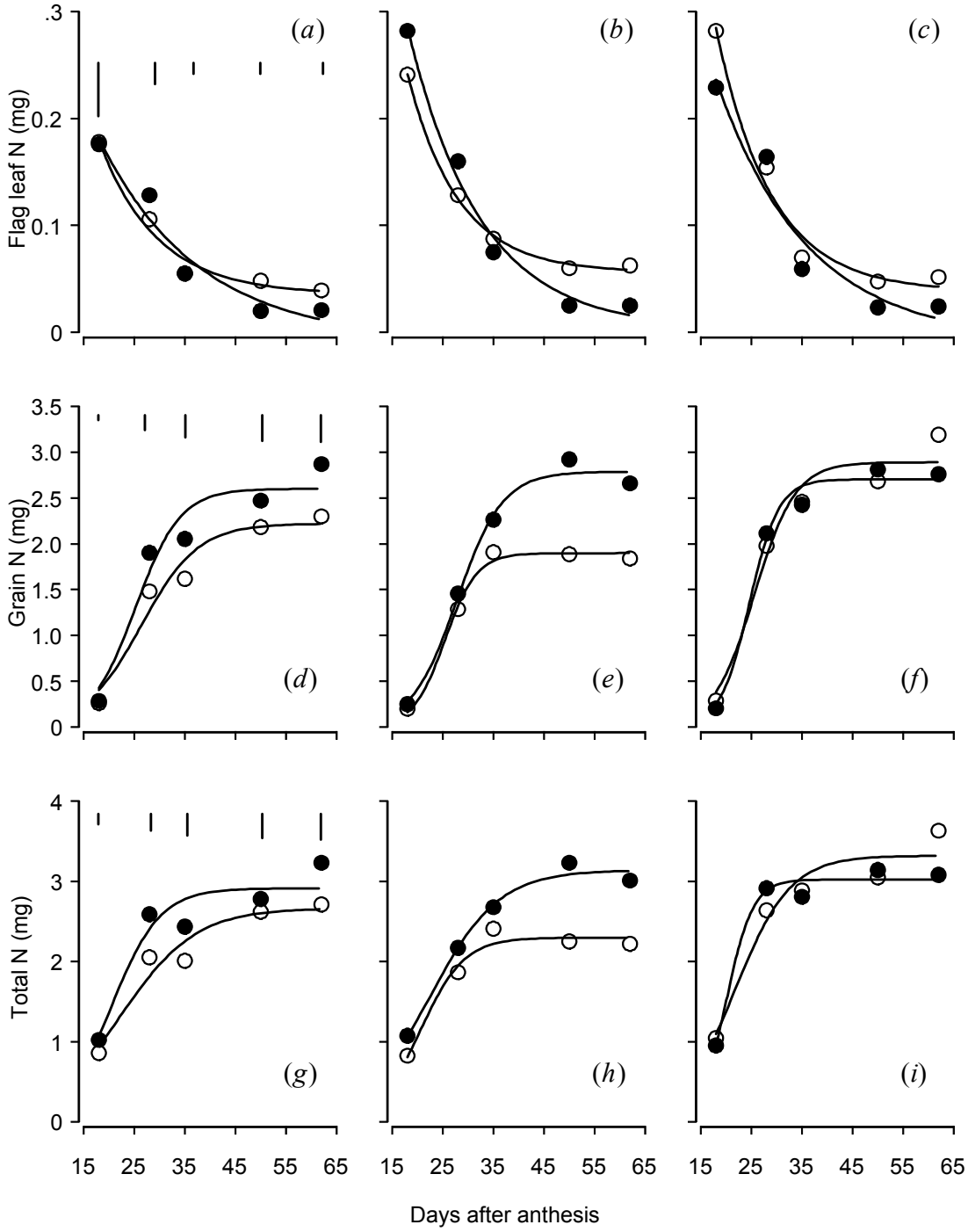

Fig. 5.24. The effect of winter wheat cultivar without (○) and with (●) fungicide treatment (63+125 g ha^{-1} of epoxiconazole + azoxystrobin applied at flag leaf emergence and again at ear emergence) on amounts of nitrogen recovered from ^{15}N-labelled late-season nitrogen fertilizer per ear bearing stem in different above ground components. Left, middle and right columns of graphs correspond to cvs Shamrock, Consort and Hereward respectively. Fitted curves are exponential (*a*-*c*) or logistic (*d*-*l*; constant omitted). Points are means of different late-season nitrogen and irrigation treatments. Vertical bars in Shamrock graphs are S.E. (min. D.F. is 32) for comparing points within a variety. Experiment F3; 2003.

5.4. Analyses over three seasons

Over all three seasons and Experiments F1 and F2, the extension the life of the flag leaf with fungicides was closely associated with grain yield and mean grain weight improvements (Fig. 5.25*a*; Table 5.33). Extending flag leaf life, or at least preventing premature senescence induced by disease, by ten days was associated with an increase in yield of 1.7 t ha^{-1} at 85% DM, an extra 5.7 g DM of thousand grain weight, and an increase of 2.5 kg hl^{-1} in specific weight. Despite these close associations, there were further significant improvements to all three models when allowing the response to vary with cultivar (Table 5.33). In all three cases Hereward, and particularly Shamrock, were less responsive to delays in senescence than the other four cultivars (Fig. 5.26-5.28). In contrast, there was no cultivar x *m* interaction for yield of nitrogen, for which a ten day delay in senescence resulted in an extra 27 kg N ha^{-1} being harvested in the grain. The relative conservatism over cultivar of the relationship between *m* and N yield, compared to *m* and grain yield resulted in the fungicide increasing the protein concentration of Shamrock, having no significant effect on protein concentration of Hereward, and reducing the protein concentration of the other cultivars, as flag leaf senescence was delayed (Table 5.33; Fig. 5.29).

Extending flag leaf life by ten days with fungicide was associated with a reduction in Hagberg falling number of 32 s (Fig. 5.25*d*), N:S ratio of 0.18 (Fig. 5.25*g*), SDS-sedimentation volume of 1.7 ml (Fig. 5.25*h*), and an increase in blackpoint severity of 1.9 ang. trans. score (Fig. 5.25*i*).

