Chapter 1

Introduction

Agricultural research relies on the use of experimental field trials to test the effects of various crop treatments on production. The aim of agricultural production is to increase the amount and therefore the value of produce per unit area, whether this be in the form of plant biomass for animal consumption (pastures) or grain and fibre for human requirements. The type of treatments include; the addition of nutrients (fertiliser, organic matter); the control of weeds, pests and diseases with herbicides, insecticides or fungicides; improving the soil environment with and without tillage; and changing the crop agronomy by altering the sowing rate or sowing depth or row spacing. The success of these treatments can be judged by the improvement in crop biomass or yield compared to a control treatment. To gain a better understanding of the processes that govern crop production it is important to be able to estimate leaf area and biomass at various intervals during the growing season. This information will assist the agronomists create crop models that can be used to predict crop responses.

The grain yield, obtained by harvesting the crops at maturity, is the end result of the interaction between the various components of the system. These components include the supply of water and nutrients to the crop as well as environmental conditions such as sunlight, rainfall and temperature. Knowing the grain yield will not always be of use in identifying the constraints to crop production.

The introduction of new varieties with improved characteristics require testing in various seasons and environments (soil or climatic) to ensure reliable results. The measurement of crop biomass and yield plays a big part in the assessment process. Improvements in the assessment process could mean either a shorter time to release, or the opportunity to include a larger number of varieties in the breeding program.

This thesis investigates the utility of a remote sensing technique for measuring crop growth. The technique is primarily aimed at applications in research but it has already been adopted in some areas of precision agriculture. The research applications are in the areas of plant breeding and the effect of weed competition on crop production.

The cropping systems research unit at Tamworth Agricultural Institute has been in operation since 1979. At that time cropping soils were being degraded by excessive erosion caused by too much cultivation and removal of ground cover. The original aim of the group was to demonstrate the environmental and economic benefits of adopting conservation farming practices such as minimum tillage and no-tillage (Felton, 1983). In the early days many problems were found with the system such as disease carryover, the need for additional nitrogen fertiliser to maintain yields, and controlling weeds during the fallow season.

The adoption of no-till by the growers in northern NSW was held back because reliable weed control using cultivation was seen to be cheaper than using herbicides such as glyphosate. There was a long period of time before the patent on glyphosate was lifted and the unit cost fell. It was during this time that the concept of spot spraying was examined as a way of reducing the amount of herbicide used per hectare to control weeds in fallow fields. The distribution of weeds in a fallow paddock is uneven or clumped (Marshall, 1988; Rew and Cussans, 1995) and it made sense to save herbicide by only spraying areas where weeds were present and leave the remaining areas unsprayed.

Remote sensing technology using satellites had been developing and it was thought that it could be applied to this problem. Research at Tamworth began with the aim of developing a weed detection system. The major ground work was performed by Felton et al. (1987). They characterised the reflectance of different plants, soils and stubble and identified some differences that could be used to discriminate between them. The concept was patented in 1990 and soon after detectors became commercially available (Felton et al., 1991). Felton continued to develop other uses for this technology in agricultural research such as the measurement of crop biomass, assessing herbicide injury, and diagnosis of nutrient deficiencies.

It was in 1997 that I first became involved with this research being used on wheat and soybean crops. In 2000 I joined a Grains Research and Development Corporation funded project to investigate yield loss due to weeds in no-tillage winter crops such as wheat, canola, fababean and chickpea grown in wider row spacings. It became apparent that the use of the weed sensors would complement the normal measurements being used in the field trials. However, there was a gap in the knowledge on the calibration of these sensors for the main winter crops grown in the region.

This thesis explores the use of reflectance sensors in agronomic research experiments as an additional method of measuring crop biomass to traditional techniques. The plan of the thesis is as follows:

Chapter 2 is a literature review of biomass estimation using remote sensing methodology. The design of weed competition experiments will also be discussed and well as the past research findings from field experiments.

The site and climatic conditions under which the field experiments were undertaken are outlined in Chapter 3. A brief statistical section is included in this chapter as the models outlined are used in a number of chapters.

The calibration of a remote sensing method using reflectance sensors for four crop types is examined in Chapter 4. A weed competition experiment using mimic weeds is examined in Chapter 5. A weed competition experiment using a number of chickpea cultivars, mimic weeds and a remote sensing technique is examined in Chapter 6 followed by a set of general conclusions in Chapter 7.

Chapter 2

Review of literature

The literature review outlines the various methods now used to measure plant biomass. Remote sensing techniques will then be examined as an alternative method to measure biomass, leaf area and ultimately potential grain yield. Finally, these new methodologies will be applied to practical work in the area of weeds research. The design and use of weed competition field experiments will be discussed and related to the use of remote sensing techniques.

2.1 Plant biomass estimation methods

The measurement of crop biomass is a routine operation made by agronomists in their study of crop growth. The amount of biomass the crop produces during the growing season largely determines grain yield potential. Grain yield is obtained by a single measurement at harvest when the crop has reached maturity, while plant biomass is a dynamic variable that can be measured during the season. In agricultural research, agronomists are interested in testing factors that may affect plant biomass. Field trials are designed to test hypotheses, and biomass estimation is a critical part of this operation.

Tucker (1980) has reviewed the traditional methods and these can be separated into destructive and non-destructive groups. Destructive methods involve the sampling or clipping a known area from a plot and weighing the resulting sample. An estimate can then be calculated for the plant biomass per unit area. Apart from being a slow and tedious operation, damage to the plot by taking a large number of samples during the growing season can affect the final grain yield of the crop.

In contrast, non-destructive methods allow crops to survive to the final harvest intact and often are considerably faster. These include visual estimation procedures, beta attenuation, capacitance meters, weighted disc techniques and remote sensing. The ideal non-destructive method should be quick, accurate and inexpensive. Many of these methods have the disadvantage of requiring an instrument to be calibrated before use. At present, remote sensing methods are gaining most acceptance due to advances in technology and the decreasing cost of equipment. Ground-based remote sensing techniques will only be dealt with in this discussion due to their application for small scale plot experiments and their use in real-time detection and application systems.

2.2 Remote sensing

Remote sensing has been defined as "the science of deriving information about an object from measurements made at a distance from that object" by D.A. Landgrebe in Swain and Davis (1978). The quantity being measured is most commonly the reflected energy, from the electromagnetic spectrum, emanating from the target. The distance from the object to the sensor is not important as the same concept applies to data collected by satellite, aerial and ground-based systems. The data collected can be displayed as an image, such as a picture in either the visible wavebands or false colours for the non-visible wavebands, to assist in the visualisation of the data. An image may show many easily distinguishable features depending on the resolution of the data.

This section begins with some basic physics on the radiation laws and geometry. This is required for an understanding of remote sensing techniques.

2.2.1 Definitions

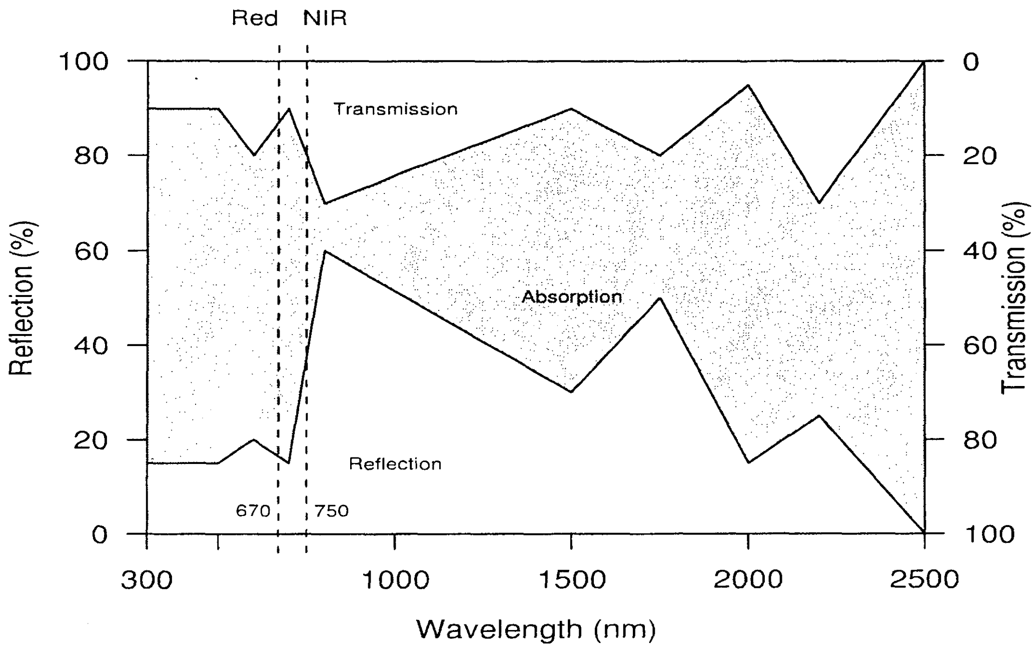
The sun emits radiation covering a wide range of wavelengths. The solar spectrum can be divided into three main regions: the ultra violet from 300 to 400 nm; the visible spectrum from 400 nm (blue light) to 700 nm (red light); and the infra-red from 700 nm to 3000 nm. Living plant foliage adsorbs most of the red and blue light and reflects most of the green light (500 nm) wavebands. This is why plant foliage appears green in colour. In this discussion the red (670 nm) and near-infrared (750 nm) are of primary interest. Figure 2.1 shows the position of these wavebands in the solar spectrum (Monteith, 1973).

Irradiance is the radiant flux density incident on a surface. The radiant flux is defined as the amount of radiant energy emitted, transmitted or received per unit of time and is usually expressed in units of watts (W). The radiant flux density is the amount of radiant flux per unit of area (W m^{-2}). The sun is the major source of energy that radiates energy to the earth. The atmosphere absorbs some of the energy coming from the sun and so the irradiance measured on a surface on earth is influenced by the length of travel through the atmosphere. The angle of the sunlight incident on a surface varies according to the time of the day and with the season.

The irradiance incident on a horizontal surface is the sum of components from direct and indirect (diffuse) radiation from the sun. The diffuse solar radiation comes from light that has been scattered by particles in the atmosphere and clouds. The direct solar radiation on a surface depends on the angle of incidence measured by its angle of elevation (β) with respect to the horizon or its zenith angle (ψ) with respect to a line perpendicular to the horizon.

When radiation (light) strikes an object it can be reflected, absorbed or transmitted. The radiance is the light emitted (reflected) from an object subject to irradiance. Absorp-

Figure 2.1: Schematic diagram of the relationship between the reflectivity, transmissivity and absorptivity of a green leaf.



tion is the radiation that is absorbed as energy by the object. Transmission is that portion of radiation that passes through an object and emerges on the other side. Reflectance is the ratio of radiance to irradiance expressed as a percentage. The reflectivity of a surface is the fraction of incident solar radiation reflected at a specific wavelength λ.

The behaviour of radiation energy incident on plant foliage can be quantified in terms by the energy balance equation (Swain and Davis, 1978)

$$\mathrm{I}_\lambda = \mathrm{R}_\lambda + \mathrm{A}_\lambda + \mathrm{T}_\lambda \tag{2.1}$$

where,

I_λ denotes incident energy or irradiance at wavelength λ,
R_λ is the reflected energy or radiance at wavelength λ,
A_λ is the absorbed energy at wavelength λ, and
T_λ is the transmitted energy at wavelength λ.

The reflected energy will vary over time due to changing atmospheric conditions and angle of the sun. Most instruments used in remote sensing, can only measure the reflected energy. By rearranging equation (2.1) it can be seen that the reflected energy is equal to the incident energy minus the sum of the absorbed and transmitted energy. However, by using the reflectance ratio, R/I, the data can be normalised so that measurements taken at different times can be compared.

The reflection coefficient or albedo is the average reflectivity over a specific waveband, weighted by the distribution of radiation in the solar spectrum (Monteith, 1973). As stated by McCloy (1983) "The reflectance of a surface is important, because it does not change unless the surface changes whereas the radiance, or energy reflected from a surface will change with season, time of day, and atmospheric conditions".

A beam of radiation aimed at a surface at an angle of incidence (ψ) normal to the surface is reflected at the same angle if the surface is a perfect reflector while a diffuse reflector will scatter the light in all directions. As long as the angle of incidence is less than 60 degrees the reflection coefficient is almost constant (Tageeva and Brandt, 1961; Monteith, 1973). The WeedSeeker® sensors, used for research in this thesis, were designed so that the emitted light is at an angle close to normal from the target. A narrow window and focusing lens are also used in the sensor to exclude some of the background radiation from the sun. This unwanted background radiation is a problem when the sun is at a high solar angle.

2.2.2 History of the development of remote sensing techniques for crops

When measuring the reflectance of an object there will always be an unwanted component in the signal referred to as noise. The noise may be from other objects or backgrounds in the field of view such as bare soil, that are not of primary interest. The ability to separate the noise from the signal relies on the differences in reflectance of a target and its background. One dimensional analysis is used when only one waveband is available to discriminate between the signal and noise. However, by using two wavebands measured simultaneously, two dimensional analysis can be performed. This analysis is superior in identifying objects into groups with a common two dimensional characteristic for example, soil, stubble and green foliage.

Two wavelengths that are particularly useful in quantifying the amount of biomass are the red (600-700 nm) and the near-infrared or NIR (750-1000 nm) wavebands as these are reflected differently from green foliage. The red region responds to the chlorophyll density of the foliage i.e. less reflectance with higher chlorophyll density due to greater absorption. The near-infrared waveband responds to the green leaf density i.e. more reflectance with higher green leaf density. The point where the electromagnetic spectrum changes from visual (including red) to near-infrared is approximately 700 nm and is known as the 'red edge' (Scotford and Miller, 2005). The application of remote sensing to agriculture relies on these differences in reflective properties of the target and background. The work by Swain and Davis (1978) compared the reflectance of green leaves, wheat stubble and grey soil and they found that there were differences in the reflection of red and NIR wavebands that could be used to discriminate between these surfaces. The ratio of the reflectance of these two wavelengths can be used to quantify the amount of plant biomass. In the field, the soil surface and stubble remains can cover a large portion of the field of view. However, Haggar et al. (1984) reported that bare soil has different reflective properties to green foliage that could be used to discriminate between them. For bare soil, the ratio of the reflectance of the red and near-infrared is close to unity while for green vegetation the ratio will increase considerably. Felton and McCloy (pers. comm) also looked at the reflectance properties of many different soil, plant and stubble targets in the development of a herbicide spot spraying system (DetectSpray®).

The first reported use of near-infrared (800 nm)/red (675 nm) ratio (simple ratio index or ratio vegetation index) being used to estimate the leaf area index for a tropical forest canopy was by Jordan (1969). Rouse et al. (1973, 1974) developed the normalized difference vegetation index (NDVI) that is defined as the ratio of (NIR-red)/(NIR+red) using the LANDSAT MSS data. The majority of the near-infrared (NIR) and red linear combination work has used LANDSAT data (Tucker, 1979). Kanemasu (1974) used ground-based reflectance to study the growth of wheat, sorghum and soybean and found that the ratio of green (545 nm)/red(655 nm) wavebands were the most useful for describing crop growth. Tucker (1979) looked at various ratios of green (520-600 nm), red (630-690 nm) and NIR (750-800 nm) bandwidths for monitoring vegetation. Specifically he used the green/red and NIR/red linear combinations to predict biomass, leaf water content and chlorophyll content. The red and NIR linear combinations had up to 14% greater regression significance than the green/red ratio. Tucker (1979) also looked at other indices derived from the red and NIR wavebands. Regression analysis was done to rank the indices and it was found that the best predictors were the vegetation index (NDVI), the transformed vegetation index and the square root of the IR/red ratio. The simple ratio (NIR/red) closely followed these indices.

Remotely sensed images can be collected by sensors mounted in satellites or aeroplanes, provided the target is illuminated by radiation from the sun and is not obscured by atmospheric conditions such as cloud or dust. This type of technique allows for rapid collection of data across a wide area. However, the resolution of the data obtainable from these techniques is low because of the large distances between the target and sensors. These techniques are also hampered by changes in environmental conditions, such as cloud cover and the angle of the sun that degrade the signal. High resolution data is needed for most small plot experimental field trials. The development of ground based systems has enabled high resolution data to be captured at a cheaper cost than aerial methods.

Ground based static systems were developed using radiometers mounted on masts or tripods above the targets areas eg. crops. However, these methods were only semi-mobile and precautions had to be taken to ensure that the crop was not damaged in the setup of the instruments. In contrast to this, continuous data collection systems were developed in which the sensors are mounted on a vehicle and driven beside the crop target. A continuous set of readings can be made, provided the sampling rate is set high enough.

2.2.3 The development of the WeedSeeker® sensor

Herbicides have reduced the cost of weed control and are an integral part of the shift away from cultivation as the primary means of weed control. The use of broad spectrum, knockdown herbicides, such as glyphosate, to control weeds during the fallow has been important in no-till farming. The distribution of weeds in a paddock can be highly variable and considerable cost savings can be made by only applying herbicide to the weeds infestation rather than spraying the whole field and so reducing the rate of application per hectare. The need for such a weed spot spraying system led to the development of a weed-detecting sprayers by Haggar et al. (1983) and the DetectSpray® system (Felton, 1990). The latter used two sensors, one facing up and the other pointed at the ground, to simultaneously measure the irradiance and radiance in the red (670 nm) and NIR (750 nm) wavebands (Felton et al., 1991). This allowed green foliage to be discriminated from bare soil or stubble. The signal from the sensor was used to control a solenoid to turn on a herbicide spray when a weed was detected. This system relied on the illumination from the sun and did not work effectively under atmospheric conditions with low light intensity eg. low sun angle or heavy cloud cover.

Fluctuations in the irradiance from the sun can cause large differences in radiance from similar targets when measured in sequential order. A standard target, such as a white spectrally flat Lambertian standard reflector, can be used as a reference to compare readings from different times and normalise the measurements. Precautions need to be taken to ensure that the environmental conditions are optimal i.e. cloud free days and high sun angle. However, even this method can be subject to errors because of variations in the irradiance, caused by atmospheric fluctuations, in the short time interval between taking measurements on the target and the reference (Duggin, 1980). Duggin and Philipson (1983) proposed a method of simultaneous measurement of the irradiance and radiance using two separate sensors and applying a correction factor. Milton (1981) argued that this correction was not valid given the non-Lambertian nature of most natural surfaces and that researchers should be paying more attention to ensure that measurements were only taken during uniform irradiation conditions. These conditions occur only on days when there is bright sunshine with no clouds or a uniform cloud cover.

The development of the WeedSeeker® sensor, with an inbuilt artificial illumination source, can be classed as a sequential sensor system. High frequency modulation of the illumination and detection signal is used to measure the radiance of the target and the background irradiance. This is effectively the same as a simultaneous measurement system but using only a single detector. The signal can be averaged over a longer time period, for practical reasons, to reduce the amount of data recorded. The WeedSeeker® uses two wavebands, red (670 nm) and near-infrared (750 nm) emitted by solid state monochromatic gallium arsenide phosphide and gallium aluminum arsenide light-emitting diodes in the sensor head to illuminate the target (Beck, 1997; Hanks and Beck, 1998). The light emitting diodes produce a high power, precise wavelength light (half-power bandwidths of 25 nm) that is focused by an emitter lens on to an area 0.5 cm by 30 cm on the ground. A detector lens and aperture plate are used to focus the reflected light onto the photodetector. The effective field of view of the sensor is reduced to a narrow strip that corresponds to the position of the light beam from the light emitting diodes. This improves the sensitivity of the instrument by allowing smaller targets to fill a larger proportion of the field of view than conventional radiometers. The chosen wavebands are in the middle of the red waveband (630-690 nm) and the lower end of the near-infrared (750-800 nm) wavebands that are commonly used in remote sensing applications. A modulated clock signal (455 kHz) is used to co-ordinate the phasing of the light beam emissions and the photodetectors. This is a three step process. First, the photodetectors are turned on and an infrared (750 nm) light beam is directed at the target. Secondly, the infrared beam is turned off and replaced by the red (670 nm) beam. Thirdly, the red beam is turned off and there is a period with no light emissions. During this last phase, the radiance from the target is solely dependent on the background irradiance from the sun. Finally the photo detectors, that convert the reflected light into a signal, are switched off. Three transfer gates record the signal from the target for the three separate stages. The three signals correspond to the radiance from the target when illuminated by the `red + sun`, `NIR + sun` and `sun` only light sources. The red and NIR beams are an artificial light source and are not prone to drift in performance over time. In contrast, the light from the sun is changing rapidly over time due to changing environmental conditions. Through a system of comparators, the background signal (`sun` only) can be subtracted from the `red + sun` and `NIR + sun` signals to obtain the 'pure' red and NIR radiance (reflected energy). The reflectance is the ratio of reflected versus incidence energy. The use of an artificial light source results in a stable incident energy and therefore the radiance is directly proportional to the reflectance. The controller outputs the ratio of the NIR/red reflectance (simple ratio SR or ratio vegetation index RVI) and this can be used to control external devices such as solenoids valves. The performance of the WeedSeeker®has been previously explored by Felton (pers. comm. 1999) in terms of the field of view and response to different targets. A new sensor, called the GreenSeeker®, has now been developed for use in variable rate fertiliser applications such as spray-topping with aqueous nitrogenous fertiliser (`http://www.NTechIndustries.com`). A similar concept using reflectance measurements to apply fertiliser differentially to a mixed species pasture was identified by Haggar et al. (1984). The GreenSeeker® sensor is similar to the WeedSeeker® sensor and has the added capability to measure both the red/NIR ratio and the NDVI. The performance of this sensor was examined by Jones (2004). The tests involved the recording of NDVI for a range of environmental conditions. These included the effect of temperature, the height of the sensor above the target and presence or absence on sunlight on the target. Temperature was found to have a minimal effect on NDVI within the temperature range 7 to 42 °C. The NDVI did not vary greatly within the range of heights tested 0.81 to 1.22 m. The presence or absence of sunlight was found to have no significant effect on the NDVI.

These sensors are being used in a number of weed spraying systems including inter-row crop spraying, control of weeds alongside road and railway lines and in orchards and horticultural crops (`http://www.NTechIndustries.com`). Felton et al. (2002) also identified several research applications for these sensors in agronomy and weed science. These studies included assessing the injury to crops from herbicides, the estimation of plant biomass, and the selection of crop varieties with greater vigour in plant breeding programs.

The WeedSeeker® sensors were used for all the experimental work in this thesis as the GreenSeeker® sensor was not commercially available at the time (2002-2003). Although the WeedSeeker® measures the red and NIR radiance in separate channels, it only outputs a signal that is proportional to the simple ratio index (SR). Jackson and Huete (1991) derived a direct relationship between the SR and NDVI in equation

$$NDVI = \frac{NIR - red}{NIR + red} = \frac{NIR/red - 1}{NIR/red + 1} = \frac{SR - 1}{SR + 1} \tag{2.2}$$

Previous research has shown that the SR is similar to the NDVI in predicting the biomass of crops (Tucker, 1979) and for the detection of weeds in a row-crop environment (Zwiggelaar, 1998).

2.3 Weed competition trials

In the northern grains belt of New South Wales, wild oat (*Avena sterilis* ssp.) is a major weed as reported in a survey of farms (Martin et al., 1988). Yield loss from competition by wild oat can be considerable in chickpea crops, due to the slow early growth characteristics of chickpea and the more rapid growth of wild oat.

Weed competition experiments are primarily set up to explore the interaction between crop and weed populations. Oats, cereal rye, and barley, are generally more competitive against weeds than wheat or oilseed rape, whereas pulses are poorly competitive (Lemerle et al., 2001). Nevertheless, in wheat crops, agronomic changes such as increasing the sowing density and reducing the row spacing can be made in order to advantage the crop rather than the weeds (Medd et al., 1985; Walker et al., 2002). These strategies are not as successful in chickpea due to their poor competitiveness.

Felton and Haigh (2001) conducted field experiments at Tamworth with wheat, chickpea, fababean and canola, grown in competition with weeds at 0, 3, 9, 27 and 81 plants m^{-2} of density. A model was fitted to this data and the predicted yield-loss calculated at two levels of weed density likely to occur in normal production paddocks. Chickpeas were found to have almost double the percentage yield loss of wheat at 10 to 20 weeds m^{-2}. They concluded that weed control is much more critical in chickpeas than in wheat. Even small weed populations can cause significant loss in yield and more so when crops are grown in wide (64 cm) rows compared to 32 cm rows. Previously, field experiments have been set up to quantify the relationship between yield-loss and weed (wild oat) density (Whish, 1999). However, the results from field experiments have been variable because of establishment problems of the weeds i.e. sporadic germination and naturally occurring populations of weeds.

An experiment using 'mimic' or 'pseudo' weeds was proposed because of the difficulties previously outlined with wild oats. Wheat, barley and triticale were used as mimic weeds to impose weed competition on the chickpea crop. Crop species have been used as mimic weeds, in weed competition trials, by Lotz et al. (1996) to partly reduce the genotypical variation of the weed species. Mimic weeds have advantages over wild oats in that the former can be sown with conventional planting equipment, have higher germination rates and can be used in conjunction with selective herbicides to control any unwanted background populations such as wild oat or phalaris in the plots. The mimic weeds are unaffected by the use of selective herbicides. More accurately controlled treatments such as weed density imposed on the experimental units results in less variation in the measured responses.

A review of previous weed competition experiments indicated that in the majority of trials the weeds have been broadcast over the plots after sowing the crop (Brain and Cousens, 1990). The germination of the weeds can be variable when heavy stubble is present on the soil surface. This problem could be avoided if the weeds could be sown conventionally, at the same time as sowing the crop. However, this introduces an added factor into the design as weeds sown in rows are not representative of the random spatial arrangement of weeds that occurs in commercial crops. Research trials at Tamworth in 1997 by Whish (1999) investigated the effect of the spatial positioning of wild oat and turnip weed in chickpea. There was no significant differences between the in-row, between-row and uniform spatial patterning treatments on yield for the 0, 2 and 8 plants m^{-2} weed density investigated. Felton and Haigh also conducted trials at Tamworth in chickpeas in which the mimic weeds were sown in rows 'with' and 'between' the crop rows. Again, results indicated there was no significant difference in yield loss between these two treatments (unpublished data).

Competition experiments are conducted to measure the effect of both crop and weed plant density on crop yield. Competition can occur between the two species (inter-specific) such as crop and weed plants. It can also occur between the same species (intra-specific) such as crop plants competing with other crop plants. There are three types of competition experiments commonly used in agricultural research. The additive design is one where the "density of one species [the crop] is kept constant in all treatments and the density of a second species [the weed] is varied" (Cousens, 1991). The replacement series design is one in which "the density of two species is varied so that their total density remains constant but their proportions vary" (Cousens, 1991). The response surface design recognises that the combination of density treatments chosen is only a small subset of all the possible combinations and that this forms a response surface. Therefore, the plant density treatments chosen should ensure that data are available across the whole of the response surface to ensure a suitable model can be fitted. The highest weed density level should be enough to ensure an impact on crop growth, but not enough to cause intra-specific competition in the weeds (Lemerle et al., 2001).

Each of these designs can be used to answer specific objectives. The additive model has the most relevance in weed management research. Crops are usually grown at a constant plant density by farmers and the type of questions they might ask is how much yield loss will a particular weed density cause and what is the economic threshold for weed control. Inter-specific competition is the major factor of interest in the additive design.

In the additive design, the allocation of suitable weed density treatments will depend on the objectives of the experiment. If the objective is to define the economic threshold for weed control, then only low weed densities are needed and an arithmetic series e.g.

2, 4, 6, 8, 10 plants m^{-2} would be suitable as the response is approximately linear. A geometric series e.g. 2, 4, 8, 16, 32 plants m^{-2} is more appropriate when the objective is to define a non-linear model across a wider range of weed densities. The number of weed density treatments used in an experiment is likely to be a compromise between the availability of resources (cost) and the ability to fit an adequate model to the data. Cousens (1985) has suggested that the best density series is a combination of both a geometric and an arithmetic series, where density increases geometrically at first, but then becomes arithmetic at higher densities. This statement was made in regard to fitting hyperbolic-type models using maximum likelihood methods available at the time. The adequacy of these models will be examined later in this thesis using the results of a chickpea competition experiment. Other models will be fitted that have better parameter estimation properties and are not as greatly influenced by the selection of weed density levels.

Previous studies on the time taken for the onset of weed competition by Felton (1985) have indicated that weed control of thornapple *(Datura* spp.), in dicotyledonous crops such as soybean can be delayed up to 56 days after sowing without incurring yield loss. This was a much longer time than for monocotyledonous crops such as maize that were also included in the trials. Weed competition studies in chickpeas at Tamworth have identified that crop yield losses can be avoided if the weeds are controlled during the first 70 days after sowing (Felton et al., 2004). A shorter time interval was found by Mohammadi et al. (2005) who estimated the critical period for weed control in chickpeas grown in Iran was between 17 and 49 days after establishment (22 and 57 days after sowing). However, the yield-loss versus weed density relationship needs to be defined before economic decisions on whether to control weeds with herbicides can be made, but defining the onset of competition is just as important. Whish (1999) investigated the critical time of a single weed removal time at Tamworth and found that wild oats removed 83 days after sowing gave the best chickpea yield. Similarly, at Warialda he found 84 days to be the best weed removal time.

The use of yield loss models, in practical applications, needs to be based on readily observable input variables that can be easily determined in the field (Lotz et al., 1996). Possible independent variables that could be measured and used in models include weed density, weed biomass and the ratio of weed to crop leaf area. Various yield loss models that use either the weed density (Cousens, 1985), relative weed area (Kropff and Spitters, 1991; Lotz et al., 1992), weed dry matter (Lutman et al., 1996) and spectral reflectance of weeds Lotz et al. (1994) have been proposed. When designing field experiments in which an evenly spaced range of weed treatments is chosen to determine the crop yield loss relationship, the only variable that can be easily controlled is the weed density. The other variables such as weed biomass and leaf area can have a range of values that cannot be adequately predicted due to environmental conditions that influence their magnitude from year to year. The range of values for the weed treatments is statistically important when fitting a model, as inadequate ranges can lead to failure in the convergence algorithms in the mathematical optimising routines.

2.4 Competitive ability of chickpea varieties against grass weeds

Chickpeas were introduced to Australia in 1891, 1893 and 1950. However, it was not until 1971 that a serious evaluation program began in Wagga Wagga, NSW. Since then the industry has expanded and new varieties are continually being released in response to industry demands. Apart from higher yields, other attributes are being introduced into the current breeding lines. These include, resistance to organisms that attack the roots (*Phytophthora medicaginis*) and root-lesion nematode (*Pratlylenchus thornei and P. neglectus*), the foliage (*Ascochyta rabiei*) and virus diseases. Increased plant height to improve harvestability; improved seed quality including grain colour, shape and size; tolerance to cold temperatures, and salt tolerance are other traits that are also selected (Knights et al., 2005).

Competitive ability (CA) is defined as the ability of the crop to tolerate weed presence and maintain grain yield (Lemerle et al., 2001). It can be measured either as suppression of weed growth and seed production by the crop, or as crop yield losses. The competitive ability is not being assessed directly in the major breeding programs in Australia as field trials are being conducted in a weed-free environment (Cousens and Fletcher, 1990; Whish et al., 1996). However, plant height, resistance to lodging and seedling vigour are desirable traits that may also be associated with competitive ability. These traits may be inadvertently being introduced into breeding lines although not directly targeted.

Weeds are a major problem in chickpeas and there are a limited number of registered herbicides that are available for use. Pre-emergence herbicides such as simazine, prometryn, cyanazine, metribuzin and isoxaflutole are useful for control of broadleaf weeds but some of these are expensive to use, and their residues can cause reductions in yield. Major broadleaf weeds found in chickpea crops in northern NSW include *Rapistrum rugosum* (turnip weed, giant mustard, bastard cabbage), milk thistle (*Sonchus oleraceus*) and black bindweed (*Fallopia convolulus*).

Grass weeds can be controlled with pre-emergence herbicides such as trifluralin, triallate and pendimethalin. Post-emergence herbicides provide more flexibility in terms of targeting grass weeds during the later stages of crop growth. These include herbicides such as haloxyfop, sethoxydim, quizalofop-p-ethyl and clethodim. The major grass weeds in northern NSW are wild oat (*Avena sterlis* spp. *lunoviciana*) and phalaris (*Phalaris paradoxa*).

A recent survey of herbicide use in chickpea crops (Haigh et al., 2005) of northern NSW indicated the predominance of herbicides such as haloxyfop (Verdict®) for control of grass weeds and simazine and isoxaflutole (Balance®) in the case of broadleaf weeds. However, problems can develop when there is too much reliance on a few selective herbicides. Verdict® is a group A herbicide, and the excessive use has contributed to the development of herbicide resistant weeds. Balance® is a newly released, group F residual herbicide with unique properties and has been widely adopted in the chickpea industry. The secondary breakdown metabolite is more phytotoxic to weeds than the primary active ingredient. Chickpeas are tolerant to Balance® in the majority of field conditions. Rainfall reactivates breakdown of the herbicide and the release of the secondary metabolite. These rainfall events can also initiate the germination of weeds, which are readily controlled by the secondary metabolites. However, in some cases crops have been damaged by Balance® when rainfall occurs immediately after sowing and there is variability in the tolerance to Balance (Felton et al., 2004).

The community expectations are for 'greener' agriculture (i.e. less use of herbicides) and this has shifted research into other methods of combating the effect of weeds. The introduction of wheat varieties that have a high competitive ability against weeds has been proposed by Ramsel and Wicks (1988) as a method for reducing the reliance on herbicides. Whish (1999) reviewed the then current literature on selection of crop varieties with traits that would increase competitiveness. Although there were many references for increased competitiveness in crops such as wheat, little was found in pulse crops such as chickpea.

Whish (1999) investigated the competitive ability of six chickpea varieties to the broadleaf weed *Rapistrum rugosum* (turnip weed, giant mustard, bastard cabbage) using one level of weed infestation. The differences in competitive ability, estimated from the percentage yield loss, between varieties was small. There was more variability in grain yield from the plots with weeds present than weed-free. However, if a range of weed density levels had been used in the experiment, a suitable model could have been fitted to the data and better predictions could have resulted. The yield-loss could also have been predicted for intermediate weed density values. In this thesis it is proposed to use two weed density treatments as well as the control to define a yield loss model for the chickpea variety experiment

Only one of the six chickpea varieties selected by Whish (1999) in his experiment has been selected for evaluation in the experimental section of this thesis. This variety, Amethyst, was described by Knights (pers. comm.) as having low vigour. Whish (1999) also looked at the effect of row spacing and weed density (0, 2, 4, 8, 16 and 32 weeds m^{-2}) of wild oat and turnip weed on yield loss in Amethyst chickpea. The chickpea variety experiment proposed in this thesis will add to the previous work by testing the competitive ability of eighteen chickpea varieties currently being used in the Tamworth breeding program.

2.5 Conclusion and experimental objectives

Plant biomass is an essential measurement required for evaluating plant performance. Traditional methods of destructive sampling are tedious and time consuming and may not be suitable in plant breeding studies Aparicio et al. (2000). With the improvement in instrumentation of remote sensing equipment many researchers have shown a good relationship between reflectance and biomass using different equipment. The introduction of the WeedSeeker® sensors with their own light source and background correction has been a major step forward in the commercial application of this technology in weed control and precision fertiliser application. There are many other applications for this technology in agriculture as will be shown in the following experiments. Most plant breeding programs could be routinely assessing competitive ability using this technology in future years.

A major difference in methodology between previous research and this thesis is in the direction of sampling across rather than along the crop rows. The change in direction of sampling has been necessary because lane ways, beside plots, are not feasible with the currently used experimental designs. However, this method of sampling across plots has advantages in terms of easier alignment and the number of sensors required. The sensors are rugged and suitable for boom mounting on a vehicle. This enables continuous sampling at high frequency across the plots, and the data captured can be displayed as a visual image. The visualisation of the data has enabled many plots to be sampled at a rapid rate and the corresponding signal for each plot to be separated out and digitised based on the time and/or distance traveled.

Remote sensing has been proved to be a viable alternative method to destructive sampling methods of measuring crop biomass. Previous research has demonstrated how remote sensing data from satellite and fixed radiometers can be used in research and in practical applications. The introduction of the WeedSeeker® sensor has enabled rapid and detailed sampling of crops to be undertaken. The objectives of this thesis are to:

1. Establish a calibration between remote sensed data and measured crop growth for a number of broad-acre winter crops using this new sensor.

2. Apply this technique in a weed competition experiment using a number of different weed types in a chickpea crop.

3. To test the usefulness of this technique, in a plant breeding context, for determining the competitive ability of a number of chickpea cultivars in a weed competition experiment.

Chapter 3

Site description and climate

3.1 Site

Field work was conducted in 2002 and 2003 in the northern grain belt of eastern Australia. The site, referred to as Tamworth, is situated at Tamworth Agricultural Institute, New South Wales Department of Primary Industries , Calala Lane, Tamworth, NSW, Australia, latitude 31° 9′ S, longitude 150° 59′ E and an elevation of 430 m above sea level.

Cropping soils at Tamworth vary in type from grey vertosol, brown vertosol to chromosol and are typical of the major soil groups in the district. The site for the trial in 2002 is indicated on the site plan and known as paddock 3 (Figure 8.1). A soil survey was conducted by Riddler (1989), included a number of soil sampling sites near the trials. A soil survey sample (No. 179) was located near the 2002 trial site and was characterised as Brown Vertosol (Isbell, 1996); (Ug5.15; Northcote, 1971). A full description of the soil profile is presented in Appendix 8.1. The location of the trial site in 2003 is indicated on the site plan and is known as paddock 19 (Figure 8.2). A soil survey sample (No. 210), located near this trial site, was characterised as a Brown Vertosol (Isbell, 1996); (Ug5.15; Northcote, 1971) and a full description is presented in Appendix 8.2.

3.2 Fallow management

Paddock preparation for the 2002 trial site began in 2001 when durum wheat was grown. The wheat stubble was left after harvest and weeds were controlled during the summer fallow by spraying with 1.25 and 1.2 L ha^{-1} of glyphosate[1] (Roundup Xtra®) on 12 February and 8 April, respectively.

Similarly in 2003, the wheat stubble was left after harvest and weeds were controlled during the summer fallow by spraying with 1.0, 1.2 and 1.3 L ha^{-1} of glyphosate (Roundup Xtra®) on 7 January, 13 March and 5 May, respectively.

