# SESSION 8B

# CROP PRODUCTION WITH REDUCED INPUTS

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| Chairman and Session Organiser: | Professor Bob Naylor<br>*Trelareg Consultants, Aberdeen, UK* |
| Papers: | 8B-1 to 8B-3 |

# A rational basis for the design of wheat canopy ideotypes

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## ABSTRACT

Canopy architecture influences the capture and use of radiation and the susceptibility of crops to disease and lodging. Architecture traits are heritable, and might therefore be exploited to develop more sustainable wheat varieties. However, a 'phenotype gap' exists between knowledge of the wheat genome and understanding of sustainable phenotypes that can provide commercially acceptable varieties. Previous research, done separately on radiation use, disease and lodging suggests that trade-offs will be necessary to optimise the benefits conferred by canopy traits (e.g. tall plants escape disease but are more prone to lodging). This paper describes work in progress to investigate whether a mathematical framework can be developed, which relates canopy traits with crop productivity, via their effect on radiation use, disease and lodging. The outputs of such a framework could be compared against benchmarks defined to measure sustainability.

## INTRODUCTION

Canopy architecture is crucial to the capacity of crops to exploit their environment because it is a key determinant of the interception of incoming radiation and the efficiency with which dry matter is produced. In wheat, canopy architecture is also a key determinant of 'field resistance' to disease (Lovell *et al.*, 1997; Parker *et al.*, 2002) and lodging (Baker *et al.*, 1998). Growers are currently dependent on agrochemical inputs to ameliorate losses in productivity caused by disease and lodging. Progress in developing efficient and environmentally responsible production systems is most likely to be achieved through better understanding and exploitation of crop genetic potential. Part of this will involve combining canopy traits that trap and use radiation efficiently whilst also minimising the risk of disease and lodging. Research done separately on radiation use, disease and lodging suggests that trade-offs will be necessary to optimise the benefits conferred by canopy traits (e.g. tall plants escape disease but are more prone to lodging).

This paper describes work in progress to investigate whether a mathematical framework can be developed, which relates canopy traits with crop productivity, via their effect on radiation use, disease and lodging. This approach will help the development of canopy ideotypes, which Donald (1968) proposed as a method for improving the effectiveness of breeding programmes.

## APPROACH

Models exist that describe how aspects of canopy architecture interrelate with (1) radiation interception and use efficiency (Campbell and Norman, 1998; Choudhury, 2000), (2) escape of splash borne foliar diseases (Parker *et al.*, 2002) and (3) lodging risk (Baker *et al.*, 1998). Only the radiation model output is a measure of crop productivity (dry matter accumulation), with the others calculating the area of disease infected leaves and lodging risk respectively. Therefore, the first objective of this paper is to identify 'coupling points' that enable the disease and lodging models to be integrated with the radiation model. The coupling points could be at the initial input stage of the radiation model or at one of the intermediate processes; radiation interception or radiation use efficiency (RUE). The concept of coupling points is well established for linking pests to crop growth models to predict yield reductions (Boote *et al.*, 1983), but is not well developed for ideotype design. As will be shown, the identification of coupling points requires the development of the disease and lodging models. The primary canopy traits that are considered by the models include leaf area index and leaf angle by the radiation model, crop height and leaf angle by the disease model and ear area, shoot height at centre of gravity and natural frequency by the lodging model. The models must consider the same traits to enable them to be optimised for productivity. Therefore the second objective of this paper will be to develop the models so that their inputs include similar canopy traits. This exercise has initially been carried out for crop height and leaf angle to demonstrate a method of working that could be applied for other characters.

## RESULTS

### Canopy and radiation

Theoretical models exist that describe how crop canopies intercept radiation (Campbell and Norman, 1998), photosynthesize and respire (Choudhury, 2000). These models can be combined to calculate dry matter accumulation from canopy architecture traits (leaf area, angle and nitrogen content) and from incoming radiation levels. We developed the models to make them more applicable to UK wheat and used them to investigate whether crop height has a significant effect on radiation capture and use.

Crop height determines the ratio of leaf area to stem area. There are two routes by which this ratio can affect the amount of radiation captured and the efficiency of dry matter production;

1. Rate of photosynthesis - due to different light response curves of lamina and sheath.
2. Rate of respiration – because stems have a greater N content per unit area of their photosynthesizing tissue, which will increase maintenance respiration.

To investigate how crop height might affect productivity we modelled the response of a crop without stems, using a leaf area index (LAI) of 4.5 and a canopy nitrogen content of 500 mmol $m^{-2}$. Then the amount of light intercepted, gross photosynthesis and respiration was calculated. The procedure was then repeated with the same LAI with a typical stem area index. This required several assumptions:

- that for a typical crop of 1m height, 25% of green area is contributed by the stem and that 50% of the canopy nitrogen is contained by the stems (Critchley, 2001). These assumptions require the addition of 1.5 units of stem area to the LAI and 500 mmol N $m^{-2}$ to the canopy nitrogen content.

- To account for changes in the mean orientation of the photosynthetic tissue due to the inclusion of stems, the leaves were assumed to have a mean angle of 57° (from horizontal) and the stems a mean angle of 90°. This gives a mean angle of 65° for the leaves and stems combined.

The mean concentration of radiation intercepted by the stems was estimated from their projected area, which is appropriate for sunny periods, and cylindrical sheath area was used for cloudy periods. Methods described by Choudhury (2000) were used to estimate the light response curve for a leaf sheath from its nitrogen content (Critchley, 2001), and this was used to estimate its gross rate of photosynthesis. Additional respiratory losses arising from the stems were also estimated. The calculations were repeated for other stem lengths by assuming that each 1 cm of stem adds 0.015 stem area index and 5 mmol N $m^{-2}$ of ground.