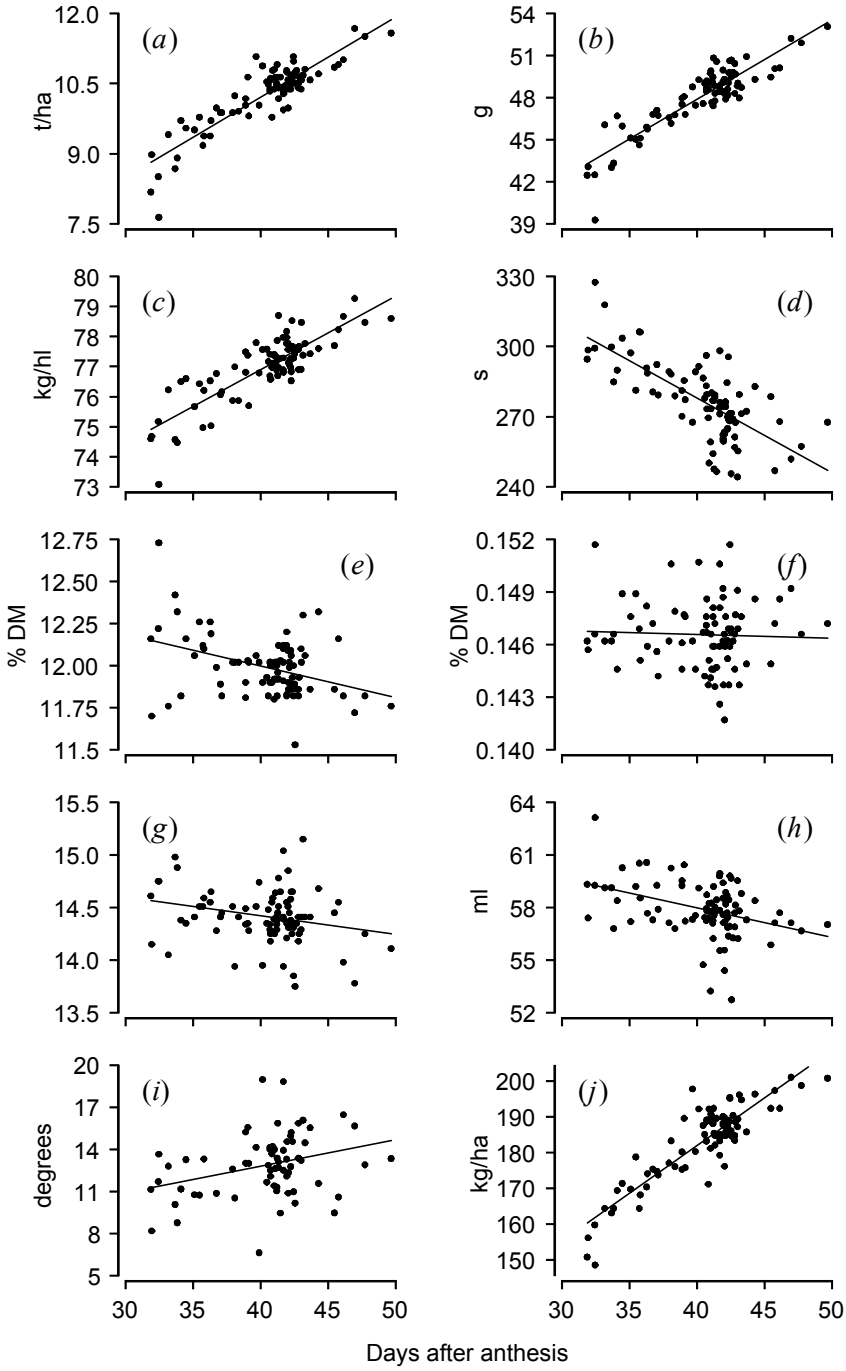

Fig. 5.25. Relationships between fungicide effects on time for the flag leaf to reach 37% green leaf area (Gompertz *m*) and fungicide effects on a) grain yield; b) thousand grain weight; c) specific weight; d) Hagberg falling number; e) protein concentration; f) sulphur concentration; g) N:S ratio; h) SDS-sedimentation volume; i) blackpoint; and j) yield of nitrogen in the grain. Points are fungicide treatment means after the main effects and interactions of cultivar, experiment, and year have been removed. Coefficients and errors are shown in Table 3.33. Note, DF=63, not *n*-2 because of the removal of effects.

Table 5.33. Relationships between the fungicide effect on the time for the green area of the flag leaf to decline to 37% (Gompertz *m*) and fungicide effects on grain yield and quality (See also Fig. 5.11)

Response variate	Main effect of *m* (day^{-1})	S.E. (63 DF)	P^a		Effects of *m* for different cultivars (where *P*<0.05 for cv.*m*)					
			m	cv.*m*	Sham-rock	Claire	Consort	Here-ward	Sava-nnah	Mala-cca
Grain yield ($t\ ha^{-1}$)	0.17	0.011	***	*	0.11	0.21	0.20	0.12	0.18	0.17
Thousand grain weight (g)	0.57	0.035	***	**	0.27	0.66	0.68	0.43	0.62	0.59
Specific weight ($kg\ hl^{-1}$)	0.25	0.021	***	***	0.13	0.36	0.29	0.11	0.18	0.39
Hagberg falling number (s)	-3.2	0.41	***	-						
Protein conc. (% DM)	-0.019	0.0057	**	**	0.032	-0.037	-0.022	-0.012	-0.037	-0.043
Sulphur conc. (% DM)	-2.23×10^{-5}	6.72×10^{-5}	-	-						
N:S ratio	-0.0176	0.00864	*	*	0.0276	-0.0718	-0.0113	0.0097	-0.0302	-0.0673
SDS sed. Volume (ml)	-0.169	0.0513	**	-						
Blackpoint (AT score)	0.19	0.078	*	-						
Yield of grain N ($kg\ ha^{-1}$)	2.67	0.176	***	-						

[a] -, *, **, *** = Probability (*P*) >0.05, <0.05, <0.01 and <0.001 respectively

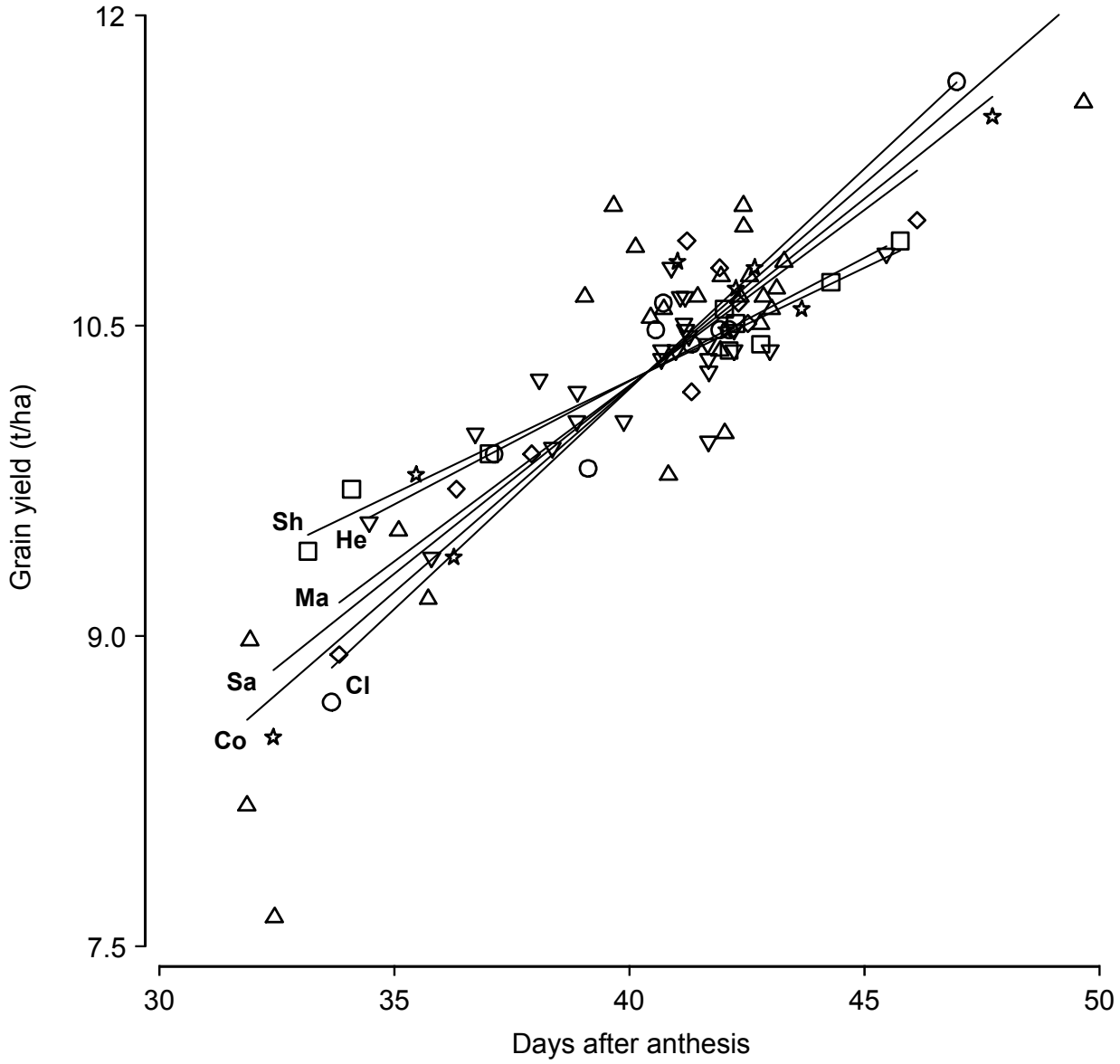

Fig. 5.26. Relationship between fungicide effect on time for the flag leaf to reach 37% green leaf area (Gompertz *m*) and fungicide effects on grain yield for Shamrock (Sh, □), Claire (Cl,○), Consort (Co, △), Hereward (He, ▽), Savannah (Sa, ☆), and Malacca (Ma, ◇). Points are fungicide treatment means after the main effects and interactions of cultivar, experiment, and year have been removed. Coefficients are shown in Table 5.33.