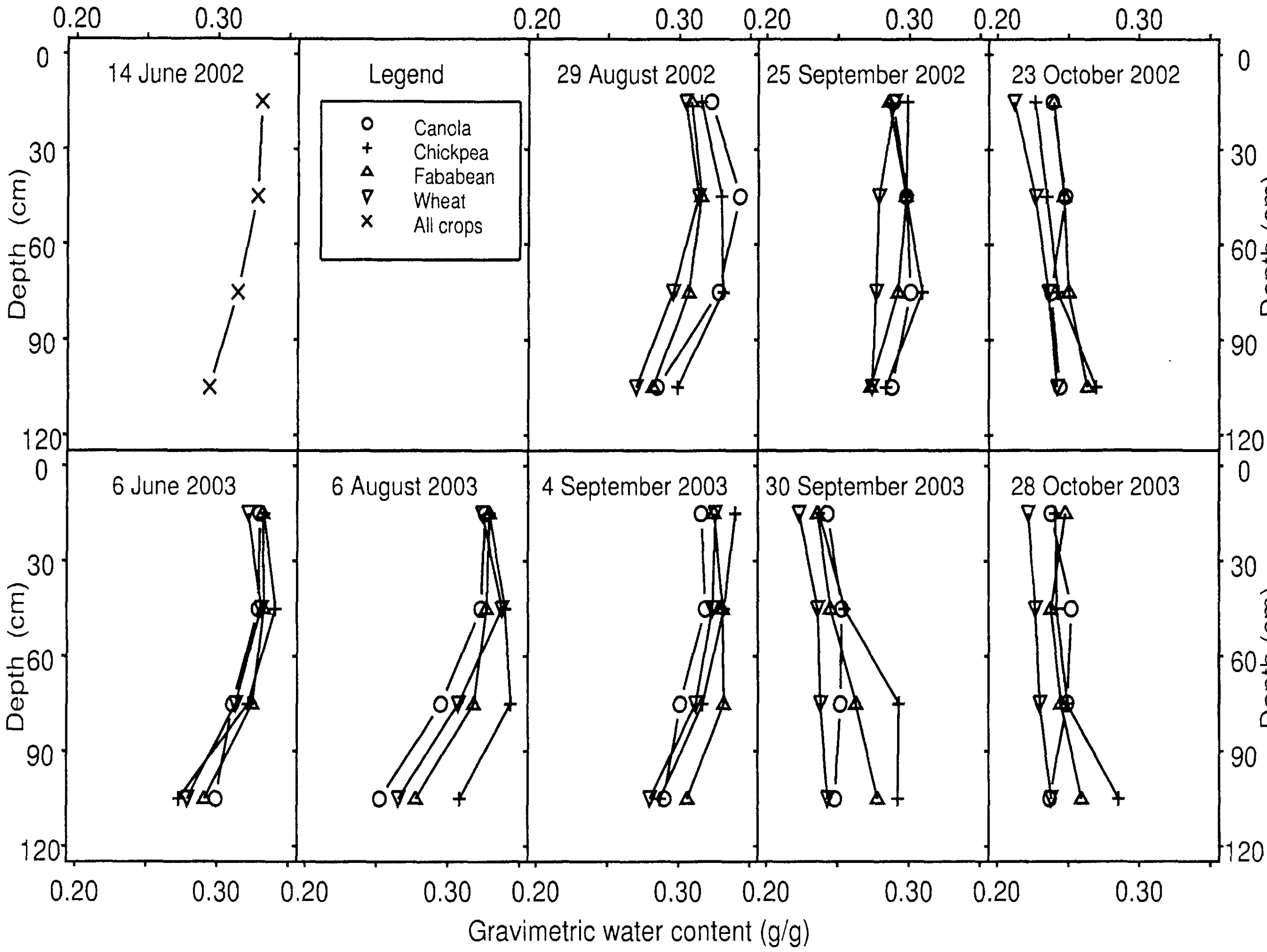
[1] All common and trade names of herbicides, fungicides and insecticides used in this thesis are listed in Appendix 8.3

3.3 Soil water content

Soil samples were taken on 14 June 2002 and 6 June 2003 to estimate the soil water content at sowing for the canola, chickpea, fababean and wheat crops. A tractor mounted hydraulic soil corer was used to obtain samples to a depth of 1.2 m. The soil samples were obtained by using a hollow steel core tube, with an internal diameter of 25 mm, at locations near the trials. The location of these samples is mapped in Appendix Figures 8.1 and 8.2. The samples were extracted from the corer and the total length measured and then trimmed into four sections corresponding to depths of 0-30, 30-60, 60-90 and 90-120 cm. The samples were placed in sealed plastic jars. In the laboratory the total mass of wet soil was measured. The samples were then dried in an oven at 105 °C for 48 hours and then re-weighed to determine the mass of dry soil.

The soil water content was also measured on 29 August, 25 September and 23 October for the crop growth experiment in 2002 to estimate the soil water used by the crops (Figure 3.1). Similarly, the soil moisture was measured on 6 August, 4 September, 30 September and 28 October for the plots in the crop growth experiment in 2003.

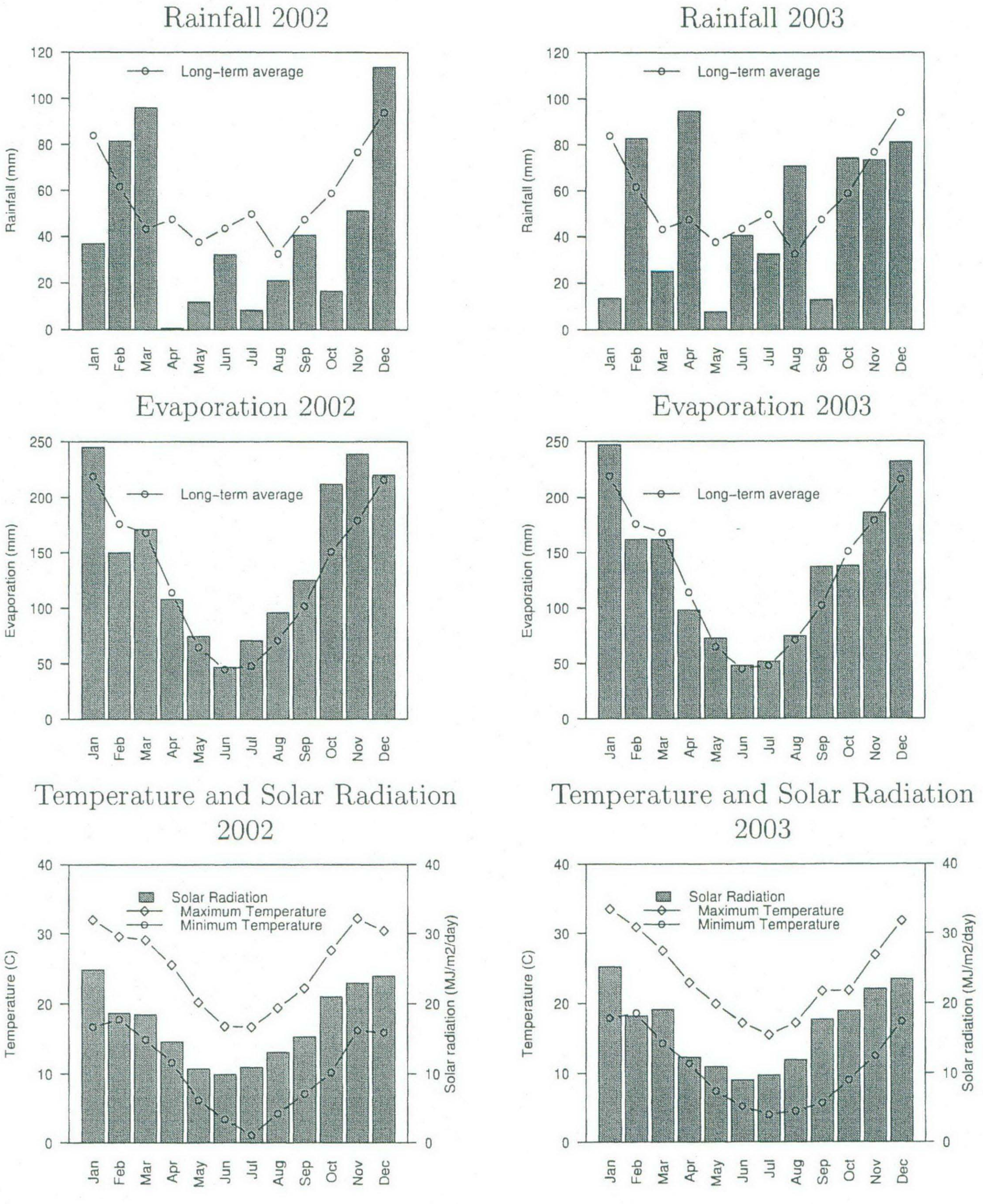
Figure 3.1: Soil gravimetric water content at monthly intervals for canola, chickpea, fababean and wheat crops in 2002 and 2003. The points are the average water content of all replicates for each depth increment.



3.4 Climate

The rainfall during the fallow from November 2001 to May 2002 was close to the long-term average (Figure 3.2). A total of 118 mm of rain fell during the winter crop growing season from June to October in 2002. This was less than the long-term average and wide spread drought conditions were experienced throughout the northern grains belt. In 2003, 231 mm

Figure 3.2: Climate data for Tamworth in 2002 and 2003



of rain fell during the growing season rainfall with good falls in June, August, October. The rainfall in these later months improved the crop yields by providing moisture to the crop during the grain filling stage.

The average monthly evaporation during the growing season in 2002 was above the long-term average while in 2003 it was close to the long-term average (Figure 3.2).

The average monthly minimum temperatures during the growing season show that 2002 was colder than 2003 (Figure 3.2). Solar radiation levels in the winter months of 2002 were higher than in 2003 and can be attributed to the amount of cloud cover. However, decreased cloud cover can cause lower minimum temperatures as long wave radiation from the surface is more easily dissipated into the atmosphere at night.

The average monthly maximum temperatures were also higher in 2002 than in 2003, especially during the months of September, October and November (Figure 3.2).

3.5 Conclusion

The difference in the in-crop rainfall between 2002 and 2003 provided a contrast in growing conditions in which to test the methodology for reflectance measurement. The dry conditions in 2002 may also cause a difference in competition between the weeds and the crop that will be examined in later chapters. The control of weeds in the summer fallow and the large amount of ground cover (stubble) contributed to the good soil water storage and was crucial to the success of the crops grown in 2002 (drought year). The trials were conducted on heavy clay soils which ensured that the stored soil water at sowing would be adequate for crop establishment.

3.6 Statistical models

A number of models have been proposed for predicting yield-loss in crops due to weeds. Some models incorporate parameters to account for the effect of crop plant density and weed density on the yield of the crop (Martin et al., 1987). The weed competition experiments proposed in this study had a fixed crop plant density and therefore the combined crop and weed density type models are not included in this discussion. Yield-loss models that describe yield-loss caused by weed density alone include two widely adopted models, the rectangular hyperbola and inverse polynomial, which are presented here as they have been used in the experiments in both Chapters 5 and 6.

Rectangular Hyperbola

Cousens (1985) has shown that yield loss in crops is suitably described by the rectangular hyperbolic model

$$Y_{loss} = \frac{iD}{1 + iD/A} \tag{3.1}$$

where,

Y_{loss} is the percentage yield loss compared to the weed free treatments
i is the slope as (D $\rightarrow$ 0),
D is the weed density, and
A is the yield asymptote.

The yield-loss of an experimental unit or plot cannot be measured directly while yield can. Therefore, the yield loss must be calculated using the equation

$$Y_{loss} = 100\left(\frac{Y_{wf} - Y}{Y_{wf}}\right) \tag{3.2}$$

where,

Y is the yield (t ha^{-1}) and
Y_{wf} is the yield of the weed free treatments (t ha^{-1}).

Therefore, yield loss can be modelled with either of two variants of the same equation. Variant (a) is a 2 parameter model and is given in equation (3.1). Variant (b) is the 3 parameter yield loss equation, shown in equation (3.3). The difference in these equations is that in (a) the dependent variable, Y_{loss}, is the percentage yield loss and in (b) the dependent, Y, is the yield.

- i is the initial slope and is used in (a) and (b)
- A is the asymptote and is used in (a) and (b)
- Y_{wf} is an estimate of the yield from weed free treatments and is used in (b) only.

A slight re-parameterisation using equation (3.2) gives variant (b)

$$Y = Y_{wf}\left(1 - \frac{iD}{100\,(1 + iD/A)}\right) \tag{3.3}$$

This model is popular amongst weed scientists because the parameters have a direct biological interpretation. However, it lacks statistical rigour because of the assumption of constant variance and that the non-linear regression may be ill-conditioned leading to unstable predictions.

Inverse polynomial

An alternative to the rectangular hyperbola may be the inverse polynomial model

$$Y = \frac{1}{\alpha + \beta D} \tag{3.4}$$

where,
- Y is the grain yield (t ha^{-1}),
- D is the weed density (number of plants m^{-2}),
- α is the intercept term, and
- β is the slope term

These are fitted as a Generalised Linear Model (GLM) where the predictive part of the model is a linear equation,

$$\eta = \beta_0 + \beta_1 D \tag{3.5}$$

and the predictive part is related to the expected value by the inverse link,

$$E(y) = \eta^{-1} \tag{3.6}$$

and the random measurement error has a Gamma distribution. Both models are non-linear.

Model (3.1) on page 22 arises from the relationship

$$\frac{d(Y_{loss})}{dD} \propto Y^{-1} \tag{3.7}$$

That is, as the yield increases, the rate decreases.

Model (3.6) arises from

$$\frac{d(Y_{loss})}{dD} \propto D \tag{3.8}$$

where the rate changes proportional to the weed density.

Both models are useful representations of the biology, and the appropriate choice is determined by the data in each situation.

Chapter 4

Calibration of a crop canopy analyser with crop growth

4.1 Introduction

Measurement of crop growth is an integral part of many field experiments used in agricultural research. Crop growth can be measured by various methods but the most accurate involve the destructive sampling of the foliage. Provided the experimental unit (area of crop) is large and the crop growth is uniform within the plot, multiple samplings can be taken from the plot without destroying too much of the crop area. However, agricultural experiments frequently use a large number of replicated treatments allocated to many plots across a small area in order to improve the statistical efficiency and reduce costs. A non-destructive method of quantifying crop growth would enable multiple samplings throughout the growing season, from the same area in each plot, and still preserve the crop for harvesting of grain. Therefore, destructive sampling techniques should be avoided where possible because of their effect on the crop. Remote sensing is one non-destructive method that will be evaluated in this chapter.

Non-destructive methods of measuring crop growth need to be tested and calibrated before replacing existing destructive sampling procedures. This involves the measurement of a range of crop growth variables throughout the crop growing season so that calibrations can be made with remotely sensed measurements. Calibrations are often only useful over a limited range of time or values.

Field experiments to quantify the growth of four winter crops (wheat, canola, fababean and chickpea) were undertaken in consecutive years to compare a destructive with a non-destructive method of estimating biomass. Intensive destructive sampling of crop foliage over time will enable the estimation of crop growth variables, such as biomass and leaf area index, throughout the growing season. A ground based, non-destructive, remote sensing method utilising the WeedSeeker® sensor was used to predict the crop growth. Statistical analysis was carried out to assess the correlation between the two data sets over time. The results of this experiment were applied in weed competition experiments in chickpea and will be examined in Chapters 5 and 6.

The initial experimental design created in 2002 had only one row spacing of 64 cm for all crops. In order to test the robustness of these methods an additional agronomic factor was added to the experimental design in 2003. This involved the planting of crops in both wide (64 cm) and narrow (32 cm) rows.

Holben (1980) has shown in soybeans that the spectral radiance in the red and NIR spectrum can be used to calculate the NDVI and simple ratio and these are strongly related to leaf area. These relationship can be a linear in the case of simple ratio or non-linear in the case of NDVI. The leaf area of the crop can also be related to the above ground biomass. Therefore, crop biomass can be estimated from reflectance measurements.

The aims of the experiment are to:

1. Demonstrate that a remote sensing technique using WeedSeeker®sensors can be used with four different field crops to estimate crop growth.

2. To define the range of values over which the relationships are reliable and determine the confidence intervals for these relationships.

3. To investigate the effect of different crop row spacing on the growth and reflectance of crops.

4.2 Materials and methods

4.2.1 Site

Descriptions of the two sites used at Tamworth in 2002 and 2003 were presented in Chapter 3. Figures 8.1 and 8.2 in the Appendix provide details for the trials in 2002 and 2003, respectively.

4.2.2 Plant material

Four contrasting types of winter crops that are commercially grown in northern NSW were selected for the trials. These were a brassica, canola (*Brassica napus*, cv. Oscar); two pulses, chickpea (*Cicer arietinum L.* cv. Howzat) and fababean (*Vicia faba*, cv. Fiord) and a cereal, wheat (*Tritium aestivum*, cv. Sunstate). These crop types provided a range of growth rates and canopy architecture on which to test the reflectance methodology and calibrate the WeedSeeker® sensors.

4.2.3 Experimental design

The 2002 experiment consisted of six replicates of the four crops. The plot size was 3.5 m by 40 m. The plots were arranged in a block with 24 columns. This reduced the longest axis of the trial to 84 m and, in so doing, minimised the variation in soil properties across the trial. The crops were sown in five rows at 64 cm (wide) row spacing.

The experimental design was altered in 2003 in order to incorporate row spacing as a factor into the design. The number of replicates was reduced from six to four in this trial due to the increased number of treatments and restrictions on the trial area. The plots with narrow row spacing had nine rows at a spacing of 32 cm, while the wide row plots had five crop rows at 64 cm spacing. The same overall seed sowing rate was used in both row spacing treatments so comparisons could be made concerning the effects of row spacing on crop growth and reflectance. The eight treatments, consisting of four crops by two row spacings, were set out in a design with 2 rows and 16 columns.

Randomised block designs were used for both trials and the randomisations were generated using the SpaDes software (Coombes and Gilmour, 1999). This reduced the risk of bias in the trial due to the spatial arrangement of the crop and row spacing treatments.

4.2.4 Sowing

2002

On 2 June 2002, a no-till planter (Felton and Smith, 1981) with narrow pointed tines and press wheels spaced at 64 cm was used to direct drill the seed for all crops (Figure 4.1). The plot width was 3.5 m and a plot length of 40 m was selected to allow sufficient area for the destructive sampling of crop biomass throughout the growing season. Felton (pers. comm.) was consulted in choosing the appropriate seeding rates of 2.5, 70, 100 and 40 kg ha^{-1} for canola, chickpea, fababean and wheat, respectively. The chickpea seed was inoculated with Group N moist peat inoculant *Mesorhizobium* strain number CC1192 (Bio-care Technology Pty Ltd, Somersby, NSW) and the fababean seed with Group F moist peat inoculant *R. leguminosaoum bv. viciae* (Bio-care Technology Pty Ltd, Somersby, NSW) in a cement mixer on the day of sowing. Granulock®12Z fertiliser (11.2 % N, 17.5 % P, 4.4 % S, 1.2 % Zn) was applied with the no-till planter at 80 kg ha^{-1} on 26 April, 5 weeks before sowing the crops.

A cone seeder was fitted to the planter for sowing canola as the 'covington' seed boxes were unsuitable for sowing the small seeds of this crop. The cone seeder gearing could not be altered sufficiently to allow the canola to be sown in one continuous run of the plot. Therefore, the canola was sown in two consecutive 20 m operations to give the desired plot length of 40 m. Each plot was sown with five rows and required 32 g of canola seed. The cone seeder was connected to a 5-way distributor that supplied seed to the rear tines of the planter.

2003

Crops were sown on 28 May 2003 in wide and narrow row configuration as outlined previously in the experimental design in this chapter. The plot length was 30 m and a 10 m lane way was left between the blocks to facilitate the maintenance, sampling and harvesting of the crops.

The canola, chickpea, fababean and wheat were sown at a rate of 3, 35, 100 and

Figure 4.1: The no-till planter used to sow the field experiments.

45 kg ha^{-1}, respectively. The chickpeas were sown at 50% of the intended sowing rate due to a miscalculation in the sowing rate when changing from the wide to narrow row configuration. The narrow row chickpea plots could have been sown at 70 kg ha^{-1} but this would have introduced another complication to the design. It was decided to leave the sowing rate at 35 kg ha^{-1} so that direct comparisons could still be made between wide and narrow row spacing treatments independent of seed sowing rate; previous work Felton et al. (1996) showed that seeding rates over this range did not influence yield. The chickpea and fababean were inoculated with rhizobium as in 2002.

Two cone seeders were fitted to the planter to enable the sowing of canola in both wide and narrow rows. The plots were sown in three consecutive sowing operations of 9.7 m in length to make up the 30 m plot length required.

The wide row plots, with 5 rows, required 27.9 g of canola seed and were sown using only one of the cone seeders. The narrow row plots were sown with two cone seeders. The first cone seeder supplying 15.5 g of canola seed per plot via a 5-way distributor to 5 rear tines and the second cone seeder supplied 12.4 g of canola seed to a 4-way distributor and the four front tines.

Granulock® 12Z fertiliser was again applied to all plots at 80 kg ha^{-1} at the time of sowing. Additional nitrogen fertiliser, as urea (42% N), was broadcast on the surface of the wheat and canola plots on 26 May at the rate of 50 kg N ha^{-1}.

4.2.5 Control of weeds, pests and diseases

2002

Immediately prior to sowing the herbicides triallate (Avadex BW®) and glyphosate (Roundup Xtra ®), were applied on 2 June at a rate of 2.5 and 0.75 L ha^{-1}, respectively.

During the growing season the major weed was wild oat which was controlled by applying the herbicide fenoxapropyl-p-ethyl (Wildcat®) with a surfactant (Supercharge®) at the rate of 0.4 L ha^{-1} and 0.15 L ha^{-1}, respectively, on 18 July and 10 September. Hand chipping of scattered broadleaf weeds was also undertaken on 26 August, prior to the first herbicide application, and subsequently to control later germinating weeds.

Major insect pests in the trials were budworm (*Helicoverpa* spp.), cutworm (Order Lepidoptera: Family Noctuidae), aphids (*Brevicoryne, brassicae*), cabbage moth (*Plutella xylostella*) and red legged earth mite (*Halotydeus destructor*). An insecticide thiocarb (Larvin®) was sprayed at a rate of 0.75 L ha^{-1} to all crops on the 12 October.

The fungicide mancozeb (Dithane®) was applied at 1 kg ha^{-1} on 2 September to control chocolate spot in fababean and *Ascochyta* in chickpeas.

2003

Immediately prior to sowing the herbicides, trillate (Avadex BW®) and glyphosate (Roundup Xtra®), were applied on the 28 May at a rate of 1.6 and 0.8 L ha^{-1}, respectively.

During the growing season wild oat which was controlled by applying the herbicide fenoxapropyl-p-ethyl (Wildcat®) with a surfactant (Uptake®) at the rate of 0.5 and 0.5 L ha^{-1}, respectively, on the 18 July. This herbicide and surfactant treatment was repeated on the 4 September at the rate of 0.4 and 0.35 L ha^{-1}, respectively. Hand chipping of weeds was also undertaken on 10 September.

Insect pests in the trials were heliothis, cutworm, aphids, cabbage moth and red legged earth mites. An insecticide thiocarb (Larvin®) was sprayed at a rate of 0.75 L ha^{-1} on all crops on the 30 September and 24 October.

The fungicide mancozeb (Dithane®) plus surfactant (Primawet®) was applied at 1.5 kg ha^{-1} and 40 ml ha^{-1}, respectively, on 20 August to control chocolate spot in fababean, *Ascochyta* in chickpeas, and yellow leaf spot in wheat. Chlorothalonil (Bravo®) was applied at 1.0, 1.0, 0.8 and 0.75 L ha^{-1} to the chickpeas on 12 and 30 September, 24 October and 6 November to control *Ascochyta*.

4.3 Crop growth

Crop biomass was estimated by destructive sampling small areas of the plots at regular intervals throughout the growing season. The location of the sampling area was chosen to give a representative sample of the foliage in the plot, and avoided areas that had been disturbed by previous samplings. A marker post was placed at opposite ends of the trial area and a strip 0.6 m wide was sampled across all plots. The canola, chickpea, fababean and wheat plots were sampled at approximately 2 weekly intervals, corresponding to 45, 59, 73, 87, 101, 115, 129, 143 days after sowing in 2002. Chickpea was the last crop to mature and an additional sampling was made at 158 days after sowing to ensure that the maximum crop biomass could be estimated. Similarly, in 2003 the plots were sampled at approximately 2 weekly intervals, corresponding to 54, 69, 84, 98, 112, 125, 139, 153 days after sowing. An additional sampling was made for chickpeas at 166 days after sowing.

In 2002, biomass samples were cut using a steel quadrat (0.6 m $\times$ 3.5 m) that was placed over the five crop rows. The number of plants in each row was counted at the same time as sampling took place. The five samples from each row were bulked into a paper bag and placed in an 'esky' (cold box) prior to processing in the laboratory. The mass of the fresh samples was recorded and then a sub-sample taken for determining the leaf area.

The biomass sampling procedure was altered in 2003 as both wide and narrow row plots were being sampled. The outside rows of crop in each plot were removed to reduce the "edge effect" on biomass and the remaining rows sampled. This also reduced the amount of biomass collected from each plot and allowed all 32 plots to be sampled on the same day. Once again a steel quadrat (0.6 m $\times$ 3.5 m) was placed over the area. The plots with narrow rows (32 cm) were trimmed to 6 rows prior to biomass sampling. This involved the removal of three rows (one on the northern and two on the southern side). The plots with wide rows were trimmed to 3 rows by removing the two outside rows.

The samples were transported to the laboratory and the mass of wet foliage measured. The plant stems were separated from the leaves and the leaf area measured with a leaf area meter (type 3100, Li-Cor Inc., Lincoln Nebraska, USA).

A different method of dissection and separation was used on each crop based on the shape and maturity of the plants. The wheat plants did not develop stems until quite late in their development and therefore the samples were not dissected into stem and leaf components. The whole plants were weighed and put through the leaf area meter. However, once the wheat had come into head, the heads were removed from the samples and the leaf area was measured on the remainder.

In the 2002 trial, the chickpea plants did not develop stems that could be easily separated from the leaves until some months after sowing. Therefore the leaf area of the whole plants was measured up to the fourth sampling at 87 days after sowing. After this date, the leaves and stems were measured separately. In 2003, the chickpea leaves and stems were separated at all the sampling times.

Fababean have large leaves that were easily separated from the stems and processed individually. Canola also has large leaves but stems did not develop until 87 days after sowing. Initially the whole canola plants were measured for leaf area but after 87 days the canola was separated into leaves and stem and processed in the same manner as fababean.

The remaining bulk sample together with the leaf and stem samples were dried at 80 °C for 48 hours before being weighed. The water content of the samples was then calculated from the difference in fresh and dry mass.

Due to the large amount of foliage harvested in the later sampling it was not feasible to measure the leaf area on all of this material. Therefore, the shoot biomass from each plot was sub-sampled and the leaf area measured. The sub-sample was dried and the ratio of leaf area per mass of dry foliage multiplied by the bulk sample dry matter to give the total leaf area for the quadrat. This value was divided by area of sampling (0.6m x 3.2m = 1.92 m^2) for each plot to give the leaf area index.

The plant height for each crop was measured with a white board, marked in 5 cm intervals, placed between the crop rows in each plot. In 2002, the plant heights of all five crop rows in each plot were measured and the mean height recorded while in 2003 two sampling points were chosen in the centre of each plot and the mean height recorded. The plant height was assumed to be zero at the time of sowing and was measured on 12, 25 September and 10 October in 2002. Similarly in 2003, measurements were taken on 28 August, 11 and 19 September.

4.4 Measurement of crop reflectance

The reflectance of the crops was carried out immediately before each plot was destructively sampled. Siting pegs were placed in the field to ensure that the same sample area of crop was used for both the reflectance measurement and the quadrat foliage cuts.

A tractor (Figure 4.2) (Kuboto model B1400) was fitted with two matching PhD 600 WeedSeeker ® sensor heads and driven across each plot at right angles to the crop rows (Figure 4.3). The sensors were matched by comparing the output of each when the same target was placed in their field of view and choosing those that had the minimum difference. A control box (CP600, Ntech Industries), mounted on the tractor, allowed adjustment of the sensor sensitivity due to the size of the target, speed of travel and background (baseline) reflectance. The controls were set for the smallest weed size and slowest tractor speed. The sensors were calibrated before each run by positioning them over an area of bare soil and stubble that contained no green living plant material. A 'soil base' button, on the control unit, was pressed and held for 5 seconds. The sensors were tested periodically by placing a piece of living green plant material in their field of view. This triggered the solenoid valves attached to the rear of the sensors. These valves were designed to turn on and off a herbicide spray nozzle in the commercially available system. However, these valves did not fulfill any function in this system apart from verifying the correct operation of the sensors when a target was identified. The valves make a clicking noise and turn on a light emitting diode when activated by the sensor.

Before each sampling run a preliminary test was conducted and the elapsed time recorded and entered into the computer software. The targeted ground speed of the tractor was 1 m s^{-1} or (3.6 km h^{-1}). This was achieved by driving the tractor in 2nd gear at an engine speed of 2500 revolution per minute (rpm). However, minor adjustments were needed to the engine speed due to the wheel slip of the tractor which was affected by the moisture content of the soil surface.

The field of view of the WeedSeeker® sensor is 300 mm and 7 mm, perpendicular and parallel to the direction of travel, respectively. The sensor uses light emitting diodes (LED) to illuminate the target as previously described in Chapter 2. This beam is visible in dark conditions and confirms the dimensions of the field of view. The desired sampling rate of the sensors is one reading for every 7 mm of forward movement. When travelling 1 m s^{-1}, the sampling rate is 143 readings m^{-1} or 143 readings s^{-1}. By multiplying the sampling rate by the elapsed time of the run the total number of readings required can be calculated. In 2002, the sensors were setup to collect 12,000 readings over a total distance of 84 m which took 84 seconds to sample.

Figure 4.2: The tractor mounted sensors and computer used to measure the reflectance of the plants.

The sensors measure the ratio of NIR/red reflectance (SR) and output a signal that varies in voltage in proportion to this ratio. The internal circuit board of each sensor was hard wired to a computer to enable the transfer of the signal as there were no interface ports on the PhD 600 WeedSeeker ® sensors. The signal (5000 mV) was sent to an analogue to digital converter DAQ700 (National Instruments) installed in a laptop computer (PC3, Gateway 2000). The software interface, between the DAQ700 card and the MS Windows95 operating system, was written by Adrian Doss in Delphi language and made use of the NI-DAQ libraries. This enabled the sensor readings to be saved to a data file.

Figure 4.3: Field of view of boom mounted WeedSeeker® sensors. The direction of travel is perpendicular to crop rows.

The data file consisted of three columns of numbers. Column one was the scan number (time) and is related to the distance traveled by the tractor, columns 2 and 3 were the readings for each of the WeedSeeker® sensors. The sensors performance was unaffected by the changing environmental conditions, such as sunlight, due to the self illumination system. The sensor response ranged from 1650 mV for a target consisting of bare soil and stubble to 3000 mV for dense green foliage. The data were graphed to check for any outliers. The x co-ordinate is the time since the start of the run while the y co-ordinate is a value proportional to the ratio of NIR/red reflectance.

The data file was graphed on a computer screen. Each data file consists of a continuous sampling across all plots in the run. The crop rows appeared as positive peaks in the graphs. White pegs were place horizontally on the ground between the plots to enhance the definition of the plot boundaries. These pegs were easily identified on the screen as negative peaks below the baseline (Figure 8.4). The data were effectively a time series measurement and digitising the position of the plot boundaries on the screen enabled the data to be divided into segments that correspond to each plot. This process was carried out with a program written in S-Plus® (InsightfulCorp, 2003) which uses the `locator` function. This function records the horizontal co-ordinate of the cross hair on the screen when it positioned over a point on the graph with a pointing device (mouse). The horizontal coordinate is recorded in units of scan number and this can be converted into units of distance or time as the speed tractor was constant across the plots. The signal is a measure of the amount of green foliage in the field of view of the sensors. A baseline value of 1650 mV for bare soil was subtracted from the signal and the area under the peaks calculated for each plot. The area is proportional to the average value of the RVI across the plot and was given the acronym CCA which stands for Crop Canopy Analyser.

$$CCA = \frac{\sum RVI_{crop}}{n} - RVI_{soil} \tag{4.1}$$

where,

RVI_{crop}	is the RVI of the crop,
RVI_{soil}	is the average RVI of the soil background,
n	is the number of RVI readings.

4.5 Harvest

The final harvest of the plots was completed after the crops had reached maturity. Fababean was the first crop to reach maturity followed by wheat, canola and chickpea. The plots were trimmed to remove all the disturbed areas that had been destructively sampled for biomass throughout the growing season. Each plot was measured prior to harvest and the area calculated. The plot lengths were approximately 16 m and 10 m in 2002 and 2003, respectively.

The plots with wide row spacing had five crop rows. However, only the three centre rows were harvested. This eliminated any edge effects that may have enhanced the yield of the plants in the outside rows and thus avoided biasing the results. In 2003, the narrow row spacing plots had nine crop rows. Three of the outer-most rows were discarded and only the six inner rows harvested. The grain samples were weighed without drying and a sub-sample taken to measure the 100 grain dry weights.

Harvesting was carried out with a plot harvester (Kingaroy Engineering Works) on the dates listed in Table 4.1. The grain was unloaded from the hopper into bags and weighed in the laboratory.

4.6 Statistical Methods

Exploratory data plots indicated that the mean responses of biomass, reflectance (CCA), leaf area index were non-linear and that for each treatment, the `plot` effect increased over time.

A mixed model was used to interpret differences amongst the observed responses. The systematic effects of growing time for each crop was represented by a spline curve and random effects of `plot` and `plot:time` were included to account for the correlation due to

Table 4.1: Harvest dates for the winter crops grown in 2002 and 2003.

	2002		2003	
Crop	Date	Days after sowing	Date	Days after sowing
Fababean	4 November	156	13 November	169
Canola	18 November	169	18 November	174
Wheat	18 November	169	18 November	174
Chickpea	19 November	170	28 November	184

repeated measures. The replicate random effects accounted for slight spatial trends across plots.

These models were fitted using ASREML (Gilmour et al., 1998). The model is:

$$\mathrm{Y}_{ijk} = \underbrace{\mathrm{crop}_i + s(\mathrm{dayno}_{ij})}_{\text{fixed}} + \underbrace{\mathrm{plot}_k + s(\mathrm{dayno}_{kj})}_{\text{random}} + \varepsilon_{ijk} \tag{4.2}$$

where,

Y_{ijk}	is the crop biomass, leaf area index, or CCA, for crop i, sampling j and plot k
the term $s()$	indicates a spline term,
i subscript	indicates the crop,
dayno_{ij}	is the j th sampling from crop i,
dayno_{kj}	is the j th sampling from plot k, and
ε_{ijk}	is the error term for crop i, sampling j and plot k.

A piecewise regression model (Neter et al., 1985), sometimes known as a bent stick model, is appropriate in some circumstances where the regression of Y on X is a two stage linear relationship. In the case of the relationship between plant height and time the initial rate of change in plant height is small until some point in time (change point) where the rate increases. Two separate but intersecting linear regression models are fitted to the data. One is for the interval from zero to the change point and the other is from the change point to the maximum time value. The piecewise model is,

$$\mathrm{Y}_i = \beta_0 + \beta_1 X_{i1} + \beta_2 \left(X_{i1} - C\right) X_{i2} + \varepsilon \tag{4.3}$$

where,

Y_i	is the plant height or leaf area index, from the i th sample,
X_{i1}	is the time (days) of the i th sample,
C	is the change point (days),
β_0	is the intercept, where: ($\beta_0 = 0$ when the line is fitting through the origin),
β_1	is the slope, when $X_{i1} \leq$ C,
β_2	is the slope, when $X_{i1} \geq$ C,
X_{i2}	is an indicator variable, where:
	$X_{i2} = 1$ if $X_{i1} \geq C$
	$X_{i2} = 0$ otherwise and
ε	is the error term.

These models were fitted using ASREML (Gilmour et al., 1998). The model is:

$$\mathrm{Y}_{ijk} = \underbrace{\text{crop}_i + \text{year} + \text{spacing}}_{\text{fixed}} + \underbrace{\text{plot}_k + s(\text{biomass}_{ij})}_{\text{random}} + \varepsilon_{ijk} \tag{4.4}$$

where,

Y_{ijk}	is the crop
	for crop i, sampling j and plot k
the term $s()$	indicates a spline term,
i subscript	indicates the crop,
dayno_{ij}	is the j th sampling from crop i,
dayno_{kj}	is the j th sampling from plot k, and
ε_{ijk}	is the error term for crop i, sampling j and plot k.

The relationship between reflectance (CCA) and biomass has generally been fitted by an exponential model. However, by their nature non-linear models, such as the exponential, have parameters that are unstable in their estimation. This can cause poor predictions from the model and particularly when it was observed that CCA was decreased as the crops reached their maximum biomass. A mixed model was considered a superior model and was fitted using ASREML with fixed terms for crop, year and row spacing and random terms for plot and biomass.

4.7 Results

4.7.1 Leaf and stem ratio

The ratio of the dry matter from the leaf and stem components in the biomass sampling indicate the decreasing ratio with time (Table 4.2). The missing values in the table are due to the different method of separating the leaves from the stems. The wheat could not be separated into leaves and stems until late in the season. The decreasing leaf mass as a proportion of the total plant mass affects the reflectance measurements by putting a increasing proportion of the plant biomass into vertical structures. The leaves are mostly horizontal structures and present a larger surface area to the sensors than the stems.

Table 4.2: Ratio of leaf to stem dry matter for crops in 2002 and 2003.

			Days after sowing							
Year	Row spacing	Crop	45	59	73	87	101	115	129	143
2002	Wide	Canola	-	-	-	8.4	2.5	0.6	0.3	-
		Chickpea	-	-	-	-	1.7	1.3	1.0	0.4
		Fababean	7.4	5.0	3.2	2.3	1.4	1.1	0.5	-
		Wheat	-	-	-	-	-	-	-	-

			Days after sowing							
Year	Row spacing	Crop	54	69	84	98	112	125	139	153
2003	Narrow	Canola	-	7.0	1.9	1.1	0.4	0.2	0.1	-
		Chickpea	2.3	1.9	1.6	1.2	0.9	0.7	0.6	-
		Fababean	2.3	1.8	1.0	0.7	0.5	0.3	0.2	-
		Wheat	-	-	-	-	-	-	0.1	-
	Wide	Canola	-	6.3	1.8	0.9	0.5	0.2	0.2	-
		Chickpea	2.4	1.8	1.6	1.2	0.9	0.7	0.6	-
		Fababean	2.5	1.7	0.9	0.7	0.6	0.3	0.2	-
		Wheat	-	-	-	-	-	0.3	0.2	-

4.7.2 Crop dry matter at physiological maturity

The dry matter at physiological maturity was estimated by comparing the biomass of the crop at each sampling time. The sampling time with the highest dry matter was considered to be the point of physiological maturity. Wheat had the highest dry matter in 2002 followed by fababean, canola and chickpea (Table 4.3).

The dry matter production for crops grown in 2003 (Table 4.4) was almost double the values for the respective crops grown in 2002 and reflects the more favourable seasonal conditions in 2003. Wheat again had the highest dry matter followed by canola, fababean and chickpea. Although dry matter for each crop was slightly higher with 32 cm rows it was not significantly different ($P \leq 0.05$) to the 64 cm row spacing.

4.7.3 Grain yield

The grain yield for each crop was much less in 2002 than in 2003. This is mainly due to the below average in-crop rainfall in 2002. However, crop yields in 2002 were close to the long-term district average. Wheat had the highest grain yield followed by chickpea, fababean and canola (Table 4.3).

Analysis of variance of the grain yield in 2003 showed that there was a significant effect of crop ($P \leq 0.001$), row spacing ($P \leq 0.05$) and their interaction ($P \leq 0.001$). Canola and chickpea had higher yield in wide rows while the fababean and wheat yielded better in narrow rows.

4.7.4 Harvest index

The harvest index is the ratio of grain yield to total dry matter at maturity, and is an indication of the efficiency of the crop to convert biomass into grain. Chickpea had the highest harvest index in 2002 which may relate to its slow early growth and therefore better use of stored soil water present late in the season. Canola had the lowest harvest index in both 2002 and 2003. The harvest index did not change greatly between years for canola, chickpea and wheat. It was higher in 2003 for fababean. Analysis of variance of harvest index in 2003 indicated no significant effect due to row spacing.

Table 4.3: Dry matter, grain yield and harvest index of winter crops grown in wide (64 cm) rows in 2002. Numbers are the mean ± the standard error.