The model outputs indicated that increased stem height produced only small increases in gross photosynthesis and this was cancelled by an increase in respiratory losses. The leaf sheath makes a small contribution of photo-assimilate because it intercepts small amounts of light (due to its relatively small area and orientation) and because it has a low photosynthetic rate (about 25% of leaves). The latter is caused by the low nitrogen content of sheaths and is supported by measurements by Angus *et al.* (1972). Therefore it appears that the main effect of reducing height is to allow more assimilate to be partitioned to the developing ear, which results in more grains per ear and a larger sink (Calderini *et al.*, 1995; Fischer, 1984). This part of the work showed that radiation interception and use can be estimated from area, angle and nitrogen content of leaves

## Canopy and disease

Foliar diseases decrease radiation interception, primarily by reducing the LAI. Parker *et al.* (2002) have identified canopy architecture traits (internode length, leaf insertion angle, leaf length and stem extension rate) that allow the upper leaves to distance themselves from sporulating lesions on leaves lower down the canopy. The main effect of crop architecture is a shift in the epidemic curve, along the time axis. This shift is the result of less spores arriving on upper leaves when the crop is taller and internodes longer (Fraaije *et al.*, 2003). This is explained by the dependence of spore dispersal on rain splash height, a variable that can be predicted from the kinetic energy of raindrops (Lovell *et al.*, 2002; Pietravalle *et al.*, 2001). Crop height thus influences the amount of inoculum initiating the epidemic on the top three leaf layers. We have modelled the relationship between plant canopy (plant height and leaf angle) and symptom area index by a two-step process. First, the step from canopy architecture to spore arrival and then the step from spore arrival to symptom area index.

The effects of disease on yield are due primarily to the associated reduction in LAI and hence impairment of light capture during the crucial grain filling period (Parker *et al.*, 2002). The disease models we have developed could therefore be coupled to the radiation model, described above, through LAI. By this route the effect of disease could be expressed in terms of dry matter accumulation.

## Canopy and lodging

Baker *et al.* (1998) outlined a model that predicts lodging when the leverage force of the shoots exceed the strength of the stem base or anchorage system. Recently this model was validated by Berry *et al.* (2003).

Alterations to canopy architecture will have a direct effect on the leverage component of the lodging model by altering the traits that determine it: height at centre of gravity, natural frequency, ear area and shoot number per plant. Changes to ear area and shoot number are easy to quantify and are measured commonly in field experiments. However, height at centre of gravity and natural frequency are more difficult to quantify and might more appropriately be estimated through their relationships to more commonly measured variables.

Height at centre of gravity can be estimated by a function of its principal components; stem height, stem and leaf fresh weight, ear fresh weight and ear length. Berry (1998) showed that the non-uniform weight distribution of the shoot (heavier base) must be taken into account for the above function to calculate height at centre of gravity accurately. A sensitivity analysis showed that the most influential component of height at centre of gravity is stem height, that stem/leaf fresh weight and ear fresh weight are moderately important and variation in ear length has a negligible effect. This analysis indicates that leaf angle will not affect lodging. Berry *et al.* (2000) showed how natural frequency can be estimated from height at centre of gravity using an empirical relationship. Hence, the effect of changes in canopy traits, such as stem height, on plant leverage can be modelled by first calculating height at centre of gravity and using this to estimate natural frequency, which can then be used to derive shoot leverage. The results of this exercise show that plant leverage increases exponentially with height.

As a gross simplification we may assume that any change in the probability of lodging, due to altering shoot leverage, will equate to the mean percentage area lodged over a large run of years. The percentage area lodged could then be related to a reduced rate of dry matter accumulation since RUE appears to be reduced by 0.5% for each percentage area of crop lodged, when averaged over each day of grain filling (Stapper and Fischer, 1990). The relationship between lodging and reduction in RUE requires testing, but this illustrates how the lodging and radiation models could be coupled via RUE.

## DISCUSSION

The ongoing work, described in this paper, identifies coupling points for linking disease and lodging models with a model for calculating radiation capture and use. These coupling points are described in Figure 1, in which the models are represented by a series of steps in which the dependent variable in one step forms the independent variable in the next step. This coupling enables the models to estimate crop productivity, in terms of dry matter accumulation ($g^{-1}m^{-2}day^{-1}$), as a common output. This paper also describes how the models can be developed to make use of common inputs describing the crop canopy. This has been done for crop height and leaf angle. The importance of using common inputs and a common output is that the canopy traits may now be optimised for crop productivity. Sylvester-Bradley *et al.* (1997) and Paveley *et al.* (2001) demonstrated the value of this approach by using it to predict the prime influences on optimum nitrogen and fungicide dose respectively.

Future work must now couple these models explicitly and carry out the model development necessary to include more canopy traits (e.g. LAI and leaf N) as inputs that are common to all of the models. Specific experimentation will be required to test some of the less well understood parts of these models. The resulting model could then be used to design crop ideotypes that are best suited to different environments and management systems. The predicted performance of different ideotypes could be tested using doubled haploid mapping populations that segregate for the important canopy traits. The plant breeding and research communities have invested substantial monies into developing mapping populations of elite genetic material, many of which already segregate for some of the traits described here.

In time, the above framework could be usefully linked with the new canopy simulation implemented in SIRIUS (described in Parker *et al.*, 2003). This simulates the development of LAI according to environmental factors such as thermal time, water and N availability. The process of simulating inter-leaf distances has also been started. Linking these models would be mutually beneficial because it would enable SIRIUS to account for more of the processes that determine dry matter accumulation. The ideotype framework would benefit from a consideration of how environmental factors during crop development determine canopy traits. The models may also be adapted to help explain competition between weed and crop growth.