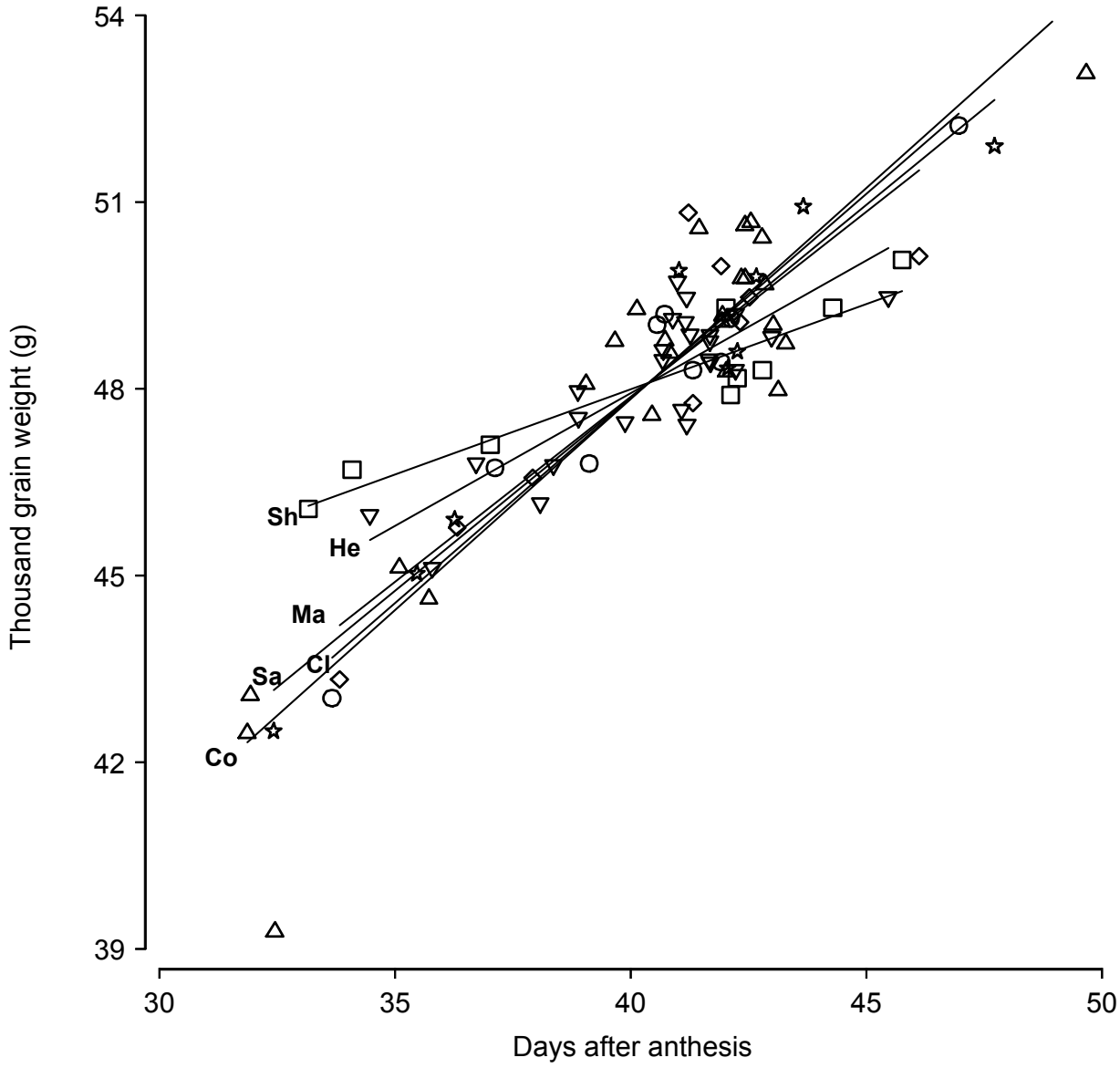

Fig. 5.27. Relationship between fungicide effect on time for the flag leaf to reach 37% green leaf area (Gompertz *m*) and fungicide effects on thousand grain weight for Shamrock (Sh, □), Claire (Cl,○), Consort (Co, △), Hereward (He, ▽), Savannah (Sa, ☆), and Malacca (Ma, ◇). Points are fungicide treatment means after the main effects and interactions of cultivar, experiment, and year have been removed. Coefficients are shown in Table 5.33.

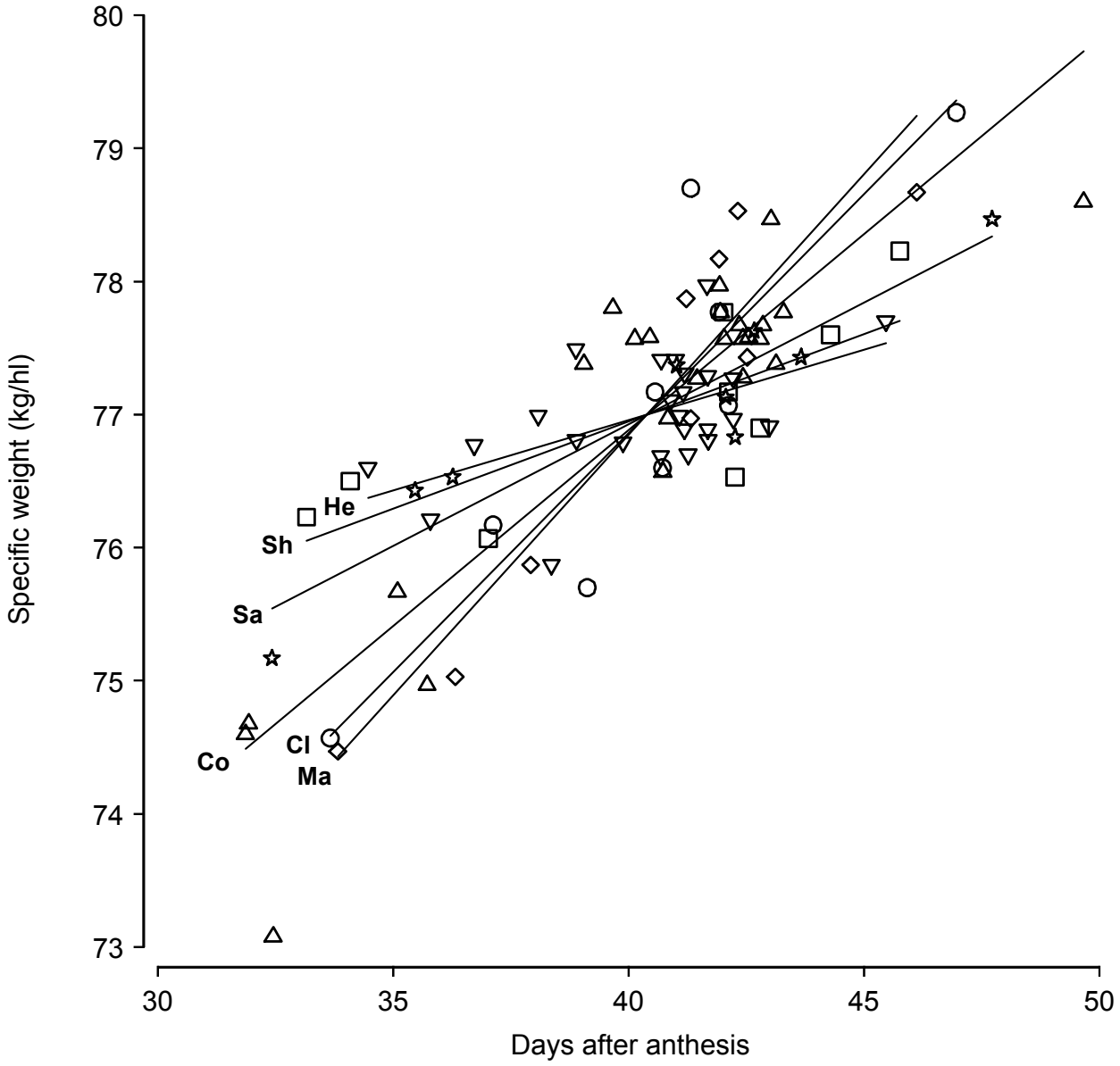

Fig. 5.28. Relationship between fungicide effect on time for the flag leaf to reach 37% green leaf area (Gompertz *m*) and fungicide effects on grain specific weight for Shamrock (Sh, □), Claire (Cl,○), Consort (Co, △), Hereward (He, ▽), Savannah (Sa, ☆), and Malacca (Ma, ◇). Points are fungicide treatment means after the main effects and interactions of cultivar, experiment, and year have been removed. Coefficients are shown in Table 5.33.