Crop	Dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest Index
Canola	4693 ± 187	1172 ± 43	0.25 ± 0.01
Chickpea	4299 ± 137	2087 ± 37	0.49 ± 0.02
Fababean	4705 ± 309	1666 ± 110	0.36 ± 0.03
Wheat	5910 ± 173	2314 ± 67	0.39 ± 0.02

4.7.5 Plant height

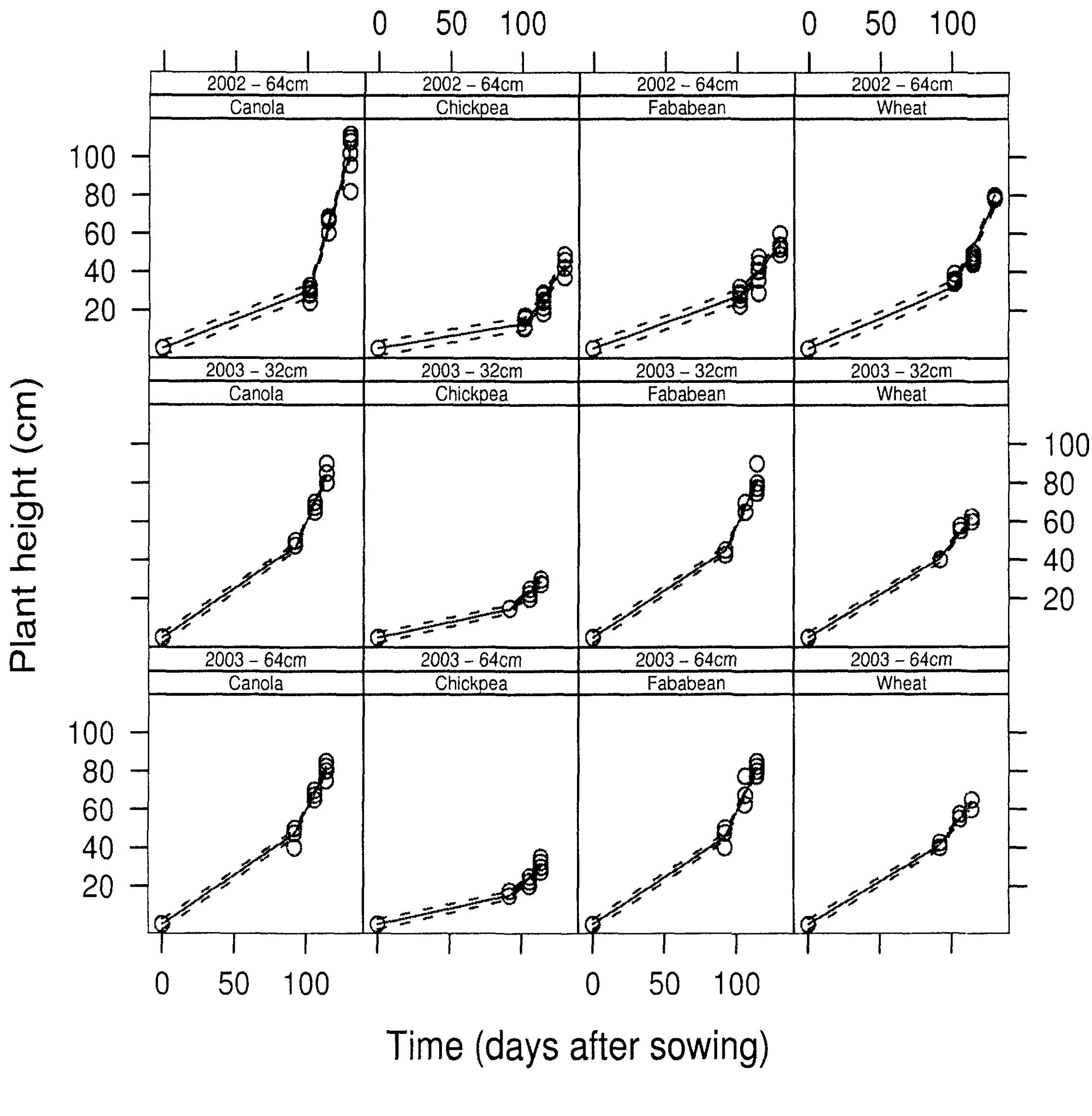
The change in plant height per unit of time is an indication of the growth rate of the crop. The height will also have an influence on the reflectance measurements as the leaves in the upper canopy will shade the lower leaves. Only a limited number of height measurements were made during the season and a piecewise regression model (4.3) was considered appropriate.

Table 4.4: Dry matter, grain yield and harvest index of winter crops grown in narrow (32 cm) and wide (64 cm) rows in 2003. Numbers are the mean ± the standard error.

	Dry matter ($kg\ ha^{-1}$)		Grain yield ($kg\ ha^{-1}$)		Harvest Index	
Crop	Narrow	Wide	Narrow	Wide	Narrow	Wide
Canola	9830 ± 726	9758 ± 1010	1654 ± 68	2051 ± 36	0.17 ± 0.01	0.22 ± 0.02
Chickpea	7895 ± 705	8290 ± 558	3787 ± 37	3843 ± 118	0.49 ± 0.04	0.47 ± 0.03
Fababean	9242 ± 207	9083 ± 1142	4552 ± 56	4233 ± 71	0.48 ± 0.01	0.49 ± 0.06
Wheat	11943 ± 888	11044 ± 452	5288 ± 91	4465 ± 100	0.45 ± 0.03	0.41 ± 0.02

The measurements of plant height in 2002 (Figure 4.4) indicated that chickpea was the shortest crop at maturity followed by fababean, wheat and canola. In 2003, the seasonal conditions were more favourable for fababean and they grew taller than the wheat (Figure 4.4). The plant height of chickpea were less than for wheat and canola. Row spacing did not have a significant effect on plant height for the crops in 2003.

Figure 4.4: Plant height for the four crops grown in narrow (32cm) and wide (64 cm) row spacing in 2002 and 2003. The points are the average plant height for each plot. The solid line is a fitted piecewise regression and the dashed lines are the 95% confidence intervals.



4.7.6 Change in crop biomass with time

Crop biomass, measured as dry matter, increased with time and most crops had reached their maximum levels by 150 days after sowing. The crop biomass, for canola and chickpea in 2002, had asymptoted by the end of the sampling period, while the fababean and wheat appeared to be still increasing. This indicates that wheat and fababean may not have reached their maximum biomass when the last sample was taken. Wheat had the highest biomass at maturity followed by fababean, canola and chickpea (Table 4.3). All crops had similar grown rates between 100 and 120 days as indicated by the similar slopes of the biomass versus time curves in Figure 4.8. Early in the season wheat had the highest rate followed by fababean, chickpea and canola, respectively. However, the biomass of canola was larger than fababean and chickpea at 90 days after sowing.

The crops grown in wide rows in 2003 showed a similar order in terms of biomass accumulation over time (Figure 4.9). Wheat was the highest and was closely followed by fababean and canola with chickpea much lower. The chickpea growth rate was less than the other crops.

There was a similar growth pattern for crops grown in the narrow rows as wide rows in 2003. The narrow row fababean reached a plateau in biomass accumulation by the last sampling time.

4.7.7 Change in leaf area index with time

The leaf area index (LAI) for canola, chickpea and wheat increased with time. and reached a peak between 110 and 130 days after sowing in 2002 (Figure 4.5). The LAI generally decreases when the older leaves drop off and the plants start to senesce. The measured data support this observation. The LAI for the fababean crop increased throughout the sampling period but never reached a definite peak. A later sampling would have confirmed whether the LAI had reached a maximum. A comparison of the LAI versus time for the four crops (Figure 4.8) showed a similar order to the biomass accumulation graphs. At any time during the season wheat had the highest biomass followed by canola, fababean and chickpea. This was also the same order in terms of the time of the crops to reach their peak LAI.

In the wide row treatments in 2003, the crops with the highest LAI values were wheat, fababean and canola, respectively, and these reached their maximums at 110 days after sowing (Figure 4.6). Interestingly, chickpea also reached a local maxima in LAI at this time but the LAI subsequently decreased and later increased to a maximum at the last sampling time (Figure 4.9).

A similar pattern of LAI was observed in the crops with narrow rows as those with wide rows in 2003. The order for crops with the highest LAI was wheat, fababean, canola and chickpea (Figure 4.10). The same local maxima was observed in the chickpea LAI as in the wide row treatments.

Later in this discussion it will be shown that the LAI value at unity (LAI=1) is a critical point when calibrating LAI with remote sensing measurements. It will be useful to compare the time, for each crop to reach a LAI value of one, as this gives an estimate of the likely time interval that reliable predictions can be made with the calibration curves. In 2002, it took 87, 96, 101 and 114 days for wheat, canola, fababean and chickpea to reach an LAI of one, respectively. Similarly, in 2003 it took 80, 94, 88 and 132 days for wheat, canola, fababean and chickpea crops grown in wide rows to reach an LAI of one, respectively. The wheat, canola and fababean grown in narrow rows in 2003 (Figure 4.7), took 72, 81, and 84 days to reach this value, respectively. This is a slightly shorter time period than in 2002. Both wide and narrow row chickpea crops reached a LAI value of one in 132 days.

4.7.8 Change in reflectance(CCA) with time

The reflectance (CCA) increased with time for all crops (Figure 4.5). The CCA for wheat was greater than the other crops during the early growth period but was subsequently overtaken by fababean, canola and wheat (Figure 4.8). Wheat reached its maximum CCA values earlier than fababean, canola and chickpea, in that order, respectively. The crops with the highest CCA values were chickpea followed by canola, fababean and wheat, respectively.

In 2003, the crops grown in wide rows (Figure 4.9) reached a maximum CCA value between 115 and 139 days after sowing, with chickpea, canola and fababean reaching their maximum slightly later than wheat. Canola had the highest CCA values followed by fababean, chickpea and wheat (Figure 4.6). The CCA of wheat was once again greater than the other crops during the early growth period. However, the crop with the maximum CCA was canola followed by fababean, chickpea and wheat (Figure 4.9).

The narrow row crops in 2003 showed a similar pattern to the wide row crops in terms of time to reach the maximum CCA values (Figure 4.7). However, the maximum CCA for narrow row wheat was substantially higher than the wide row treatment which reflects the dry matter and yield differences between these treatments (Table 4.4).

The same data are replotted in Figures 4.8 - 4.10 on pages 44 - 45 as superposed profiles of the crop responses so that a comparison amongst crops is readily apparent.

Figure 4.5: Change in crop biomass, leaf area index and reflectance (CCA) with time for **wide row** canola, chickpea, fababean and wheat in **2002**. Unbroken lines are the fitted spline curves. Shaded areas indicate the 95% confidence intervals. The graphs are arranged in columns for the measurement variables and rows for the crop types.

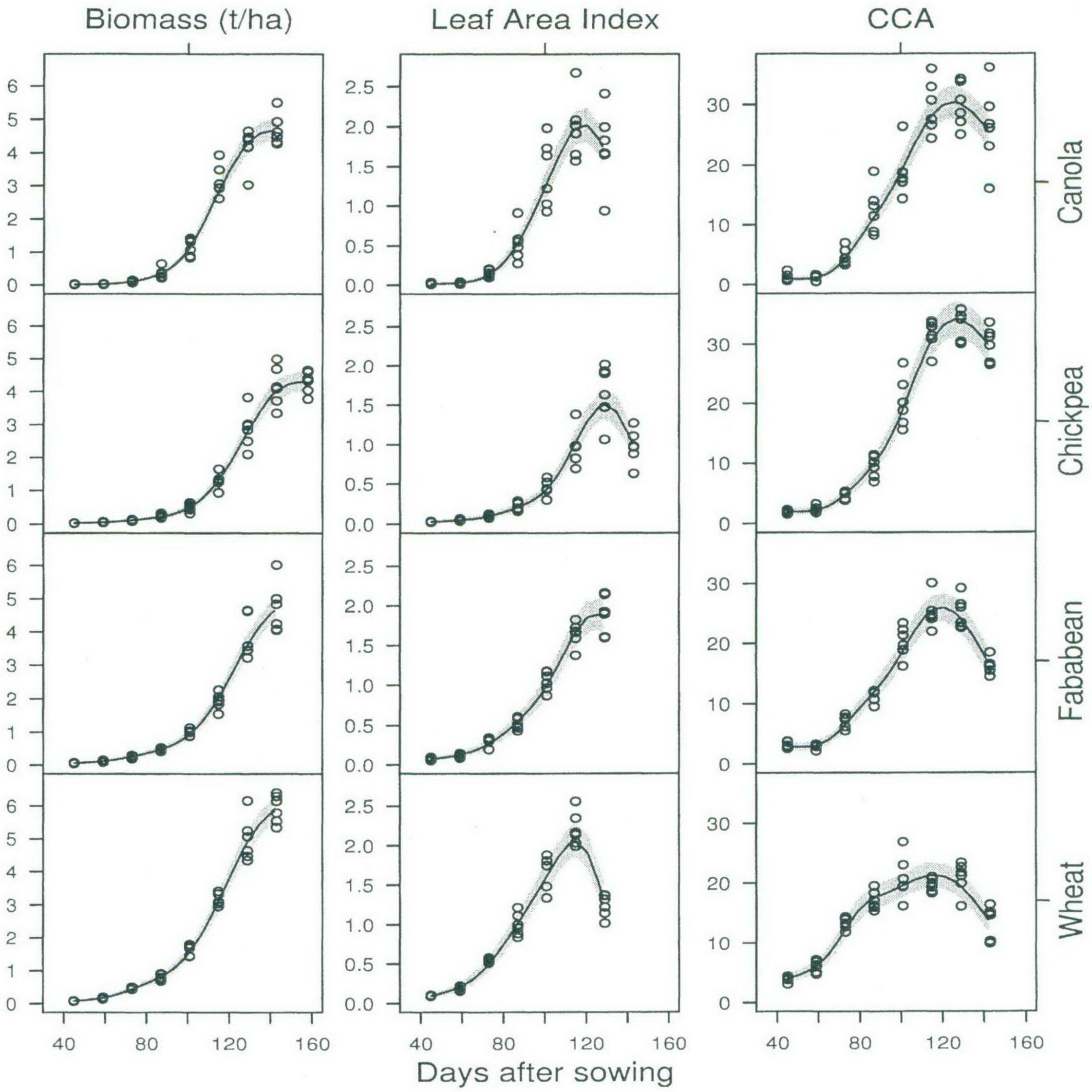


Figure 4.6: Change in crop biomass, leaf area index and reflectance (CCA) with time for **wide row** canola, chickpea, fababean and wheat in **2003**. Unbroken lines are the fitted spline curves. Shaded areas indicate the 95% confidence intervals. The graphs are arranged in columns for the measurement variables and rows for the crop types.

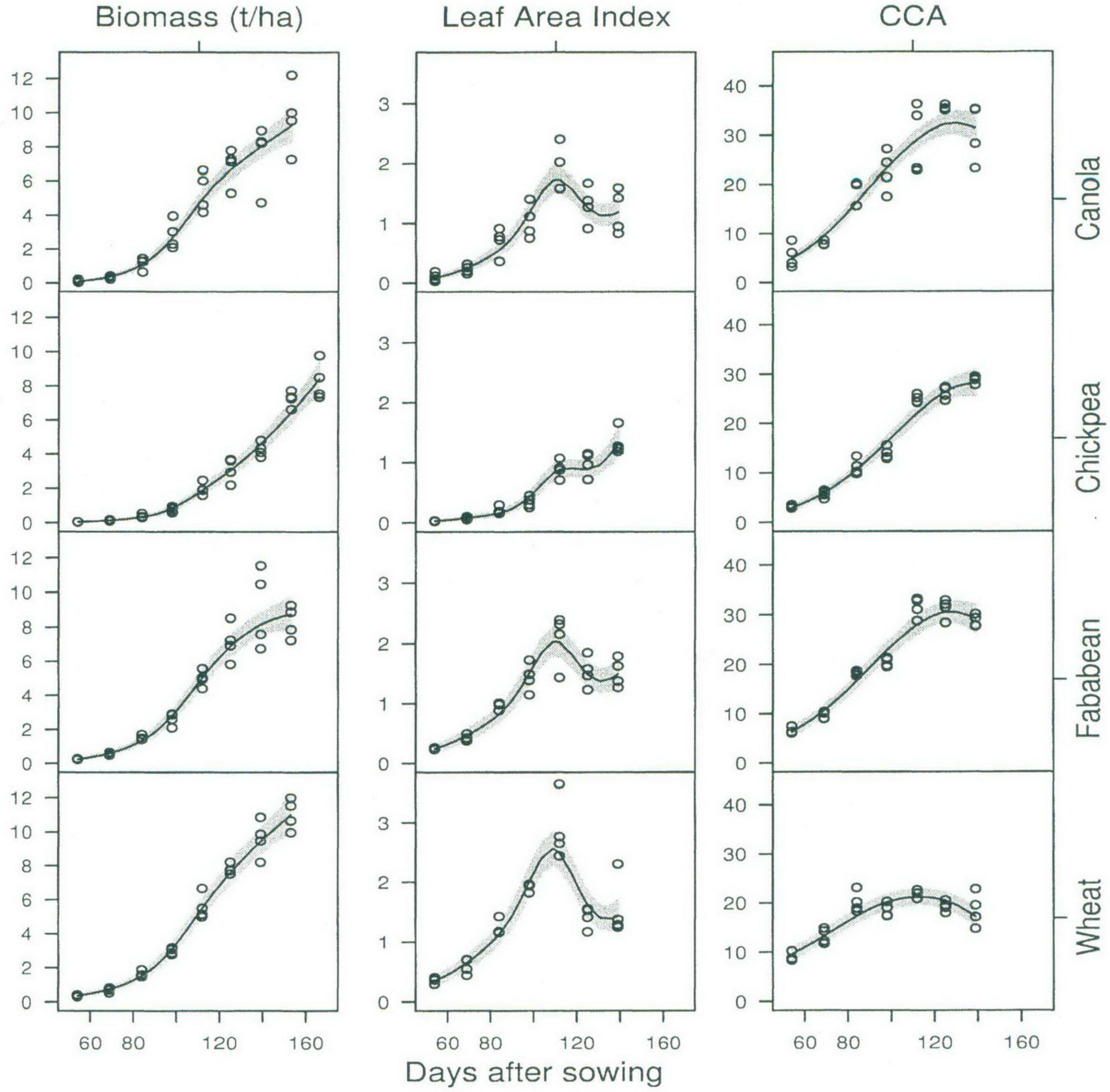


Figure 4.7: Change in crop biomass, leaf area index and reflectance (CCA) with time for **narrow row** canola, chickpea, fababean and wheat in **2003**. Unbroken lines are the fitted spline curves. Shaded areas indicate the 95% confidence intervals. The graphs are arranged in columns for the measurement variables and rows for the crop types.

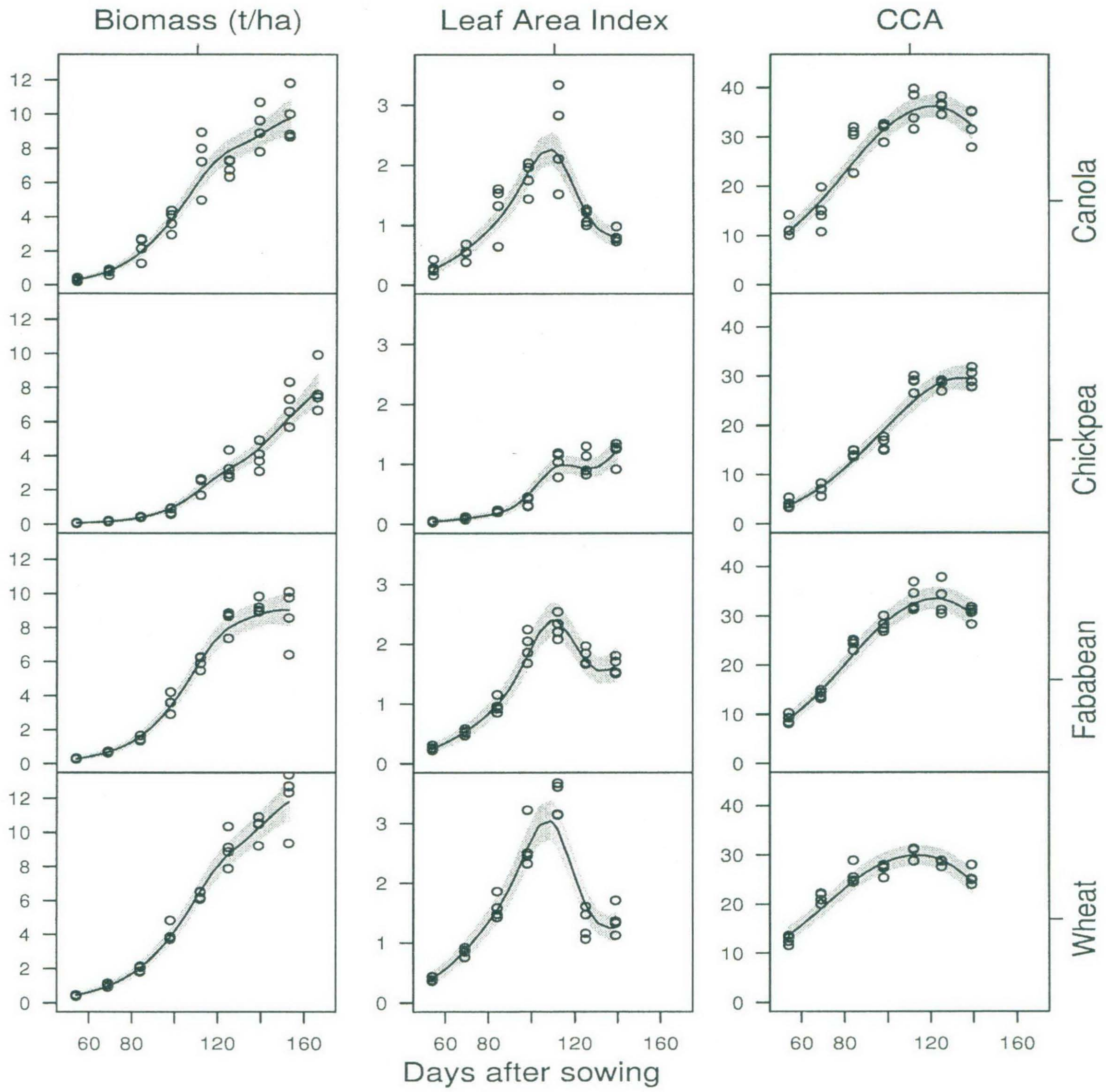


Figure 4.8: Comparison between crops for biomass, leaf area index and reflectance versus time in **2002**. The lines are the fitted spline curves previously shown in Figure 4.5 and the observed data points have been omitted to enable greater clarity.

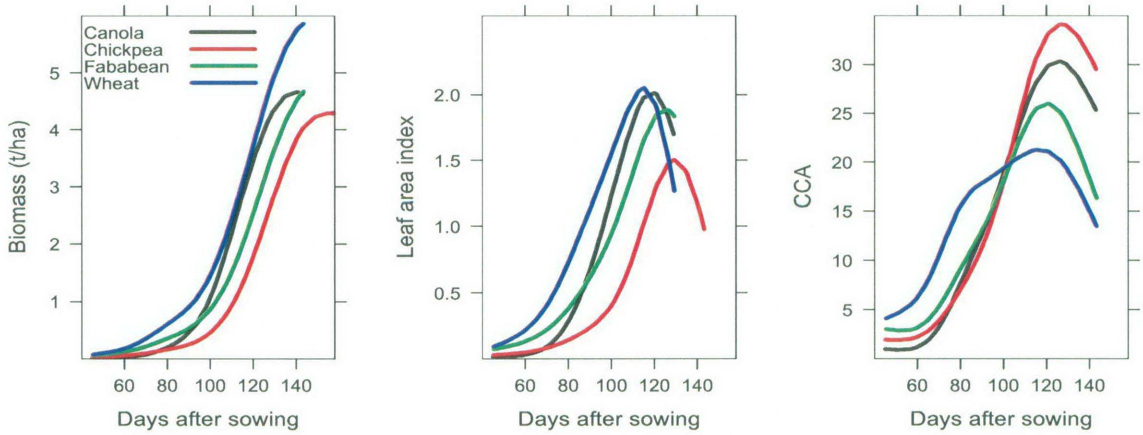
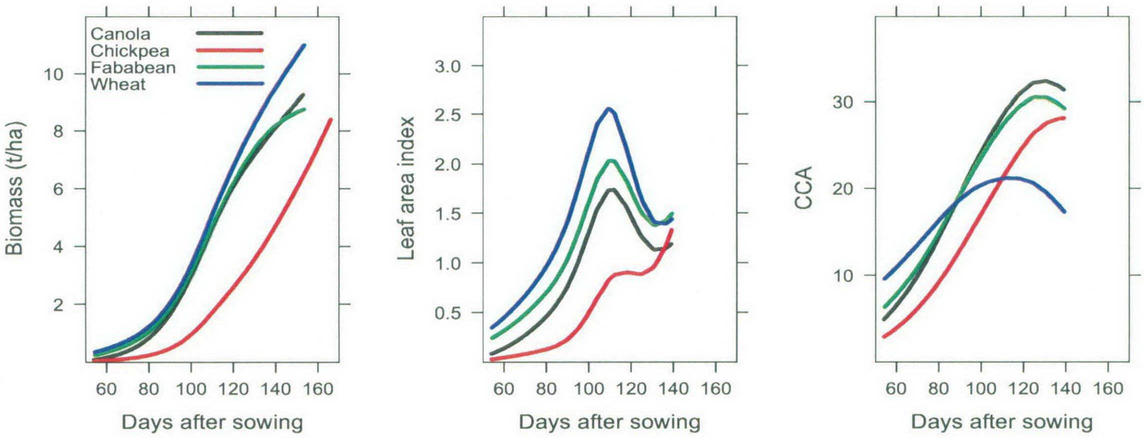


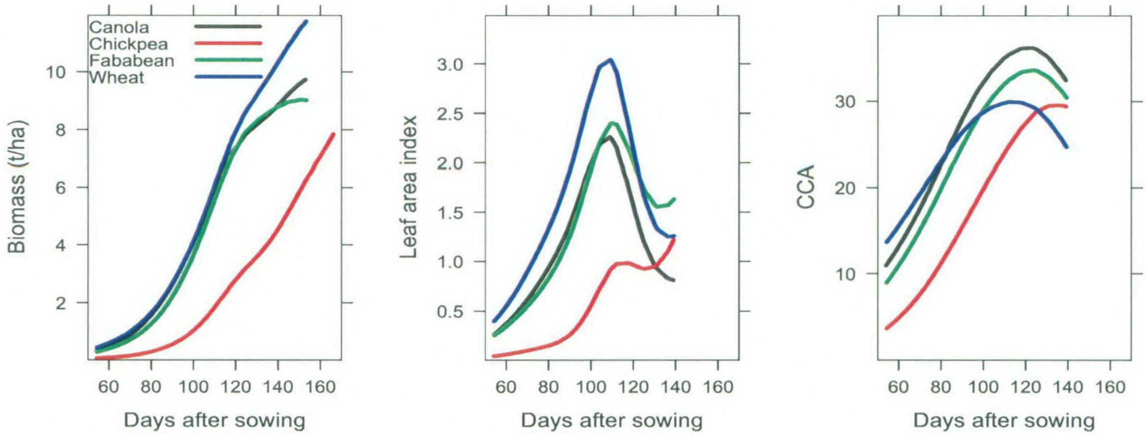
Figure 4.9: Comparison between crops for biomass, leaf area index and reflectance versus time for **wide row** treatments in **2003**. The lines are the fitted spline curves previously shown in Figure 4.6 and the observed data points have been omitted to enable greater clarity.



The order in terms of maximum CCA values was canola, fababean, wheat and chickpea (Figure 4.10).

The lower CCA values for chickpea in 2003 was probably associated with the change in sowing rate from 70 kg ha^{-1} to 35 kg ha^{-1}. Generally the narrow row crops had a higher maximum CCA than their equivalent wide row crops.

Figure 4.10: Comparison between crops for biomass, leaf area index and reflectance versus time for **narrow row** treatments in **2003**. The lines are the fitted spline curves previously shown in Figure 4.7 and the observed data points have been omitted to enable greater clarity.

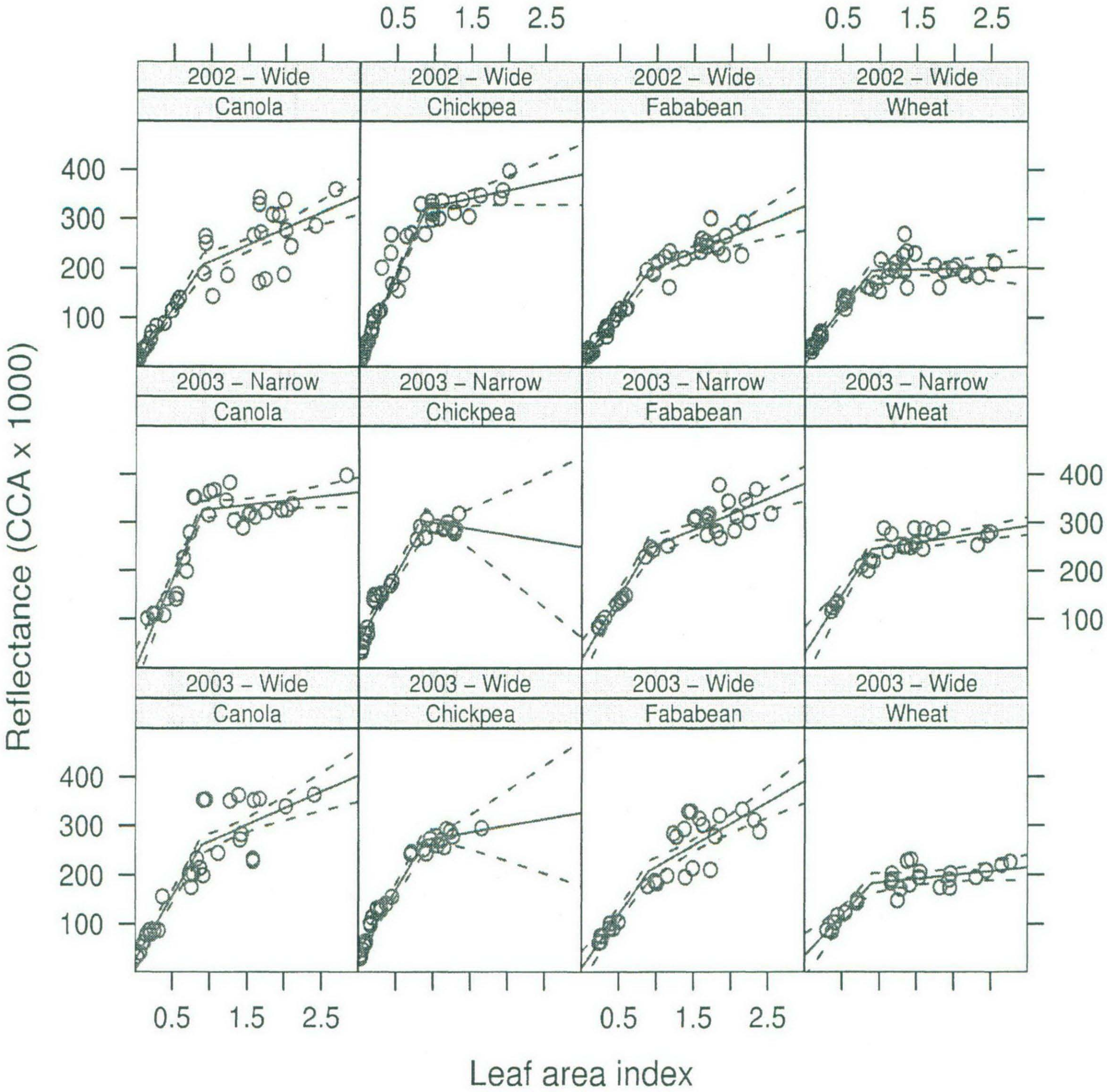


4.7.9 Leaf area index and crop reflectance

The leaf area index (LAI), for all crops was highly correlated with the reflectance (Figure 4.11). This was especially so during the early growth stage when the LAI was less than 1. When the crop LAI exceeded 1, the gradient was reduced and the reflectance was more variable. The point on the graph where this discontinuity occurs is known as the change point. The relationship between LAI and CCA (RVI) was examined and found to exhibit two distinctive phases. Previous research by Serrano et al. (2000) indicated a linear relationship between LAI and RVI. A piecewise linear regression model (4.3) was fitted to the observed responses as this accommodated the two different phases and used the same linear regression fitting process as a linear model. A change point at an LAI= 1, was used to model the response and the fitted values and confidence intervals are displayed in Figure 4.11.

In 2002, a linear regression was fitted to a restricted range of values (LAI$\leq$ 1) so that comparisons could be made between crop types. This range of LAI values is where the model has the narrowest confidence intervals and so the model predictions will have the greatest accuracy. The intercept term in the model was only significant in the wide row crops. Chickpea had the steepest regression line slope of 324 followed by canola, fababean, wheat with 242, 194 and 155, respectively. There was a significant ($P \leq 0.05$) difference in the slope values between all crop types. The correlations (R^2) between reflectance and LAI were 0.98, 0.98, 0.92 and 0.92 for canola, fababean, wheat and chickpea, respectively. Similarly in 2003, the same linear regression model was fitted with the inclusion of a row spacing factor. There was a significant ($P \leq 0.001$) effect of row spacing with narrow rows having a higher reflectance than wide rows at the same LAI values.

Figure 4.11: The relationship between reflectance (CCA) and leaf area index for canola, chickpea, fababean and wheat grown in wide (64 cm) rows in 2002, narrow (32 cm) rows in 2003, and wide (64 cm) rows in 2003.



In the crops grown in wide rows, canola had the steepest regression line slope of 259 followed by chickpea, fababean and wheat with 254, 167 and 152, respectively. There was a significant ($P \leq 0.05$) difference in the slope between fababean and the other three crop types. The correlations (R^2) between reflectance and LAI were 0.84, 0.96, 0.99 and 0.93 for canola, chickpea, fababean and wheat, respectively.

In the crops grown in narrow rows, canola had the steepest regression line slope of 348 followed chickpea, fababean and wheat with 282, 230 and 187, respectively. There was a significant ($P \leq 0.05$) difference in the slope between the crop groups (canola and chickpea) and (fababean and wheat). The correlations (R^2) between reflectance and LAI were 0.79, 0.94, 0.99 and 0.97 for canola, chickpea, fababean and wheat, respectively.

4.7.10 Relationship between biomass and leaf area index

Figure 4.12 shows a linear relationship between crop biomass and leaf area index for all crops. The limit of linearity is where the leaf area index is less than 2. A model was not fitted to the data as the prediction of biomass from leaf area is not a practical method of estimation. For canola, fababean and wheat the leaf area index increases with time and asymptotes as biomass reaches a maximum near the end of the growing season. However, chickpea grown in wide and narrow rows in 2003 did not reach an asymptote near the end of the growing season.

4.7.11 Relationship between biomass and CCA

Figure 4.13 shows the relationship between biomass and CCA. The biomass can be accurately predicted from the CCA for crop biomass up to 1000 kg ha^{-1} because of the strong linear relationship between them. However, as biomass increased above this level, the relationship becomes less predictable as indicated by the non-linear curvature of the data. The confidence intervals also tend to increase as the biomass increases, indicating more variability in the data. The results in 2002 are better than in 2003 due to the lower biomass and the longer time associated with reaching 1000 kg ha^{-1}. Chickpeas, in particular, showed that the linear relationship extended for the longest period as indicated by the graph in 2002, where the majority of the data were within the linear range.

Figure 4.12: The relationship between leaf area index and biomass for canola, chickpea, fababean and wheat grown in wide rows in 2002, wide and narrow rows in 2003.