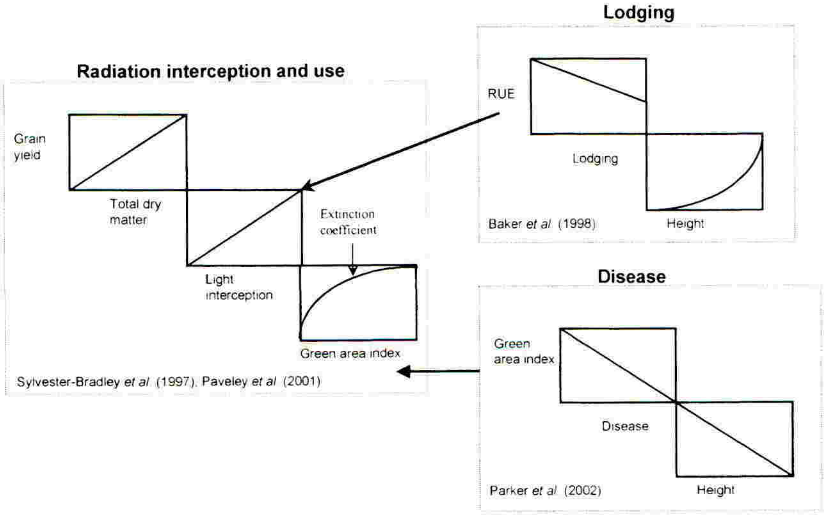

Figure 1. Hypothetical framework for integrating light, disease and lodging models for optimising wheat canopy ideotypes. In these sequences of steps the dependent variable of one step forms the independent variable of the next step.

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# Novel sensors for measuring soil nitrogen, water availability and strength

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## ABSTRACT

The availability of water and nitrogen to plant roots are very important factors determining the yield of crops. In soil these two factors are closely linked as nitrogen is chiefly available to crops as nitrate that is very soluble in water. Therefore environmental monitoring of both soil water and nitrate availability is important for crop production with reduced inputs. Progress in this area is limited by the lack of methods for *in situ* estimates of nitrogen status, soil strength and water availability in the field. In this paper we describe approaches to measure these soil variables in the field environment. We describe the development of sensors to measure soil matric potential between 0 to –300 kPa. An explanation of how these data can be used with soil water content data to estimate soil strength is presented. In other research, flexible N-sensors suitable for monitoring soil mineral nitrogen have been developed. These probes have been produced using a new type of nitrate-selective electrode that has been successfully used in rivers and drainage waters for environmental monitoring. The information obtained from the electrodes can be used to provide diagnostic decision support for fertiliser recommendations and for more general field monitoring by farmers.

## INTRODUCTION

The root environment has a major effect on crop growth, both directly through the supply of water and nutrients to the shoot, and indirectly through root to shoot signalling (Mulholland *et al.*, 1996). Developing more sustainable agriculture systems requires accurate and easy to use methods for measuring the main soil parameters that are likely to limit yield. Water and nitrogen supply are the two most important parameters for most UK crops. Measuring soil water and nitrogen availability and then matching supply to the changing crop demands is important for improving the efficient use of these resources. An imbalance between supply and demand leads to waste that has both economic and environmental costs.

Better management of crop root systems through agronomic practice and breeding has the potential to improve the efficiency of water and nutrient uptake, and limit root restrictions to crop growth. However, progress in this area is currently limited by the lack of sensors for *in situ* estimates of soil water, strength and nutritional status in the field. The challenge is to develop sensors that will report these parameters during the growing season of a crop which will then permit greater precision in the targeting and management of inputs.

In this paper we describe new types of sensors to directly measure soil strength, matric potential and nitrate availability. For the soil matric potential measurements, an explanation of how to use the effective stress theory to estimate soil strength from water content and matric potential data is presented, together with a laboratory validation of the effective stress theory. The nutrient measurements have adapted ion-selective electrode technology to give a robust sensor that can be directly inserted into the soil to report the concentration of nitrate that is available to the plant.

## MATERIALS AND METHODS

### Sensor for soil water matric potential

Hydraulic tensiometers can measure the matric potential of soil water between 0 (saturation) and approximately –85 kPa. In drier soils there are currently no reliable sensors available to measure matric potential. Whalley *et al.* (2001) describe the development of a sensor to measure matric potential, in the range 0 to –60 kPa, which is based on the measurement of the water content of a porous ceramic in hydraulic equilibrium with the soil. In this work, Whalley *et al.* (2001) described how to take hysteresis into account to achieve a better accuracy when calculating matric potential from the measured water content of the ceramic and the sensor worked over a narrow range of water potentials. Here, we have developed a sensor that can give estimates of matric potential between 0 and –300 kPa. We measured the water retention characteristics of a number of ceramics and selected one of these to form the basis of our porous material sensor of soil water matric potential. We used the method of Gaskin & Miller (1996) to measure the water content of the selected ceramic. This gives us the possibility of a sensor that can be powered by a 12V battery and therefore an easily-logged analogue output.

### Use of effective stress to predict soil strength

Soil tensile strength can be predicted using the effective stress theory which states that the tensile strength, $Y$, of a soil is given by,

$$Y = c - \left\{ \frac{\chi\psi}{f(s)} \right\}$$

where c is the soil's cohesion, $\chi$ is a factor that takes into account the proportion of failure surface occupied by water films at a matric potential of $\psi$ and $f(s)$ is a pore shape factor Mullins (2000). In wet soils, $f(s)$ is a constant and $\chi$ is approximately equal to the degree of saturation, $S$. As the matric potential, $\psi$, can be estimated over a wide range of soil moisture with the new sensor and $S$ can be estimated from dielectric sensors of soil water content, we can in principle calculate soil tensile strength from soil moisture measurement. In this paper we will examine if the theory of effective stress can be used to give a calibration between soil moisture status (i.e. the product $\psi S$) and soil penetrometer strength in a range relevant to root growth.