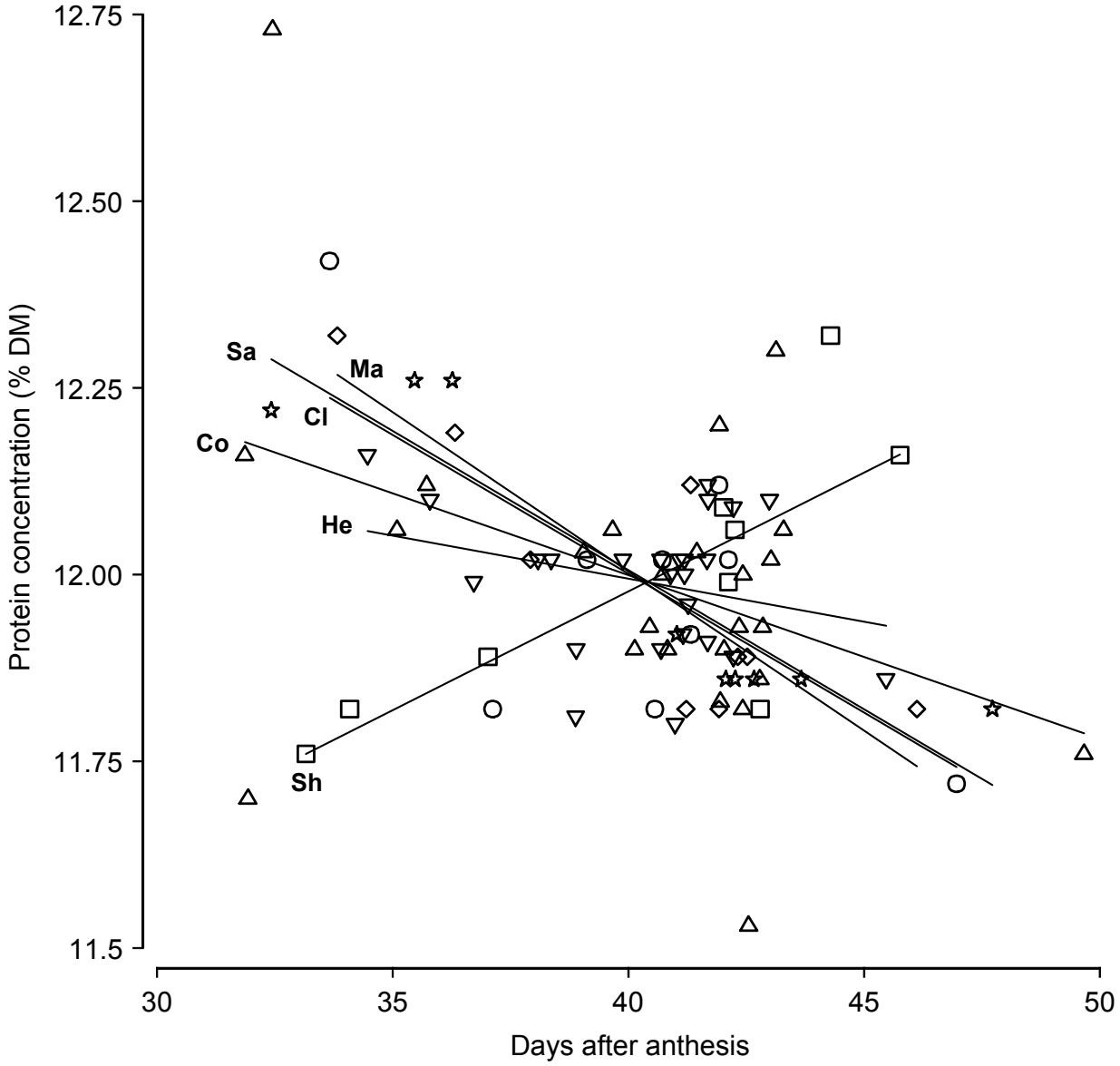

Fig. 5.29. Relationship between fungicide effect on time for the flag leaf to reach 37% green leaf area (Gompertz *m*) and fungicide effects on grain protein concentration for Shamrock (Sh, □), Claire (Cl,○), Consort (Co, △), Hereward (He, ▽), Savannah (Sa, ☆), and Malacca (Ma, ◇). Points are fungicide treatment means after the main effects and interactions of cultivar, experiment, and year have been removed. Coefficients are shown in Table 3.33.

6. Discussion of fungicide experiments (F1-F3)

A major aim of these experiments was to determine whether root extent and activity late in the season might influence the yield and quality responses of cultivars to disease control and late-season nitrogen applications. Root length densities in the plough layer at the start of, and during grain filling were comparable to other wheat crops (Barraclough, 1989) and can be regarded as sufficient not to limit the uptake of water and mobile ions (King *et al*., 2003). However, average root length densities below the plough layer were much lower and the ranges of 0.6 to 1.2 cm/cm^3 in 2001 and of 0.2 to 0.9 cm/cm^3 in 2002 suggesting that the soil was not being fully exploited by any of these modern cultivars (Barraclough, 1989; Sylvester-Bradley *et al*., 2001; King *et al*., 2003).

We have shown clearly that elite lines of wheat, grown under commercially relevant agronomy within the UK, differ with respect to quantity and distribution of roots both at and after anthesis. By the soft dough stage there were cultivars, such as Savannah in 2001, which had comparatively large root densities in the plough layer but low densities below it. In contrast, Shamrock was notable in having high root densities below the plough layer in both 2001 and 2002. Modelling approaches suggest that having a greater proportion of the root system at depth, rather than in the surface layers, would result in a more efficient use of resources (King *et al*., 2003) and would imply that the root distribution of Shamrock was more favourable than that of Savannah.

6.1. Grain yield

We found no evidence that grain yields of the cultivars studied, or the grain yield responses to disease control or late-season fertilizer application were related to post-anthesis rooting extent or distribution, in either a comparatively dry (2001) or wet (2002) season. However, this work is generally supportive of previous studies showing linear relationships between flag leaf life extension by fungicides and wheat yields (Gooding *et al*., 2000; Dimmock and Gooding, 2002*b*). The mean response of wheat yields increased by 0.17 t/ha for each day the flag leaf remained green; a response that was consistent with other estimates from experiments on sandy-loam soils (Dimmock and Gooding, 2002*b*; Ruske *et al*., 2003*a*). The simultaneous increase in thousand grain weight of 0.57 g/day and specific weight of 0.25 kg/hl/day occurs mostly because duration (Dimmock and Gooding, 2002*a*), and sometimes also rate (Pepler *et al*., 2005*c*), of grain filling is increased.

It appears that the main mechanism by which these fungicides delay senescence is via disease control. Direct physiological effects of fungicides cannot be ruled out, but the greatest fungicide effects on maintaining flag leaf green area were on the most disease susceptible cultivars in the year with most disease on the control plots (Treatment 1). Although not presented here, it was also possible to fit close linear relationships between fungicide treatment means of time to 37% green leaf area (Gompertz *m*) and logit transformed areas of disease in these (Pepler *et al*., 2005*b*) and neighbouring experiments (Ruske *et al*., 2003*a*) using similar fungicides. Increases in grain yield following disease control were via increases in both harvest index and above ground biomass (Ruske *et al*., 2003*a*).

Despite the overall, linear relationships between the persistence of flag leaf green area and yield, the results from Experiment F1 in 2002 suggest that improvements in yield are at least more variable, and may even be curtailed, as senescence is delayed beyond 700 ˚Cd post anthesis. This limit was also suggested by some other neighbouring experiments (Pepler *et al*., 2005*a*) and is consistent with the reanalysis of data from 2000 (Dimmock and Gooding, 2002*a*) presented in Fig. 1.1. The results from Experiment F1 2002 remove some of the ambiguity raised from Fig. 1.1, because they demonstrate a limit in the response of Consort, as well as in Hereward. It does not appear that any curtailment in the association between flag leaf green area duration and yield is due to extending canopy life into a period of severe drought because the effect was most evident in the wettest summer. Indeed, in the drier summers of 2001 and 2003 it was difficult to extend flag leaf life significantly beyond 700 ˚Cd post anthesis, presumably because canopy duration was ultimately limited more by the warmer and drier conditions (Shah and Paulsen, 2003) than by disease. When data from several years were considered, Pepler *et al*. (2005*a*) concluded that this limit to the association between leaf life and yield is more consistent when expressed in terms of thermal time, rather than in terms of days. This supports the hypothesis that the limit of association between canopy life and grain yield is more closely related to crop developmental stage, rather than to overall irradiance which would be expected to be associated more closely with days rather than thermal time.