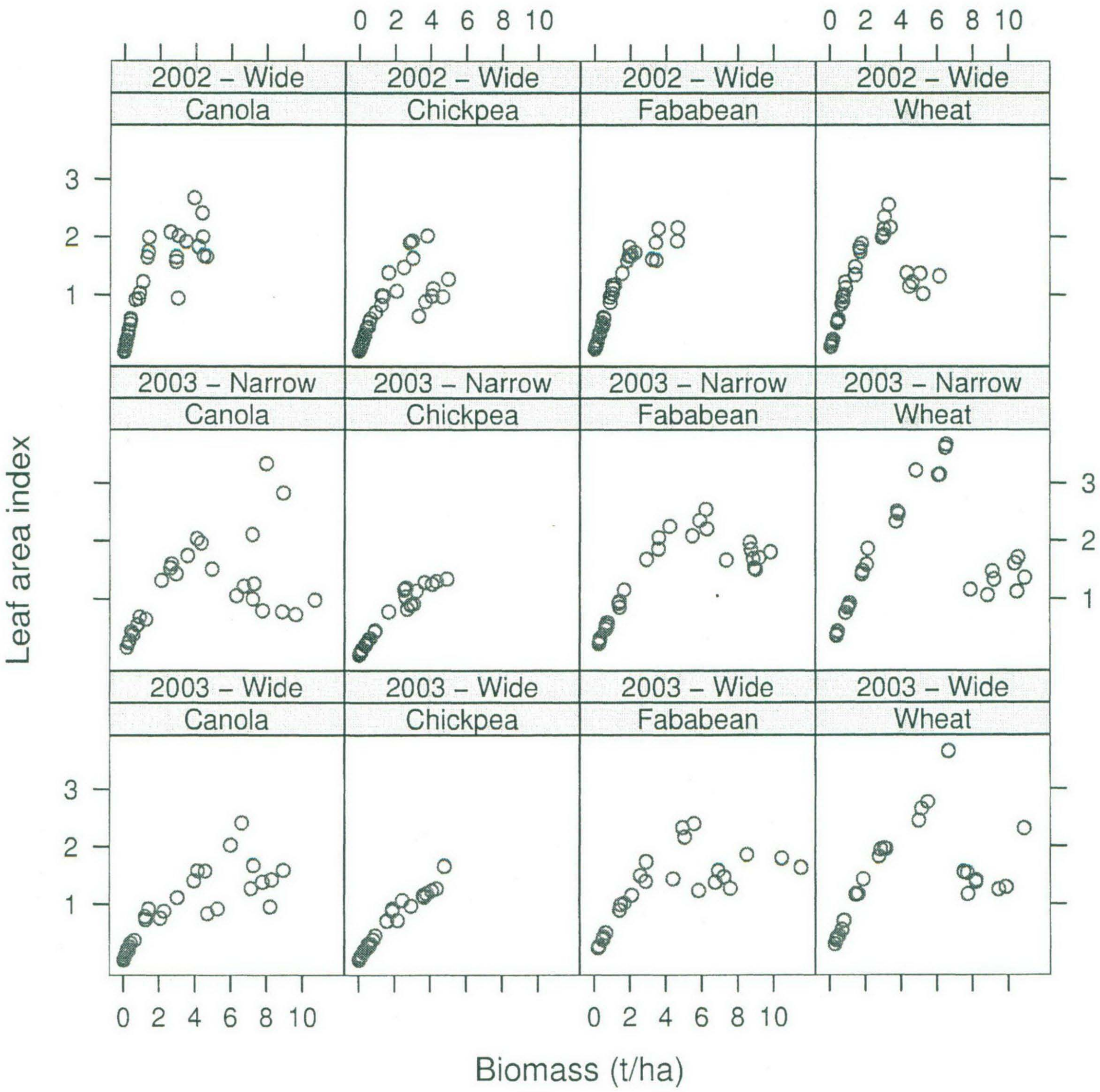
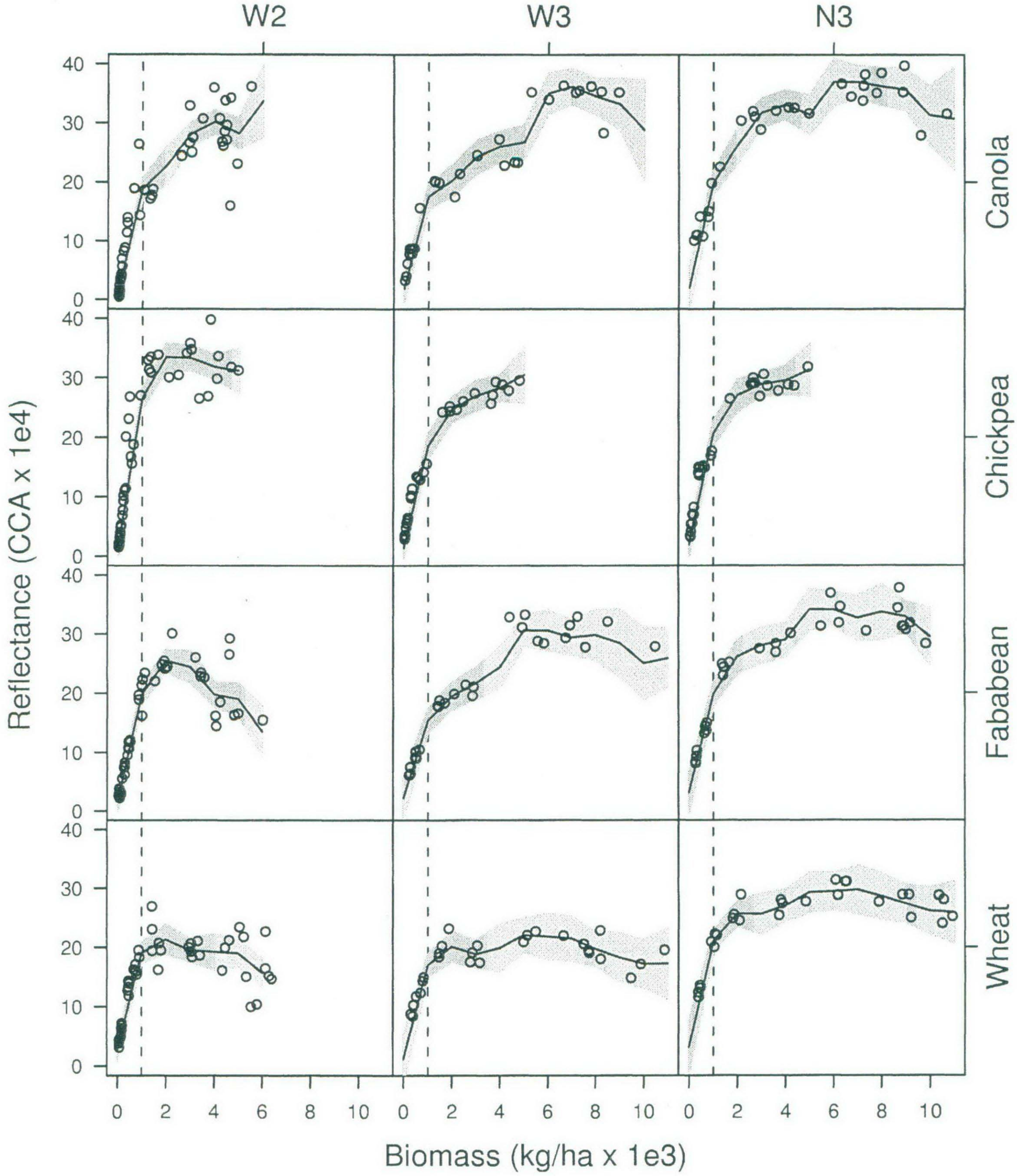


Figure 4.13: Spline curves fitted to CCA and biomass data using ASREML. Columns of graphs refer to the row spacing by year factor: (W2) wide row in 2002; (W3) wide row in 2003; and (N3) narrow row in 2003. Rows of graphs refer to the crops. Shaded area indicates the 95% confidence interval. The dashed line is at 1000 kg ha^{-1} biomass.



4.8 Discussion

Crop growth can be quantified by various measurements against time. These include the biomass and its sub-components such as leaves and stems. During early growth the leaves are the major component of the total biomass. The reflectance of the crop is dependent on the chlorophyll density in the foliage and leaves have a higher concentration of chlorophyll than the stems. Reflectance was found to be highly correlated with leaf area during the early stages of growth for all crops.

The slope of the regression lines fitted to reflectance (CCA) and leaf area index (LAI) is a measure of the sensitivity to changes in leaf area. In 2002 chickpeas had the greatest response in CCA per unit of LAI (Figure 4.11). This is despite the chickpea having a lower biomass and LAI than the other crops (Figure 4.8). The chickpeas have a greater leaf area per unit of biomass and therefore a greater reflectance in 2002, a drought year. The correlations (R^2) between reflectance and LAI for all crops were greater than 0.92 and support the hypothesis that reflectance is a good predictor of LAI.

In 2003, canola was the crop with the greatest sensitivity in reflectance per unit of leaf area. This trend was consistent for canola growing in both narrow and wide row spacings. Canola has a larger leaf size compared to the other crops and favourable growing conditions in 2003 resulted in larger leaves than in 2002. Canola also has a higher leaf to stem ratio than the other crops during the first 100 days after sowing (Table 4.2) and would have covered a greater area of ground per unit of biomass.

The correlations between reflectance and LAI for canola in 2003 were lower than for the other crops for both the wide and narrow row spacing treatments. Poor correlations can be the result of variable data or by fitting a reduced range of independent variables. In the case of canola, the leaf size at the first sampling time would have been larger than in 2002 and so there would be few data points near the origin.

The leaf area index of canola, fababean and wheat was greater when the crops were grown in narrow (32 cm) versus wide (64 cm) row spacing and in chickpeas there was no difference. If row spacing was decreased further, below the minimum spacing (32 cm) used in this experiment, then LAI would be expected to increase for these crops.

The reflectance (NDVI and RVI) increases with increasing green cover but this holds true only until canopy closure. Dampney et al. (1998) and Danson et al. (2003) found that the canopy closure occurs when the crop has a LAI of up to 3. The LAI at canopy closure can vary depending on the growing environment and row spacing. Full canopy closure usually occurs later for crops grown in wide rows.

In the experiments in this chapter the wheat reached a maximum LAI value of 2, 2.5 and 3 in wide, wide and narrow row spacing treatments in 2002, 2003 and 2003, respectively. The piecewise regression model fitted to the data indicate that reflectance was still increasing up until the last sampling time for canola, fababean and had asymptoted for chickpea and wheat. However, reliable predictions of LAI can only be made from reflectance in the first section of the piecewise regression. Therefore, reflectance measurements need to be taken before a LAI of 1 is reached for canola, chickpea, fababean and wheat crops grown in wide rows at Tamworth. In contrast to the 'bent stick' response of reflectance versus LAI found in this study, Serrano et al. (2000) found that the reflectance (simple ratio) increased linearly for LAI values from 0 to 8 in winter wheat. This difference may be due to the different definitions used to describe LAI. Tucker (1977) defined LAI as "the ratio of the total leaf area of the plant canopy to the ground area in the field of view", while in these experiments the field of view was the plot width (1.92 m). The crops grown in wide rows would also have gaps between the rows.

The relationship between reflectance measured as CCA and wheat biomass (Figure 4.13) was found to be curvi-linear and reached an asymptote near the end of the growing season. Felton et al. (2002) found similar results for spring wheat (var. Janz) grown at Tamworth in 2000 using the same WeedSeeker sensors. In the initial growth stage this curvi-linear relationship is almost linear and a simple linear model can be used to make biomass predictions. However, the limit of this linear model was found to be at a crop biomass (dry matter) of 1000 kg ha^{-1} for wheat grown in 2002 and 2003. This was higher than the 500 kg ha^{-1} linear limit estimated by Felton et al. (2002). An artificial method of inducing wheat biomass changes was also carried out by Felton et al. (2002) in North Platte, USA. The relationship between reflectance (CCA) and biomass of two wheat varieties, Arapahoe and Centura, was examined when the crop biomass had reached 11000 and 5000 kg ha^{-1}, respectively. The plant biomass was progressively removed by thinning and the reflectance was re-measured at each instance. The curvilinear relationship was also found between reflectance and biomass with the limit of linearity being less than 2000 kg ha^{-1}. The limit of linearity of 1000 kg ha^{-1} estimated in the current experiments is between the levels previously estimated and is probably more reliable due to the use of a better experimental design that included more replication, sampling times and the comparisons over two years of field trials.

The relationship between reflectance and biomass for the other crop types showed a similar shaped curvi-linear line to wheat and it would be safe to assume that the same limits of linearity would apply to these crops. Felton et al. (2002) conducted a field trial in which the reflectance (CCA) of 76 chickpea cultivars was measured and destructively sampled for biomass. The range in biomass between cultivars was from 100 to 900 kg ha^{-1} and a linear regression line was fitted. This limit agrees with the limit found in the current experiment. There were no references found in the literature on the use of the WeedSeeker®sensors for canola or fababean crops.

This experiment provided data from various field crops and allowed the following hypotheses to be tested: LAI is related to the biomass; reflectance is related to the LAI; biomass can be estimated from the reflectance. Many of the relationships between these variables could be fitted with a non-linear model but these models are less practical and would require calibration for changes in the growing environment each year. However, the relationship between the variables in the early growth stages can be approximated by a linear regression model for at least part of the range of values. The limit of linearity in the relationship between: biomass and LAI was at a LAI value of 2; reflectance and LAI was at a LAI value of 1. However, methods of measuring LAI are labourious, destructive and remote sensing is the only practical method of measurement. Reflectance measurements also have disadvantages due to the non-responsiveness to additional leaf area of crops at

LAI values between 1 and 2. This is caused by overlapping leaves and saturation of the field of view. In these experiments the limit of linearity in the relationship between biomass and reflectance occurred when the crops reached a LAI value of 1. For crops in these trials the limit was at 1000 kg ha^{-1} biomass.

The leaf are index for canola, fababean and wheat in 2003 increased with time and peaked at 110 days after sowing. The chickpeas also showed a local maxima in LAI at this time and then a period without increase was observed before a return to the normal growth pattern. This period of stagnation might have been associated with the low rainfall and high temperatures in September 2003 (Table 3.2). The biomass was steadily increasing during this period even though the leaf area index was stagnant (Figures 4.6 and 4.7).

A comparison of the biomass, leaf area index and reflectance versus time between crops indicated that wheat had different characteristics to the other crops. Although wheat had the highest biomass, fastest growth rate and highest leaf area index of the crops it did not have the highest reflectance. Indeed, the reflectance of wheat was less than the canola, chickpea and fababean in the majority of the experiments. The reasons for this result might be due to wheat being a grass (monocotyledon) and its plant architecture is more upright than the other broad-leaved (dicotyledon) crops.

The graphs of CCA versus time for wheat do not have the sharp peak at 115 days after sowing that is indicated in the leaf area index. This may be due to shadowing of the lower leaves in wheat that causes the sensors to see the leaf surfaces of only the top leaves of the plant. The leaf area measurement for wheat is different to other crops in that the leaves and stem are difficult to separate. This meant that when measuring the leaf area, the stems were included in the sample. The wheat stems usually grow vertically and so do not have a large surface area when viewed from above by the sensors. The conclusion from these observations is that although wheat has a larger biomass and leaf area than the other crops, the vertical architecture of the canopy does not allow the sensors to detect the extra biomass. This situation was slightly improved in the narrow row treatments where the same wheat biomass was produced from the same area as the wide row treatments. However, the narrow row treatments had a higher proportion of the sample area occupied with foliage due to the reduced row spacing.

The sampling for crop biomass should have continued for a longer period for wheat and fababean in 2002 and canola, chickpea and wheat in 2003 as this would have confirmed whether the maximum biomass had been reached. Continued sampling for leaf area would only be of value for chickpeas in 2003 where there appears to be a stalling in the growth curve at 120 days after sowing.

The WeedSeeker sensors should be positioned at a height of 800-1200 mm above the target for optimum response. As the crop height increased with time the boom height of the sensor was increased to maintain the same distance from the target. In the early growth stages of the crop the same boom height was used for all crops. However, canola grew to such a height that the boom could not be raised above the crop. The higher crop height also means that some leaves are not in the line of sight of the sensors. Therefore, the ground based remote sensing methods are more ideally suited to crops with lower crop height such as chickpea.

Chickpea was also the slowest of the crop to reach canopy closure and therefore reflectance measurements can be used for a longer period of time compared to fababean, canola and wheat. Comparisons between crops as to the suitability of using the reflectance to predict biomass indicates that chickpea was superior to canola, fababean and wheat. This is due to the linear relationship between reflectance and leaf area index for almost the entire growing season.

4.9 Conclusion

Crop biomass can be accurately predicted from the CCA up to when the crop biomass (dry matter) is 1000 kg ha^{-1}. This technique can be used in field trials to non-destructively estimate the difference in biomass between treatments. If the technique is combined with limited biomass data from normal destructive sampling a calibration equation can be calculated. This equation can be used to predict the biomass from areas where destructive measurements cannot be made. The differences in response between 2002 and 2003 indicate that a calibration curve needs to be established in each year as changing environmental conditions can cause different responses.

Leaf area index was shown to be accurately predicted from the CCA. A linear regression model could be used to accurately predict the leaf area index for all crops. However, the data suggest this to be a two stage process with accurate predictions able to be made when the leaf area index was less than 1. At leaf area index values greater than 1 there was a change in the slope of the linear regression model and more variability was observed in the data. The technique has applications in models where estimates of the leaf area of crop and weed can be used to make predictions of yield loss early in the season.

The results from the field experiment would suggest that chickpea is the preferred crop for using the reflectance measurements to model crop growth. Chickpea has a low initial growth rate and a branching plant structure that is more easily detected by the sensors than the other crops. The slow growth rate means that reflectance measurements can be used to predict biomass for a longer time interval than the other crops.

Chapter 5

The use of mimic weeds as a substitute for wild oats in chickpea competition field experiments

5.1 Introduction

Grass weeds, such as wild oat, are a major cause of yield loss in chickpea crops grown in northern NSW. This is partially due to chickpeas having a slower early growth rate that allows the weeds to become well established before crop canopy closure occurs.

Extensive work has been done outside Australia on the effect of weeds on yield loss in crops (Cousens, 1985). In Australia, research has concentrated on the problems caused by grass weeds in crops such as lupins (Allen, 1977; Arnold et al., 1985), triticale (Lemerle et al., 1979) and wheat (Barrett and Campbell, 1973; Smith and Levick, 1974; Reeves, 1976; Lemerle et al., 1979; Martin et al., 1987). The purpose of these studies has been to either define a relationship between yield-loss and weed density in a single crop (Allen, 1977; Martin et al., 1987) or to compare yield-loss in a number of different crops using the same level of weed infestation. Lemerle et al. (1995) conducted a series of field experiments, in southern NSW, to compare the competitiveness of eight winter crops (oats, cereal rye, triticale, oilseed rape, wheat, spring wheat, spring barley, field peas and lupins) to annual ryegrass (*Lolium rigidum* Gaud). The purpose of the study was to identify crops and cultivars with the potential to suppress grass weeds while maintaining acceptable grain yields. This may lead to a reduction in the reliance of herbicides for weed control. The weeds were sown at only one rate and the resulting weed density was 300 plants m^{-2}. The relationship between weed density and crop yield loss, in the majority of cases, was non-linear (Cousens, 1985); making comparisons between crop species at only one weed density ignores the possible interactions between crop and weed at other levels.

Weed seeds collected from the field have genetic variability that can cause problems when used in experiments. These include variations in germination and seed dormancy. Obtaining the desired levels of weed density treatments can be difficult when using this seed.

Cousens and Mokhtari (1998) suggested that one of the main problems encountered whilst conducting weed competition experiments was achieving uniform plant (weed) density at the various treatment levels. A crop species could be used as a mimic (pseudo) weed in these trials provided the crop species had similar competitive abilities. The use of the mimic weeds has advantages such as greater germination reliability, and tolerance to many registered herbicides. This allows herbicides to be used to control any volunteer weeds in the trial. The weed density levels can be more closely controlled and are more likely to be close to the target levels.

In the present experiment, a comparison was made between the use of a naturally occurring weed, wild oat, and mimic weeds wheat, barley and triticale. A number of weed density treatments were imposed on the plots and the yield loss measured. A model was fitted to these data so that yield loss can be predicted from the weed density.

In previous studies, the emphasis has been on the identification of crop species or cultivars with greater competitive ability against weeds. In this study a range of different weed types will be grown in competition with a single chickpea cultivar. The competitiveness of the weed types will be estimated from parameters in the fitted model.

In addition to the physical measurements undertaken on this trial, a series of non-destructive remote-sensing measurements will be taken at various intervals during the growing season. The following section is a brief background on reflectance techniques and yield-loss models.

In the previous chapter the reflectance of canola, chickpea, fababean and wheat crops, grown in mono culture, has been shown to be linearly correlated with the leaf area index up to 100 days after sowing. Similar findings were reported by Steven et al. (1983) in sugar beet. Crops grown in the presence of weeds should have a higher reflectance due to additional leaf area contributed by the weeds. This point is supported by a preliminary experiment at Tamworth in 2001 (Appendix 8.5). The weeds may grow above the crop or visa versa and so obscure some of the lower canopy foliage. However, this does not cause a serious problem in reflectance techniques as the leaves from the lower canopy layer also contribute to the total near-infrared canopy reflectance (Clevers, 1989). Kropff and Spitters (1991) proposed a yield-loss model based on the measurement of a weed species to the total leaf area index (relative leaf area of the weed). Lotz et al. (1994) suggested that the reflectance techniques could be useful in determining the relative leaf area of the weeds provided the crop is emerging homogeneously and the weeds and crop are not substantially covering each other. These conditions would exist in the early stages of crop development. The relative leaf area of the weeds could be determined by comparing the reflectance of an area of crop with weeds to an area of crop that is weed-free (Lotz et al., 1994).

Lotz et al. (1994) identified that a simple remote sensing technique to estimate relative leaf area of weeds and could potentially be applied to real time selective spray system such as the DetectSpray ® (Felton et al., 1991). If a suitable predictive relationship can be found between the relative leaf area of weeds and yield loss, then this concept could be extended to a system that will spot spray areas of high weed infestation in chickpeas.

The hypotheses to be examined in this experiment are:

1. Mimic weeds can be used instead of wild oats in weed competition experiments to define yield-loss relationships.

2. The weed density can be estimated from reflectance measurements.

3. The reflectance can be used to define yield-loss relationships in chickpeas.

The aims of the experiment are to:

1. Assess the difference in yield-loss behaviour in chickpea caused by the presence of either mimic weeds or wild oats.

2. Define models to predict yield-loss in chickpea caused by various weed density treatments.

3. Define models to predict yield-loss in chickpea from weed biomass and reflectance as an alternative method to measuring weed density.

5.2 Materials and methods

5.2.1 Site

Descriptions of the two sites used at Tamworth in 2002 and 2003 were presented in Chapter 3. Figures 8.1 and 8.2 in the Appendices show maps of paddocks 3 and 19 that were used for the trials in 2002 and 2003, respectively.

5.2.2 Plant material

The chickpea variety, Howzat, was selected for this weed competition experiment. This was the same variety used in the sensor calibration experiment in Chapter 4.

Three winter cereals, wheat (*Triticum aestivum*, cv. Sunstate), barley (*Hordeum vulgare* cv. Gardiner), triticale (*XTriticosecale* cv. Everest) were selected to act as mimic weeds in the experiment. The control of volunteer weeds in weed competition trials is necessary as they cause yield loss and compromise the results. By using these cereals as mimic weeds, selective post emergence herbicides can be used to control the volunteer weeds without adversely affecting the experiment.

Wild oat (*Avena sterilis* ssp. *ludoviciana*) seeds were collected in 2001 from nearby paddocks and dried until ready for sowing in 2002. In 2003 de-hulled wild oat seed was obtained from a commercial seed cleaner.

5.2.3 Experimental design

A randomised complete block design with four replicates was used in 2002 and 2003. There were 20 treatments per replicate consisting of four weed types, each with five weed density treatments. The weed types included the three mimic weeds (wheat, barley, triticale) and one naturally occurring weed (wild oat). Five weed density treatments of 0, 3, 9, 27 and 81 plants m^{-2} were chosen so that a non-linear model could be fitted to the data. The treatments were allocated to each replicate using `SpaDes` (Coombes and Gilmour, 1999) to randomise their position in respect to both row and column balance. The plots were arranged in the field with 20 rows and 4 columns. The longest side of the plots was aligned along the slope in 2002 and down the slope in 2003 due to constrains in the paddock size.

The plots were 3.5 m wide by 6.4 m long in 2002 and 3.5 m by 6.5 m in 2003. The weeds were sown in a strip 1.92 m wide in the centre of each plot. The overall trial size was 70 m by 40 m, allowing for lane ways, in both years.

5.2.4 Sowing

The chickpeas were treated with thiram (P-Pickel T. ®) at 10 ml kg^{-1} and inoculated with chickpea Group N moist peat inoculant (Bio-care Technology Pty Ltd, Somersby, NSW) in a cement mixer and then sown at a rate of 70 kg ha^{-1} on 4 June and 24 May in 2002 and 2003, respectively. Granulock®12Z fertiliser (11.2 % N, 17.5 % P, 4.4 % S, 1.2 % Zn) fertiliser was added at sowing to the crop rows at the rate of 80 kg ha^{-1}. The chickpeas were sown in 5 rows at 64 cm spacing using a no-till planter. The planter had five fluted coulters mounted in front of narrow-pointed tines with press wheels behind, to enable sowing into stubble. An additional draw bar was fitted to the planter ahead of the five crop tines to enable six offset discs to be mounted. These discs provided a soil opening to sow the mimic weed, triticale.

The weed seeds were arranged in sowing trays and four plots were sown in each run. A set of six offset discs were mounted in front and 16 cm to the side of the tines and the weed seeds were delivered by dropper tubes from a cone-seeder attached to a six way distributor. Each sowing run consisted of four plots. The chickpeas were sown continuously across the four plots via the covington seed boxes. The weeds were sown in furrows with the cone seeder at the same time. The tines were set to a planting depth of 7 cm.

There were no blockages in the cone seeder when sowing wheat, barley and triticale in 2002. The wild oats could not be sown mechanically however, because of the large husks on the seed. This necessitated the sowing of the wild oat seed by hand across the soil surface and incorporating these with a rake. The de-hulled wild oat seed used in 2003 allowed the seed to be sown using the cone seeder.

General maintenance of the plots involved hand weeding where existing weed populations were present. The wild oats sown by hand or with the planter could not be distinguished from the natural population so these were not removed. However, weeds in the lane ways and between plots were removed as they were obviously not sown. Selective herbicides were used on the wheat, barley and triticale plots to eliminate the naturally occurring wild oat and *Phalaris paradoxa* (paradoxa grass). Diclofop-methyl + fenoxaprop-p-ethyl (Tristar®) was applied at 1.5 L ha^{-1} on 16 August 2002 to control weeds. The lane ways between plots were slashed, and later sprayed with glyphosate (Roundup Xtra®) using a shielded sprayer to enable a clear path for the tractor mounted sensors to run across the plots.

Seed viability in field conditions is difficult to determine precisely from a seed germination test performed in the laboratory. Whish et al. (2002) measured the emergence of wild oats in a glasshouse at values between 66 to 75%. Factors such as soil temperature, moisture, plant depth and loss through preditation by animals can also affect the establishment. In 2002 the seed viability/establishment was assumed to be 50, 70, 80 and 80 % for wild oats, triticale, barley and wheat, respectively, and was deliberately underestimated to ensure that there would be an adequate number of plants. The mass of 100 weed seeds was 3.7, 3.4, 5.5 and 4.2 g for wild oats, triticale, barley and wheat, respectively. The number of seeds per plot for each treatment was calculated by multiplying the intended weed density by the plot area. To calculate the total mass of seeds needed per plot, the number of seeds per plot was multiplied by the single seed weight and is given in Table 5.1.

Table 5.1: Sowing rate and intended weed density for the four weed types sown in 2002.

Intended weed density	Sowing plant density (number per plot)				Sowing rate (g per plot)			
(number m^{-2})	Barley	Wheat	Triticale	Wild Oat	Barley	Wheat	Triticale	Wild Oat
0	0	0	0	0	0	0	0	0
3	46	46	53	74	2.5	1.9	1.8	2.7
9	138	138	158	221	7.6	5.8	5.4	8.2
27	415	415	474	664	22.8	17.4	16.2	24.6
81	1244	1244	1422	1991	68.3	52.2	48.7	73.7

A new seed source was used in 2003 and seed viability was slightly different to 2002. The seed viability was assumed to be 50, 75, 75 and 75 % for wild oats, triticale, barley and wheat, respectively. The mass of 100 weed seeds was 3.60, 4.55, 5.36 and 3.17g for wild oats, triticale, barley and wheat, respectively. The number and mass of seeds used for each weed treatment, was calculated as previously in 2002 and is given in Table 5.2.

5.2.5 Weed biomass

Weed biomass cuts were taken on 29 October (147 days after sowing) and 16 October (115 days after sowing) in 2002 and 2003, respectively. The area sampled included the six rows of weeds with a width of 1.92 m, a length of 0.52 m and a total area of 1 m^2. Two samples were taken from either end of the plots giving a combined area of 2 m^2. The number of weed plants in the sample was recorded. The weed biomass samples were dried at 80 °C for 48 hours and the resulting weed dry matter weighed.

Table 5.2: Sowing rate and intended weed density for the four weed types sown in 2003.

Intended weed density (number m^{-2})	Sown weed density (number per plot)				Sowing rate (g per plot)			
	Barley	Wheat	Triticale	Wild Oat	Barley	Wheat	Triticale	Wild Oat
0	0	0	0	0	0	0	0	0
3	50	50	50	75	2.7	1.6	2.3	2.7
9	150	150	150	225	8.0	4.8	6.8	8.1
27	450	450	450	674	24.1	14.3	20.5	24.3
81	1350	1350	1350	2002	72.4	42.8	61.4	72.8

5.2.6 Weed density

The established weed density of the plots was estimated by counting the number of weeds in a quadrant 1.04 m in length and 1.92 m wide that included the six rows of weeds. The first count was carried out on 16 September (104 days after sowing) in 2002 and 30 July (67 days after sowing) in 2003. A second count was taken in conjunction with the weed biomass sampling at the times previously outlined.

5.2.7 Grain yield

On the 5 November 2003, the mature heads of the barley, wheat, triticale and wild oats were removed with a garden trimmer so that there would be less weed seed contamination in the chickpea grain samples.

Harvesting of the chickpeas was carried out on the 19 November (168 days after sowing) in 2002 and 28 November (188 days after sowing), in 2003. A plot harvester (Kingaroy Engineering Works) was used to cut the three centre chickpea rows from each plot. The grain samples were put into bags and taken back to the laboratory for separation of the weed seeds from the chickpea grain. The grain separation was carried out with a combination of hand sieving and threshing in a stationary unit (Kingaroy Engineering Works).

The sampling plot lengths for each block (replicate) were measured prior to harvesting the plots and the area calculated. The plot yields were adjusted for the differences in area.

5.2.8 Reflectance measurements

The reflectance of each plot was measured using a tractor mounted with two WeedSeeker®sensors as outlined previously on page 29. The area sampled was a strip 0.6 m wide across the top and bottom ends of each plot and was perpendicular to the direction of crop sowing. The data were collected and stored on a laptop computer and later downloaded for processing. The two readings from each plot were averaged.

In 2002, measurements were taken at 51, 62, 84, 100 and 120 days after sowing. This ensured that a suitable model could be fitted to the data. Examination of the results in 2002 revealed that the main time period of interest was between 60 and 100 days after sowing. Subsequently in 2003, the measurements were taken at 60, 96 and 110 days after sowing. Measurements were not taken at the time of sowing (0 days after sowing) but the reflectance was assumed to be near zero as no weeds or crop were present.

5.3 Methods for statistical analysis

5.3.1 Yield loss

Yield and yield loss were modelled against the fixed effects, such as weed density as well as the effects resulting from these treatments i.e. weed biomass (dry matter) and weed leaf area.

The weed leaf area was not measured directly so it was calculated from the difference in reflectance of the plots with weeds versus the weed-free plots. This assumes that the leaf area is directly proportional to the reflectance as demonstrated in Chapter 4. It also assumes that the leaf area of the crop and weed are unaffected by the presence or absence of either. This would occur when there is a large spatial separation between them as in the case of this experiment where a wide crop row spacing was used and the weeds were sown between the crop rows.

Yield loss was modelled with either a linear, rectangular hyperbola or an inverse polynomial model. The derivation of these models has been discussed previously on page 21. The rectangular hyperbola model was fitted to the data using the non-linear spline `nls` procedure in R (Ihaka and Gentleman, 1996).

The rectangular hyperbola equation is known to have rather poor estimation properties as it is often ill-conditioned (Ratkowsky, 1986). The reciprocal or inverse polynomial model (Shinozaki and Kira, 1956) was suggested as an alternative by Ratkowsky (1990) because of its excellent estimation properties.

The reciprocal model is,

$$Y = \frac{1}{\alpha + \beta D} \tag{5.1}$$

where,

Y	is the grain yield (t ha^{-1}),
D	is the weed density (number of plants m^{-2}),
α	is the intercept, and
β	is the slope.

This model has two parameters; α is equal to the inverse of yield when $D = 0$ and β is related to the degree of curvature. The form of equation (5.1) indicates that it is a generalized linear model and can be fitted using the `glm` procedure in R (Ihaka and Gentleman, 1996) with a linear predictor $\alpha + \beta D$, a gamma error distribution and an inverse (reciprocal) link function.

The 95% confidence intervals were calculated for all the fitted models. These confidence intervals indicate that the fitted line has a 95% probability of being between the upper and lower limits. The confidence intervals for the linear and generalised linear models were calculated in R using the `lm` and `glm` procedures, respectively. The `predict` procedure allows standard errors to be calculated that can be converted to confidence intervals. The confidence intervals for the non-linear models were calculated from a relationship developed by Ratkowsky (1983).

Kropff and Spitters (1991) proposed a one parameter (q) yield loss model based on the leaf area rather than the weed density. This model was claimed to be more appropriate than the rectangular hyperbolic model as it accounts for the difference in time of emergence between the crop and the weed. Lotz et al. (1994) added an extra parameter (m) to the Kropff and Spitters (1991) model to account for the asymptote in yield loss to a maximum level. The Kropff and Spitters (1991) one parameter model is the same as the Lotz et al. (1994) two parameter model when the m parameter is equal to one.

The dependent term in both models is the relative leaf area that is defined as

$$L_w = \frac{LAI_{weed}}{LAI_{crop} + LAI_{weed}} \qquad (5.2)$$

where,

L_w	is the relative leaf area of weeds,
LAI_{weed}	is leaf area index of weeds, and
LAI_{crop}	is leaf area index of crop.

The Lotz 2 parameter model is,

$$Y_{loss} = \frac{qL_w}{1 + (q/m - 1)L_w} \qquad (5.3)$$

where,

Y_{loss}	is the yield loss (%),
L_w	is the relative leaf area of weeds,
q	is the relative damage coefficient, and
m	is maximum relative yield loss of the crop.

This model can be rearranged and expressed in terms of yield rather than yield loss by a simple substitution of Y_{loss}. The model then becomes

$$Y = Y_{wf}\left(1 - \frac{qL_w}{100\,(1 + (q/m - 1)L_w)}\right) \tag{5.4}$$

where,

Y	is the yield (t ha^{-1}), and
Y_{wf}	is the yield in the absence of weeds.

The measurement of the relative leaf area of the weeds can be laborious and requires destructive sampling. However, comparison can be made with the reflectance of the weedy and weed-free treatments to estimate the contribution of the weeds to the total reflectance. This can be expressed in the equation

$$CCA_w = \frac{CCA_{crop+weed} - CCA_{crop}}{CCA_{crop+weed}} = \frac{CCA_{weed}}{CCA_{crop+weed}} \tag{5.5}$$

where,

CCA_w	is the relative reflectance of weeds,
CCA_{crop}	is the measured reflectance of the crop, in the weed-free treatments,
$CCA_{crop+weed}$	is the measured reflectance of the crop with weeds present, and
CCA_{weed}	is reflectance of weeds, estimated by the difference in reflectance between $CCA_{crop+weed}$ and CCA_{crop}

5.3.2 Reflectance

The reflectance measurements over time were modeled by a linear mixed model. The predictive terms of the model are (i) weed type, (ii) weed density, and (iii) time. Changes over time are represented by a spline curve which is fitted using the ASREML (Gilmour et al., 1998) software.

A saturated model was fitted with these components;

1. weed type,
2. weed density,
3. days after sowing (linear),
4. spline functions of days after sowing, and
5. interactions between weed type, weed density, days after sowing.

Non significant terms were removed by backwards elimination. The final model is

$$Y_{ijkl} = \mu + \alpha_i + \theta_{ij} + \beta_{ij} \cdot \tau_{ijk} + u_l + \text{spl}(\text{dayno})_{ijkl} + \epsilon_{ijkl} \tag{5.6}$$

where,

Y_{ijkl}	is the CCA from plot l, with weed type i, weed density j, and sampling k
α_i	is the effect of weed type i, $\alpha_1 = 0$
θ_{ij}	is the effect of weed density j within weed type i
β_{ij}	is the linear trend due to sampling time
τ_{ijk}	is the effect of sampling time k within weed density j within weed type i
u_l	is a random plot effect assumed to be distributed $N(0, \sigma_u^2)$
spl(dayno)	is a random component which fits the spline and is distributed $N(0, \sigma_s^2)$
ϵ_{ijkl}	is a $N(0, \sigma^2)$ random variable for measurement error.

The model was used to predict the CCA. The spline term used 5 knot points in 2002 and 3 in 2003. These correspond to the number of sampling times of each experiment in their respective years.

5.4 Results

5.4.1 Weed density

The weed densities, at the first sampling on the 16 September 2002, were close to the expected values for the mimic weeds barley, triticale and wheat, at 0, 3, 9 and 27 weeds m^{-2} (Table 5.3). The wild oat density was too high in the 3 weeds m^{-2} treatment and too low in the 27 weeds m^{-2} treatment. The wild oat treatment was the most difficult to control and the intended range in weed density treatments was not achieved. The number of weeds counted in the 81 weeds m^{-2} treatment was lower than the targeted level for all weed types. This may have been caused by the observers inability to distinguish between individual plants when there is a high weed population, and the result of intra-specific competition.

The weed densities, at the second sampling on the 29 October 2002, were similar to the previous sampling. Once again the density of the mimic weeds was close to the targeted levels at 0, 3, 9 and 27 weeds m^{-2} . The wild oat weed density had not changed greatly from the previous count. The 81 weeds m^{-2} treatments all had less weeds than intended.

In 2003 the weed density at the first sampling on 30 July were close to the targeted levels for both the mimic weeds and wild oats for the 3, 9 and 27 weeds m^{-2} treatments (Table 5.3). The small number of weeds in the weed-free treatments were removed by hand after the counting and would not have contributed greatly to the yield loss of the crop at that stage of growth. The 81 weeds m^{-2} treatments for all weed types had lower densities than intended.

The weed densities had dropped by the time of the second sampling on the 16 October for all weed types. The weed density for barley in the 3, 9, 27 and 81 weeds m^{-2} treatments were generally higher than the equivalents in the other weed types. However, the weed density in the 9, 27 and 81 weeds m^{-2} treatments for all weed types were generally below the targeted levels. The weed density levels in the wild oat treatments in 2003 were much improved on the levels achieved in 2002.

Table 5.3: Targeted and actual weed densities (number m^{-2}) at two sampling dates for the weed treatments in 2002 and 2003. B=barley, T=triticale, W=wheat and WO=wild oat.

Targeted	2002								2003							
weed	16 September				29 October				30 July				16 October			
density	B	T	W	WO	B	T	W	WO	B	T	W	WO	B	T	W	WO
0	0	0	0	0	0	0	0	0	2	2	2	2	0	0	0	0
3	3	3	3	11	5	3	3	12	5	5	5	6	4	3	3	6
9	13	9	8	10	11	8	7	11	11	11	10	9	11	5	5	6
27	23	18	19	15	23	17	20	18	27	22	19	24	18	11	8	12
81	46	37	34	22	45	35	39	24	67	51	50	51	22	20	22	19

5.4.2 Grain yield

The average grain yield for the weed-free treatments in 2002 was 2.4 t ha^{-1} while in 2003 it was 4.0 t ha^{-1}, due mainly to higher seasonal rainfall in 2003 (Figures 5.1 and 5.2). In each replicate there were four control treatments, plots sown in the absence of weeds, that correspond to the four weed types. An analysis of variance of the yield of the weed-free plots showed no significant differences between the `weed type` factors in either 2002 or 2003. This is important for the subsequent analysis as the yield in the absence of weeds is used as a base level of comparison with the other levels of weed density.

There was more variability in yield for all weed types and weed density levels in 2002 than in 2003 (Figures 5.1 and 5.2). This is indicated by the wider confidence intervals for the fitted GLM. The high variability in yield for wild oats in 2002 was reduced in 2003 and was probably associated with the use of the different sowing method. In 2002, un-hulled wild oat seed was sown by incorporation on the surface of the plots while in 2003 the de-hulled seed was sown in rows with the no-till planter.

5.4.3 Yield and weed density

Grain yield was negatively correlated with weed density in all years. The response was non-linear and the generalised linear model (GLM), outlined previously, was fitted to the data (Figures 5.1 and 5.2). This also enabled the `weed` and `density` terms to be tested for significance in the model. The GLM was chosen in preference to the linear and rectangular hyperbolic equation because of the non-linearity of the data and the more stable estimation of model parameters.

The analyses of deviance indicated that in 2002, the `weed`, `density` and `weed:density` terms were all significant ($P \leq 0.05$), while in 2003 only the `weed:density` terms were significant.

The estimated parameters for the GLM are presented in Table 5.4. The β parameter in the model is an indication of the competitiveness of the weed species. Barley was found to be the most competitive weed type in 2002 followed by triticale, wheat and wild oat. However, the high variability in yield for the wild oat treatments resulted in a fitted model with a higher α and a lower β value than the other weed types. The α valve of 0.556 is an estimate of the intercept of the model when weed density is zero. The reciprocal of this parameter, 1.8 t ha^{-1}, gives an estimate of the weed-free yield. This is a lower valve than the 2.4 t ha^{-1} estimated for the other weed types. Therefore, the parameter estimates for wild oat in 2002 probably does not reflect the true competitiveness of this species.

In 2003, the most competitive weed type was wild oat followed by barley. triticale and wheat (Table 5.4). The GLM provided a good fit to the observed data and the narrow confidence intervals indicate that the `plot` variability had been reduced compared to 2002. The reciprocal of the α parameter indicates that the weed-free yield, ranged in value from 3.9 to 4.4 t ha^{-1} for wheat and wild oat, respectively.

Figure 5.1: Grain yield versus weed density for chickpea sown in 2002. The line of best fit is the generalised linear model. The broken lines indicate the 95% confidence intervals.