We measured the pressure needed to push a rotating penetrometer into two soils packed to dry bulk densities of 1.2 and 1.7 g $cm^{-3}$ at matric potentials between 0 and –300 kPa. The silty soil contained 19% clay, 70% silt and 11% sand and the sandy soil contained 9% clay, 24% silt and 67% sand. A rotating penetrometer is thought to give good estimates of the pressure that roots need to exert to deform soil (Bengough *et al.,* 1997). For these soils, in work not reported here, we confirmed that a common relationship existed between soil tensile strength and effective stress.

### Sensor for soil nitrate measurements

Nitrate-sensors for long term monitoring of nitrate in drainage water have recently been developed (Le Goff *et al*., 2002a). These nitrate-selective electrodes are made by covalently bonding the sensor molecule N,N,N-triallyl leucine betaine chloride to a polystyrene-*block* -polybutadiene-*block*-polystyrene polymer (SBS rubber). In river waters these electrodes have been used for two months continuous measurement of nitrate ($NO_3^-$) without any major decline in the response of the electrode. The characteristics of this electrode were a linear Nernstian range of 1 M to 5 x $10^{-6}$ M $NO_3^-$, a limit of detection of 3.4 x $10^{-7}$ M $NO_3^-$, with response times of 1 min or less and a three-fold selectivity for nitrate against chloride. These figures represented a significant improvement on current commercial $NO_3^-$ sensors and their stability of response and electrode lifetime in continuous use was also very satisfactory. The SBS rubber $NO_3^-$ sensor membranes have been further improved by the addition of clay to the membrane to give a threefold improvement in both tensile strength and resistance to penetration relative to the clay-free membranes (Le Goff *et al.*, 2003b). Field performance was also improved by at least a 20% increase in lifetime. These nitrate-electrodes are being tested for their feasibility to monitor soil $NO_3^-$ availability.

## RESULTS

### A porous material for the matric potential of soil water

The full design of this new sensor will be described in a later paper. In Figure 1 the output of our new sensor is given as a function of matric potential. The buriable part of the sensor is shown in the insert in Figure 1.

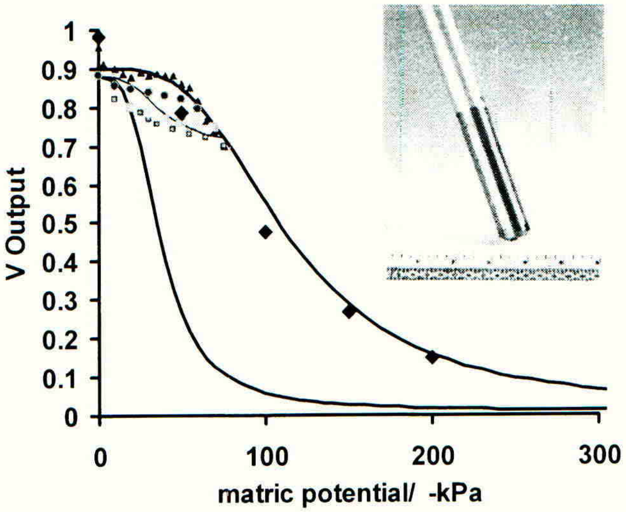

Figure 1. The voltage output of the porous material sensor of matric potential as a function of matric potential. Between matric potentials of 0 and –70 kPa wetting and drying scanning curves are shown. These are used in the calibration of the sensor with a model of hysteresis described by Whalley *et al.* (2001).

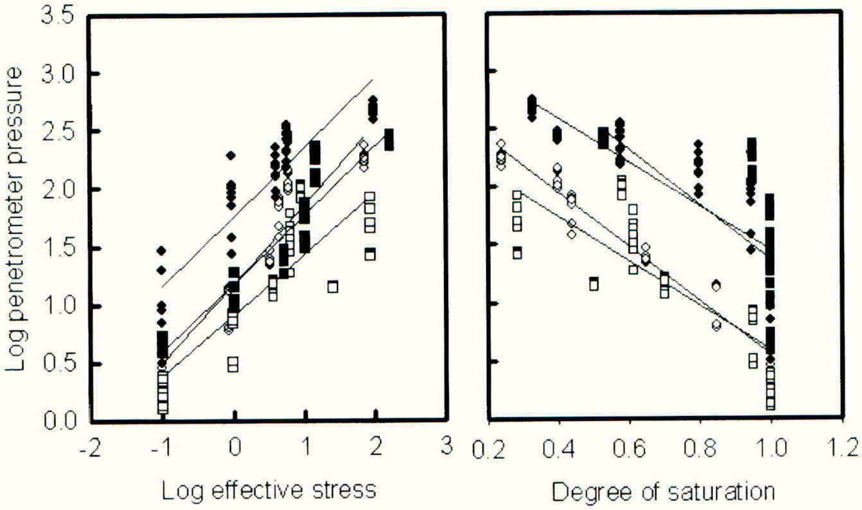

Figure 2. Log penetrometer pressure plotted against log effective stress (left panel) and the degree of saturation (right panel). The data shown is for a sandy soil (circles) and for a silty soil (squares). The soil was packed to bulk densities of 1.7 g $cm^{-3}$ (closed symbols) and 1.2 g $cm^{-3}$ (open symbols). The linear fits shown were all significant to $P<0.001$ and the percentage of variance accounted for is given in Table 1.

Table 1. Percentage of variance accounted for on the fits shown in Figure 2.

| Soil type | Bulk Density g $cm^{-3}$ | Percentage of variance accounted for between Log (Q) and | |
|---|---|---|---|
| | | S | Log (ψ S) |
| Sandy soil | 1.2 | 87 | 96 |
| | 1.7 | 76 | 62 |
| Silty soil | 1.2 | 59 | 63 |
| | 1.7 | 43 | 88 |

**Predicting soil strength from soil moisture status**

Figure 2 shows penetrometer pressure for two soils at two densities plotted against effective stress and the degree of saturation. Interestingly the relationship between penetrometer pressure and effective stress is linear on a log-log plot. It is already accepted that the relationship between penetrometer pressure and the degree of water saturation is linear when plotted as a log-linear plot. When the log of penetrometer pressure is plotted against degree of saturation, the data group according to bulk density. The use of effective stress reduced the grouping effect that resulted from bulk density, but did not eliminate it.