The value of 700 ˚Cd is broadly consistent with duration to the end of grain filling for wheat crops at this site (Pepler *et al*., 2005*a*,*c*). It is tempting to suggest, therefore, that grain filling requires the flag leaf to remain green until this late stage in order to maximise yield. Alternatively, it is possible that such maintenance of flag leaf life could have been associated with causative effects occurring earlier in the maturation process. For example, it has been suggested that endosperm cell number, and/or maximum water content per grain, attained during the first two to three weeks after anthesis

is related to final grain weight (Brocklehurst, 1977; Cochrane and Duffus, 1983; Schnyder and Baum, 1992; Chandra and Singh, 1998). We have found that although disease control can lead to increases in maximum water content, neither this effect, nor an early increase in endosperm cell numbers is necessary for late-season fungicides to increase grain yields (Pepler *et al*., 2005*c*).

A value of about 700 ˚Cd is not necessarily constant for all cultivars. Indeed, cultivars can vary widely in their potential durations of grain filling (Zahedi and Jenner, 2003). However, it might be supposed that elite lines selected for the UK would have a similar grain filling duration if this was optimal for yield in our conditions.

What is clear is that the extent and distribution of roots for all of the cultivars tested here was not seriously limiting to yield or the response of yield to fungicide. In contrast to studies with older cultivars (e.g. Gregory et al., 1978) and elsewhere (e.g. Gregory 1994b), we found no evidence of significant net root senescence between anthesis and the soft-dough stage; indeed, in terms of root length density, the root system often appeared to grow during this period. There was no positive correlation between cultivar yield and root prevalence at any depth. Indeed, the comparatively high rooting densities of Hereward and Shamrock in 2002 were negatively associated with yields when disease had been controlled, and also with lower yield responses to fungicide applications. This result is not entirely unexpected as much of the variation in yield and fungicide response between cultivars was presumably due to differences in above ground biomass production, harvest index and disease susceptibility, and was therefore unlikely to be closely associated with rooting. The analyses over all years for F1 and F2 showed that yield, thousand grain weight and specific weight responses to an extension of leaf life following fungicide application were least for Hereward and Shamrock. This means that even when the differences in disease susceptibility are accounted for, there was no indication that the better rooting of Hereward and Shamrock allowed for an improved functioning of the canopy to generate grain yield despite green area duration being extended by fungicide use. Indeed, the results from 2002, and the analyses over all seasons suggest that the reverse may have been true. This suggestion is also supported by both F1 and F2 in 2001 when fungicide use simultaneously controlled disease, delayed senescence and increased grain yield, yet reduced the length of the rooting system. Such results would seem to indicate that greater yields might have been supported on smaller root systems than those actually present during grain filling. Despite this overall finding, it is possible that yields and yield responses may have been somewhat compromised by the size of the root system during grain filling in some circumstances. For example, the fungicide response in 2001 suggests some competition for dry matter between the various sinks, so that increased dry matter above ground was at the expense of root development.

6.2. Grain nitrogen and protein concentration

In contrast to the conclusions for yield, the results support the hypothesis that the size of the rooting system late in the season is important for increasing nitrogen uptake. We confirm that modern, elite lines of wheat accumulate large quantities of nitrogen after anthesis (Ruske *et al*., 2003*a*). The increase in grain nitrogen yield of 2.67 kg/N/ha for each day that the flag leaf was maintained is broadly consistent with analysis of other data sets (Dimmock and Gooding, 2002*b*; Ruske *et al*., 2003*a*), although we also demonstrate that, as with yield, the responses are likely to be less clear as senescence is delayed beyond 700 ˚Cd post anthesis. We show that about half of this extra nitrogen derives from improved uptake from below ground, and the remainder from more efficient remobilisation. We also show that the ability of a variety to accumulate nitrogen, and also to maintain or increase protein concentration as yields are increased following disease control, is associated with the length of roots below the plough layer late in the season. Although most nitrogen uptake late in the season is thought to derive from surface layers, significant quantities are available below the plough layer (Sylvester-Bradley *et al*., 2001). Low root length may limit the uptake of such N so that the increased root length of cultivars at depth can be advantageous.

Although the association between rooting at depth and the response of grain protein concentration to fungicide application was statistically significant in two seasons, there are other explanations or potential contributory factors to the fungicide x cultivar interactions on protein in these experiments. The increases in protein concentration following fungicide use on Consort in F1, 2001 and on Shamrock in F2 in 2001 and 2002 are consistent with many other observations that protein concentrations increase when rusts are the principal diseases controlled (Dimmock and Gooding, 2002*b*). Clearly, in such circumstances the pathogens must be more deleterious to nitrogen accumulation and/or partitioning within plants than they are to dry matter accumulation and/or partitioning. It has long been known that brown rust (*P. recondita*) can increase protein concentration in leaves and stems at the same time as reducing protein concentration in the grain (Caldwell *et al*.,1934; Greaney *et al*., 1941) commensurate with the results presented here. The retention of assimilate in plant organs infected by biotrophic pathogens such as rusts has been frequently reported (Crowdy & Manners 1971) and Lucas (1998) also suggests that rusts disturb the nutrient balance of the plant through physical damage to leaves. What has been less well documented, but clearly and repeatedly demonstrated here, is that infection by more necrotrophic pathogens, such as *Septoria tritici* can also lead to the retention of nitrogen within leaf laminae. Fungicide use has, therefore, increased both nitrogen uptake from the soil, and the remobilisation of

nitrogen from green tissues to the grain, irrespective of which foliar pathogen or pathogen complex has been controlled. It is also clear that fungicide use improves the uptake and remobilisation of nitrogen applied at and after anthesis as a urea spray or as solid ammonium nitrate prills. These beneficial effects of fungicides for nitrogen recovery and partitioning mean that fungicide impacts on grain protein concentration are small and inconsistent particularly compared with the dilution of protein that commonly occurs through other practices such as the selection of high yielding cultivars, or by growing wheat in some high yielding climates (Ruske *et al*., 2003*a*). The increased soil N uptake following fungicide use may have the added practical benefit that the risk of nitrate leaching in the subsequent autumn is reduced (Bryson, 2000; Ruske *et al*., 2003*a*).

A further explanation for the beneficial effects of fungicide on N uptake and grain N content may lie in the interaction of green leaf area persistence with the persistence of the root system. Many studies with older wheat cultivars demonstrate not only a decrease in root length but also a loss of N from the plant during grain filling (Gregory et al., 1979). The pathways of N loss from wheat during grain-filling are several, but loss via a degenerating root system has been frequently cited as a major pathway. The beneficial effects of fungicide in sustaining a green canopy and a corresponding increase in root system longevity may also be beneficial in retaining plant N for subsequent transfer to the grain.

Late-season foliar urea often increased grain protein concentrations, and the yield of grain nitrogen. Neither effect, however, interacted with variety so we found no evidence that rooting extent or distribution was limiting response to foliar urea. We did not find that recovery of N from foliar urea applied at anthesis was consistently better than solid ammonium nitrate prills applied at the same time.

In addition to nitrogen, sulphur is an important component of protein complexes necessary for the production of bread (Zhoa *et al*., 1999*a*,*b*). The associations between rooting extent and sulphur yields and concentrations reported here may, therefore, indicate a further potential link between rooting ability and baking quality. Grain yields of sulphur were increased as senescence was delayed such that we found no evidence here that maintaining the canopy was to the detriment of grain sulphur concentration, nor N:S ratios (Pepler *et al*., 2005*b*). The pronounced losses of plant sulphur (up to 50% of that taken up at anthesis) during grain filling determined in older studies with wheat (Gregory et al., 1979) support that notion that the linked persistence of canopy and root system effected by fungicide use may be an important factor in sulphur retention, uptake and translocation to grain.

6.3. Hagberg falling number

The reduction in Hagberg falling number by fungicides in these experiments is consistent with previous observations (Gooding *et al*., 1986*b*; Kettlewell, 1997; Dimmock and Gooding, 2002*c*; Ruske *et al*., 2003*b*). This effect has been associated with delayed grain drying (Gooding *et al*., 1987; Kettlewell, 1997; Kettlewell and Cashman, 1997; Dimmock and Gooding, 2002*c*), a relationship that is consistent with the observation of Gale *et al*. (1983) that *alpha*-amylase activity in non-sprouted grain was greatest when grain drying during grain maturation had been slowed. Alternatively, Evers *et al*., (1995) proposed that large grains have impaired control over *alpha*-amylase, which emanated from the aleurone layer around the endosperm cavity (Greenwell *et al*., 2001). Larger grains have also been found to have large endosperm cavities (Evers *et al*., 1995), and the size and the extent of the disruption of these cavities has been related to *alpha*-amylase production (Kindred *et al*., 2005). Hence, fungicides may reduce Hagberg falling number via their effect on grain filling (Dimmock and Gooding, 2002*c*).