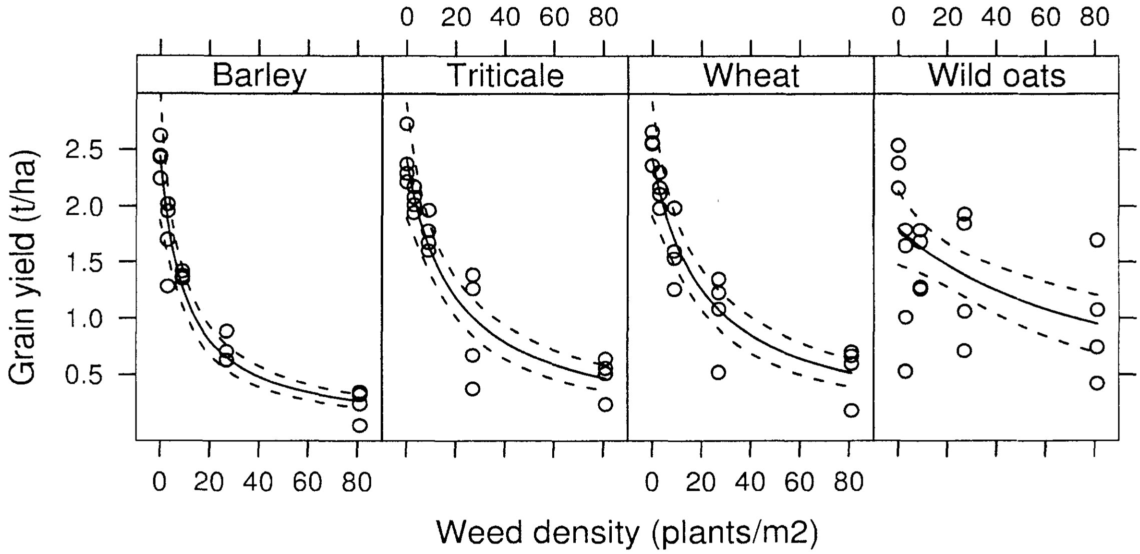


Figure 5.2: Grain yield versus weed density for chickpea sown in 2003. The line of best fit is the generalised linear model. The broken lines indicate the 95% confidence intervals.

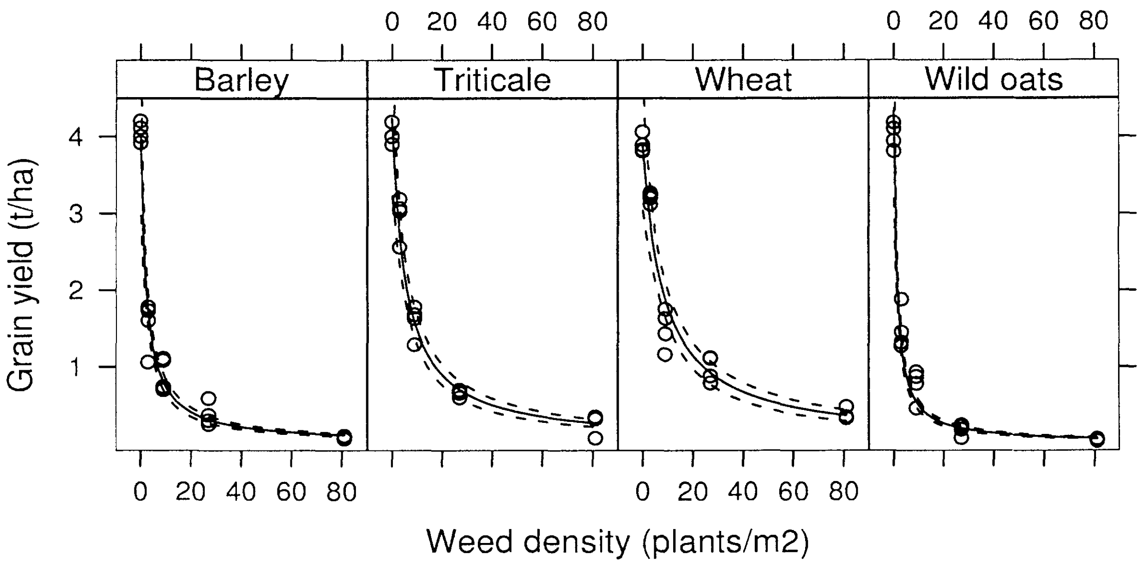


Table 5.4: Parameter estimates (s.e.'s in brackets) for the generalised linear model used to predict chickpea grain yield from sown weed density in 2002 and 2003.

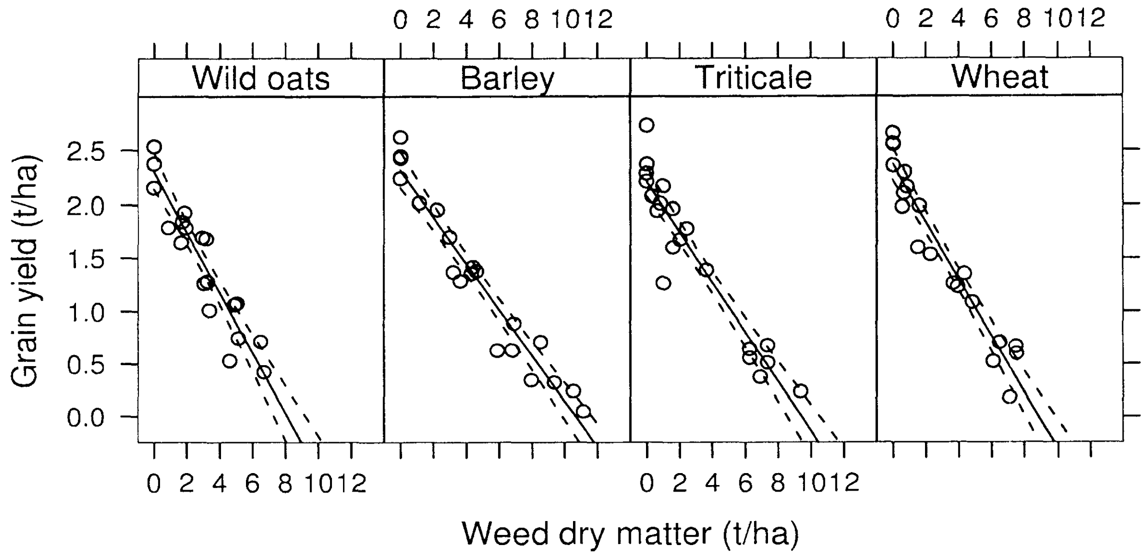
	2002				2003			
Weed type	α		β		α		β	
Barley	0.410	(0.048)	0.042	(0.005)	0.249	(0.032)	0.110	(0.010)
Triticale	0.415	(0.044)	0.021	(0.003)	0.236	(0.028)	0.044	(0.005)
Wheat	0.413	(0.043)	0.019	(0.003)	0.256	(0.026)	0.031	(0.004)
Wild oats	0.556	(0.051)	0.006	(0.002)	0.229	(0.026)	0.180	(0.014)

5.4.4 Weed dry matter

2002

A linear regression model was fitted to chickpea grain yield and weed dry matter data in 2002 for four different weed treatments (Figure 5.3). The parameter estimates are listed in Table 5.5.

Figure 5.3: Grain yield versus weed dry matter for chickpea sown in 2002. The line of best fit is the linear model. Points are the value for each replicate and broken lines indicate the 95% confidence interval.



The intercept term in the model is an estimate of the yield for the weed-free treatments. There was no significant difference ($P \leq 0.001$) in the intercept term for the four weed types (Table 5.5). This was expected as the weed-free treatments for each weed type were

Table 5.5: Parameter estimates (s.e.'s in brackets) for the linear regression model used to predict chickpea grain yield from weed dry matter (t ha^{-1}) in 2002.

Weed type	Intercept (t ha^{-1})		Slope	
Barley	2.32	(0.08)	-0.218	(0.014)
Triticale	2.21	(0.07)	-0.235	(0.016)
Wheat	2.37	(0.07)	-0.268	(0.018)
Wild oat	2.31	(0.08)	-0.284	(0.024)

treated identically in terms of agronomy during the trial.

The chickpea grain yield was negatively correlated with weed dry matter (Figure 5.3). The slope is an estimate of the change in yield per unit of weed dry matter; the steeper the slope the more competitive the weed. The weed type that caused the greatest yield loss per unit of weed dry matter was wild oat followed by wheat, triticale and barley. The treatment with the highest weed dry matter (11 t ha^{-1}) was barley at a weed density of 81 plants m^{-2}. Barley was the only weed type with a significant difference ($P \leq 0.05$) in slope to wild oat. Table 5.6 shows the predicted chickpea yield when two levels, 5000 and 8000 kg ha^{-1}, of weed biomass are present. Barley was less competitive, per unit (kg ha^{-1}) of weed biomass, than the other weed types.

Table 5.6: Predicted values (s.e's in brackets) of chickpea grain yield (t ha^{-1}), from the fitted linear model, at weed dry matter values of 5000 and 8000 kg ha^{-1} in 2002.

	Weed dry matter kg ha^{-1}					
Weed type	0		5000		8000	
Barley	2.32	(0.08)	1.23	(0.05)	0.58	(0.07)
Triticale	2.21	(0.07)	1.03	(0.06)	0.33	(0.10)
Wheat	2.37	(0.07)	1.03	(0.06)	0.23	(0.10)
Wild oat	2.31	(0.08)	0.88	(0.07)	0.03	(0.13)

2003

In 2003, the relationship between chickpea yield and weed dry matter appeared to be non-linear. A generalised linear model was fitted to the data but the confidence intervals tended to diverge at low weed density. A better fit was obtained with the rectangular hyperbolic equation. This was fitted separately for each weed type (Figure 5.4).

The estimates of the i parameters (Table 5.7) indicate that wild oat was the most competitive weed type followed by barley, wheat and triticale. Barley and wild oat are significantly different to wheat and triticale.

Figure 5.4: Grain yield versus weed dry matter for chickpea sown in 2003. The line of best fit is the rectangular hyperbolic equation. Points are the value for each replicate and broken lines indicate the 95% confidence interval.

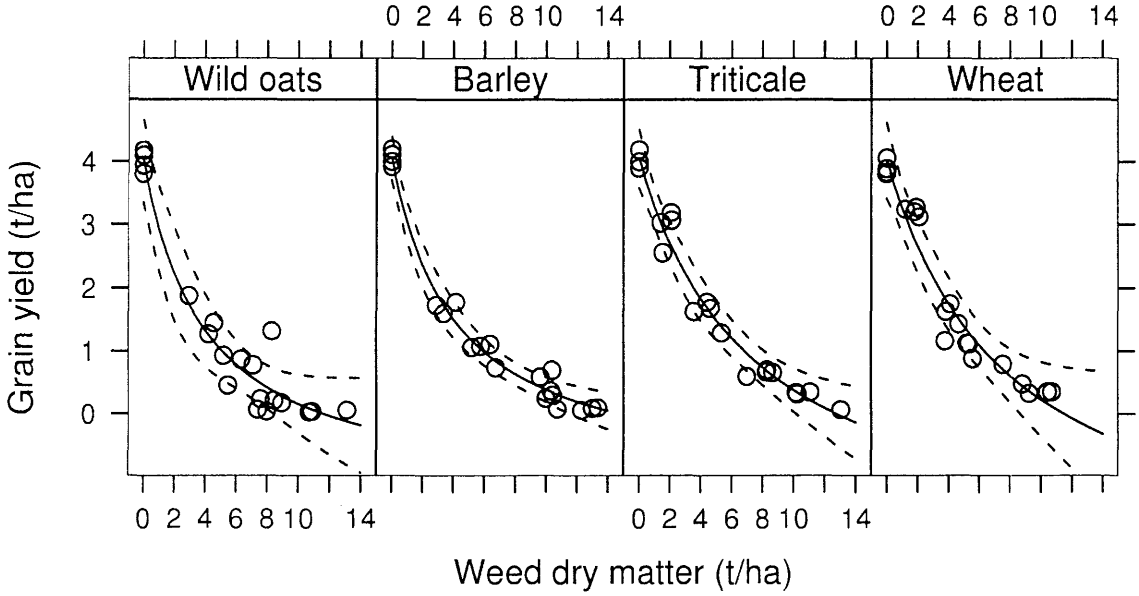


Table 5.7: Parameter estimates (s.e.'s in brackets) for the rectangular hyperbolic model used to predict chickpea grain yield from weed dry matter in 2003.

Weed type	Y_{wf} (t ha^{-1})		i (%m^2 $plant^{-1}$)		A (%)	
Wild oat	4.01	(0.16)	33.1	(7.0)	135	(15)
Barley	4.05	(0.09)	30.7	(3.1)	128	(6)
Wheat	4.02	(0.15)	21.2	(3.3)	170	(29)
Triticale	4.05	(0.12)	20.7	(2.6)	161	(18)

The maximum yield loss or A parameter theoretically should not exceed 100%. However, the weed density treatments chosen for this trial and the resulting dry matter were not of sufficient magnitude to allow the predicted yield to asymptote. As a result the estimated values for the A parameter were greater than 100%.

The predicted yield, from the rectangular hyperbolic, at weed dry matter levels of 5000 and 10000 kg ha^{-1} is presented in Table 5.8. Wild oats was found to be the most competitive weed type followed by barley, wheat and triticale with 5000 kg ha^{-1} of weed biomass. At 10000 kg ha^{-1} the order was wild oat, wheat, triticale and barley.

Table 5.8: Predicted values and standard errors of grain yield (t ha^{-1}), from the fitted rectangular hyperbolic model, at selected weed dry matter values in 2003.

	Weed dry matter kg ha^{-1}					
Weed type	0		5000		10000	
Barley	4.05	(0.17)	1.22	(0.13)	0.39	(0.10)
Triticale	4.05	(0.23)	1.50	(0.16)	0.38	(0.17)
Wheat	4.02	(0.30)	1.40	(0.19)	0.23	(0.30)
Wild oat	4.01	(0.33)	1.03	(0.23)	0.16	(0.23)

5.4.5 Reflectance

The reflectance from each plot increased with time after sowing and followed a sigmoidal shaped curve (Figure 5.5). At most sampling times, the average reflectance of the chickpea crop with weeds present was higher than the weed-free. This was the case with the barley and triticale treatments in 2002. However, the wheat at 9 plants m^{-2} appears to be out of sequence compared to the 27 plants m^{-2} weed density treatment. At 60 days after sowing, the measured reflectance of the wild oats weed density treatments was in the reverse order to the other weed types. The weed-free had a higher reflectance than the 3, 9, 81 and 27 weeds m^{-2} treatments, respectively. From day 60 to day 100 there is little difference in the reflectance between any of the treatments. The order of differences in reflectance at day 120 is similar to that at day 60.

The higher reflectance of the weedy plots is due to sowing the weeds between the crop rows resulting in a greater combined area of ground coverage. As the crop approaches maturity, complete canopy closure occurs and the difference in reflectance of the weedy and weed-free treatments is reduced. The maximum separation in the reflectance between treatments occurred between 60 and 100 days after sowing.

The reflectance measurements in 2003 (Figure 5.7), showed an improved separation between weed density treatments for all weed types, including the wild oats, compared with the results in 2002. The reflectance of the weed-free treatments was always the lowest and was followed in order by the 3, 9, 27 and 81 weeds m^{-2} treatments, respectively. The barley treatment showed the greatest separation between treatments followed by triticale, wild oat and wheat. There were only 3 sampling times for the reflectance measurement so the fitted curves are not as pronounced in curvature as in the 2002 results. This is due to the lack of reflectance data early and late in the season.

The differences in the reflectance measurements over time, for each weed density treatment, are small and are not easily compared using the present graphical scaling parameters. A more appropriate variable for comparing responses is the relative reflectance of the weed, as defined previously in equation (5.5) on page 63. This transformation of the data accentuates the differences.

In 2002, the relative reflectance of the weed (CCAw) increases with time and peaked between 60 and 80 days after sowing (Figure 5.6). Thereafter CCAw decreases to zero due to the canopy closing over the ground and saturation of the field of view. The wild oat treatments all started with a negative CCAw value and increased to a peak at 80 to 90 days after sowing. The maximum CCAw value for wild oat was far less than the other weed types. The 3 weed m^{-2} treatments tended to peak at a later time than the other treatments. The CCAw values in 2003 were more consistent with expectations for all the weed types (Figure 5.8).

Figure 5.5: Reflectance of chickpea crop + weeds in 2002 for the four different weed types. The coloured lines represent the predicted values from model (5.6) for the weed density treatments 0, 3, 9, 27 and 81 plants m^{-2}.

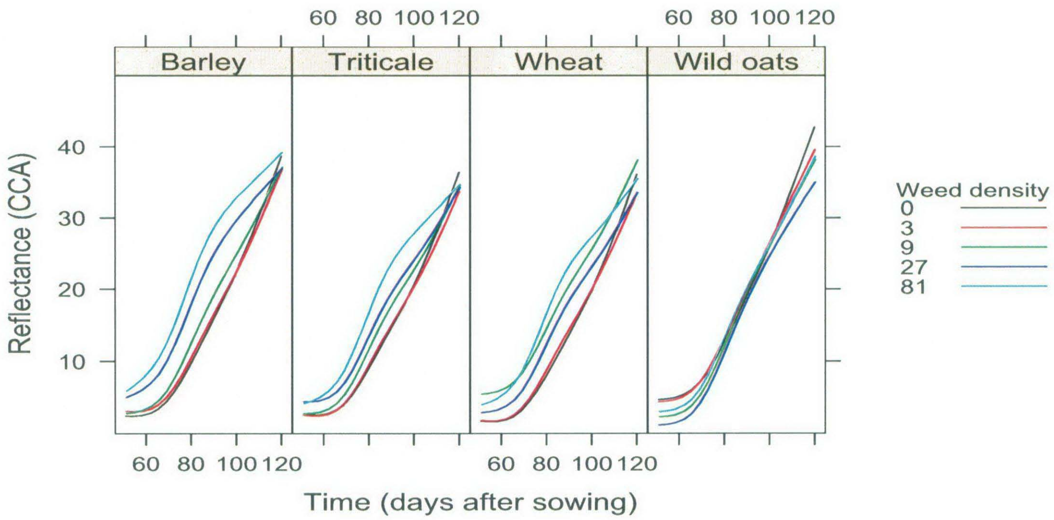


Figure 5.6: Profiles of reflectance (CCA) ratios of weed density treatments 3, 9, 27, 81 plants m^{-2} to the weed-free over time derived from the reflectance ratios in Figure 5.5

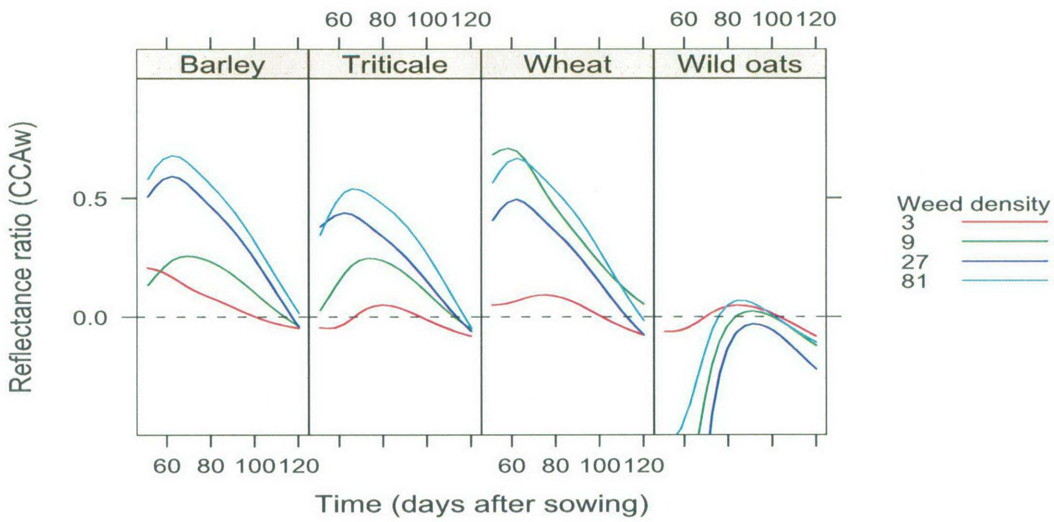


Figure 5.7: Reflectance of chickpea crop + weeds in 2003 for the four different weed types. The coloured lines represent the predicted values from model (5.6) for the weed density treatments 0, 3, 9, 27 and 81 plants m^{-2}.

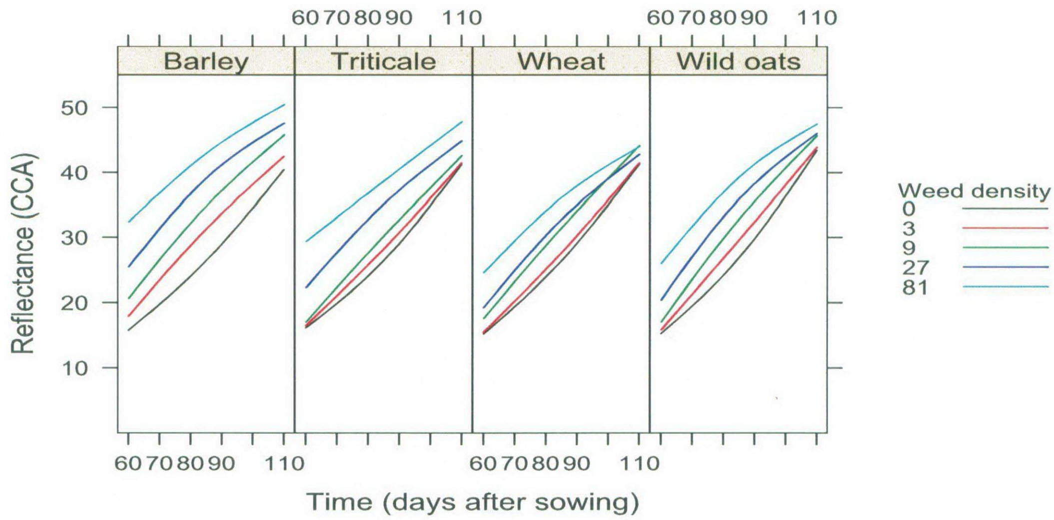
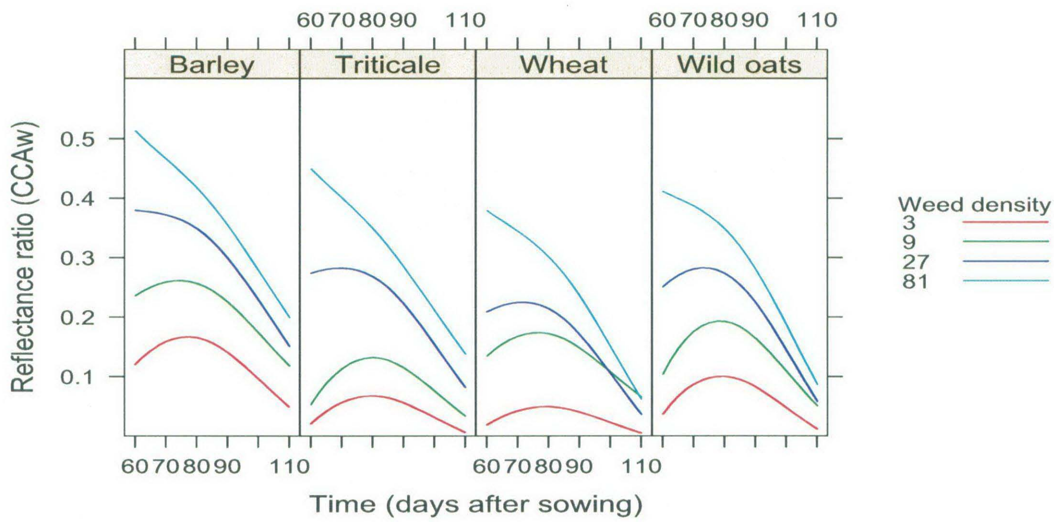


Figure 5.8: Profiles of reflectance (CCA) ratios of weed density treatments 3, 9, 27, 81 plants m^{-2} to the weed-free over time derived from the reflectance ratios in Figure 5.7



5.4.6 Estimation of yield loss with reflectance measurements

The relationship between chickpea grain yield loss and the relative leaf area of weeds compared to the crop, was examined. Yield loss has previously been shown to be related to weed density and weed dry matter so weed leaf area is another independent variable which can be used to predict yield loss.

The leaf area of the weeds can be estimated by destructively sampling the weeds although this is not very practical for field experiments. However, the weed leaf area might be correlated with the reflectance. The reflectance of the crop and weed components can be estimated provided they are spatially separated. In the case of the designed experiment using wide crop rows and weeds sown between these rows, the weed component could be measured directly. This would involve digitising the boundary between the crop and weeds on the reflectance versus distance graph and integrating the areas for each component. As the crop and weed grows, the canopy will close over, the foliage begins to overlap and the separation between them decreases. It then becomes impossible to discriminate between the crop and weed components of the reflectance.

An indirect method of measurement would be to find the difference in reflectance of the plots with weeds and those without weeds. This procedure assumes that the weed and crop do not compete with each other for water and light within the plot area. During the early growth period this would be a reasonable assumption, especially in crops grown in wide rows.

The relationship between yield and relative reflectance of the weeds in 2002 is shown in Figure 5.9 for the different sampling times after sowing. The derivation of the independent term, relative reflectance of weeds, can be found in equation (5.5) on page 63. The relative reflectance of the weeds should never be less than 0. However, the results in 2002 were variable and sometimes the reflectance of the weed-free treatments is more than the weedy treatments. This occurs when the targeted weed density levels have not been reached. In cases where the relative reflectance of the weeds was negative the values were assigned to zero. There was a poor relationship between reflectance and yield loss in 2002, as indicated by the large scattering of values.

The Lotz *et al.* 2 parameter model (5.3) was found to give a poor fit to the data in 2002. The starting values of the parameters were manually manipulated to see if a suitable shaped curve to fit the data could be found. However, this process was unsatisfactory. A linear regression model was fitted in preference and the slope of the regression lines indicated that the relative reflectance of weeds was a poor predictor of yield loss. Barley appeared to be the only weed type with a consistent trends across sampling times. The model predictions tended to be less reliable when the relative reflectance was high as indicated by the wider confidence intervals. At the sampling time of 84 DAS there was a good range of values for the relative reflectance and the fitted model was more reliable than the other sampling times in that year. By 120 DAS the relative reflectance values were close to zero and a model could not be fitted as the was no relationship with yield.

The results in 2003 (Figure 5.10) were less variable as indicated by the narrower confidence intervals. The reflectance at 60 days after sowing in 2003 suggests a non-linear relationship. However, the reflectance at 96 and 110 days after sowing would suggest a linear relationship. A non-parametric model (`loess`) was fitted to all data except for wheat at 110 days after sowing where a linear regression model was considered more appropriate. The exploratory data plots indicated a curvi-linear change in yield with increasing relative reflectance ratio. This shape was similar across all weed types. Yield can be reliably predicted from reflectance for all weeds and at the three sampling times. However, at sampling times 96 and 110 DAS, the prediction of low yields is unreliable. The average standard errors of the predicted values at sampling 60 DAS for barley, triticale, wheat and wild oats are 0.22, 0.32, 0.22, 0.45 respectively so that predictions are more accurately determined for the barley and wheat mimic weeds.

Figure 5.9: The relationship between chickpea yield and the relative reflectance of the weeds at 51, 62, 84, 100 and 120 days after sowing for the mimic weed experiment in **2002**. The line of best fit is the linear regression model and broken lines indicate the 95% confidence intervals.

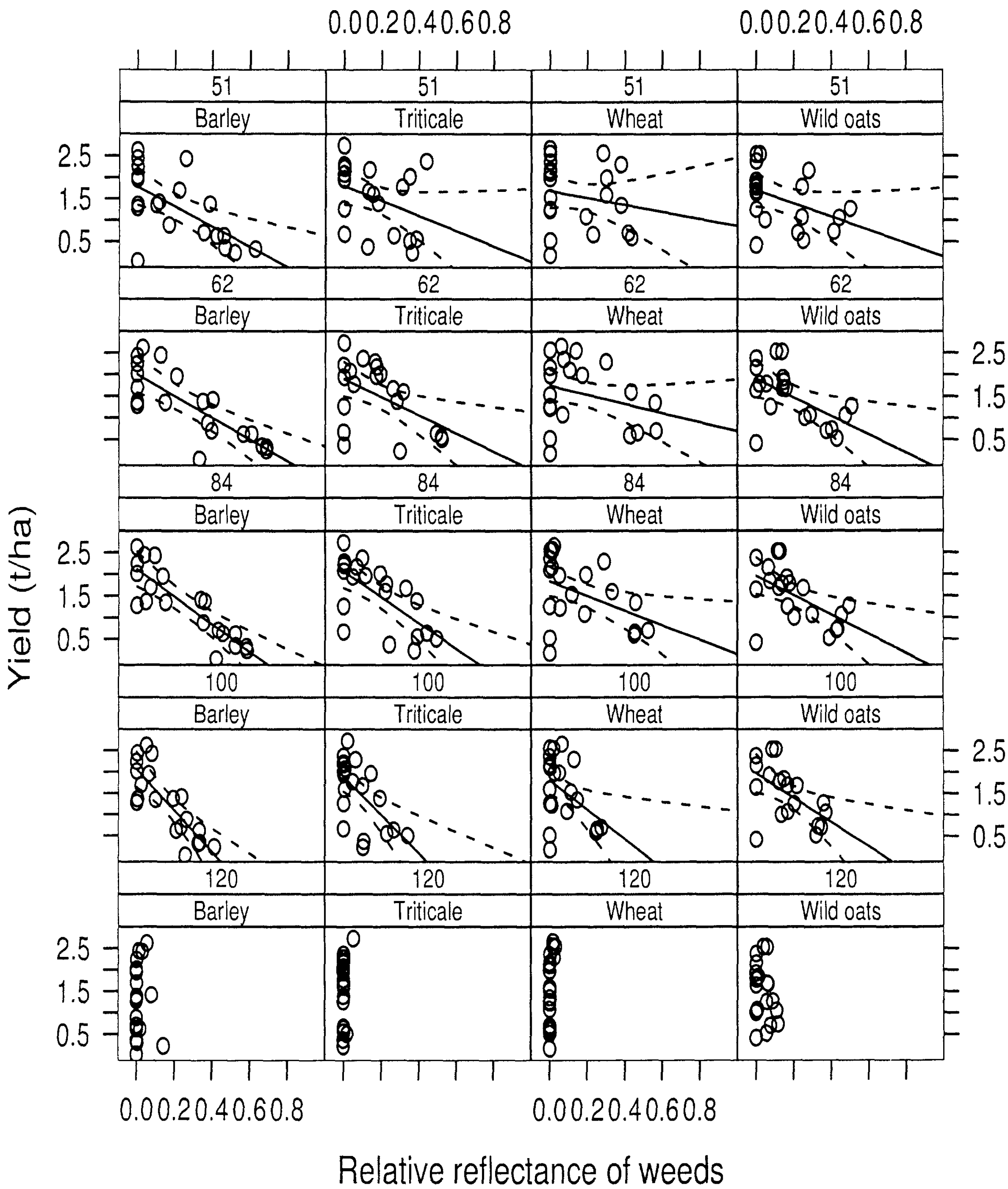
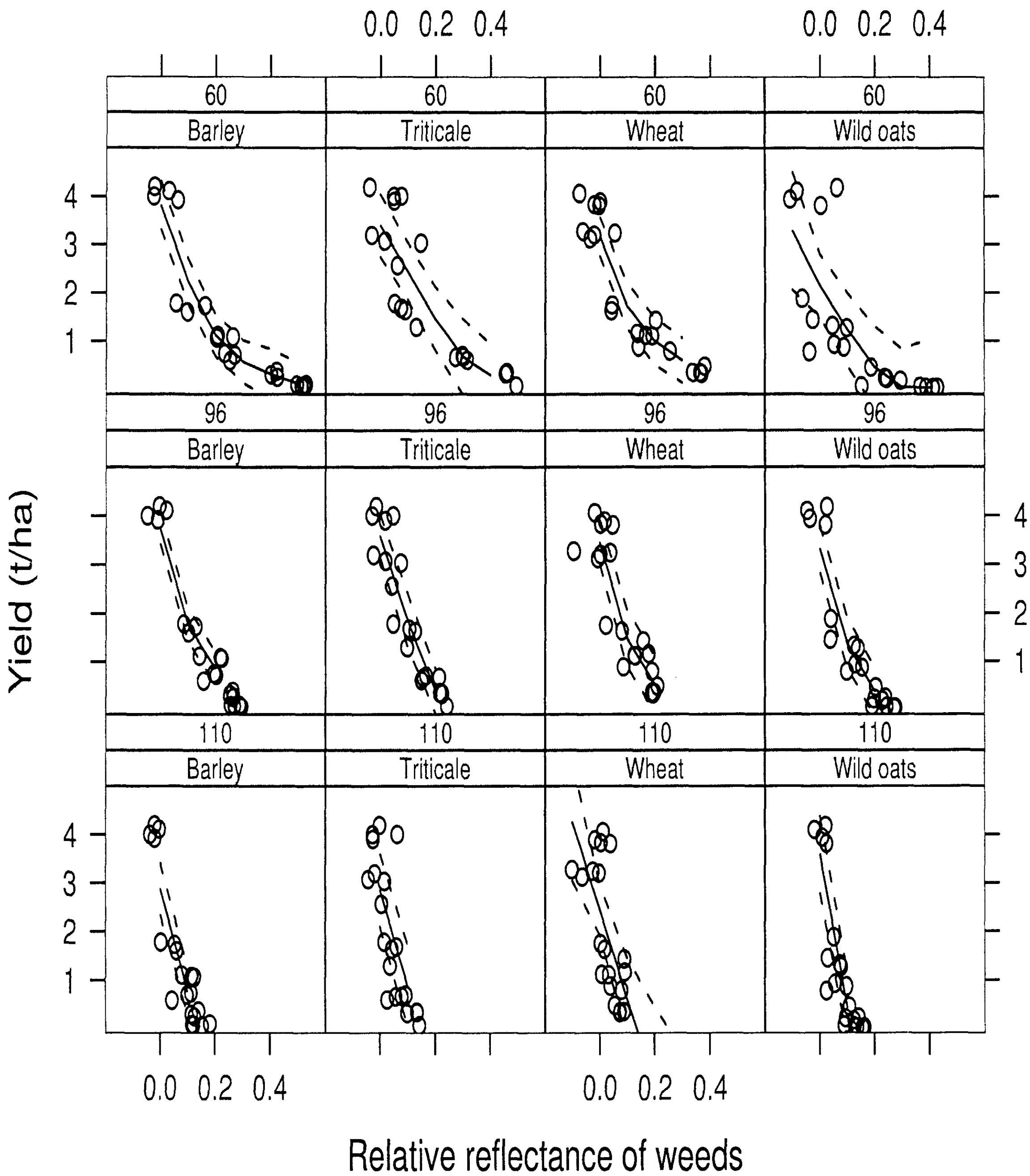


Figure 5.10: The relationship between chickpea yield and the relative reflectance of the weeds, at 60, 96 and 100 days after sowing (DAS), for the mimic weed experiment in **2003**. The line of best fit is the non-parametric model (loess) except for wheat at 110 DAS where a linear regression model was fitted. The broken lines indicate the 95% confidence intervals.



5.5 Discussion and conclusions

Yield loss in chickpeas was found to increase in response to higher weed density. The imposed weed density treatments provided weed competition of sufficient magnitude to cause greater than 90% yield loss compared to the control.

The reflectance measurements for wild oat in 2002 were inconsistent with the results for the other weed types. This may have been caused by the broadcasting of wild oat seed rather than the tine sowing method used for the other weed types. The observed wild oat distribution in the plots was patchy. The small sampling area used for reflectance measurements, at the end of the plots, may not have been representative of the average plot weed density. However, the over-all plot weed density was of sufficient magnitude to cause considerable yield loss.

The observed differences in reflectance of the wild oat treatments may also have been caused by the amount of stubble present on the plots. The plots with wild oats treatments were raked clean of stubble and wild oat seed broadcast on the surface. The stubble was then returned to the plot and uniformly distributed. The weed-free treatments did not have any soil surface disturbance and so the chickpeas may have been able to emerge earlier and get established more quickly without the extra stubble cover.

The low rainfall in 2002 caused the chickpea grain yield to be low. However, competition from the weeds was also less in 2002 than in 2003. At the equivalent weed density level weeds were more damaging in 2003 than in 2002. The average percentage yield loss in 2002 was 80% while in 2003 it was over 90%.

Yield loss was also found to be related to weed biomass (dry matter) and weed leaf area. Reflectance measurements during the first 100 days after planting, could be used to predict grain yield loss at the end of the season. This approach could have applications in a real time spot spraying system.

Various yield loss models were used to model the results of the weed competition experiments in this chapter. Models based on parameters with biological significance were not always the best ones to explain the variation in observed responses. The linear and generalised linear models were often more desirable models in terms of the stability of parameter estimation. Comparisons were often made between the model parameters for the different weed types. These comparisons were easier to calculate with the linear models.

Wild oats was found to be the more competitive than the other mimic weeds. This was confirmed by comparing the estimated parameter in the yield-loss models. The relationship between weed density and chickpea yield was modeled with a GLM in both 2002 and 2003. The slope (β) of this model is an estimate of the competitiveness of the weed against the chickpea crop. In 2002 the experimental results for wild oat were compromised by the poor establishment. This meant that the targeted weed density levels were not achieved. Consequently the GLM fitted to the data had the lowest slope of all the weed types (Table 5.4). This is in contrast to the results in 2003 where the fitted GLM for wild oats was much improved and had narrower confidence intervals (Figure 5.2). The results in this year could be considered more reliable as the same shaped yield-loss responses were observed for all the weed types. In 2002 barley was the most competitive weed type followed by triticale, wheat and ignoring wild oats. In 2003 wild oats was the most competitive weed type followed by barley, triticale and wheat.

Another method of assessing the competitiveness of a weed is to model the relationship between yield and weed dry matter. In 2002 a linear model was fitted to the data and wild oats was found to be the most competitive followed by wheat, barley and triticale (Table 5.5). A hyperbolic model was used in 2003 and by inspection of the 'i' parameters wild oats was found to be the most competitive followed by barley, wheat and triticale (Table 5.7).

The use of mimic weeds in weed competition experiments was found to give similar yield loss relationships to naturally occurring weeds such as wild oat. The mimic weed with greatest similarity in competitiveness to wild oats was barley. Wheat and triticale had much lower competitiveness than barley and but were very similar to each other.

In a weed competition experiment with wheat and wild oats Martin et al. (1987) found that wheat and wild oats behaved as near-equal competitors. However, the results in this chapter support the hypothesis that wild oats are far more competitive than wheat when grown in a chickpea crop.

Chapter 6

Chickpea variety experiment

6.1 Introduction

In previous chapters, reflectance measurements were demonstrated to be a useful technique to estimate crop growth in chickpeas. In Chapter 5, mimic weeds were found to be a valid alternative to natural weeds such as wild oats in weed competition experiments. This chapter will expand on the technique by introducing a range of different chickpea varieties for evaluation in weed competition experiments using a mimic weed.

Chickpeas are know to have poor competitive ability against weeds compared to other crops (Lemerle et al., 1995). Various traits are thought to provide an advantage to some varieties against weed competition. Crop height and seedling vigour are two that are being introduced into breeding lines. Other traits such as the canopy coverage may also be important. Crop and weed competition trials are one way that the competitive ability of varieties can be measured directly and compared with these traits.

This field experiment investigates the response in grain yield of eighteen chickpea cultivars to two levels of weed competition. The yield from these treatments will be compared to the control (weed-free) and the percentage yield loss for each cultivar will be estimated, and a yield-loss model will be fitted to the data.

It is intended that the `variety` × `weed density` experimental design will produce enough variation in yield to be able to assess the usefulness of the method as a means of ranking varieties. However, if there is no significant varietal differences in yield, the technique may be still be able to demonstrate that yield-loss can be predicted from reflectance measurements for a wide selection of chickpea varieties.