**Electrode measurements of soil nitrate availability**

The nitrate-selective membranes are hot-pressed at 150 °C and 220 kN as described previously (LeGoff *et al*., 2002a) and then small circular discs of 7 mm diameter are cut and pre-conditioned in 100 mM potassium nitrate solution for at least 7 days. Each disc was then clamped into a nylon housing that could be directly inserted into the soil. The final dimensions of the probe are very similar to those of the matric potential probe shown in Figure 1. The $NO_3^-$ probe was calibrated before and after three days of continuous recording in soil. The sample was a silty clay loam topsoil taken from the Broadbalk wheat experiment at Rothamsted (Goulding *et al*., 2000) to which 1 ml of distilled water per 2g of dried soil had been added 6 h before the $NO_3^-$ recordings were started. This soil was taken from the plot receiving no additional fertiliser and the soil water has a pH of 8.3.

The $NO_3^-$ electrode calibration measurements show that the detection limit of the electrodes (0.013-0.018 mM) is much lower than the values recorded from a soil that had received no additional fertilizer. These measurements were made on soil that had been previously air-dried and sieved, so after re-hydration of the soil there was a gradual decrease in $NO_3^-$ concentration from 15 mM after 6 h to a value of 2.5 mM after 3 days.

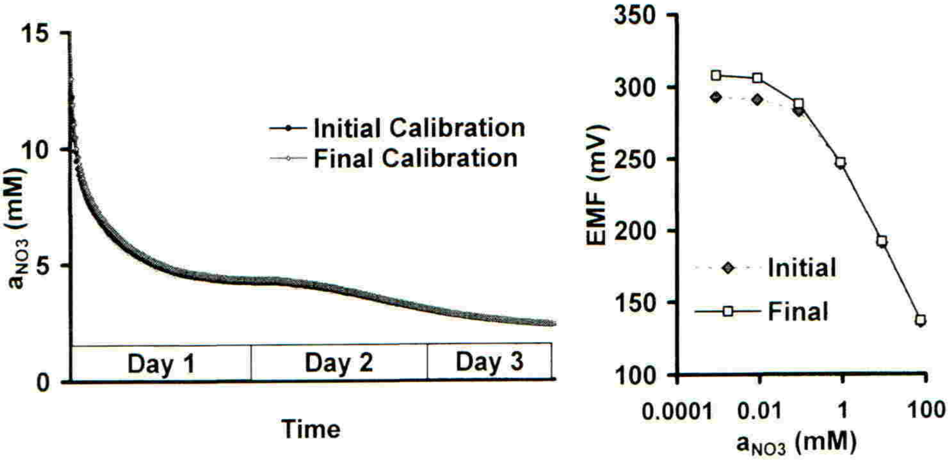

Figure 3. Continuous $NO_3^-$ electrode recording for 3 days in soil (left) showing the calibration before and after the measurement (right). Calibration shows electrode output (EMF) plotted against the $\log_{10}$ nitrate activity.

## DISCUSSION

The porous material sensors for soil water matric potential described in this paper are currently being tested in field experiments. The sensors will help us understand how crop growth is affected by soil strength and water stress in the field. The data in Figure 2 shows that it is possible to achieve high soil strengths (up to an equivalent root growth pressure of 400 kPa) at matric potentials as high as –300 kPa. This suggests that in UK conditions it is more likely that soil strength will limit plant growth than water stress. The integration of the assessment of water stress and soil strength will be an important tool in determining the plant response to the root growth environment.

Nitrate availability in the soil after the addition of water to an air dried sample has been measured using the electrode measuring system. The soil $NO_3^-$ concentrations are within the range of values obtained from porous suction cup samples collected under a similar type of soil (Barraclough, 1986). One major advantage of this type of soil measuring system is that the electrodes only report the local $NO_3^-$ concentrations that are available to the plant. An electrode placed alongside a root will directly report the $NO_3^-$ that is available to the plant in the soil.

In Figure 3 the gradual decrease in soil nitrate availability may result from an initial flush of bacterial denitrification, after an initial release of $NO_3^-$ on the addition of water. Nitrate is the main form of soil available nitrogen for crops, but in more acidic soils and at low temperatures more nitrogen is available as ammonium. Soil ammonium can also be measured using an ammonium-selective electrode (Wells & Miller, 2000).

Preliminary results for these two new types of soil sensing probes suggest an opportunity for the direct measurement of soil parameters that are major determinants of crop yield. By measuring water matric potential and nitrate availability in the soil these measurements can identify environmental conditions that may limit yield long before symptoms appear in the crop itself. These measurements can be used to feedback advice to management decisions thus enabling more efficient targeting of fertiliser and water to the crops requirements. However, these are early days for these new sensor systems and more work is required to establish how these measurements compare with current soil evaluation methods and to relate the data obtained to crop yields. For example, the relationship between soil depth and nitrate concentration that is optimal for crop yield but giving minimal leaching can be measured.