The results presented here do not support the suggestion that fungicide effects on Hagberg falling number may be related to effects on grain protein concentration (Kindred *et al*., 2005). Fungicide reduced Hagberg falling number of all varieties, but had different effects on grain protein concentration, increasing it in Shamrock but reducing it in other varieties. The fungicide effect on Hagberg falling number was not associated with rooting extent and distribution.

6.4. Blackpoint

The increase in blackpoint severity following fungicide use was consistent with other observations (Ellis *et al*., 1996; Dimmock and Gooding, 2002*c*; Ruske *et al*., 2003*b*). Although *Alternaria* spp. can often be isolated from blackpointed grain (King *et al*., 1981), reliable control with fungicides has not been achieved (Conner and Kuzyk, 1988; Gooding *et al*., 1993). Cochrane (1994*a*,*b*) demonstrated that the blackpoint discolouration results from peroxidases acting on phenols released following tissue damage. Damage can be caused by fungi, but sufficient damage may also result from pericarp cells being crushed during normal grain filling. For example, Williamson (1997) showed that differences in blackpoint severity between varieties were more closely associated with the activity of peroxidase isoenzymes than the amount of mycelium present. Crushing of pericarp cells may be more likely in larger grains and this might explain why heavier grains are more commonly affected by blackpoint (Lorenz, 1986; Cromey and Mulholland, 1988) and therefore why

fungicide programmes might exacerbate the problem. Fungicide applications at flag leaf emergence are particularly effective at increasing thousand grain weight and incidence of blackpoint (Ruske *et al*., 2003*b*) whereas applications at ear emergence can reduce infection pressures without greatly increasing grain size and hence might occasionally reduce blackpoint severity (Wang *et al*., 2002; Ruske *et al*., 2003*b*).

7. Conclusions

The major conclusions of this study were:

- The temporal pattern of wheat root growth in rainfed conditions was broadly consistent with previous work showing rapid growth during spring and a maximum at about anthesis. There was, though, little evidence of a marked decline in either root mass or length in the post-anthesis period and in many cases root length, though not mass, increased between anthesis and the soft dough stage.
- On this site, with a sandy loam soil that rapidly increases in bulk density below the cultivated layer, the distribution of roots tended to exhibit a bimodal character with similar root length from 0-30 cm and a smaller but almost constant value from 30-80 cm. Typical values of root length were 4 cm root cm^{-3} soil from 0-30 cm and 0.7 cm root cm^{-3} soil from 30-80 cm.
- There were significant differences between cultivars in the total length and distribution of roots in the soil profile. Hereward and Savannah had comparatively high root length in the top 10 cm, while Shamrock was the only cultivar to consistently have more than 1 cm root cm^{-3} soil below 30 cm depth. Savannah had less than 1 cm root cm^{-3} soil throughout the 30-80 cm zone.
- Applications of fungicide had only small, but seasonally variable, effects on root growth. In one season where disease pressure was low, fungicide had small negative effects on root length and dry matter at a few depths, while in a second season with higher disease incidence, fungicide increased root length at 10-20 cm.
- Applications of fungicide consistently increased the duration of green leaf area. Application at flag leaf emergence generally gave good control of all diseases with little benefit from a further application at ear emergence, although in some instances, application at ear emergence maintained the life of the flag leaf for longer. There were significant differences between cultivars in their responsiveness to fungicides with Consort being most affected.
- Fungicide applications significantly increased grain yields even in a year with comparatively low disease incidence. The main effect of fungicide was to increase thousand grain weight and specific weight.
- There was no relation between grain yield and post-anthesis rooting extent or distribution, but the size of the root system during the post-anthesis period was related to the uptake of late season N and hence to the quality of grain. Grain yield was related linearly to the duration of green leaf area after anthesis (yield increased by 0.17 t ha^{-1} for each day that the

flag leaf remained green), and the principal effect of fungicides was to delay leaf senescence via disease control.

- Application of fungicide generally increased the quantity of N in grain although the effect on grain protein concentration was more variable depending on whether the benefits of fungicide were greater for grain mass or grain N accumulation.
- Grain nitrogen content increased by 2.67 kg N ha^{-1} for each day that the flag leaf remained green, with about 50% of the additional nitrogen derived from improved uptake from the soil and 50% from more efficient remobilisation.
- The benefits to grain yield and nitrogen content to be gained from extending the green area duration of the flag leaf appear to be limited to the period less than 700 ^{o}Cd after anthesis.
- It is hypothesized that the beneficial effect of fungicide in delaying leaf senescence also delays the senescence of the root system leading to increased N in the grain either through the continued uptake of N into the crop or through the retention of N in the plant that would otherwise leak from the plant in a senescing system.
- Overall, the differences in rooting that exist between cultivars (especially in relation to the length below 30 cm) and the effect of water on late-season rooting, coupled with the relation between grain N content and the size of the post-anthesis root system, suggest that breeding/variety selection and agronomy could be exploited to optimise late-season rooting to use N more efficiently and to improve grain N content.
- Further experimentation to test the hypothesis outlined above is required on a wider range of soils than the single site used for these experiments.

References

ANON. (1976) *Manual of Plant Growth Stages and Disease Assessment Keys*. Ministry of Agriculture, Fisheries and Food (publications), Pinner, London, UK, 122 pp.

ANON. (2001) *A framework to optimise cereal root systems.* Ministry of Agriculture, Fisheries and Food. Project Reports AR 0902.

AUSTIN R B, FORD M A, EDRICH J A AND BLACKWELL R D (1977) The nitrogen economy of winter wheat. *Journal of Agricultural Science*, *Cambridge* **88**, 159-167.

BISCOE P V AND GALLAGHER J N (1978) A physiological analysis of cereal yield I. Production of dry matter. *Agricultural Progress* **53**, 51-70.

BRYSON R J (2000) The residual effects of strobilurin fungicides on soil nitrogen for the following crop. *HGCA project report no. 221.*

BRYSON R J, LEANDRO L AND JONES D R (2000) The physiological effects of kresoxim-methyl on wheat leaf greenness and the implications for crop yield. In *The Brighton Crop Protection Conference.* British Crop Protection Council, Thornton Heath, UK. pp. 739-746.

BARRACLOUGH P B (1984) The growth and activity of winter wheat roots in the field: root growth of high yielding crops in relation to shoot growth. *Journal of Agricultural Science* **103**, 439-442.

BARRACLOUGH P B (1989) Root growth and nutrient uptake by field crops under temperate conditions. *Aspects of Applied Biology 22, Roots and the Soil Environment* pp. 227-233.

BARRACLOUGH P B AND WEIR A H (1988) Effects of compacted subsoil layer on root and shoot growth, water-use and nutrient uptake of winter wheat. *Journal of Agricultural Science, Cambridge* **110**, 207-216.

BERTELSEN J R, DE NEERGAARD E AND SMEDEGAARD-PETERSEN V (2001) Fungicidal effects of azoxystrobin and epoxiconazole on phyllosphere fungi, senescence and yield of winter wheat. *Plant Pathology* **50**, 190-205.

BINGHAM I J (2001) Soil-root-canopy interactions. *Annals of Applied Biology* **138**, 243-251.

BOUMA T J, NIELSEN K L AND KOUTSTAAL B (2000) Sample preparation and scanning protocol for computerised analysis of root length and diameter. *Plant and Soil* **218**, 185-196.

BROCKLEHURST P A (1977) Factors controlling grain weight in wheat **266**, 348-349.

BROUWER R (1962) Nutritive influences on the distribution of dry matter in the plant. *Netherlands Journal of Agricultural Science* **10**, 399-408.

CALDWELL R M, KRAYBILL H R, SULLIVAN J T AND COMPTON L E (1934). Effect of leaf rust (*Puccinia triticina*) on yield, physical characters and composition of winter wheats. *Journal of Agricultural Research* **12**, 1049-1071.

CHANDA S V AND SINGH Y D (1998) Cell enlargement as an important factor in controlling grain weight in wheat. *Journal of Agronomy and Crop Science -Z. Acker Pflanzenbau* **181**, 223-228.