Investigations of the data will reveal if some chickpea cultivars are more competitive with weeds and so are less susceptible to yield loss. A remote sensing method of testing competitiveness between cultivars would be quick, non-invasive and repeatable.

The aims of the experiment are to:

1. Define the relationship between yield-loss and weed density for each cultivar.

2. Define the relationship between yield-loss and reflectance for each cultivar.

3. Determine parameters to estimate the competitive ability of cultivars.

4. Compare the weed density and reflectance methods for determining the competitive ability of cultivars.

5. Demonstrate that a remote sensing method can be employed in a practical way for assessing the competitive ability of chickpea cultivars in a weed competition experiment.

6.2 Materials and methods

6.2.1 Site

The same experimental design was used at two sites at Tamworth in 2002 and 2003, respectively. Trials were conducted in the same paddock as that used for the sensor calibration and mimic weed experiments. The descriptions of the soil at these sites were presented in Chapter 3 and a map of the area is presented in Figures 8.1 and 8.2 in the Appendix.

6.2.2 Experimental design

A factorial randomised block design was used with three replicates. There were 54 treatments per replicate consisting of 18 chickpea varieties by three weed density treatments (0, 9 and 27 plants m^{-2}). The trial layout in both years was 18 rows by 9 columns, with the crops sown across the slope in 2002 and down the slope in 2003. In field trials, spatial fertility trends are sometimes correlated with the direction of slope. The design, generated with a computer program `SpaDes` (Coombes and Gilmour, 1999), allocates treatments to rows and columns in a balanced manner that allows corrections for possible effects of fertility trends.

6.2.3 Plant material

New chickpea (*Cicer arietinium L.*) cultivars are being bred in Australia in response to recent disease outbreaks such as phytophthera and ascochyta blight that have decimated some crops (Knights et al., 2005). Growers are now altering their selection of varieties to grow from year to year with the introduction of these newer lines. In order to make this study relevant to the present practices in the chickpea industry, a number of commercial chickpea varieties and lines from the breeding program at Tamworth were selected for evaluation. This included 15 desi and 3 kabuli types (Table 6.1). The chickpea genotypes used in this experiment are referred to by cultivar or varietal names. At the time of the experiment some genotypes did not have a varietal name.

Results from previous experiments in Chapter 5 indicate that triticale (*XTriticosecale* cv. Everest) was a suitable species to use as a mimic weed in this experiment. The mimic weed will simulate the effect of naturally occurring weeds, such as wild oats.

Table 6.1: Seed weight and sowing rate for chickpea cultivars sown in trials in 2002 and 2003.

Number	Variety	Cultivar	Type	100 Seed Wt (g)	Sowing rate (kg/ha)
1	Howzat	8511-19	Desi	23.1	109
2	Jimbour	8813-63H	Desi	18.9	89
3	Amethyst		Desi	14.6	69
4	Gully	T1315	Desi	25.4	119
5	Yorker	9113-13N-2	Desi	22.5	106
6	Flipper	93011-1021	Desi	20.0	94
7	91025-3021	91025-3021	Desi	13.9	65
8	94-012*98V4006	94-012*98V4006	Desi	21.7	102
9	Heera*98CZH4003	Heera*98CZH4003	Desi	15.5	73
10	Heera98PBC4010	Heera98PBC4010	Desi	18.2	86
11	BarwonMR Composite	BarwonMRComp	Desi	16.1	76
12	9105-33N	9105-33N	Desi	19.0	89
13	Sona 4028	Sona4028	Desi	21.0	99
14	Genesis 836	ICCV96836	Desi	18.0	85
15	Genesis 508	FLIP94-508C	Desi	16.9	79
16	Bumper		Kabuli	51.4	216
17	Kaniva		Kabuli	43.9	184
18	S95405		Kabuli	31.3	131

6.2.4 Sowing

A no-till planter was used in both years to sow 5 rows of chickpeas at a spacing of 64 cm in each plot. The planter configuration is shown in Figure 6.1.

The planter had two cone seeders, one for the chickpeas and a second for the triticale weed treatments. The cone seeder, mounted on the left side of the planter, was attached to a 5-way distributor and supplied chickpea seeds to each tine. The plant populations were 47 and 42 plants m^{-2} for the desi and kabuli varieties, respectively. The seeding rates for each cultivar in kg ha^{-1} were calculated from the 100 seed weight (Table 6.1). The kabuli chickpeas (Bumper and Kaniva) were difficult to sow due to their large seed size that tended to jam in the cone seeder so were hand-sown within a week of sowing the trial.

The mimic weed was sown with a second cone seeder mounted on the right side of the planter. The seeder was connected to a 6 way distributor that supplied seed to 6 offset discs. The 6 rows of weeds were sown 16 cm either side of the chickpea rows at a density of 0, 3 or 27 "weeds" m^{-2}.

The planting dates were June 5th in 2002 and May 25th in 2003. At sowing the

Figure 6.1: Schematic diagram of the sowing configuration used on the no-till planter for sowing the chickpea variety trial in 2002 and 2003. Three separate distribution system were used to supply the weed seeds, crop seeds and fertiliser to the sowing discs and tines.

Implement	Disc	Tine	
Tool bar	Middle	Rear	
Seed box	Right cone seeder	Left cone seeder	Norsden
Additive	Weed seed	Crop seed	Fertiliser
Type	Triticale @ 0,3,27 /m2	Chickpea Variety	Granulock12Z
Distributor	6 way	5 way	-

<table>
<tr><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td><td>32 cm</td><td>32 cm</td><td rowspan="19">Crop plot width = 320 cm</td></tr>
<tr><td>Crop Row 1 (Buffer)</td><td>Crop Row 1 (Buffer)</td></tr>
<tr><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td></tr>
<tr><td rowspan="13">Weed plot width = 192 cm</td><td>16 cm</td></tr>
<tr><td>Weed Row 1</td></tr>
<tr><td>32 cm</td><td>Crop Row 2</td><td>Crop Row 2</td></tr>
<tr><td>Weed Row 2</td><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td></tr>
<tr><td>32 cm</td></tr>
<tr><td>Weed Row 3</td></tr>
<tr><td>32 cm</td><td>Crop Row 3</td><td>Crop Row 3</td></tr>
<tr><td>Weed Row 4</td><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td></tr>
<tr><td>32 cm</td></tr>
<tr><td>Weed Row 5</td></tr>
<tr><td>32 cm</td><td>Crop Row 4</td><td>Crop Row 4</td></tr>
<tr><td>Weed Row 6</td><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td></tr>
<tr><td>16 cm</td></tr>
<tr><td rowspan="3">64 cm</td><td rowspan="3">64 cm</td></tr>
<tr><td>Crop Row 5 (Buffer)</td><td>Crop Row 5 (Buffer)</td></tr>
<tr><td>32 cm</td><td>32 cm</td></tr>
</table>

chickpeas were treated with thiram (P-Pickel T. ®) at 10 ml kg^{-1} to control fungal diseases and inoculated with chickpea Group N moist peat inoculant (Bio-care Technology Pty Ltd, Somersby, NSW). Each plot measured 3.5 m wide by 6.7 m in length. Granulock®12Z fertiliser (11.2 % N, 17.5 % P, 4.4 % S, 1.2 % Zn) was applied at 80 kg ha^{-1} with the chickpea seed at planting.

6.2.5 Control of weeds, pests and diseases

2002

Immediately prior to sowing the herbicides, triallate (Avadex BW®) and glyphosate (Roundup Xtra®), were applied on the June 5th at a rate of 2.5 and 1.0 L ha^{-1}, respectively.

During the growing season the major weed was wild oat which was controlled by applying the herbicide fenoxapropyl-p-ethyl (Wildcat®) plus a surfactant (Supercharge®) at the rate of 0.4 L ha^{-1} and 0.15 L ha^{-1}, respectively, on July 18th and September 10th.

Major insect pests in the trials were *Helicoverpa* spp., cutworm (Order Lepidoptera: Family Noctuidae), aphids (*Brevicoryne, Brassicae*), cabbage moth (*Plutella xylostella*) and red legged earth mites (*Halotydeus destructor*). These were controlled by spraying an insecticide thiocarb (Larvin®) at the rate of 0.75 L ha^{-1} on the October 12th.

The fungicide mancozeb (Dithane®) was applied at 1 kg ha^{-1} on September 2 to control *Ascochyta* blight.

2003

Immediately prior to sowing, the herbicide triallate (Avadex BW®) was applied on May 25th at a rate of 1.6 L ha^{-1}.

During the growing season the major weed was again wild oat which was controlled by applying the herbicide fenoxapropyl-p-ethyl (Wildcat®) plus a surfactant (Supercharge®) at the rate of 0.5 L ha^{-1} and 500 ml/100 L of water, respectively, on the July 18th.

Once again helicoverpa was a major pest. The insecticide thiocarb (Larvin®) was sprayed at a rate of 0.75 L ha^{-1} on the September 26, October 24th and November 6.

Ascochyta blight was controlled by the use of two registered fungicides. On August 20th, mancozeb (Dithane®) with an adjuvant (Primwet®) were applied at 1.5 kg ha^{-1} and 40 ml per 100 L, respectively. Chlorothalonil (Bravo®) was applied at 1 L ha^{-1} on August 28, September 12th and 30th, October 24th and again on November 6, at 0.75 ha^{-1}.

6.2.6 Harvest

Prior to harvesting the chickpeas, the grain heads of the mimic weed (triticale) were removed with a garden trimmer to minimise the contamination of the crop grain sample. The plots were trimmed by removing the unwanted plants at both ends of the plots with a plot harvester (Kingaroy Engineering Works). The length of each plot was measured to determine the area.

The plots were harvested with a plot harvester at crop maturity on 20 November 2002 and 9 December 2003. This harvester had a cutting width of 2 m, that enabled the three centre crop rows to be cut in one pass. The grain from the harvester was unloaded into bags at the end of each plot. The grain was cleaned prior to weighing on an electronic balance (Mettler SBS3200). The plot grain yield was calculated from the mass of grain collected from each plot divided by the plot area.

6.2.7 Reflectance

The reflectance for each plot was measured at 43, 60, 82, 98, 118 days after sowing in 2002, and 59, 95, 109, 141 days after sowing in 2003. Laneways were cut across both ends of the plots with a slasher to enable the sensor boom on the tractor to access a undisturbed, uniform area of the plot. This also had the added benefit of removing the furrows left from the planter and making the tractor ride more smoothly over the soil surface. The same equipment used in the previous experiments was used to sample a strip 60 cm wide across the top and bottom end of the plots. The data from these two samplings were averaged to give an estimate of the reflectance for the whole plot.

6.3 Results

6.3.1 Grain yield

The analysis of variance of the grain yield in 2002 for the weed-free treatments indicated a significant ($P < 0.01$) effect of cultivar. One cultivar, BarwonMR Composite, was found to have a significantly higher yield of 2.86 t ha^{-1} than all the other cultivars. The average weed-free yield for all cultivars was 2.29 t ha^{-1}, a level that was considered good given the low in-crop rainfall that year.

In 2003, the mean grain yield for all cultivars for the weed-free treatments was 2.9 t ha^{-1} in 2003. Once again there was a significant ($P < 0.01$) effect of cultivar. However, in this year the cultivars FLIP94-508C, Kaniva, Bumper and Gully had significantly lower yields of 2.30, 2.07, 1.72 and 1.31 t ha^{-1}, respectively compared with the average for all cultivars.

6.3.2 Yield loss

Yield loss was related to the weed density. The 27 weeds m^{-2} treatments had the lowest grain yield for all cultivars and hence the greatest percentage yield loss. The relationship between yield and weed density was non-linear in both 2002 and 2003.

The GLM as described in equation (3.4) on page 22 was found to be a better representation of the data compared with the rectangular hyperbola equation (3.1) on page 21. The latter also had problems with lack of convergence in the model fitting process with some cultivars.

The percentage yield loss, at equivalent weed density levels, was greater in 2003 than in 2002 (Table 6.3) and is shown graphically by the reduced slope of the fitted model in 2002 (Figure 6.2).

The grain yield data were analysed to compare the effects of increasing weed density on yield for each chickpea cultivar. In 2002, the yield declined in response to increasing weed density but there were no significant cultivar $\times$ density interactions (Figure 6.2). Only one cultivar (BarwonMRComposite) shows any divergence from the rest. The weed density effect for BarwonMRComposite indicates that it was more susceptible to yield-loss at the lower weed density than the other cultivars.

The grain yield responses to weed density in 2003 differed among cultivars (Figure 6.3).

Figure 6.2: **2002**. Grain yield versus sown weed density for 18 chickpea cultivars. The line of best fit is the generalised linear model. The broken lines indicate the 95% confidence intervals.

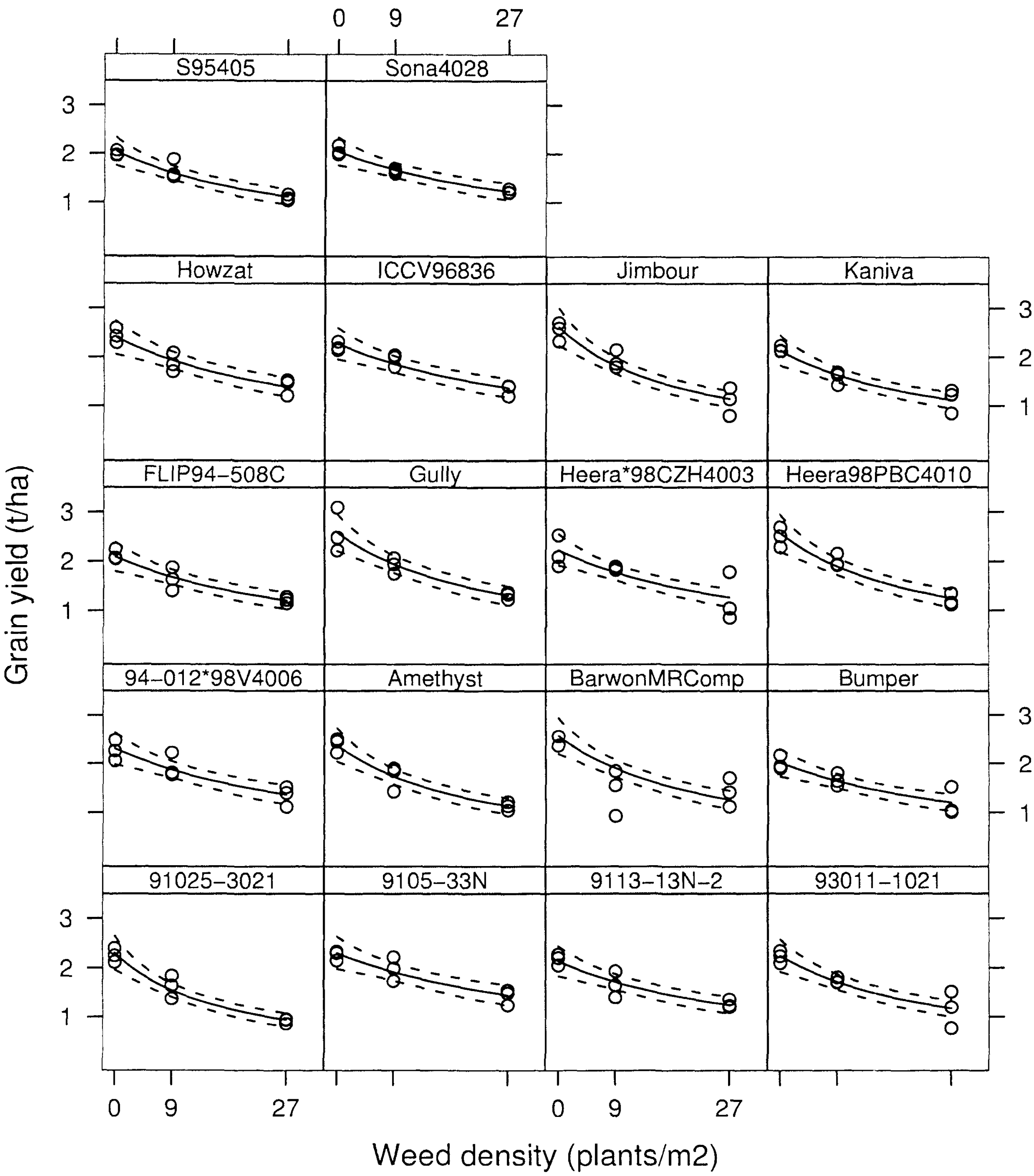


Figure 6.3: **2003**. Grain yield versus sown weed density for 18 chickpea cultivars. The line of best fit is the generalised linear model. The broken lines indicate the 95% confidence intervals.

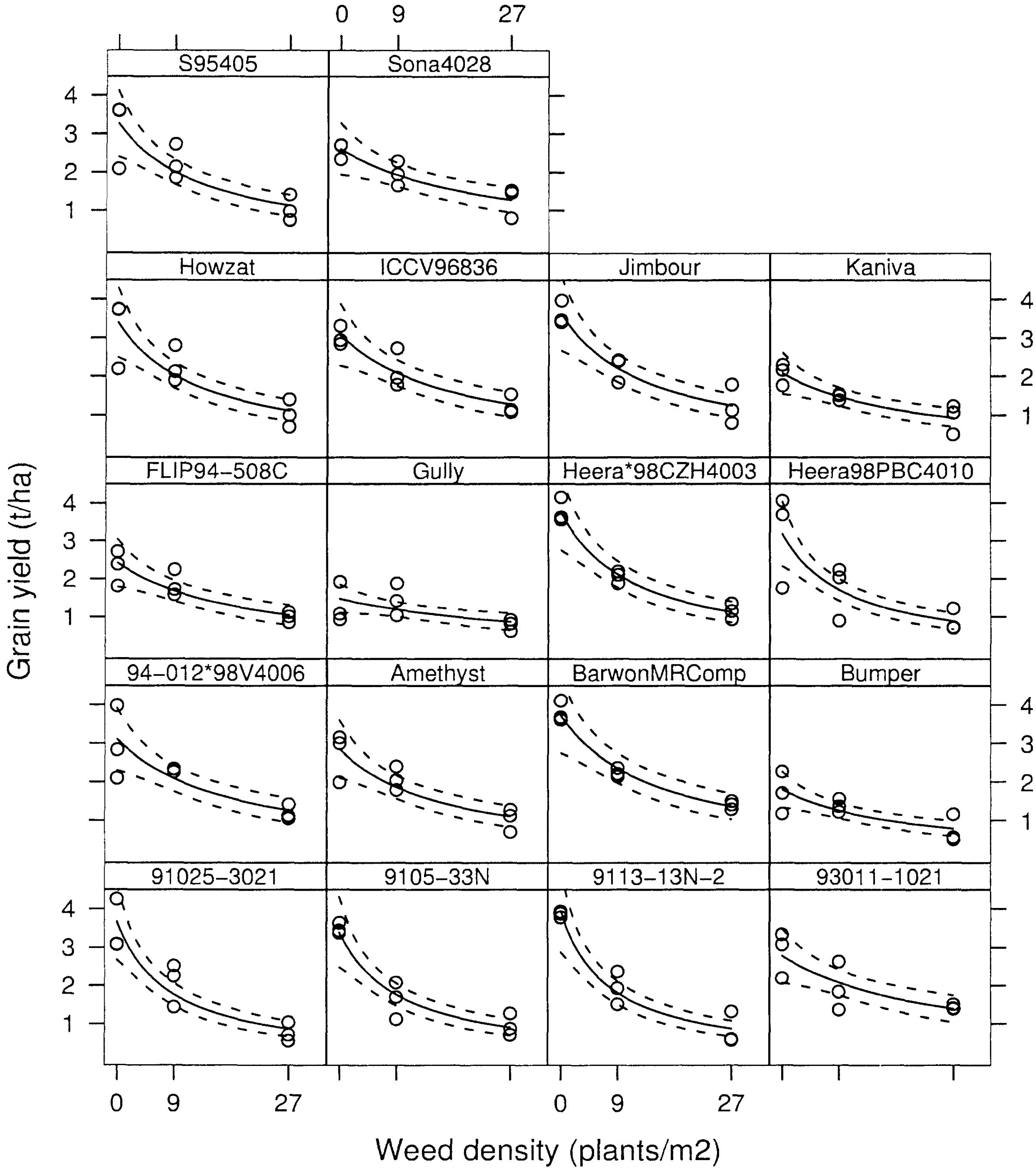


Table 6.2: Predicted yield loss (t ha^{-1}) from the fitted generalised linear model for chickpea cultivars sown in 2002 and 2003 at weed densities of 9 and 27 plants m^{-2}. Values are the mean, and standard errors in brackets and are sorted in ascending order using values for 2002.

	2002				2003			
	9 weeds m^{-2} (t ha^{-1})		27 weed m^{-2} (t ha^{-1})		9 weeds m^{-2} (t ha^{-1})		27 weed m^{-2} (t ha^{-1})	
Variety								
9105-33N	0.38	(0.09)	0.86	(0.11)	1.63	(0.15)	2.49	(0.11)
Bumper	0.38	(0.08)	0.83	(0.09)	0.54	(0.10)	1.02	(0.10)
Sona4028	0.38	(0.08)	0.83	(0.09)	0.68	(0.16)	1.33	(0.16)
9113-13N-2	0.42	(0.08)	0.90	(0.09)	2.13	(0.15)	3.07	(0.10)
FLIP94-508C	0.42	(0.08)	0.90	(0.09)	0.73	(0.14)	1.36	(0.13)
ICCV96836	0.42	(0.09)	0.91	(0.10)	0.99	(0.17)	1.81	(0.16)
94-012*98V4006	0.44	(0.09)	0.95	(0.10)	1.01	(0.17)	1.84	(0.16)
S95405	0.45	(0.07)	0.93	(0.08)	1.26	(0.16)	2.13	(0.14)
Heera*98CZH4003	0.46	(0.08)	0.98	(0.09)	1.64	(0.17)	2.62	(0.14)
Howzat	0.47	(0.09)	1.02	(0.10)	1.37	(0.17)	2.27	(0.14)
Kaniva	0.50	(0.07)	1.02	(0.08)	0.61	(0.12)	1.15	(0.12)
93011-1021	0.53	(0.08)	1.08	(0.08)	0.70	(0.17)	1.39	(0.18)
Gully	0.64	(0.09)	1.29	(0.09)	0.28	(0.10)	0.61	(0.11)
Amethyst	0.65	(0.08)	1.26	(0.08)	0.99	(0.15)	1.75	(0.14)
BarwonMRComp	0.67	(0.09)	1.32	(0.09)	1.36	(0.19)	2.36	(0.17)
Heera98PBC4010	0.68	(0.09)	1.33	(0.09)	1.47	(0.14)	2.29	(0.11)
91025-3021	0.76	(0.07)	1.37	(0.07)	1.90	(0.15)	2.80	(0.10)
Jimbour	0.79	(0.08)	1.48	(0.08)	1.42	(0.18)	2.39	(0.15)

Table 6.3: Predicted yield loss (percent) from the fitted generalised linear model for chickpea cultivars sown in 2002 and 2003 at weed densities of 9 and 27 plants m^{-2}. Values are the mean and standard errors in brackets and are sorted in ascending order using values for 2002.

	2002				2003			
	9 weeds m^{-2} (%)		27 weed m^{-2} (%)		9 weeds m^{-2} (%)		27 weed m^{-2} (%)	
Variety								
9105-33N	16.7	(4.6)	37.6	(7.4)	47.9	(8.3)	73.4	(11.9)
ICCV96836	18.3	(4.6)	40.2	(7.4)	32.2	(8.1)	58.7	(12.5)
Sona4028	18.6	(4.6)	40.6	(7.4)	25.9	(8.1)	51.2	(12.8)
Bumper	18.8	(4.6)	41.0	(7.3)	30.2	(8.1)	56.5	(12.6)
94-012*98V4006	18.9	(4.6)	41.2	(7.3)	32.7	(8.1)	59.3	(12.5)
9113-13N-2	19.6	(4.6)	42.2	(7.3)	54.0	(8.5)	77.9	(11.7)
Howzat	19.8	(4.6)	42.5	(7.3)	40.4	(8.2)	67.0	(12.2)
FLIP94-508C	20.1	(4.6)	43.1	(7.3)	30.2	(8.1)	56.5	(12.6)
Heera*98CZH4003	20.7	(4.6)	43.9	(7.3)	43.7	(8.3)	69.9	(12.1)
S95405	21.9	(4.6)	45.7	(7.3)	38.7	(8.2)	65.4	(12.3)
Kaniva	23.4	(4.6)	47.8	(7.3)	29.2	(8.1)	55.3	(12.6)
93011-1021	23.6	(4.6)	48.1	(7.3)	25.0	(8.1)	50.0	(12.8)
Gully	25.0	(4.6)	49.9	(7.2)	18.9	(8.1)	41.1	(13.0)
BarwonMRComp	26.0	(4.6)	51.3	(7.2)	36.6	(8.2)	63.4	(12.4)
Heera98PBC4010	26.4	(4.6)	51.9	(7.2)	46.1	(8.3)	72.0	(12.0)
Amethyst	27.2	(4.6)	52.9	(7.2)	34.6	(8.1)	61.3	(12.4)
Jimbour	30.3	(4.6)	56.6	(7.1)	39.2	(8.2)	65.9	(12.3)
91025-3021	33.0	(4.6)	59.6	(7.1)	51.8	(8.4)	76.3	(11.8)

6.3.3 Ranking of cultivar in terms of yield loss

The ideal cultivar would have a high weed-free yield and a low susceptibility to yield loss through competition with weeds.

There are a number of different ways in which the cultivars can be ranked. In the first method the mean grain yield for each cultivar and density are calculated from the observed data and graphed. Figure 6.4 shows the chickpea grain yield potential (weed-free) and the yield in the presence of weeds for each cultivar at densities 9 or 27 weeds m^{-2}. The optimum region of the graph for the cultivar to be located is near to the 45 degree line, that defines a 0% theoretical yield loss. In 2002 there was small variation between cultivars in yield as indicated by the cluster of values in both the 9 and 27 weeds m^{-2} treatments. The yield loss for cultivars at 27 weeds m^{-2} tended to be further away from the 0% yield loss line than the 9 weeds m^{-2}, indicating a greater yield loss. There was greater variation between cultivars in terms of weed-free yield in 2003 than in 2002.

The second method is to calculate the predicted yield loss (percent) for each cultivar from the fitted generalised linear model (Table 6.3). The best cultivars would be those with the lowest percentage yield loss. However, this method does not account for some cultivars being ranked poorly because of a high percent yield loss but also having a high weed-free yield.

The third method is to calculate the predicted yield loss in absolute units (t ha^{-1}) for each cultivar from the fitted generalised linear model (Table 6.2). This produced a slightly different ranking order than the second method. This method does not account for the differences in weed-free yield for each cultivar.

The fourth method of ranking the cultivars is to look at the parameter estimates from the generalised linear model (equation 3.4) of yield versus weed density. The `intercept` term in the model is proportional to the weed-free yield, while the slope is proportional to the `rate` of yield loss per unit of weed density. Cultivars with desirable characteristics would have a high value for the `intercept` and a low value for `rate`. The estimated parameter values from the GLM for cultivars in 2002 and 2003 are plotted in Figure 6.5. In 2002 there was little variation between cultivars and no particular cultivar could be seen as having a vastly superior competitive ability compared to another. In 2003, there was a larger variation between cultivars. Cultivar number 4 (Gully) stood out as a low yielding cultivar (in the absence of weeds) with a low `rate` value (high competitive ability). At the other extreme, cultivar number 5 (9113-13N-2 or Yorker) was high yielding but showed severe yield loss in the presence of weeds. Cultivar number 6 (93011-1021 or Flipper) was a cultivar that had a yield, close to the experimental average, and a low `rate` value.

Figure 6.4: Comparison of the yield of the weed-free versus the 9 and 27 m^{-2} weed density treatments for chickpea cultivars in 2002 and 2003. The line represents a theoretical yield loss of 0%. The numbers are the mean for all replicates and refer to the cultivar number in Table 6.1.

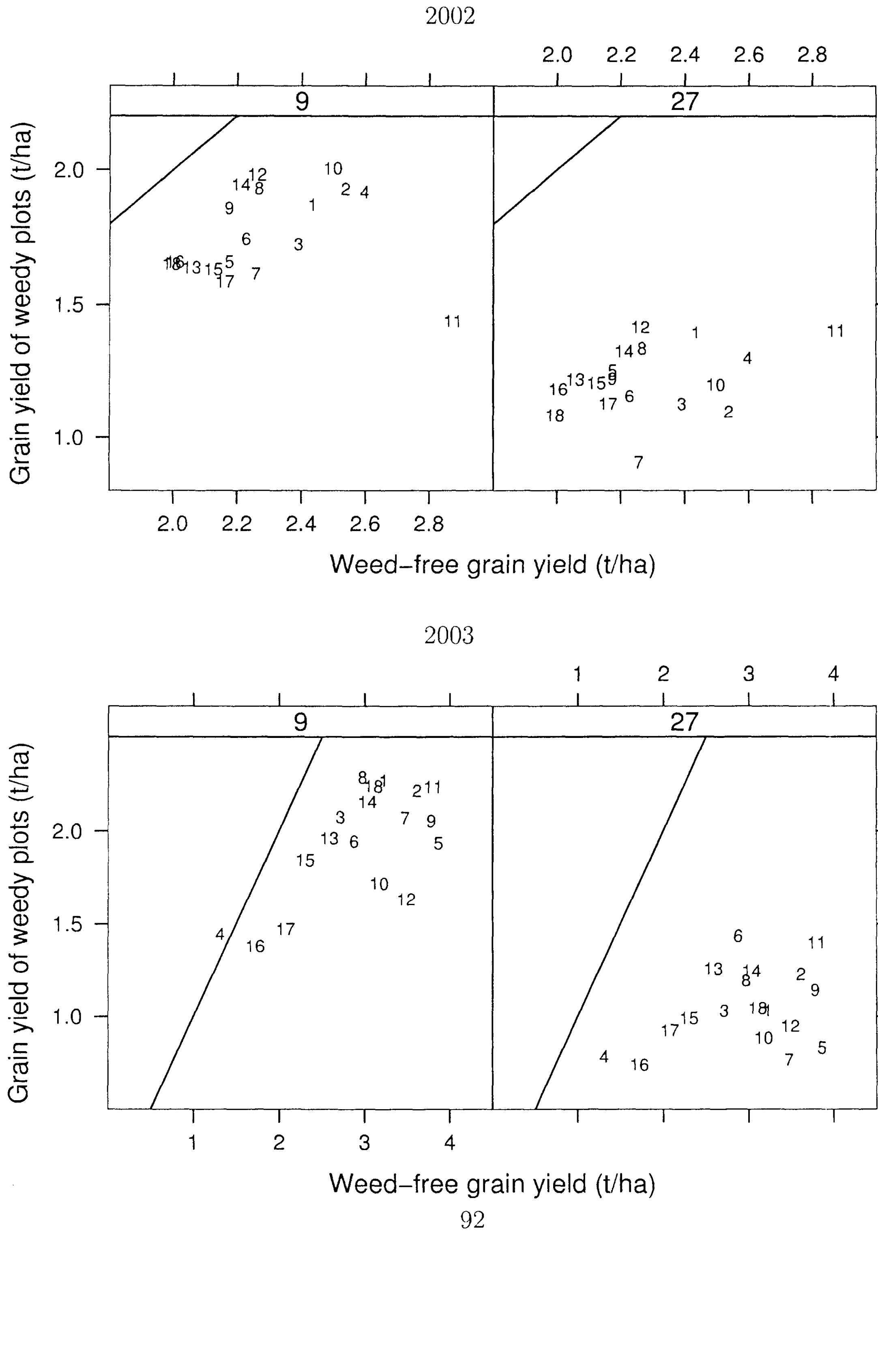
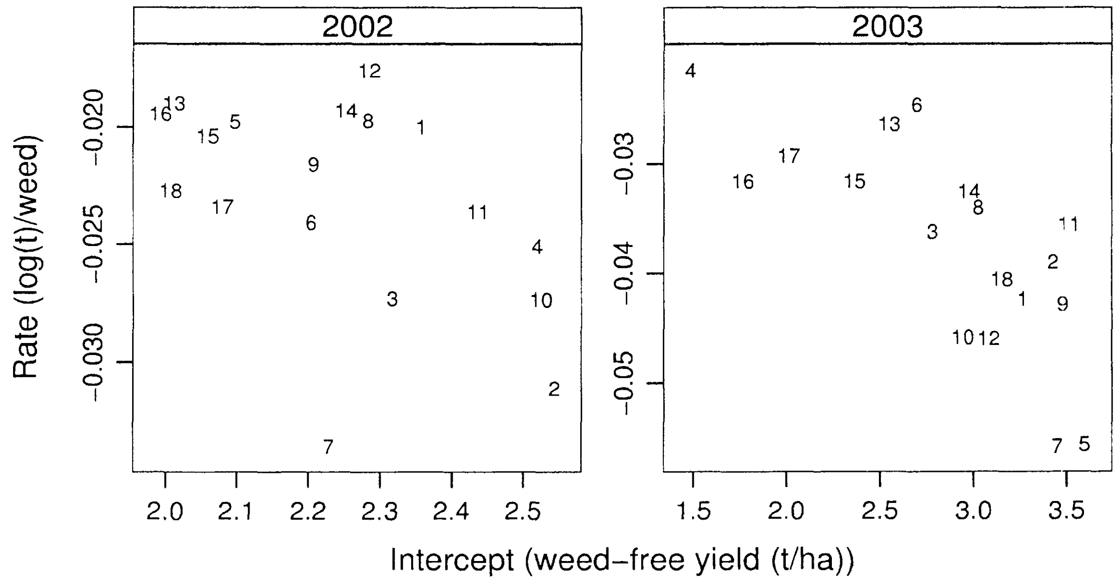


Figure 6.5: Slope and intercept parameters for the GLM model (equation 3.4) of yield versus weed density for chickpea cultivars in 2002 and 2003. The numbers refer to the variety numbers in the table below.



Number	Variety
1	Howzat
2	Jimbour
3	Amethyst
4	Gully
5	Yorker
6	Flipper
7	91025-3021
8	94-012*98V4006
9	Heera*98CZH4003
10	Heera98PBC4010
11	BarwonMR Composite
12	9105-33N
13	Sona 4028
14	Genesis 836
15	Genesis 508
16	Bumper
17	Kaniva
18	S95405

6.3.4 Reflectance

The reflectance over time were modeled by a linear mixed model. The predictive terms of the model are (i) cultivar, (ii) weed density, and (iii) time. Changes over time are represented by a spline curve which is fitted using the ASREML software (Gilmour et al., 1998).

A saturated model was fitted with these components;

1. cultivar,
2. weed density,
3. days after sowing (linear),
4. spline functions of days after sowing, and
5. interactions between cultivar, weed density, days after sowing

Non significant terms were removed by backwards elimination. The final model is

$$Y_{ijkl} = \mu + \alpha_i + \theta_{ij} + \beta_{ij} \cdot \tau_{ijk} + u_l + \text{spl}(\text{dayno})_{ijkl} + \epsilon_{ijkl} \tag{6.1}$$

where,

Y_{ijkl}	is the CCA from plot l, with cultivar i, weed density j and sampling k,
α_i	is the effect of cultivar i, $\alpha_1 = 0$,
θ_{ij}	is the effect of weed density j within cultivar i,
β_{ij}	is the linear trend due to sampling time,
τ_{ijk}	is the effect of sampling time k within weed density j within cultivar i,
u_l	is a random plot effect assumed to be distributed $N(0, \sigma_u^2)$,
spl(dayno)	is a random component which fits the spline and is distributed $N(0, \sigma_s^2)$, and
ϵ_{ijkl}	is a $N(0, \sigma^2)$ random variable for measurement error.

The CCA responses to weed density in 2002 from the fitted model are presented in Figure 6.6. The observed values are excluded to reduce clutter. The CCA values in the 27 weeds m^{-2} treatments were generally higher than the 0 and 9 weed m^{-2} treatments. However, the CCA values for all weed densities were approximately the same at 40 and 120 days after sowing. The CCA responses for the 0, 9 and 27 weeds m^{-2} treatments had a maximum separation between 80 and 100 days after sowing.

The differences in the reflectance of the weedy versus the weed-free treatments are difficult to compare in Figures 6.6 and 6.8 . A new reflectance ratio was derived for this comparison and is similar to the relative reflectance of the weeds previously defined on page 63. The ratio of the reflectance of the weedy treatments and the weed-free treatment is defined in the equation

$$CCA_r = \frac{CCA_{crop+weed}}{CCA_{crop}} \tag{6.2}$$

where,

CCA_r	is the ratio of reflectance of weedy and weed-free treatments
CCA_{crop}	is the measured reflectance of the crop, in the weed-free treatments, and
$CCA_{crop+weed}$	is the measured reflectance of the crop with weeds present.

The reflectance ratios r_9:r_0 and r_{27}:r_0 for 2002 are plotted in Figure 6.7 with r_0, r_9 and r_{27} denoting the CCA reflectance at a weed density 0, 9, 27 weeds m^{-2}. These indicate the time (days after sowing) where the differences between reflectance is at a maximum. This is the best sampling time to use for relating reflectance to yield loss.

The CCA responses in 2003 (Figure 6.8) were higher than those of 2002 (Figure 6.6) and can be explained by the higher crop biomass and yield in 2003. The separation between the CCA responses for the 0, 9 and 27 weeds m^{-2} treatments was also greater in 2003 and there was a consistent ordering in the responses according to the weed density. In 2002, the differences in responses between the weed density treatments were small and the comparison between cultivars of these differences showed inconsistent trends.

In 2003, the reflectance ratios were calculated for the 9 and 27 weeds m^{-2} treatments over time and show a different response for each weed treatment (Figure 6.9). The trends in reflectance ratios were not as consistent in 2002 and there were smaller differences between treatment responses for some cultivars (Figure 6.7).

Figure 6.6: **2002**. Change in reflectance values over time for chickpea cultivars. The lines of best fit are from the ASREML model. The black, red and green lines are the responses for the 0, 9 and 27 weeds m^{-2} treatments.