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# Adjusting the fungicide input in winter wheat depending on variety resistance

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## ABSTRACT

For 3 seasons, different fungicide input was tested in varieties with different degrees of resistance to septoria (*Septoria tritici*) and yellow rust (*Puccinia striiformis*). The yearly variation in benefits from fungicide application was considerable due to differences in climate and disease pressure. In individual years the differences in margin over fungicide cost from different fungicide inputs were small compared with the yearly variations. The economic optimum in resistant varieties was a TFI (Treatment Frequency Index) between 0.25 and 0.5. Most typically, only an ear application was profitable. In more susceptible varieties, the optimum TFI was 0.5-0.9, and a 2-spray programme gave a larger flexibility with regard to the dose needed at the 2nd application. The decision support system Crop Protection Online gave competitive disease control and margin over fungicides cost in line with or better than the standard treatments. A general TFI in winter wheat lower than the present target figure at 0.75 is possible if varieties with good resistance to septoria diseases and yellow rust increase significantly in area.

## INTRODUCTION

More than a 50% reduction in fungicide input in winter wheat has taken place during the last 20 years mainly due to use of appropriate and reduced dosages. Input of pesticides in Denmark is today generally measured as Treatment Frequency Index (TFI), which quantifies the number of full dosages applied in the field. The target figure in Pesticide Action Plan II for fungicide input in winter wheat has been recommended to 0.75. This target has generally been reached in 2002 (Anon., 2003). On average the number of treatments is two, and the average dose/TFI of fungicides is 0.35 per treatment (Farmstat & Kleffmann, 2002).

If further reduction plans are to be suggested, cropping of resistant varieties and adjusting of fungicide input according to the need in specific varieties are believed to become of increasing importance. In order to establish the economic optimal input of fungicides in varieties with different degrees of resistance, trials were carried out investigating the response from different input of TFI. The trials were carried out by both the Danish Institute of Agricultural Sciences (DIAS) and the Danish Agricultural Advisory Service (DAAS).

## MATERIALS AND METHODS

For 3 seasons (2000-2002), trials have been carried out investigating the response from different inputs of fungicides in varieties with significant differences in resistance levels. Following the national resistance ratings, varieties are grouped according to the degree of resistance (0-3; 3 = most susceptible). In this investigation, a variety is categorised as resistant if the variety has shown good resistance to both *Septoria tritici* and yellow rust (*Puccinia striiformis*). Severe attack of mildew (*Erysiphe graminis*) is regarded as having less impact on yields and is therefore not included in the categorisation in this paper. The following fungicides were used in the trials:

| **Products** | **normal rate** | **active ingredients per litre** | **Code** |
|---|---|---|---|
| Amistar | 1.0 l/ha | Azoxystrobin (250 g) | Az; |
| Folicur EW | 1.0 l/ha | Tebuconazole (250g) | Teb; |
| Opus | 1.0 l/ha | Epoxiconazole (125 g) | Epo; |
| Opus Team | 1.5 l/ha | Epoxiconazole (84 g) + fenpropimorph (250g) | EpoFen. |

### Control of diseases in 4 varieties with different dosages at heading (DIAS).

Four varieties (Table 1) were investigated using 3 different dosages of the tankmix Azoxytrobin + Tebuconazole as well as testing the recommendation given by the decision support system (DSS) Crop Protection Online (Hagelskjær & Jørgensen 2002) based on weekly assessments. In 2 of the 3 trial years, only applications at heading were investigated. In the 3rd year, ear treatments were tested with and without application at GS 31 (0,25 of normal dose of EpoFen). Ear treatments were in all 3 years:
1) Untreated; 2) 0.75 TFI (GS 51-55); 3) 0.5 TFI (GS 51-55); 4) 0.25 TFI (GS 51-55); 5) Recommendation given by Crop Protection Online.

Table 1. Number of trials and varieties investigated in the trials with different degrees of resistance. R= resistant; S = Susceptible.

| | 2000 | 2001 | 2002 |
|---|---|---|---|
| No. of trials (DIAS) | 2 | 2 | 2 |
| Varieties | Variety mixture | Variety mixture | Variety mixture |
| | Ritmo (S) | Ritmo (S) | Ritmo (S) |
| | Stakado (R) | Stakado (R) | Stakado (R) |
| | Hussar (S) | Hussar (S) | Kris (S) |
| No. of trials (DAAS) | 8 | 13 | 9 |
| Varieties | Kris (S) | Kris (S) | Kris (S) |
| | Ritmo (S) | Ritmo (S) | Baltimor (S) |
| | Stakado (R) | Stakado (R) | Boston (R) |

### Control of diseases in 3 varieties with different TFI's during the season (DAAS).

For 3 seasons, DAAS has carried out trials with different numbers of treatments and TFI applied in 3 major variety types (Table 1). The total input varied between 0.25 and 1.25 TFI divided into 1, 2 or 3 treatments (Table 2). A total of 30 trials were carried out according to these plans.

Net yield is calculated in dt/ha as the yield response in treated plots compared with untreated plots with costs of fungicides and application subtracted. The cost of application is set at 8 EUR per hectare, and the grain price at 8.7 EUR per decitonne.

Table 2. Trial plan carried out in DAAS trials 2000-2002 with variable numbers of treatments and dosages.

| Trial plan 2000-2001<br>Treatments (g a.i/ha) | GS | TFI | Trial plan 2002<br>Treatments (g a.i/ha) | GS | TFI |
|---|---|---|---|---|---|
| a. Untreated | | | a. Untreated | | |
| b. EpoFen (32+94) | 30-31 | 0.88 | b. EpoFen (32+94) | 30-31 | 0.88 |
| Teb (31) + Az (31) | 35-37 | | Epo (16) + Az (31) | 35-37 | |
| Teb (31) + Az (31) | 59-61 | | Epo (16) + Az (31) | 59-61 | |
| c. EpoFen (63+188) | 35-37 | 1.25 | c. Epo (16) + Az (31) | 35-37 | 0.50 |
| Teb (63) + Az (63) | 59-61 | | Epo (16) + Az (31) | 59-61 | |
| d. EpoFen (32+94) | 31-32 | 0.63 | d. EpoFen (32+94) | 31-32 | 0.63 |
| Teb (31) + Az (31) | 45-51 | | Epo (16) + Az (31) | 45-51 | |
| e. EpoFen (32+94) | 31-32 | 0.88 | e. EpoFen (32+94) | 31-32 | 0.88 |
| Teb (63) + Az (63) | 45-51 | | Epo (31) + Az (63) | 45-51 | |
| f. Teb (31) + Az (31) | 45-51 | 0.25 | f. Epo (16) + Az (31) | 45-51 | 0.25 |
| g. Teb (63) + Az (63) | 45-51 | 0.50 | g. Epo (31) + Az (63) | 45-51 | 0.50 |