CLARKE M P (2002) *Irrigation Effects on Growth, Yield and Quality of Winter Wheat as Predicted by Models and Observed in Field Experiments.* PhD Thesis, The University of Reading. 239 pp.

CLARKE M P, GOODING M J AND JONES S A (2004) The effects of irrigation, nitrogen fertilizer and grain size on Hagberg falling number, specific weight and blackpoint of winter wheat. *Journal of the Science of Food and Agriculture* **84**, 227-236.

COCHRANE M P (1994*a*) Observations on the germ aleurone of barley – morphology and histochemistry. *Annals of Botany* **73**, 113-119.

COCHRANE M P (1994*b*) Observations on the germ aleurone of barley – phenol oxidase and peroxidase activity. *Annals of Botany* **73**, 121-128.

COCHRANE M P AND DUFFUS C M (1983) Endosperm cell number in cultivars of barley differing in grain weight. *Annals of Applied Biology* **102**, 177-187.

CONNER R L AND KUZYK A D (1988) Effectiveness of fungicides in controlling stripe rust, leaf rust, and blackpoint in soft white spring wheat. *Canadian Journal of Plant Pathology* **10**, 321-326.

COSSER N D, GOODING M J, THOMPSON A J AND FROUD-WILLIAMS R J (1997) Competitive ability and tolerance of organically grown wheat cultivars to natural weed infestations. *Annals of Applied Biology* **130**, 523-535.

CROMEY M G AND MULHOLLAND R I (1988) Blackpoint of wheat: fungal associations, cultivar susceptibility, and effects on grain weight and germination. *New Zealand Journal Agricultural Research* **31**, 51-56.

CROWDY S H AND MANNERS J G (1971) Microbial disease and plant productivity. *Symposia of the Society of General Microbiology* **21**, 103-123.

DIMMOCK J P R E AND GOODING M J (2002*a*) The effects of fungicides on rate and duration of grain filling in winter wheat in relation to maintenance of flag leaf green area. *Journal of Agricultural Science, Cambridge* **138**, 1-16.

DIMMOCK J P R E AND GOODING M J (2002*b*) The influence of foliar diseases, and their control by fungicides, on the protein concentration in wheat grain: A review. *Journal of Agricultural Science, Cambridge* **138**, 349-366.

DIMMOCK J P R E AND GOODING M J (2002*c*) Effects of fungicides on Hagberg falling number and blackpoint in winter wheat. *Crop Protection* **21**, 475-487.

DRAPER S R AND STEWART B A (1980) Procedures for the comparative assessment of quality in crop varieties. III. Methods used in assessing grain protein content, Hagberg falling number, ease of milling and the baking quality of wheat varieties. *Journal of the National Institute of Agricultural Botany* **15**, 1-14.

ELLIS F B (1979) Roots and their function in soil. In *The Yield of Cereals*. National Agricultural Centre, Stoneleigh. pp. 3-5.

ELLIS S A, GOODING M J AND THOMPSON A J 1996 Factors influencing the relative susceptibility of wheat cultivars (*Triticum aestivum* L) to blackpoint. *Crop Protection* **15**, 69-76.

EVANS L T, WARDLAW I F AND FISCHER R A (1975) Wheat. In *Crop Physiology* (ed. Evans L T), Cambridge University Press, Cambridge. pp. 101-149.

EVERS A D, FLINTHAM J AND KOTECHA K (1995) *Alpha*-amylase and grain size in wheat. *Journal of Cereal Science* **21**, 1-3.

FARRAND E A (1972) Potential milling and baking value of home grown wheat. *Journal of the National Institute of Agricultural Botany* **12**, 464-470.

FOULKES M J, SYLVESTER-BRADLEY R AND SCOTT R K (1998) Evidence for differences between winter wheat cultivars in acquisition of soil mineral nitrogen and uptake and utilization of applied fertilizer nitrogen. *Journal of Agricultural Science* **130**, 29-44.

GALE M D, FLINTHAM J E, ARTHUR E D (1983) Alpha-amylase production in the late-stages of grain development – an early sprouting damage risk period. In *Third International Symposium on Pre-harvest Sprouting in Cereals* (eds Kruger J E and LabBerge D E). Westview Press, Boulder, CO, USA. pp. 29-35.

GALE M R AND GRIGAL D F (1987) Vertical root distributions of northern tree species in relation to successional status. *Canadian Journal of Forest Research* **17**, 829-834.

GENSTAT 5 COMMITTEE (1993) *Genstat 5 Release 3 Reference Manual*. Clarendon Press, Oxford.

GOODING M J AND DAVIES W P (1992) Foliar urea fertilization of cereals: A review. *Fertilizer Research* **32**, 209-222.

GOODING M J AND DAVIES W P (1997) *Wheat Production and Utilization: Systems, Quality and the Environment*. CAB International, Wallingford, UK. 355pp.

GOODING M J, KETTLEWELL P S, DAVIES W P AND HOCKING T J (1986*a*) Effects of spring nitrogen fertilizer on the Hagberg falling number of grain from breadmaking varieties of winter wheat. *Journal of Agricultural Science, Cambridge* **107**, 475-477.

GOODING M J, DAVIES W P, KETTLEWELL P S AND HOCKING T J (1986*b*) The influence of late-season fungicide application and disease on the Hagberg falling number of grain from breadmaking varieties of winter wheat. *Cereal Research Communications* **14**, 245-249.

GOODING M J, KETTLEWELL P S, DAVIES W P AND HOCKING T J (1987) Do fungicides reduce Hagberg falling number of wheat by maintaining grain moisture content during grain development. *Aspects of Applied Biology 15, Cereal Quality* pp. 413-416.

GOODING M J, THOMPSON A J, COLLINGBORN F M B SMITH S P AND DAVIES W P (1993) Blackpoint on wheat grain: Influences of cultivar, management and season on symptom severity. *Aspects of Applied Biology 36, Cereal Quality III.* pp. 391-396.

GOODING M J, DIMMOCK J P R E, FRANCE J AND JONES S A (2000) Green leaf area decline of wheat flag leaves: the influence of fungicides and relationships with mean grain weight and grain yield. *Annals of Applied Biology* **136**, 77-84.

GREANEY F J, WOODWARD J C AND WHITESIDE A G O (1941). The effect of stem rust on the yield, quality, chemical composition, and milling and baking properties of Marquis wheat. *Scientific Agriculture* **22**, 40-60.

GREENWELL P, CAUVIN S P, BHANDARI D, FLINTHAM J, GALE M, BRIARTY G AND EVERS A D (2001). *Prediction and Prevention of Excessive Enzyme Activity in Cereals Through Investigation and Manipulation of Causal Factors.* Project Report No. 247. Home-Grown Cereal-Authority, London.

GREGORY P J, CRAWFORD D V and MCGOWAN M. (1979). Nutrient relations of winter wheat 1. Accumulation and distribution of Na, K, Ca, Mg, P, S and N. *Journal of Agricultural Science, Cambridge* **93,** 485-494.

GREGORY P J, MCGOWAN M, BISCOE P W AND HUNTER B (1978) Water relations of winter wheat. 1. Growth of the root system. *Journal of Agricultural Science, Cambridge* **91**, 91-102.

GREGORY P J (1994*a*) Root growth and activity. In *Physiology and Determination of Crop Yield.* American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. Madison, WI. pp. 65-93.

GREGORY P J (1994*b*) Resource capture by root networks. In *Resource Capture by Crops* (eds Monteith J L, Scott R K and Unsworth M E). Nottingham University Press, Nottingham. pp. 77-97.

GREGORY P J, PALTA J A AND BATTS G R (1997) Root systems and root:mass ratio – carbon allocation under current and projected atmospheric conditions in arable crops. *Plant and Soil* **187**, 221-228.

GROSSMANN K AND RETZLAFF G (1997) Bioregulatory effects of the fungicidal strobilurin kresoxim- methyl in wheat (*Triticum aestivum*). *Pesticide Science* **50**, 11-20.

HARRIS G A AND CAMPBELL G S (1989) Automated quantification of roots using a simple image analyser. *Agronomy Journal* **81**, 935-938.

HOPKINS J W (1968) Protein content of Western Canadian hard red spring wheat in relation to some environmental factors. *Agricultural Meteorology* **5**, 411-431.

KAY F F (1936) The soil series. In *A soil survey of the University Farm, Sonning, Berks*., Department of Agricultural Chemistry, The University of Reading, Reading, UK, pp.10-26.