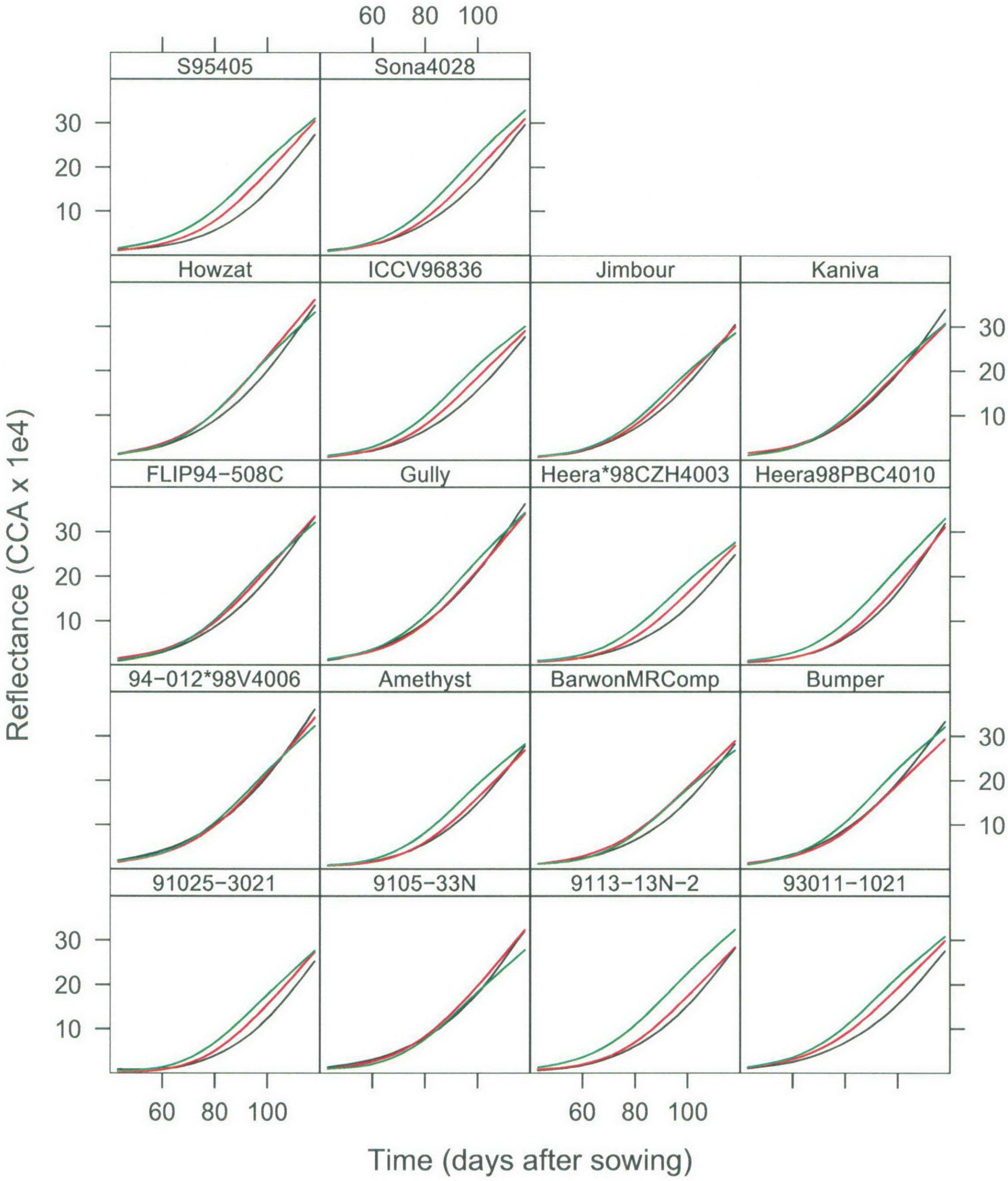


Figure 6.7: **2002**. Profiles of reflectance for the 9 and 27 weeds m^{-2} treatments compared to the weed-free treatment over time, derived from the reflectance in Figure 6.6. The black, red and green lines are the responses for the 0, 9 and 27 weeds m^{-2} treatments.

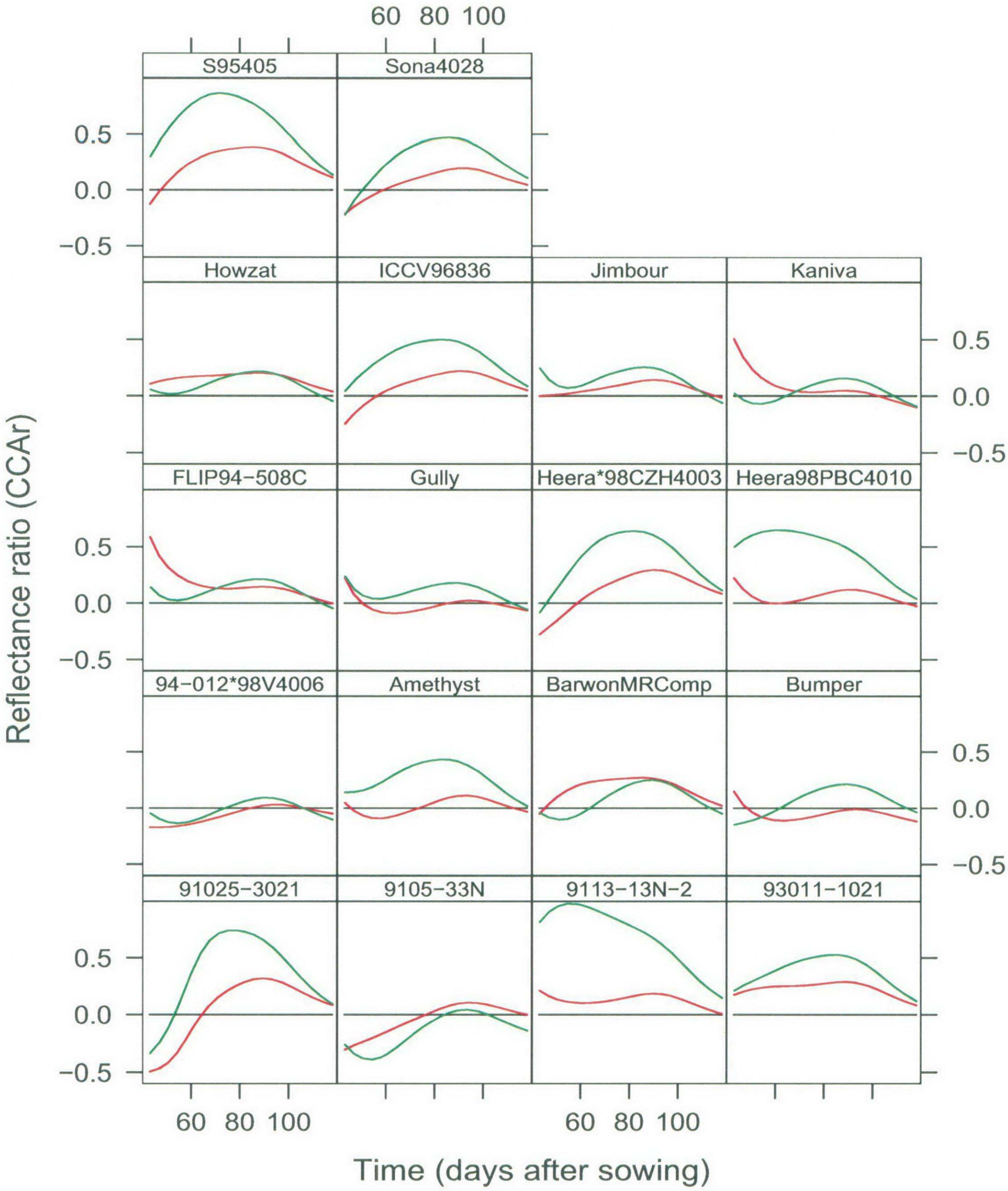


Figure 6.8: **2003**. Change in the reflectance values over time for chickpea cultivars. The lines of best fit are from the ASREML model. The black, red and green lines are the responses for the 0, 9 and 27 weeds m^{-2} treatments.

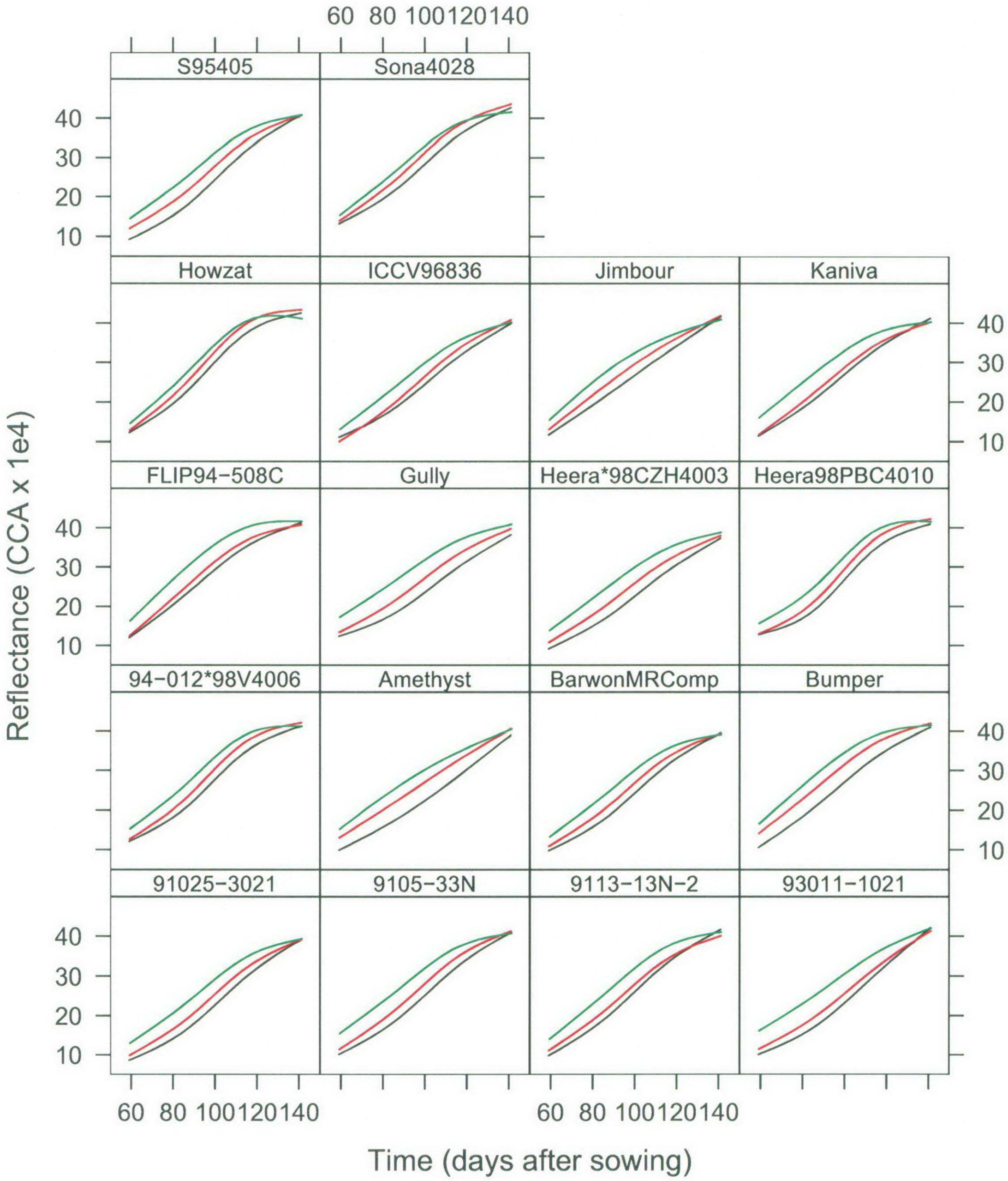
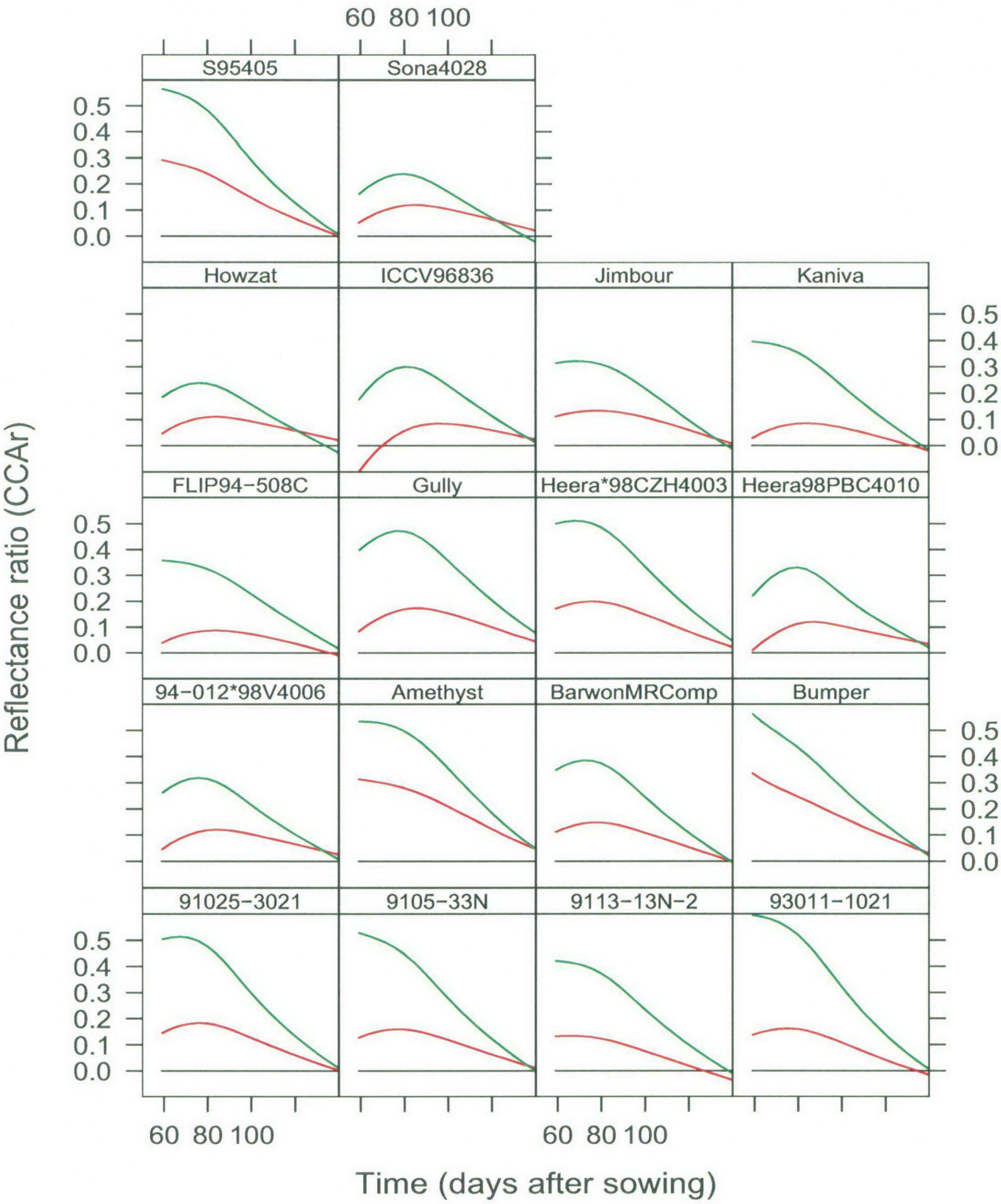


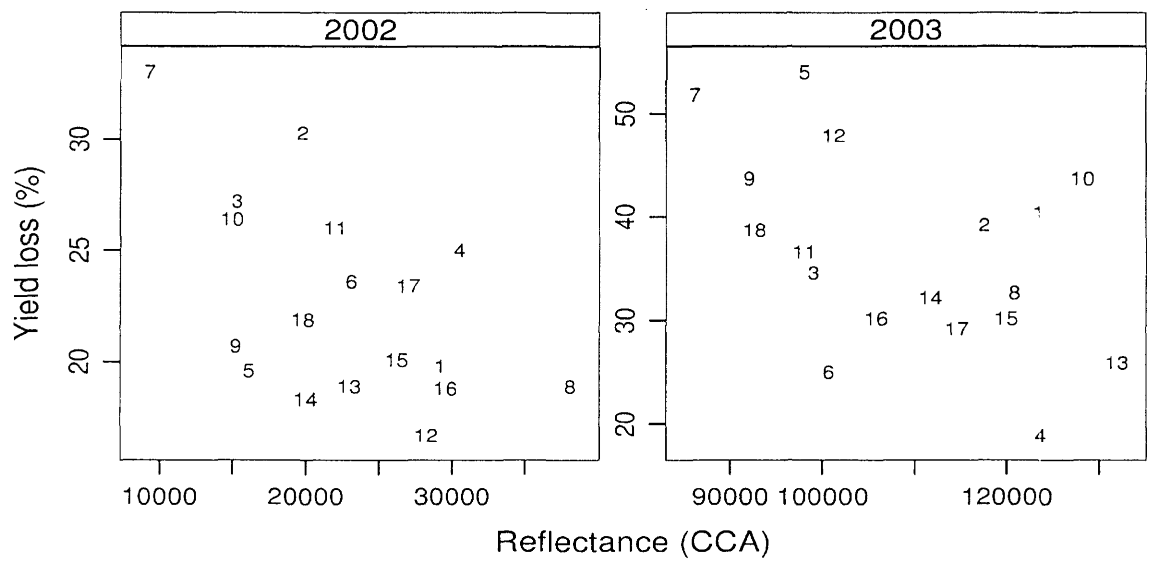
Figure 6.9: **2003**. Profiles of reflectance for the 9 and 27 weeds m^{-2} treatments compared to the weed-free treatment over time, derived from the reflectance in Figure 6.8. The black, red and green lines are the responses for the 0, 9 and 27 weeds m^{-2} treatments.



6.3.5 Seedling vigour

The seedling vigour for each cultivar can be estimated from the biomass early in the season. The crop biomass could not be measured without destructive sampling the plots in this experiment. However, reflectance measurements could be used to estimate the biomass of each cultivar in the same manner used in Chapter 4. The predicted reflectance calculated from the fitted splines of the weed-free treatments were used in the analysis. The percentage yield loss was estimated from the predicted yield from the GLM for the 9 weeds m^{-2} treatment. However, any weed density level could have been used to estimate the percentage yield loss as the proportionality between cultivars is constant throughout the weed density range. A linear regression line was fitted to the percent yield versus reflectance data to indicate if there were any trends across the range of cultivars tested. The percentage variance accounted for by the reflectance was 30 and 24% in 2002 and 2003, respectively. The results are presented in Figure 6.10 and labelled with the cultivar number. The data suggests a trend with reflectance being inversely proportional to the percent yield loss.

Figure 6.10: Estimated biomass (seedling vigour) of the cultivars in 2002 and 2003. The biomass was estimated from the reflectance of the weed-free treatments at 59 and 58 days after sowing for 2002 and 2003, respectively. The percentage yield-loss is for the 9 weeds m^{-2} treatments. The cultivar numbers are from Table 6.1.



6.3.6 Predicting yield loss from reflectance measurements

The 2003 data set of grain yield and weed density was chosen to explore the relationship between yield-loss and reflectance. This year was considered preferable to 2002 because the weed density treatments resulted in higher yield losses and there were greater differences in competitiveness between cultivars.

Yield loss was previously shown to be related to the weed density and generalised linear models (equation 3.4) were used to describe the observed responses (Figures 6.2 and 6.3).

The 9 and 27 weeds m^{-2} treatments were found to have a higher reflectance than the weed-free treatments (Figure 6.8). The differences in reflectance over time were more easily recognised in the profiles of the reflectance ratio (Figure 6.9). These show a good separation in the three fitted spline curves for each weed density level. The fitted splines allow the reflectance to be estimated at any point in time. However, it was decided to use the observed reflectance values at the sampling times of 59 and 109 days after sowing as a predictor of yield loss.

The effectiveness of reflectance measurements to estimate yield loss, as compared with using density as a predictor, is done by comparing the fits of 3 statistical models. Each model is a GLM of the form,

$$\mu_{ijk} = \mathrm{E}(y_{ijk}) = g(\mathrm{Rep}_i + \mathrm{Cult}_j + \mathrm{Cult}_j \cdot \mathrm{X}_k) \tag{6.3}$$

$$var(y_{ijk}) \propto {\mu^2}_{ijk} \tag{6.4}$$

where,

y_{ijk} is the grain yield for the i th replicate, j th cultivar, and k th weed density level,

i indicates the replicate,

j indicates the cultivar,

k indicates the weed density level.

This is a Gamma model where X denotes

(i) weed density

(ii) Reflectance ratio at 59 days or

(iii) Reflectance ratio at 109 days.

A log function was chosen for the link g(.).

In (i) the weed density is the targeted density of 0, 9 and 27 weeds m^{-2}. In (ii) and (iii) the reflectance ratio is the ratio of reflectance from the "weedy" plots to the reflectance from the weed-free plot in the same replicate.

All models contain terms to estimate the systematic effects of replicate and cultivar differences. The similarity of models (ii) and (iii) to model (i) is shown by the correlations between the Pearson residuals of each fit. Multivariate analysis of variance was used to estimate these correlations and are presented in Table 6.4. The correlations between the

GLM's, using reflectance measurements at 59 and 109 days after sowing, ranged from 0.44 to 0.97 and 0.65 to 0.95, respectively.

The fitted values for all three models were aggregated over replicates and plotted on the same graph for comparison (Figure 6.11).

Table 6.4: Correlations between the GLM (6.3) for yield loss in chickpea cultivars in 2003. The second column is the correlation between models using (i) weed density and (ii) relative reflectance at 59 days after sowing and the third column is the correlation between models using (i) weed density and (iii) relative reflectance at 109 days after sowing.

Cultivar	59 DAS	109 DAS
ICCV96836	0.44	0.90
Heera98PBC4010	0.57	0.65
BarwonMRComp	0.63	0.90
FLIP94-508C	0.69	0.82
9113-13N-2	0.73	0.81
Gully	0.76	0.91
94-012*98V4006	0.81	0.65
91025-3021	0.84	0.90
S95405	0.84	0.81
Amethyst	0.85	0.87
Kaniva	0.87	0.85
Bumper	0.89	0.81
Sona4028	0.89	0.82
93011-1021	0.92	0.90
Howzat	0.95	0.86
9105-33N	0.96	0.95
Heera*98CZH4003	0.97	0.95
Jimbour	0.97	0.89

Bivariate plots of the mean yield loss and the rate of loss on the log scale from the 3 yield loss models (i.e. weed loss as functions of (i) weed density, (ii) relative reflectance at 59 days after sowing and (iii) relative reflectance 109 days after sowing) are used to interpret the performances of cultivars, Figure 6.12. An ideal cultivar has a high mean yield (x-axis) and a low yield loss rate (y-axis). Thus the cultivars in the upper right quadrant are the best.

Some of these cultivars, numbers 4,6,8,9,15 and 17, had a similar position in frames (a) (b) and (c). The position of cultivar number 1 in (b) and (c) does not correspond with its position in (a) and indicates that for this cultivar the relationship between yield loss predicted by (i) weed density and (ii) reflectance is poor.

Figure 6.11: Comparison of the fit of the GLM for yield loss, (6.3), using predictor variables (i) weed density (black line), (ii) relative reflectance ratio at 59 days after sowing (DAS) (red line), and (iii) relative reflectance ratio at 109 DAS (blue line).

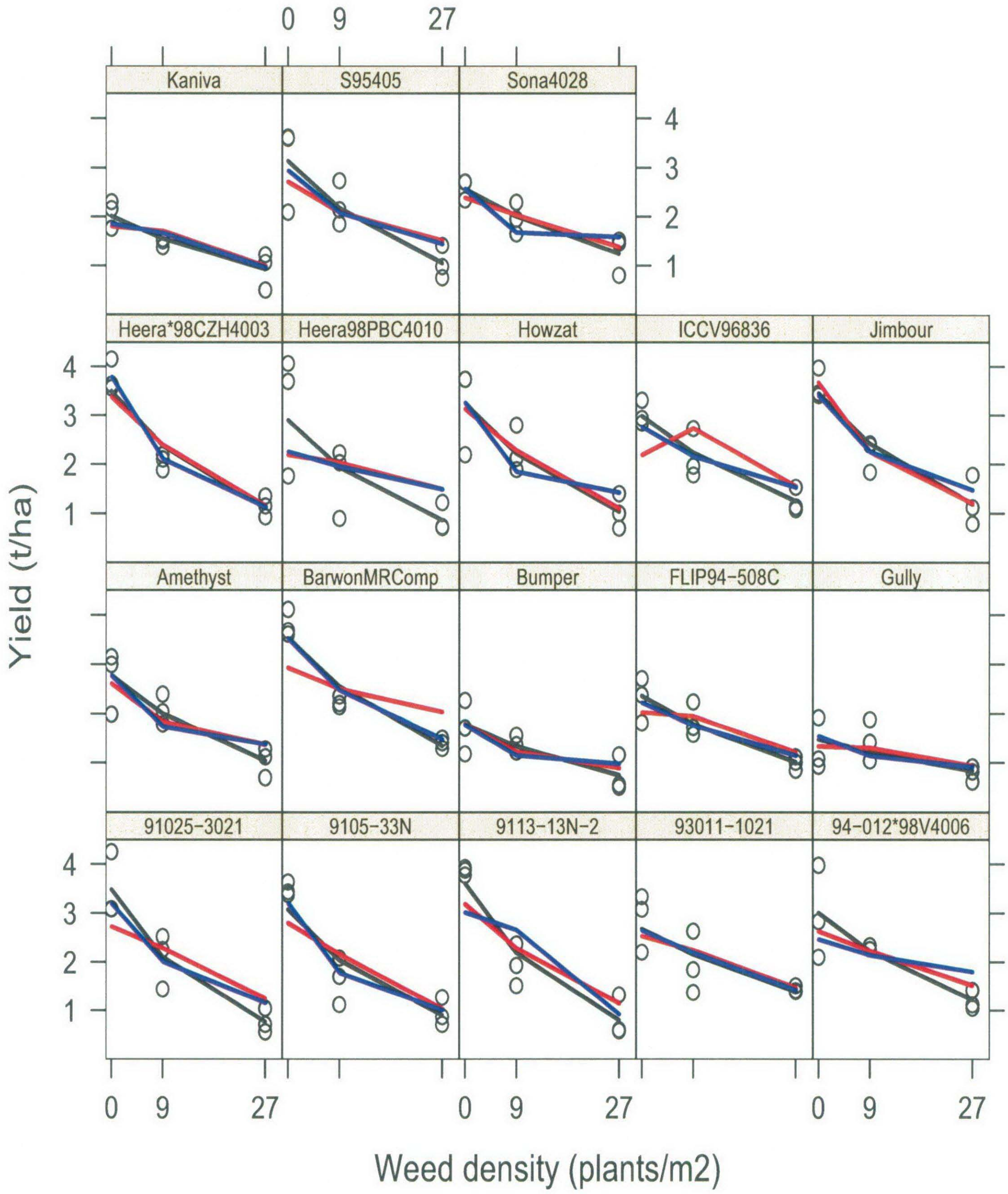
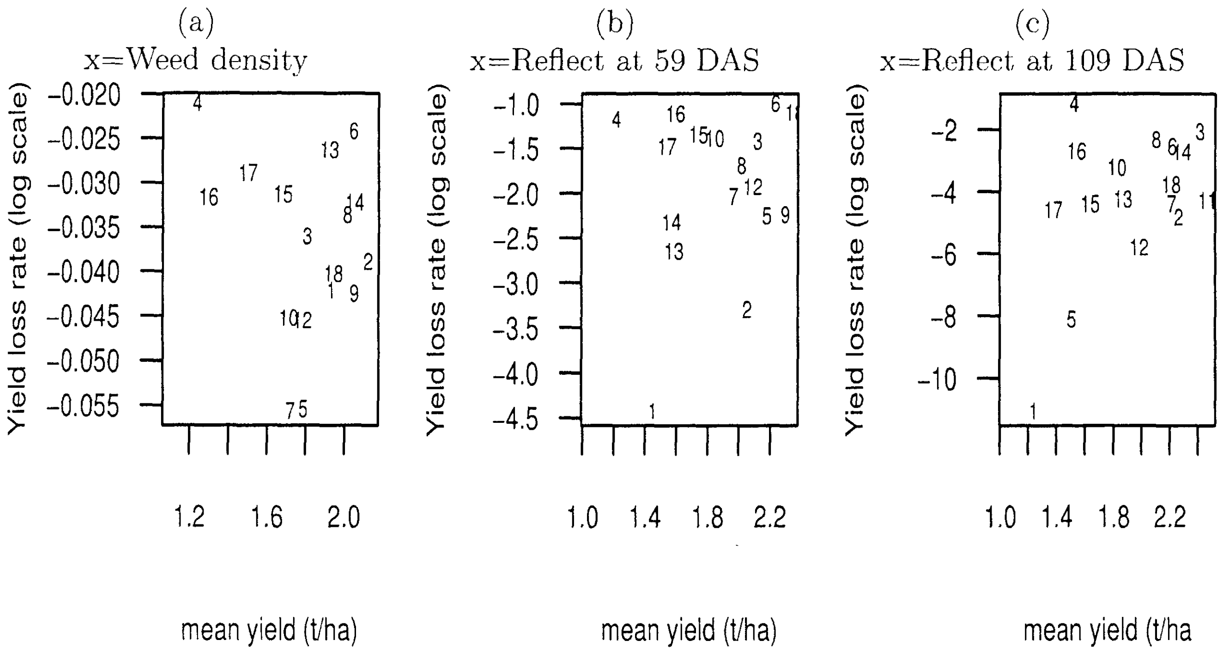


Figure 6.12: Bivariate plots of rate of yield loss and mean yield (t ha^{-1}) for chickpea cultivars in 2003. The cultivar numbers are from Table 6.1.



6.4 Discussion

Crops and weeds compete with each other for limited resources within a finite plot area. Initially the weeds are small and their distance from the crop rows causes low inter-specific competition.

Grass weeds such as wild oat or a mimic weed, have a faster growth rate than chickpea and make up a large proportion of the total plot biomass and canopy cover early in the season. Therefore, the higher weed density treatments tend to have a higher reflectance due to the weeds filling the empty spaces between the rows. As the chickpea develop the canopy widens until all the inter-row space is fully covered. The reflectance of the plots at this stage is the same for all treatments as the weeds do not add to the reflectance from the crop.

Comparison of the percentage yield loss in 2002 and 2003 at an equivalent weed level showed that the weeds in 2003 had a greater affect on the crop than in the 2002. This might be associated with different water utilisation of the crop in each year. The low rainfall in 2002 resulted in the crop relying more on stored soil water for survival. The weeds were also using some of this stored water but were not able to extract the water from the deeper soil layers as efficiently as the chickpea later in the season. In 2003, the rainfall was closer to the long-term average and the weeds would have been utilising the higher rainfall. The mimic weed triticale has a faster growth rate than chickpea and would have been able to utilise this rainfall when the crop still had a low growth rate. In the weed-free treatments the extra rainfall would be stored in the soil profile for utilisation by the crop later in the season.

There was no difference in using the 9 or 27 weeds m^{-2} treatments to rank the cultivars in terms of the predicted percentage yield loss. This is a result of using a GLM which is constrained to fit a smooth response curve through all the data points. This means that the GLM fitted for each cultivar will never intersect with one another apart from the yield at zero weed density.

High early seedling vigour is an expression of high relative growth rate or large initial size or biomass and is often correlated with seed size (Lemerle et al., 2001). This is likely to confer a competitive advantage over the surrounding weeds. However, the difference in competitiveness between chickpea and the weeds is so great that a difference in competitive ability between cultivars would only result in a small advantage. The kabuli chickpea cultivars have a larger seed size and would be expected to have a higher seedling vigour. The reflectance of kabuli cultivars in Figure 6.10 did not show that they were at the higher end of the observed range. It is not known if the differences in canopy architecture of the cultivars in the early stages of growth are affecting the reflectance measurements and hence the biomass estimation.

Increasing the number of replicates used in this experiment would have improved the precision of the estimated parameters. Competition experiments generally have a greater residual variance than single species experiments of the same size (Cousens, 1991). There is always a possibility of the values used to estimate the mean will be from the extreme ends of the distribution. This results in an estimate that is well above or below the true mean. The detection of small varietal differences in competitive ability can be difficult because of the variability introduced by the variety × environment × weed interactions (Lemerle et al., 2001). This was evident in the conflicting order or ranking of the chickpea cultivars in 2002 compared to 2003.

The spatial arrangement of the plots is also an important consideration in the experimental design. The weed-free and weedy plots should be in close spatial proximity to each other. However, in large experiments with many varieties this cannot be achieved. In this experiment with 18 chickpea cultivars the weed free treatments in each replicate were randomly positioned within an area of 30 m by 63 m with plots arranged in 3 columns and 18 rows. The alternative is to use split plot design but these can also introduce bias and lessen the chance of measuring differences between main plots (varieties).

6.5 Conclusion

The results of the field experiment show a range in competitive ability for the chickpea cultivars examined. The differences in competitive ability were more evident in 2003 than in 2002. The ranking order of cultivars in terms of percentage yield loss or absolute yield loss between the two year was not consistent. This inconsistency between results in each year may be caused by experimental error or the variation in the CA of cultivars according to the environmental conditions.

The slope and the intercept parameter from the GLM were used as the basis for a two dimensional comparison of the competitive ability and yield potential of each cultivar. In 2003 there was a large range of values for both the intercept and rate parameters in the GLM. Cultivars at the extreme ends of the range were identified as having either low weed-free yield potential and low rate of yield loss or high weed-free yield potential and high rate of yield loss.

Seedling vigour, expressed as higher crop biomass, and estimated with reflectance measurements was able to account for between 25 and 30% of the observed variation in competitive ability between cultivars. If this relationship was more reliable then the competitive ability of cultivars could be calculated by the use reflectance measurements to estimate crop biomass in the early growth stages using only the weed-free treatments. The results demonstrate reflectance to be a very useful tool in genotype comparisons as a adjunct to yield data. Further studies are warranted to examine the potential in more detail.

This experiment demonstrated that a remote sensing technique could be used to predict the yield-loss due to weeds for the majority of the cultivars included in the trial. A strong association was found between the yield-loss predicted by models based on either weed density or ratios of weed to crop reflectance.

However, the results of this experiment were not consistent enough to be able to make reliable estimates of the comparative competitive ability between all the cultivars. The reflectance ratio alone could not rank the cultivars in a similar order to that obtained from analysis of parameter estimates for the GLM of yield versus weed density.

The inclusion of more weed density treatments would have improved the predictions from the weed density yield-loss model. The number of remote sensing measurements during the first 100 days after sowing would have improved the fit of the yield-loss model based on the ratio of relative weed to crop reflectance. Chickpeas require a high level of insect and disease management at critical times during the final stages of grain development. These factors can also influence the final yield of the crop and may account for some of the observed variation.

Chapter 7

Conclusions

7.1 Introduction

The estimation of crop biomass is an essential measurement in most agronomy field experiments. The use of non-destructive, remote sensing techniques has become popular in research and now is becoming more common in commercial applications such as precision agriculture. The WeedSeeker® and GreenSeeker® sensors are now used commercially in both weed spot spraying and variable rate nitrogen application. However, there is little published literature on the performance of these sensors on different crop types.

The research objectives were to conduct field experiments in which both destructive and non-destructive measurements of crop growth were taken to enable the calibration of the WeedSeeker® sensors. Three field experiments were conducted that included a range of different types of crops, weeds and chickpea cultivars. The interactions between crops and weeds was also explored in chickpea weed competition experiments. These provided data to assess the usefulness of a non-destructive method for the prediction yield-loss.

This chapter draws together the findings of all three experiments with respect to the aims, discussion and future research.

7.2 Calibration of a crop canopy analyser with crop growth

The growth of canola, chickpea, fababean and wheat was examined over two years and calibrated with a remote sensing method. The inclusion of an additional row spacing treatment into the design in the final year, enabled testing as to the robustness of the method.

The reflectance was closely related to the leaf area index (LAI) for all crops. The relationship appears to be a two stage process and was modeled using piecewise regression. The linear model fitted the data and gave accurate estimates of the LAI of the crops for values less than 1. When LAI values were greater than 1, the relationship had a lower predictive capability and the variability of the response increased.

The crop biomass was closely related to the LAI of the crops. Although leaf area is an impractical measurement to use for the prediction of biomass, it can be estimated quickly and non-destructively with reflectance sensors. The limit of linearity of this relationship was when the crop had reached a LAI value of 2.

The crop biomass was accurately predicted from the reflectance for all crops. The relationship became less reliable when the crop biomass exceeded 1000 kg ha^{-1}. The limit of linearity in this relationship could have been improved further if the sensors had been able to extend the range of predictions to a leaf area index value of 2.

Reducing the distance between the crop rows resulted in higher leaf area indices in canola, fababean and wheat crops. However, there was no effect of row spacing on the relationship between reflectance and LAI. The use of wide row spacings tends to concentrate the plants in narrow strips. The sensors tend to reach saturation at low LAI values and as crop growth continues the LAI increases but the additional biomass is not detected. This is particularly evident in the crops that have a tall canopy structure like wheat. The problem is less likely to occur in crops with a spreading canopy like chickpea as the extra area of ground cover will increase the reflectance.

7.3 The use of mimic weeds as a substitute for wild oats in chickpea competition field experiments

The use of mimic weeds in chickpea weed competition experiments was explored in chapter 5. Yield-loss relationships were defined for each weed type using a number of measurement variables including; weed density, weed biomass and relative reflectance of weeds.

Weed density was shown to affect the yield of chickpea in a predictable manner for both natural occurring and mimic weeds. The response was non-linear and the inverse polynomial model was found to be superior to the rectangular hyperbolic model in fitting the data. The sowing of weeds in rows between the crop rows improved the establishment of the weeds so that their densities were closer to the targeted levels. This sowing method reduced variability in the yield response for wild oats treatments in 2003 compared to broadcasting methods used in 2002.

Yield-loss was predicted by weed biomass with a linear and rectangular hyperbolic model in 2002 and 2003, respectively.

Yield-loss could also be predicted by the comparing the reflectance of a weedy versus a weed-free crop area. The increased reflectance of the weedy plot is due to the additional leaf area. The spatial separation between the crop and weed rows resulted in easier detection and measurement of reflectance from each species. In the early growth stages the difference in reflectance between the weedy and weed-free crops was large. However, in the later growth stages the crop canopy widens and the weeds become harder to detect. This results in a smaller difference in reflectance and subsequently the predictions of yield-loss are poor.

The Lotz 2 parameter model was originally devised to predict yield loss from the relative leaf area of weeds versus crop. The reflectance is dependent on the leaf area of the crop and weeds. Therefore the intent of the Lotz 2 parameter model is to predict yield-loss by replacing the relative leaf area of weeds versus crop with the relative reflectance of weed versus crop. However, the model did not fit the observed responses and a non-parametric model (`loess`) was found to be a better representation of the relationship between yield loss and relative reflectance.

Wild oats was found to have the highest competitiveness with chickpeas. The mimic weeds had similar effects to wild oats on the yield of chickpeas with the order of decreasing competitiveness being barley, triticale and wheat.

7.4 Chickpea variety experiment

This experiment demonstrated the variability in competitive ability (CA) between cultivars. The weeds density treatments in 2002 caused less yield loss per unit of weed density than in 2003 in both percentage and absolute terms. The number of replicates and the weed density levels used in this experiment were insufficient to extract any significant differences in CA between cultivars. However, experimental results from Chapter 5 where the Howzat chickpea was grown in competition with triticale, indicate that with more replication and a greater number of sampling times more accurate predictions of yield loss could be made. The observed variability in the CA of cultivars can be caused by either experimental error within years or differences in cultivar competitiveness with weeds in dry (2002) versus wet (2003) years.

The differences in CA between cultivars can be presented in a number of ways. The expression of CA in terms of percentage yield loss does not take account of the different weed-free yield of each cultivar and so cannot be used in gross margin economic analysis. Alternate methods take account of this by comparing absolute yield-loss in t ha^{-1}. The use of generalised linear models of yield-loss gives better predictions as all the data is used to fit the model. However, comparisons between cultivars of the CA still involves two parameters; the intercept (weed-free yield) and the slope (yield-loss per unit of weed density).

Yield loss was fitted as a function of (i) weed density and (ii) relative reflectance using a GLM with log link and Gamma distribution. Yield losses predicted from relative reflectance were very similar to the predictions using actual weed densities, correlations being as high as 0.97 . Thus relative reflectance is a reliable surrogate for predicting yield loss rather than resorting to the labour-intensive and inaccurate sampling of weed densities.

The reflectance of the crop is dependent on the canopy shape and degree of ground cover. In this experiment it was assumed that the different cultivars all had similar canopy structure. This fact would need to be addressed in more detailed experiments.