## RESULTS

### Control of diseases in 4 varieties using different dosages for ear-application (DIAS).

In the 3 seasons, large differences in disease levels and obtained yield responses from ear application were found (Table 3). 2002 was a year with a very severe attack of septoria and high yield responses. The difference in yield response between varieties was only significant in 2002, where Stakado gave the lowest yield increase (Table 3; Figure 1). In 2000 and 2001, the net yields were only marginal. The dose response curves in all 3 years were very flat for the 3 tested dosages.

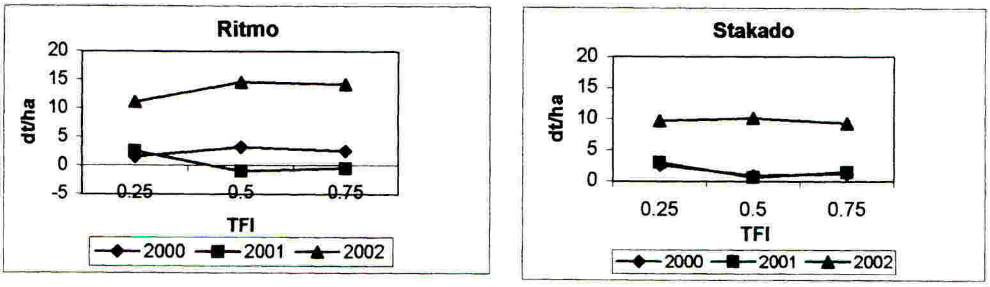

Figure 1. Margin over fungicide cost in Ritmo and Stakado using 3 different TFIs for ear treatments. Data from 3 years. 2 trials per year.

There is a tendency to an input of 0.5 TFI being optimal on Ritmo and Kris and 0.25 on Stakado (Figure 1). This was particularly the case in 2002 where the septoria attack was severe. Crop Protection Online has given a margin over fungicide cost at the same level as the best standard treatments (Table 3). The input from Crop Protection Online in the resistant variety Stakado was lower in 2 of the 3 years compared with the other varieties.

Trials in 2002 showed that treatment at GS 31 had a positive effect on net yield on susceptible varieties like Kris and Ritmo but not on the resistant variety Stakado (Figure 2). The results on Ritmo indicated that ear treatments with TFI =0.5 (63 g a.i. Az + 63 g a.i. Teb) were optimum. If no treatment had been applied earlier, an ear application of TFI = 0.25 was sub-optimal. If treatments had been applied before ear application, very little difference was seen between the 3 tested dosages investigated at heading, indicating that in susceptible varieties an early treatment (T1) gave a higher degree of flexibility regarding the choice of dose at heading. For the resistant variety Stakado, the optimum in 2002 was half dose both with and without treatment at GS 31; however, only with a minor and not significant difference to ¼ dose. Growing the variety mixtures generally reduced the level of septoria marginally compared with individual varieties and the optimum input was in line with susceptible varieties.

Table 3. Gross and net yield (dt/ha) in 4 varieties treated with different ear treatments in 3 years, 2 trials per year. In brackets under Crop Protection Online is given the TFI in the specific year and variety.

| Variety and year | **0.75 N**<br>94 g a.i. Az +<br>94 g a.i. Teb | | **0.5 N**<br>63 g a.i. Az +<br>63 g a.i. Teb | | **0.25 N**<br>31 g a.i. Az +<br>31 g a.i. Teb | | **Crop Protection Online** | |
|---|---|---|---|---|---|---|---|---|
| | gross | net | gross | net | Gross | net | gross | net |
| Variety mixture* | - | - | - | - | - | | - | |
| 2000 | 5.7 | -0.6 | 5.4 | 0.9 | 2.1 | -0.6 | 5.6 | 0.9 (0.5) |
| 2001 | 7.7 | 1.4 | 8.0 | 3.5 | 5.0 | 2.3 | 10.5 | 6.2 (0.56) |
| 2002 | 18.5 | 12.2 | 16.6 | 12.1 | 13.6 | 10.9 | 19.0 | 11.7 (0.75) |
| Ritmo | - | - | - | - | - | | - | |
| 2000 | 8.8 | 2.5 | 7.7 | 3.2 | 3.8 | 1.1 | 7.2 | 2.5 (0.5) |
| 2001 | 5.8 | -0.5 | 3.5 | -1.0 | 5.2 | 2.5 | 5.4 | 1.1 (0.56) |
| 2002 | 20.5 | 14.2 | 19.1 | 14.6 | 13.8 | 11.1 | 22.4 | 15.0 (0.76) |
| Stakado | - | - | - | - | - | | - | |
| 2000 | 7.5 | 1.2 | 5.4 | 0.9 | 5.3 | 2.6 | 4.6 | 1.0 (0.38) |
| 2001 | 7.8 | 1.5 | 3.9 | -0.6 | 5.7 | 3.0 | 4.8 | 1.3 (0.41) |
| 2002 | 15.6 | 9.3 | 14.5 | 10.1 | 12.4 | 9.7 | 17.0 | 9.4 (0.8) |
| Hussar/Kris | - | - | - | - | - | | - | |
| 2000 | 8.5 | 2.2 | 7.2 | 2.7 | 5.3 | 2.6 | 11.3 | 6.0 (0.57) |
| 2001 | 8.8 | 2.5 | 8.3 | 3.8 | 6.8 | 4.1 | 10.0 | 5.8 (0.56) |
| 2002 | 20.0 | 13.7 | 17.2 | 12.7 | 11.8 | 9.1 | 20.0 | 12.8 (0.74) |
| Average | 11.3 | 5.0 | 9.7 | 5.2 | 7.6 | 5.0 | 11.2 | 6.0 |