KETTLEWELL P S (1997) Seasonal variation in the response of Hagberg falling and liquefaction numbers to propiconazole fungicide in wheat. *Annals of Applied Biology* **130**, 569-580.

KETTLEWELL P S AND CASHMAN M M (1997) Alpha-amylase activity of wheat grain from crops differing in grain drying rate. *Journal of Agricultural Science* **128**, 127-134.

KETTLEWELL P S (1999) The response of *alpha*-amylase activity during wheat grain development to nitrogen fertiliser. *Annals of Applied Biology* 134, 241-249.

KINDRED D R, GOODING M J AND ELLIS R H (2005) Nitrogen fertilizer and seed rate effects on Hagberg falling number and hybrid wheats and their parents are associated with alpha-amylase activity, grain cavity size and dormancy. *Journal of the Science of Food and Agriculture* (In press).

KING J E, EVERS A D AND STEWART B A (1981) Black-point of grain in spring wheats of the 1978 harvest. *Plant Pathology* **30**, 51-53.

KING J, GAY A, SYLVESTER-BRADLEY R, BINGHAM I, FOULKES J, GREGORY P, ROBINSON D (2003) Modelling cereal root systems for water and nitrogen capture: Towards an economic optimum. *Annals of Botany* **91**, 383-390.

KIRCHHOF G (1992) Measurement of root length and thickness using a hand held computer scanner. *Field Crops Research* **29**, 79-88.

KLEPPER B (1991) Crop root-system response to irrigation. *Irrigation Science* **12**, 105-108.

LOOMIS R S AND CONNOR D J (1992) *Crop Ecology: Productivity and Management in Agricultural Systems*. Cambridge University Press, Cambridge.

LORENZ K (1986) Effects of blackpoint on grain composition and baking quality of New Zealand wheat. *New Zealand Journal of Agricultural Research* **29**, 711-718.

LUCAS J A (1998) *Plant Pathology and Plant Pathogens* 3rd Edition. Oxford: Blackwell Science.

LUCAS M E, HOAD S P, RUSSELL G AND BINGHAM I J (2000). *Management of Cereal Root Systems.* HGCA Research Review 43. Home Grown Cereals Authority, London.

MACDONALD A J S AND DAVIES W J (1996) Keeping in touch: responses of the whole plant to deficits in water and nitrogen supply. *Advances in Botanical Research* **22**, 229-300.

MACLEOD J (1993) The United Kingdom variety evaluation system: present and potential service to the industry. *Proceedings of the Cereals R & D Conference, Cambridge.* Home Grown Cereals Authority, London. pp. 1-20.

MATTHEWS G A (2000) *Pesticide Application Methods* 3rd edn. Blackwell Science, Oxford, UK, 448 pp.

MCGRATH S P AND ZHAO F J (1995) A risk assessment of sulfur deficiency in cereals using soil and atmospheric deposition data. *Soil Use and Management* **11,** 110-114.

PEPLER S, GOODING M J, FORD K E AND ELLIS R H (2005*a*) A temporal limit to the association between flag leaf life extension by fungicides and wheat yields. *European Journal of Agronomy* (In Press)

PEPLER S, GOODING M J, FORD K E, ELLIS R H AND JONES S A (2005*b*) Delaying senescence of wheat with fungicides has interacting effects with cultivar on sulphur concentration but not with nitrogen : sulphur ratios. *European Journal of Agronomy* (In Press)

PEPLER S, GOODING M J AND ELLIS R H (2005*c*) A conjoint model of grain water content and dry matter during grain development and maturation to interpret fungicide effects on mean grain dry weight in wheat. *Field Crops Research* (Submitted).

POWLSON D S, HART P B S, POULTON P R, JOHNSTON A E AND JENKINSON D S (1992) Influence of soil type, crop management and weather on the recovery of ^{15}N-labelled fertilizer applied to winter wheat in spring. *Journal of Agricultural Science, Cambridge* **118**, 83-100.

PUSHMAN F M AND BINGHAM J (1976) The effects of a granular nitrogen fertilizer and a foliar spray of urea on yield and bread-making quality of ten winter wheats. *Journal of Agricultural Science, Cambridge* **87**, 281-292.

READMAN R J, BECKWITH C P AND KETTLEWELL P S (2002) Effects of spray application of urea fertilizer at stem extension on winter wheat: N recovery and nitrate leaching. *Journal of Agricultural Science*, *Cambridge* **139**, 11-25.

ROBINSON D, LINEHAN D J AND GORDON D C (1994) Capture of nitrate from soil by wheat in relation to root length, nitrogen inflow and availability. *New Phytologist* **128**, 297-305.

RUSKE R E, GOODING M J AND JONES S A (2003*a*) The effects of triazole and strobilurin fungicide programmes on nitrogen uptake, partitioning, remobilization and grain N accumulation in winter wheat cultivars. *Journal of Agricultural Science, Cambridge* **140**, 395-407.

RUSKE R E, GOODING M J AND JONES S A (2003*b*) The effects of adding picoxystrobin, azoxystrobin and nitrogen to a triazole programme on disease control, flag leaf senescence, yield and grain quality of winter wheat. *Crop Protection* **22**, 975-987

RUSKE R E, GOODING M J AND DOBRASZCZYK B J (2004) Effects of triazole and strobilurin fungicide programmes, with and without late-season nitrogen fertiliser on the baking quality of Malacca winter wheat. *Journal of Cereal Science* **40**, 1-8.

SCHNYDER H AND BAUM U (1992) Growth of the grain of wheat (*Triticum aestivum* L.). The relationship between water content and dry matter accumulation. *European Journal of Agronomy* **1**, 51-57.

SHAH N H AND PAULSEN G M (2003) Interaction of drought and high temperature on photosynthesis and grain-filling of wheat. *Plant and Soil* **257** 219-226.

SMITH G P AND GOODING M J (1996) Relationships of wheat quality with climate and nitrogen application in regions of England (1974-1993). *Annals of Applied Biology* **129**, 97-108.

SMITH G P AND GOODING M J (1999) Models of wheat grain quality considering climate, cultivar and nitrogen effects. *Agricultural and Forest Meteorology* **94**, 159-170.

SYLVESTER-BRADLEY R, STOKES D T AND SCOTT R K (2001) Dynamics of nitrogen capture without: ferililizer: the baseline for fertilizing winter wheat in the UK. *Journal of Agricultural Science* **136**, 15-34.

TAYLOR A C AND GILMOUR A R (1971) Wheat protein prediction from climatic factors in southern New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry* **11**, 546-549.

VAN NOORDWIJK M (1983) Functional interpretation of root densities in the field for nutrient and water uptake. In *Root Ecology and its Practical Appliecation*. Proceedings of the International Symposium, Gumpenstein. pp. 207-226.

VERRELL A G AND OBRIEN L (1996) Wheat - protein trends in northern and central NSW, 1958-1993. *Australian Journal of Agricultural Research* **47**, 335-354.

WANG H, FERNANDEZ M R, CLARKE F R, DEPAUW R M AND CLARKE J M (2002) Effect of leaf spotting diseases on grain yield and seed traits of wheat in southern Saskatchewan. *Canadian*

Journal of Plant Science **82**, 507-512.

WELBANK P J, GIBB M J, TAYLOR P J AND WILLIAMS E D (1974) Root growth of cereal crops. *Rothamsted Experimental Station Report 1973* **2**, 26-66.

WILLIAMSON P M (1997) Black point of wheat: in vitro production of symptoms, enzymes involved, and association with *Alternaria alternata*. *Australian Journal of Agricultural Research* **48**, 13-19.

ZAHEDI M AND JENNER C F (2003) Analysis of effects in wheat of high temperature on grain filling attributes estimated from mathematical models of grain filling. *Journal of Agricultural Science, Cambridge* **141**, 203-212.

ZADOKS J C, CHANG T T AND KONZAK C F (1974) A decimal code for the growth stages of cereals. *Weed Research* **44**, 415-421.

ZHAO F J, HAWKESFORD M J, MCGRATH S P (1999*a*) Sulphur assimilation and effects on yield and quality of wheat. *Journal of Cereal Science* **30**, 1-17.

ZHAO F J, SALMON S E, WITHERS P J A, MONAGHAN J M, EVANS E J, SHEWRY P R AND MCGRATH S P (1999*b*) Variation in the breadmaking quality and rheological paroperties of wheat in relation to sulphur nutrition under field conditions. *Journal of Cereal Science* **30**, 19-31.