7.4.1 Seedling vigour

Plant breeders select cultivars with high early vigour in their breeding programs as this trait is believed to be an advantage for the crop if weeds are germinating at the same time as the crop. In previous field studies at Tamworth (E. Knights, pers. comm.) where seventy six chickpea cultivars were sown, the early vigour was estimated by destructive sampling of the foliage at 500 growing degree days (GDD) after sowing. Reflectance measurement, using the same equipment and techniques described in Chapter 4, were also taken prior to sampling. Results show a high correlation (R^2=0.73) between crop biomass and reflectance (CCA) and that the ranking of cultivar by biomass and reflectance was similar (Felton et al., 2002).

The early vigour of chickpea has also been associated with seed size as the cotyledons are produced from tissue in the seed. The kabuli cultivars, such as Kaniva, Bumper and S95405 had the largest seed weight and therefore should have higher early vigour. Measurements of the crop biomass early in the season were not taken in this study and the reflectance measurements did not indicate any significant difference of these varieties compared to the desi cultivars.

Cultivars with high early vigour do not always produce higher yield at the end of the season. The reflectance of the cultivars early in the season could be used to estimate the biomass and is supported by the results in Chapter 4 where there was a high correlation between biomass and reflectance for the cultivar Howzat. The reflectance measurements taken at 59 DAS was poorly correlated with the grain yield for the eighteen cultivars in this study.

The conclusion from these results is that reflectance can play a useful role in plant breeding by providing non-destructive method of estimating biomass early in the season, but this may not be a good predictor of the final grain yield.

7.5 Remote sensing as a tool

The remote sensing methods used in this study for the measurement of crop growth have advantages over previous destructive sampling techniques. These include the ability to assess the performance of crops in a faster time frame and generally at a cheaper cost. The non-destructive sampling of crops means that repeated measurements can be made on the same area of crop. This minimises some of the inherent variation in the data due to spatial effects. The use of spline curves for data that changes with time can also account for some of the inherent variability and improve the estimation of the treatment effects.

The disadvantages of remote sensing techniques include the need for specialised equipment and some degree of operator skill in collecting and processing of the data. The limitations of the techniques must be known before the commencement of the experiment so that sampling can be restricted to the period of crop growth where the instrument response is within its effective capabilities. The prediction of final crop yield using reflectance measurements in the early growth stages can be poor. This is due to the dependence of the spectral data on biophysical parameters such as LAI or biomass and the subsequent relationship between these parameters and final crop yield (Lamb, 2000). Therefore traditional destructive methods of sampling crop biomass at physiological maturity are needed to estimate the maximum crop biomass and to calculate the harvest index.

7.6 Applications

The possibility of utilising some characteristics of the reflectance traces in the mimic weed experiment for a spot spraying system is discussed here. Although the examples relate to the experimental design in which weeds were sown in an artificial environment, between the crop rows, there are similarities between this environment and the occurrence of weeds in a commercial field situation.

The spot spraying system has the potential to reduce the amount of herbicide used per unit area and still control the weeds. Depending on the degree of weed infestation and the positioning (patchiness) of the weeds, the savings in the amount of herbicide used could be considerable. This would allow expensive selective herbicides to be used in situations where the high cost of conventional blanket spraying would preclude their use.

The visualisation of the reflectance profiles for the mimic weed triticale in chickpea shows how the increasing weed density gives rise to an increased area under the peaks. In the weed-free plot the peaks are regularly spaced, in proportion to the crop row spacing, and are approximately the same height. As the weed density increases the traces show the appearance of new peaks between the crop rows. These peaks correspond to the weeds growing between the crop rows. At a weed density of 3 plants m^{-2} the peaks are about half the height of the crop peaks. This is due to the gaps between the weeds along the row and the likelihood that the sensor will not always travel directly over the top of the weed. With increasing weed density the weeds become more closely spaced and the height of the corresponding peaks also increases. The sensor is more likely to see a number of weeds in the field of view. At the highest weed density treatment there are no gaps between the weeds along the row. The peaks attributed to the weeds and crop then merge into one broad peak.

The characteristics of the traces could be used in a system to discriminate the areas of crop with a weed infestation above a set economic threshold. The WeedSeeker®system is already in commercial use for spot spraying weeds in bare fallows. A similar system could be developed for in-crop spot weed spraying. The difference would be in the background targets in each system. In the case of the bare fallow the soil and stubble is the background and this has different spectral reflectance to the green vegetation (Felton et al., 1991). In the case of the in-crop sprayer, the crop rows are the background. These appear as regularly spaced peaks on the trace. The weeds appear as smaller peaks between the crop rows. An algorithm could be designed to discriminate areas of the crop with weeds present from those without weeds based on a number of quantities. These include differences based on the increased area under the peaks and the number of extra peaks within a set time interval in weed infested crop. A threshold level would need to be set to stop false triggering due to noise. The time interval between the crop peaks would need to be adjustable depending on the distance between the crop rows and the speed of the vehicle.

There are many other possible ways to identify weeds in crops including shape, size and spectral differences. Scotford and Miller (2005) have reviewed some of the current methods and their likelihood of being employed in spot spraying systems. However, he concluded that all of the current methods are not practical without the use of complex mathematical manipulations. If these systems are to be practical then they need to be able to detect weeds at a level that is equal or below the economic threshold level. Lamb et al. (1999) has been able to detect wild oats densities as low as 17 plant m^{-2} but the required detection limit is in the order of 1 plant $^{-2}$ (Scotford and Miller, 2005).

7.7 Future research

The weed competition experiment has demonstrated that areas of high weed density can be identified by the increased reflectance compared to weed-free areas. The spatial geometric effect of sowing weeds in rows has made discrimination between the crop and weeds easier. The use of mimic weeds sown in rows has resulted in better control of the weed density levels.

Future research may involve the use of the WeedSeeker sensors for the detection of naturally occurring weeds in commercial crops. Such a system could provide the opportunity to use a spot spraying system and map the occurrence of weeds with the aid of a global positioning systems (GPS).

References

Allen, J. (1977). The effect of weeds on grain lupin yields. *Australian Journal of Experimental Agriculture and Animal Husbandry 17*, 112–116.

Aparicio, N., D. Villegas, J. Casadesus, J. Araus, and C. Royo (2000). Spectral vegetation indices as nondestructive tools for determining durum wheat yield. *Agronomy Journal 92*, 83–91.

Arnold, G., J. Weeldenberg, and A. Grassia (1985). Competition between wimmera ryegrass and narrow-leafed lupins. *Australian Journal of Experimental Agriculture 25*, 824–831.

Barrett, D. and N. Campbell (1973). An evaluation of competition between wheat and wimmera ryegrass *Lolium rigidum* during early stages of growth. *Australian Journal of Experimental Agriculture and Animal Husbandry 13*, 581–586.

Beck, J. (1997). Reduced herbicide using photoelectronic detection. In *Proceedings of the Western Society Weed Science, USA*, Volume 50, pp. 102–107.

Brain, P. and R. Cousens (1990). The effect of weed distribution on predictions of yield loss. *Journal of Applied Ecology 27*, 735–742.

Clevers, J. (1989). The application of a weighted infra-red vegetation index for estimating leaf area index by correcting for soil moisture. *Remote Sensing of Environment 29*, 25–37.

Coombes, N. and A. Gilmour (1999). *SpaDes reference manual.* Wagga Wagga, NSW, Australia: NSW Agriculture, Biometrics Department.

Cousens, R. (1985). A simple model relating yield loss to weed density. *Annals of Applied Biology 107*, 239–252.

Cousens, R. (1991). Aspects of the design and interpretation of competition (interference) experiments. *Weed Technology 5*, 664–673.

Cousens, R. and D. Fletcher (1990). Experimental design for screening for competitiveness of crop cultivars. In J. W. Heap (Ed.), *Proceedings of the 9th Australian Weeds Conference, Adelaide, South Australia*, pp. 163–165. Crop Science Society of South Australia: Adelaide.

Cousens, R. and S. Mokhtari (1998). Seasonal and site variability in the tolerance of wheat cultivars to interference from *Lolium rigidum*. *Weed Research 38*, 301–307.

Dampney, P., R. Bryson, W. Clark, M. Strang, and A. Smith (1998). The use of sensor technologies in agricultural cropping systems. a scientific review and recommendations for cost effective developments. Technical Report Project Code CE 0140, ADAS Contract Report, Review Report to MAFF.

Danson, F., C. Rowland, and F. Baret (2003). Training a neural network with a canopy reflectance model to estimate crop leaf area index. *International Journal of Remote Sensing 24*, 4891–4905.

Duggin, M. (1980). The field measurement of reflectance factors. *Photogrammetric Engineering and Remote Sensing 46*, 643–647.

Duggin, M. and W. Philipson (1983). Field measurement of reflectance: some major considerations. *Applied Optics 21*, 2833–2833.

Felton, W. (1983). Introduction to the regional research program. In R. Martin and W. Felton (Eds.), *Proceedings of the No-tillage Crop Production in northern New South Wales project meeting, Tamworth, NSW, May 4*, pp. 1–6.

Felton, W. (1985). Ecology and control of thornapple (Datura spp) in irrigated soybeans in the Namoi Valley of New South Wales. Master's thesis, Faculty of Agriculture, University of Sydney.

Felton, W. (1990). Use of weed detection for fallow weed control. In *Proceedings of the Great Plains Conservation Tillage Symposium, Bismark, North Dakota, August 21-23*, pp. 214–244.

Felton, W., C. Alston, B. Haigh, P. Nash, G. Wicks, and G. Hanson (2002). Using reflectance sensors in agronomy and weed science. *Weed Technology 16*, 520–527.

Felton, W., A. Doss, P. Nash, and K. McCloy (1991). A microprocessor controlled technology to selectively spot-spray weeds. In *Proceedings of the Symposium, Automated Agriculture for the 21st Century, Chicago, Illinois, December 16-17*, pp. 427–432.

Felton, W. and B. Haigh (2001). Weed competition in winter crops grown in no-till. *Update of Research in Progress at the Tamworth Centre for Crop Improvement 2001*, 22–25.

Felton, W., B. Haigh, and S. Harden (2004). Comparing the competition in chickpea, fababean, canola and wheat. In *Proceedings of the fourteenth Australian Weeds Conference*, Wagga Wagga, NSW, pp. 304–307.

Felton, W., T. Knights, B. Haigh, and S. Harden (2004). Tolerance of chickpea to isoxaflutole. In *Proceedings of the fourteenth Australian Weeds Conference*, pp. 257–260.

Felton, W., H. Marcellos, and R. Murison (1996). The effect of row spacing and seeding rate on chickpea yield in northern New South Wales. In *Proceedings of 8th Australian Agronomy Conference, Toowoomba, Queensland, 30 Jan - 2 Feb*, pp. 251–253.

Felton, W. and G. Smith (1981). The no-tillage planter developed at Tamworth. In *Proceedings of a National Tillage Workshop on Tillage Systems for Crop Production, Roseworthy Agricultural College, Adelaide, South Australia*, pp. F–44.

Gilmour, A., B. Cullis, S. Welham, and R. Thompson (1998). *ASREML. Program users manual.* Orange Agricultural Institute, Forest Rd, Orange NSW Australia: New South Wales Agriculture.

Haggar, R., C. Stent, and S. Issac (1983). A prototype hand-held patch sprayer for killing weeds, activated by spectral differences in crop/weed canopies. *Journal Agricultural Engineering Research and Weed Technology 28*, 349–358.

Haggar, R., C. Stent, and S. Issac (1984). Measuring spectral differences in vegetation canopies by a reflectance ratio meter. *Weed Research 24*, 59–65.

Haigh, B., N. Elias, S. Harden, R. Martin, and S. Belfield (2005). Factors affecting chickpea yields in northern NSW. In *Chickpeas in farming systems: Proceedings of a national conference on chickpeas in farming systems*, Goondiwindi, Queensland, pp. 51–55.

Hanks, J. and J. Beck (1998). Sensor controlled hooded sprayer for row crops. *Weed Technology 12*, 308–314.

Holben, B. (1980). Spectral assessment of soybean leaf are and leaf biomass. *Photogrammetric Engineeering and Remote Sensing 46*(5), 651–656.

Ihaka, R. and R. Gentleman (1996). R: A language for data analysis and graphics. *Journal of Computational and Graphical Statistics 5*(3), 299–314. R (http://www.r-project.org/).

InsightfulCorp (1988, 2003). S-plus 6.2 for windows professional edition.

Isbell, R. (1996). *The Australian soil classification.* CSIRO Publishing, Melbourne, Australia.

Jackson, R. and A. Huete (1991). Interpreting vegetation indices. *Preventive Veterniary Medicine 11*, 185–200.

Jones, C. (2004). Greenseeker (Red NDVI) performance review testing summary (external). *http://nue.okstate.edu/Greenseeker_Review_2004.htm*, 1–5.

Jordan, C. (1969). Derivation of leaf area index from quality of light on the forest floor. *Ecology 50*, 663–666.

Kanemasu, E. (1974). Seasonal canopy reflectance patterns of wheat, sorghum and soybean. *Remote Sensing of Environment 3*, 43–47.

Knights, T., M. Ryan, J. Thompson, K. Hobson, M. Materne, T. Khan, H. Clarke, K. Moore, and J. Wood (2005). Review of chickpea breeding in Australia. In *Chickpeas in farming systems: Proceedings of a national conference on chickpeas in farming systems*, Goondiwindi, Queensland, pp. 20–31.

Kropff, M. and C. Spitters (1991). A simple model of crop loss by weed competition from early observations on relative leaf area of the weeds. *Weed Research 31*, 97–105.

Lamb, D. (2000). The use of qualitative airborne multispectral imaging for manageing agricultural crops - a case study in south-eastern Australia. *Australian Journal of Experimental Agriculture 40*, 725–738.

Lamb, D., M. Weedon, and L. Rew (1999). Evaluating the accuracy of mapping weeds in seedling crops using airborne digital imaging: *Avena* spp. in seedling triticale. *Weed Research 39*(6), 481–492.

Lemerle, D., G. Gill, C. Murphy, S. Walker, R. Cousens, S. Mokhtari, S. Peltzer, R. Coleman, and D. Luckett (2001). Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Australian Journal of Agricultural Research 52*, 527–548.

Lemerle, D., P. Michael, and B. Sutton (1979). The competitive abilities of wheat and triticale against different densities of *Lolium rigidum*. In *Proceedings 7th Asian Pacific Weed Science Society Conference, Sydney*, pp. 447–450.

Lemerle, D., B. Verbeek, and N. Coombes (1995). Losses in grain yield of winter crops from *Lolium rigidum* competition depends on crop species, cultivar and season. *Weed Research 35*, 503–509.

Lotz, L., S. Christensen, D. Cloutier, C. F. Quintanilla, A. Legere, C. Lemieux, P. Lutman, A. P. Iglesia, J. Salonen, M. Sattin, L. Stigliana, and F. Tei (1996). Prediction of the competitive effects of weeds on crop yields based on the relative leaf area of weeds. *Weed Research 36*, 93–101.

Lotz, L., M. Kropff, B. Bos, and J. Wallinga (1992). Prediction of yield loss based on relative leaf cover of weeds. In *IWCC Proceedings of the first International Weed Congress, Melbourne, Australia*, Volume 2, pp. 290–292.

Lotz, L., M. Kropff, J. Wallinga, H. Bos, and R. Groeneveld (1994). Techniques to estimate relative leaf area and cover of weeds in crops for yield loss prediction. *Weed Research 34*, 167–175.

Lutman, P., R. Risiott, and H. Ostermann (1996). Investigation into alternative methods to predict the competitive effects of weeds on crop yield. *Weed Science 44*, 290–297.

Marshall, E. (1988). Field scale estimates of grass weed populations in arable land. *Weed Research 28*, 191–198.

Martin, R., B. Cullis, and D. McNamara (1987). Prediction of wheat yield loss due to competition by wild oats (*Avena* spp.). *Australian Journal of Agricultural Research 38*, 487–499.

Martin, R., M. McMillan, and J. Cook (1988). Survey of farm management practices of the northern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture 28*, 499–509.

McCloy, K. (1983). *Characteristics of surface reflectance* (Advisory Note 26 ed.). New South Wales Department of Agriculture.

Medd, R., B. Auld, D. Kemp, and R. Murison (1985). The influence of wheat density on spatial arrangement in annual ryegrass, *Lolium rigidum* Gaudin, competition. *Australian Journal of Agricultural Research 36*, 361–371.

Milton, E. (1981). Does the use of two radiometers correct for irradiance changes during measurement. *Photogrammetric Engineering and Remote Sensing 47*, 1223–1225.

Mohammadi, G., A. Javanshir, F. Khooie, S. Mohammadi, and S. Zehtab (2005). Critical period of weed interference in chickpea. *Weed Research 45*, 57–63.

Monteith, J. (1973). *Principles of environmental physics* (First ed.). Edward Arnold.

Neter, J., W. Wasserman, and M. Kutner (1985). *Applied linear statistical models* (Second ed.). Irwin.

Northcote, K. (1971). *A factual key for the recognition of Australian soils* (2nd ed.). Divisional Report. Division of Soils, CSIRO: Australia.

Ramsel, E. and G. Wicks (1988). Use of winter wheat (*Triticum aestivum*) cultivars and herbicides in aiding weed control in eco-fallow corn (*Zea maysmays*) rotation. *Weed Science 36*, 394–398.

Ratkowsky, D. (1983). *Non linear regression modeling: a unified practical approach*, Volume 48 of *Statistics: textbooks and monographs*. New York: M. Dekker.

Ratkowsky, D. (1986). A suitable parameterization of the michaelis-menten enzyme reaction. *Journal of Biochemistry 240*, 357–360.

Ratkowsky, D. (1990). *Handbook of nonlinear regression models*, Volume 107 of *Statistics: textbooks and monographs*. New York: M. Dekker.

Reeves, T. (1976). Effect of annual ryegrass (*Lolium rigidum* Gaud.) on yield of wheat. *Weed Research 16*, 57–63.

Rew, L. and G. Cussans (1995). Patch ecology and dynamics - how much do we know? *Proceedings 1995 Brighton Crop Protection Conference - Weeds*, 1059–1068.

Riddler, A. (1989). Soil survey of Tamworth Agricultural Research Centre. Technical Report Soil Survey Bulletin 8 Agdex 524, NSW Agriculture and Fisheries.

Rouse, J., R. Haas, J. Schell, and D. Deering (1973). Monitoring vegetation systems in the great plains with erts. In *Third ERTS Symposium*, pp. 309–317. NASA SP-351 I.

Rouse, J., R. Haas, J. Schell, D. Deering, and J. Harlan (1974). Monitoring the vernal advancement and retrogradation (greenwave effect) of natural vegetation. Type III final report, NASA/GSFC.

Scotford, I. and P. Miller (2005). Applications of spectral reflectance techniques in northern European cereal production: a review. *Biosystems Engineering 90*(3), 235–250.

Serrano, L., I. Fiella, and J. Penuelas (2000). Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. *Crop Science 40*, 723–731.

Shinozaki, K. and T. Kira (1956). Intraspecific competition among higher plants, vii: Logistic theory of the C-D effect. *J. Inst. Polytech Series D7*, 35–72.

Smith, D. and G. Levick (1974). Effect of infestation by *Lolium rigidum* Gaud. (annual ryegrass) on yield of wheat. *Australian Journal of Agricultural Research 25*, 381–391.

Steven, M., P. Biscoe, and K. Jaggard (1983). Estimation of sugar beet productivity from reflection in the red and infra-red spectral bands. *International Journal of Remote Sensing 4*, 325–334.

Swain, P. H. and S. M. Davis (Eds.) (1978). *Remote Sensing - The Quantitative Approach* (First ed.). USA: McGraw-Hill International Book Company.

Tageeva, S. and A. Brandt (1961). *Optical properties of leaves*, Chapter Progress in photobiology. Amsterdam: B.C. Elsevier.

Tucker, C. (1977). Asymptotic nature of grass canopy spectral reflectance. *Applied Optics 16*(5), 1151–1156.

Tucker, C. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment 8*(2), 127–150.

Tucker, C. (1980). A critical review of remote sensing and other methods for non-destructive estimation of standing crop biomass. *Grass and Foliage Science 35*, 177–182.

Walker, S., R. Medd, R. Robinson, and B. Cullis (2002). Improved management of *Avena ludoviciana* and *Phalaris paradoxa* with more densely sown wheat and less herbicide. *Weed Research 42*(4), 257–270.

Whish, J. (1999). *The competitive interactions between weeds and chickpea (Cicer Arietinum L.): Towards the development of an integrated weed management system.* Ph. D. thesis, Agronomy and Soil Science School of Rural Science and Natural Resources, University of New England.

Whish, J., B. Sindel, and R. Jessop (1996). Current status of weed control in chickpea in northern New South Wales. In R. Shepherd (Ed.), *Eleventh Australian Weeds Conference Proceedings, Melbourne, Australia*, pp. 170–172. Weed Science Society of Victoria.

Whish, J., B. Sindel, R. Jessop, and W. Felton (2002). The effect of row spacing and weed density on yield loss of chickpea. *Australian Journal of Agricultural Research 53*(12), 1335–1340.

Zwiggelaar, R. (1998). A review of spectral properties of plants and their potential use for crop/weed discrimination in row-crops. *Crop Protection 47*(3), 189–206.

Chapter 8

Appendix

Table 8.1: Soil description of the research area at Tamworth in 2002. Survey point number 179, Riddler (1989).

Horizon	Depth	Description
A_p	0 cm	Very dark brown (10YR3/2) light clay. Moderately moist (2). Weak (1) crumbly consistence (pulverent 1, coalescent 4). (I SABL 2cm). Slightly vesicular. Trace of small, soft carbonate concretions. pH of 7.5
$B_{2\ 1}$	10 cm	Dark brown (10YR3/3) light to light-medium clay. Moderate moist (3). Moderate (2) labile consistence (pulverent 0, coalescent 5). (I SABL 4cm). Shiny cutans. Occasional slickensides. Occasional gravel. Trace of small, soft carbonate concretions. pH of 8.0
$B_{2\ 2}$	60 cm	Very dark brown (10YR3/2, 10YR3/3) light-medium clay. Moderately moist (2). Moderate (2) crumbly consistence (pulverent 1, coalescent 4). (I SABL 4cm). Thin shiny cutans. Occasional slickensides. Slight, small, soft carbonate concretions. pH of 8.0
B_3	100 cm	Brown, grey brown (10YR3/4, 10YR3/3) medium clay. Moderately moist (2). Weak (1) crumbly consistence (pulverent 1, coalescent 4). (I SABL 2cm). Thin cutans. No slickensides. Mottled dark brown and brown. Slight, small, soft carbonate concretions. pH of 8.0
$2B_{2\ 1}$	135 cm	Brown (7.5YR4/4) light medium clay. Moderately moist (1). Weak (1) crumbly consistence (pulverent 1, coalescent 4). (I SABL 2cm). Thin shiny cutans. Occasional slickensides. Occasional black mottles. Moderate effervescence in the fine earth. Moderate, soft carbonate concretions, increasing to heavy with depth. pH of 8.0
$2B_{2\ 2}$	175 cm	Brown (7.5YR4/4) light medium clay; similar to above, but with grey mottles. Heavy, soft carbonate concretions.
$2B_{2\ 2}$	195 cm	Similar to above. pH 9.0 Maximum, continuing.

Table 8.2: Soil description of the research area at Tamworth in 2003. Survey point number 210, Riddler (1989).

Horizon	Depth	Description
A_p	0 cm	Dark greyish brown (10YR4/2, dry; 7.5YR3/2 moist) light clay. Earthy fabric. pH of 8.0
A_1	7 cm	Very dark greyish brown (10YR3/2) light-medium clay. Weak pedal structure. pH of 8.5
B_1	31 cm	Dark brown (7.5YR3/2) light clay. Very weak pedal structure. pH 8.5
B_2	44 cm	Dark brown (10YR3/3) light-medium clay. Moderate pedal structure. Some small (2 mm) carbonate concretions. pH 8.5
B_3	87 cm	Dark reddish brown, yellowish red (5YR3/4, 5YR4/6) light-medium clay. Moderate pedal structure. Occasional (3 mm) carbonate concretions. pH 8.5
$2B_{2\ 1\ ?}$	134 cm	Brown, dark yellowish brown (7.5YR4/4, 10YR6/4) light-medium clay. Moderate pedal structure. pH 8.5
$2B_{2\ 2\ y}$	160 cm	Dark yellowish brown (10YR4/4, 10YR6/4) light clay. Moderate pedal structure. Occasional gypsum concretions (5 mm). Occasional (5 mm) carbonate concretions. Strong effervescence in the fine earth. pH 9.0
$2B_{2\ 2\ y}$	192 cm	Maximum, continuing.

Figure 8.1: Site plan of trial area in 2002. Letters refer to experiment (A) Mimic weeds (B) Chickpea variety (C) Crop growth. Crosses are the location of the soil moisture samples at sowing.

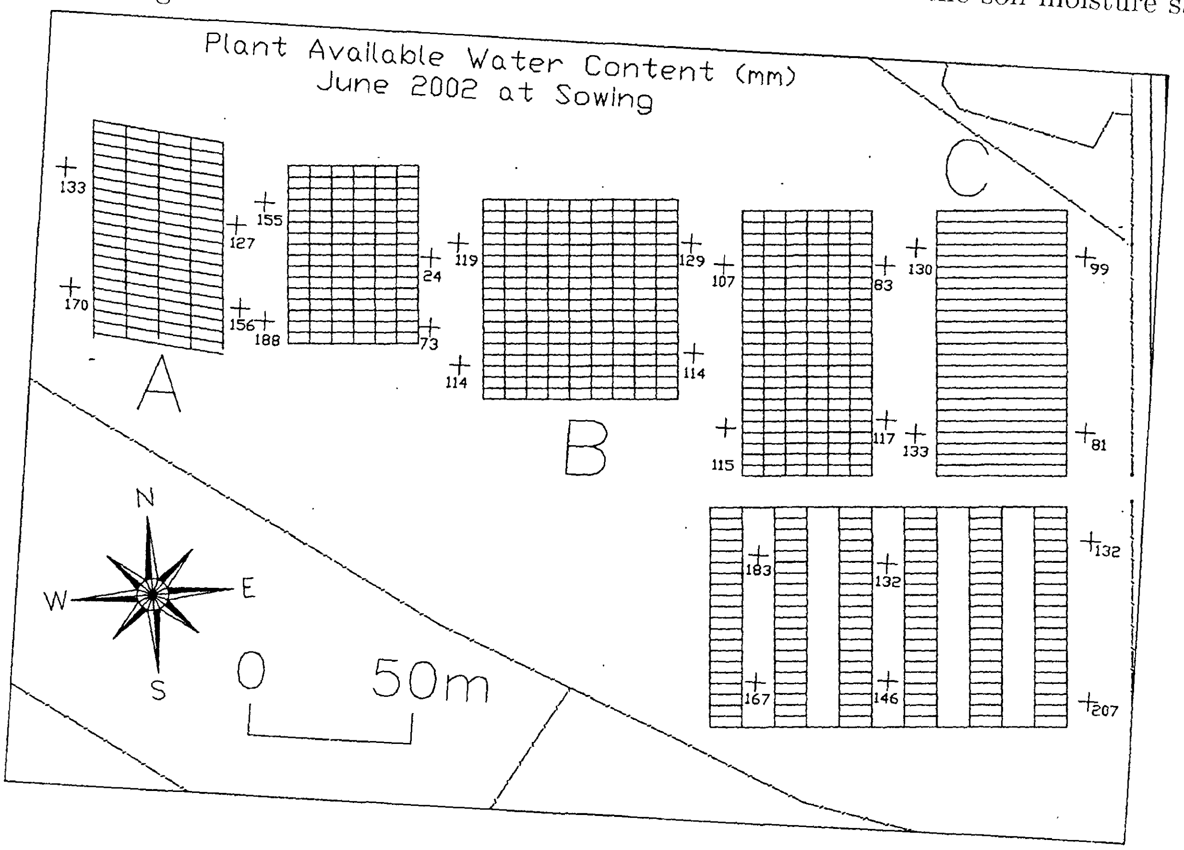


Figure 8.2: Site plan of trial area in 2003. Letters refer to experiment (A) Mimic weeds (B) Chickpea variety (C) Crop growth. Crosses are the location of the soil moisture samples at sowing.

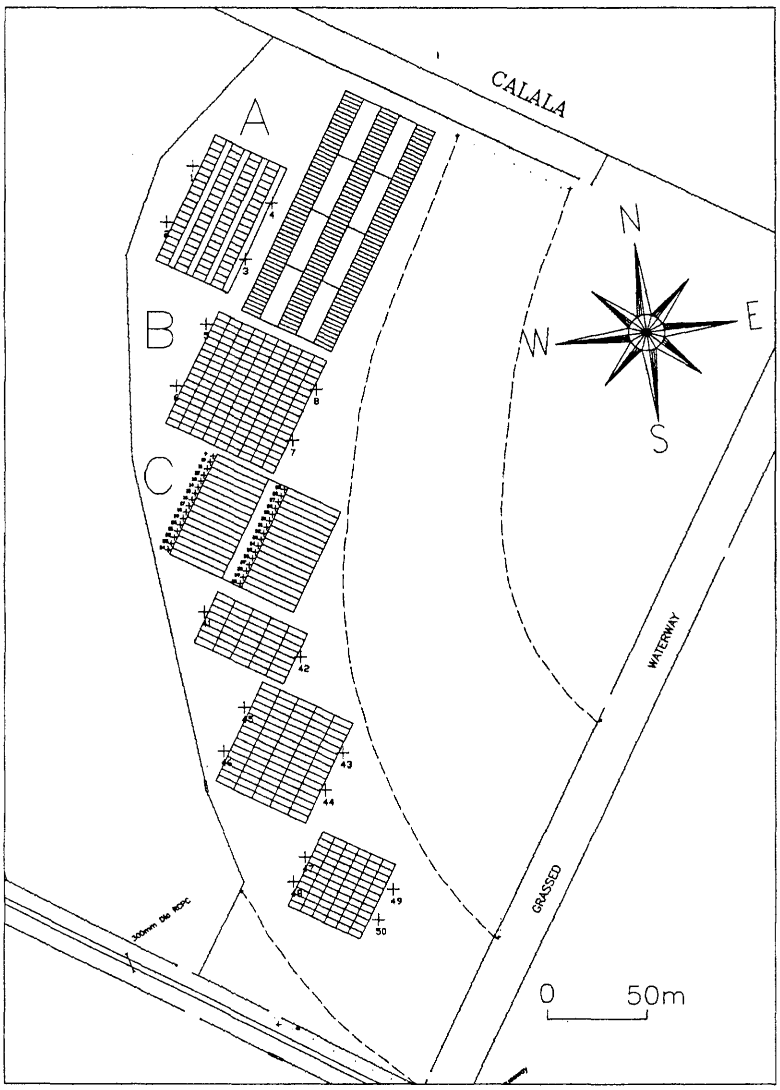


Figure 8.3: Schematic diagram of the WeedSeeker®sensor.

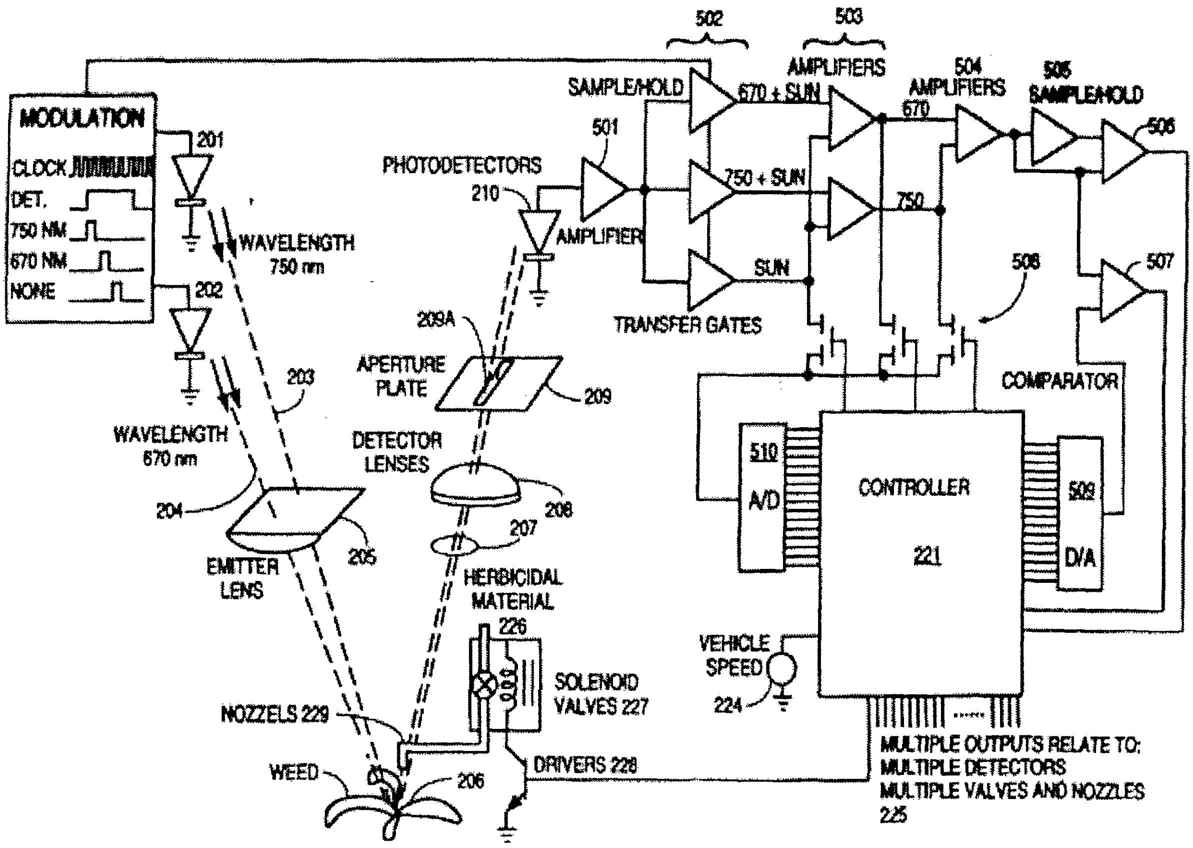


Figure 8.4: Example of a reflectance (CCA) data file collected from the calibration experiment on 31 July (59 days after sowing) and 11 September (101 days after sowing) in 2002.

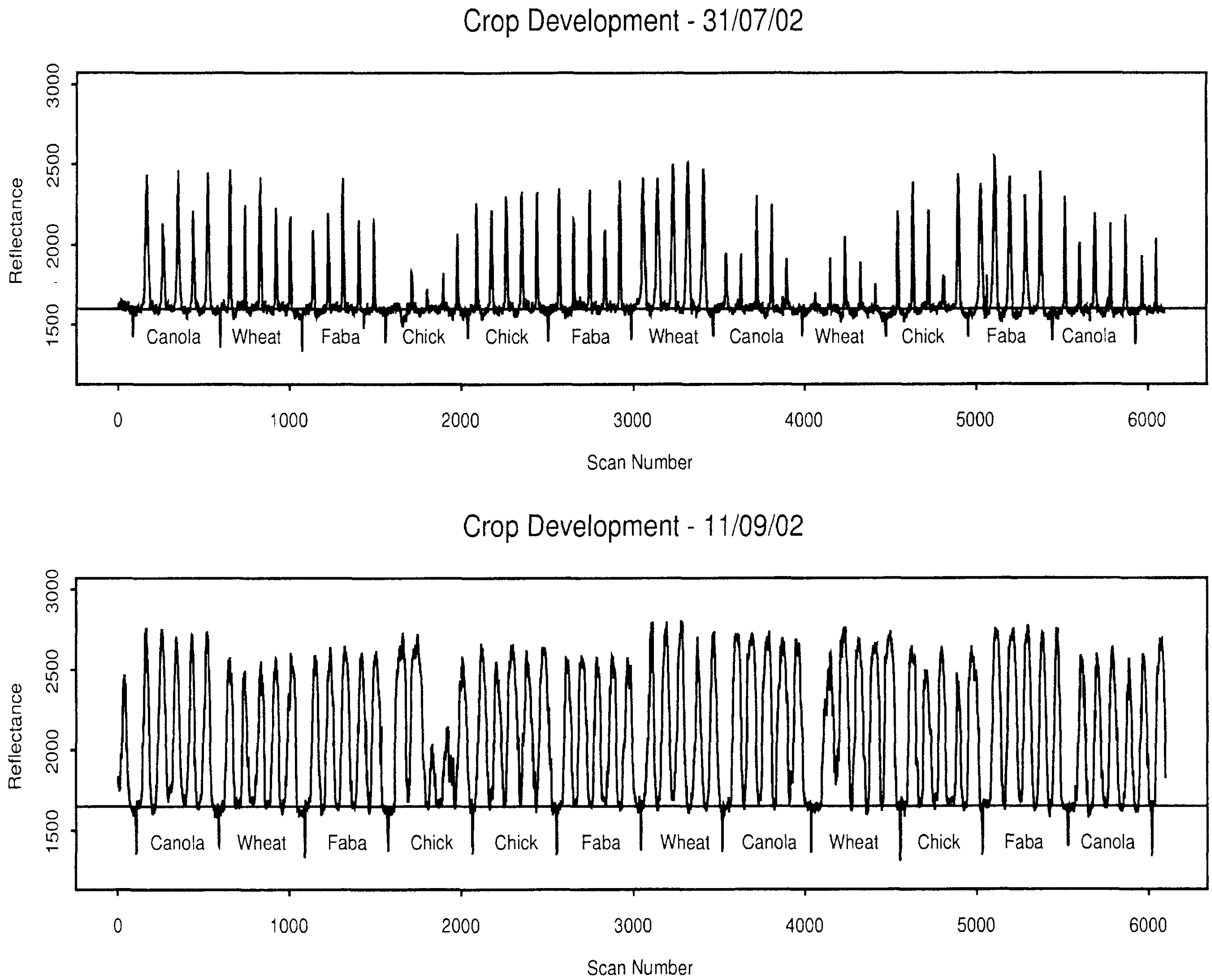


Table 8.3: Trade name, active ingredient and formulation for pesticides used in experiments

Trade name	Active ingredient	Concentration	Manufacturer
Herbicide			
Avadex BW	triallate	500 g L^{-1}	Monsanto
Fusilade	fluazifop-p	212 g L^{-1}	Syngenta Crop Protection
Roundup	glyphosate	360 g L^{-1}	Monsanto
Roundup CT	glyphosate	450 g L^{-1}	Nufarm
Roundup Xtra	glyphosate	490 g L^{-1}	Nufarm
Roundup PowerMax	glyphosate	540 g L^{-1}	Monsanto
Tristar	dichlofop+	250 g L^{-1}	Bayer CropScience
	fenoxaprop	13 g L^{-1}	
Verdict	haloxyfop	520 g L^{-1}	Dow Agroscience
Wildcat	fenoxapropyl-p-ethyl	110 g L^{-1}	Aventis CropScience
Fungicide			
Bravo	chlorothalonil	720 g kg^{-1}	Bayer
Dithane	mancozeb	750 g kg^{-1}	Dow Agrosciences
P. Pickle T	thiram+	360 g L^{-1}	Crop Care
	thirabendazole	200 g L^{-1}	Crop Care
Insecticide			
Larvin	thiocarb	800 g L^{-1}	Bayer CropScience

Figure 8.5: Reflectance traces and photos of plots at 89 days after sowing with chickpea (var. Howzat) and a mimic weed (triticale) at Tamworth.

Weed Density

Reflectance

0 weeds m^{-2}

3 weeds m^{-2}

9 weeds m^{-2}

27 weeds m^{-2}

81 weeds m^{-2}