*Variety mixture =Ritmo. Stakado. Hussar/Kris

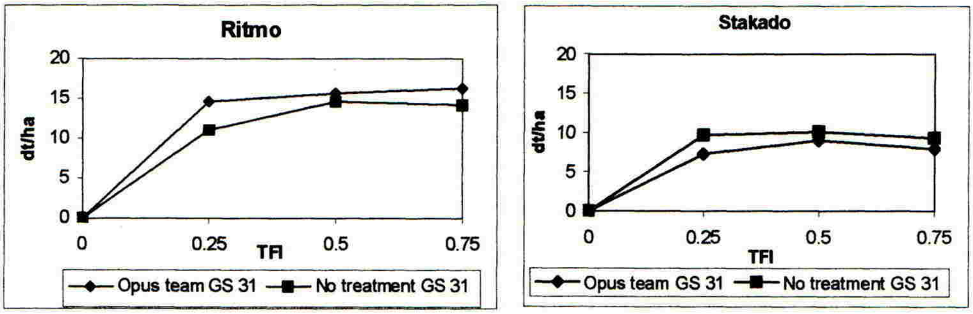

Figure 2. Margin over fungicide cost for ear application with 3 different dosages of the tank mix Amistar + Folicur in Ritmo and Stakado. The ear application is done with and without a treatment at GS 31 using EpoFen (32+94 g a.i./ha).

## Control of diseases in 3 varieties with different TFI's during the season (DAAS).

Results from the DAAS trials carried out showed generally small differences in margin over fungicide cost from the different input of fungicides measured as TFI (Figure 3-4). Stakado and Boston, which both have shown good resistance to septoria and yellow rust, generally gave the greatest margin over fungicide cost using TFI between 0.25 and 0.5. A single ear application was sufficient in those resistant varieties. In more susceptible varieties, the best margin was obtained using 0.5-0.9 TFI. Fungicide input above TFI = 1 generally did not give the optimal net return. In 2 trials with Stakado, the variety developed a severe attack of brown rust (*Puccinia recondita*). In those trials, higher net yields were obtained but one single ear application using 0.5 TFI gave the best margin. In 3 trials with Baltimor and Kris, a severe attack of yellow rust developed. In those trials, a TFI of 0.5-0.88 has been the optimal divided into 2 or 3 applications.

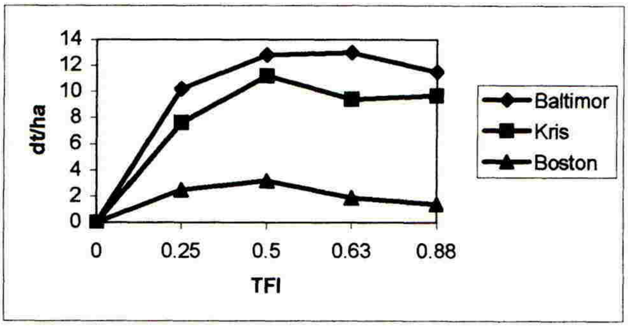

Figure 3. Margin over fungicide cost from different fungicide input (TFI) in 3 varieties with different resistance. 9 trials 2002.

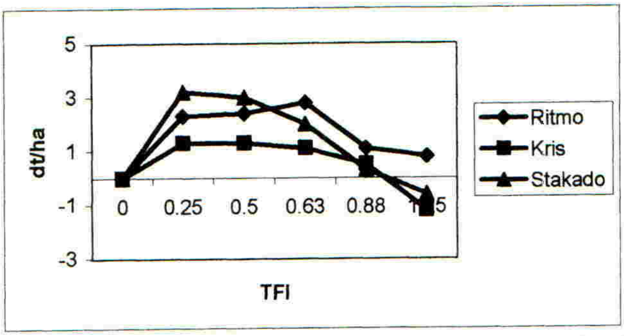

Figure 4. Margin over fungicide cost from different input of fungicides (TFI) in 3 varieties with different resistance. 21 trials 2000-2001.

## DISCUSSION

The optimal input with fungicides in wheat depends on the disease pressure and the climate in the individual season, but the susceptibility of the variety also plays a major role for the optimal input. The difference in margin between resistant and susceptible varieties was greatest in seasons with severe attacks of septoria and yellow rust. One single ear treatment was often sufficient in varieties with good resistance to rust and *Septoria tritici*, where more susceptible varieties needed 2 and more rarely 3 applications.

The dose-response curves for ear treatment were generally very flat. This was particularly the case if treatments at GS 31-32 had been applied prior to ear treatment leaving a great deal of flexibility regarding the choice of dose. In the most resistant varieties, a fungicide input of 0.25-0.5 TFI applied as an ear application gave the best economic result in all 3 seasons. A quarter dose was optimal at low levels of attack and a half dose in severe attacks. In more susceptible varieties, a fungicide input of 0.25-0.5 TFI was optimal under moderate attack, while 0.5-0.75 TFI was optimal under more severe attacks. Control of yellow rust generally required 2-3 treatments depending on when the epidemic starts. For control of this disease timing is more important than the dose.

Use of DSS like Crop Protection Online provide the possibility of adjusting input depending on disease pressure and susceptibility of the varieties. Recently, new varieties on the Danish market with good resistance to septoria and rust have increased the possibilities of reducing the TFI in wheat to a lower level than the present TFI input of approximately 0.75.

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