CHAPTER ONE: INTRODUCTION

The experiments conducted for this thesis were mainly concerned with answering one question. Can canola be grown efficiently in low rainfall environments of Australia and in particular in central western New South Wales? To investigate this, experiments were conducted at Condobolin in central western New South Wales to determine the best sowing time and variety required to produce a successful canola crop under two varying water regimes.

Until recently canola has been grown successfully in higher rainfall regions, (> 450 mm of annual rainfall: McRae *et al.* 2003). As cropping extends further into lower rainfall environments, and in this case further west in New South Wales (average annual rainfall of 328mm during the experiment), alternative crops to wheat are required to ensure the success of the farming system by producing successful crop rotations. Canola can be grown in similar climatic regions to wheat (Buzza, 1979; 1991); however, it performs poorly when compared with wheat under extreme conditions, such as high temperatures (Buzza, 1991) and high water deficits (Buzza, 1979). These are the two major constraints facing canola production in low rainfall environments of Australia.

The importance of canola as an alternative crop in the cropping rotation arises from its ability to reduce the severity of cereal borne diseases (Kirkegaard *et al.* 1994; Kirkegaard *et al.* 1997). Therefore, with increases in cropping, and subsequent increased disease risk, canola is an ideal alternative crop to ensure the continued success of cereal cropping in central western New South Wales.

The work presented in this thesis compared eight canola varieties, sown over three different sowing times in 2002 and six canola varieties, sown over four different sowing times in 2003, under two water regimes (water deficit one and water deficit two). It aimed specifically at determining the most productive time of sowing and varieties for use within each sowing time, which, in the field for canola growers, would depend on when rainfall occurred to allow sowing to start. The results from this thesis provide clear indications on optimum sowing time and variety choice and how to manage crops when sowing time is unavoidably delayed in lower rainfall environments. However, they do not fully take into account the effects of adverse environmental condition such as frost on plant growth, yield and yield components because, during the two years of field experiments frost events were limited.

Detailed measurements of plant growth, water use, grain yield and yield components were recorded, accompanied by visual assessments of crop development. The cultivars used in the experiments were chosen for their suitability to the area in which the experiments were conducted (McRae *et al.* 2003). Measurements were conducted under predominantly field conditions, however the experiments conducted in 2002 and 2003 experienced well below average rainfall which led to the need for rainfall supplementation by sprinkler irrigation in both experiments to ensure the trials viability (water deficit one). This allowed for a comparison between different levels of water deficit in each year and effectively allowed the experiments to explore two different environmental conditions, with the application of sprinkler irrigation surplus to that required for crop viability creating an 'irrigation treatment' (water deficit two). The thesis represents one of the first detailed reports of canola growth, yield and yield components and water use in low rainfall environments of Australia under field conditions. It follows a systematic approach addressing plant growth (Chapter four), grain yield and yield components (Chapter five) and water use (Chapter six).

CHAPTER TWO: LITERATURE REVIEW

2.1 Brassicaceae

Brassicas in the world

Brassica napus, otherwise referred to as canola, is a member of the Brassicaceae or Cruciferous family. It is only one of many species of Brassicaceae but is the centre of discussion in this thesis. The *Brassicaceae* family is mostly comprised of temperate species. The primary form of the plant is a basal rosette of leaves from which stem elongation, flower buds and siliquas are produced. The flowers form with four sepals and four petals diagonally disposed and the siliqua has a characteristic midrib and pointed segment or 'beak'. At maturity, the siliqua separates into two sections and the seeds are released (Auld and Medd, 1992).

The origin of these species is debatable, however there is evidence to suggest Brassicas were found throughout Europe, Asia and Africa for several centuries (Downey and Robbelen, 1989). *Brassica napus* is thought to be an amphidiploid derived from the diploid species *B. oleracea, B. nigra and B. rapa* (Downey *et al.* 1975), although Downey and Robbelen (1989) argue that it has been derived from only *B. rapa* and *B. oleracea*, while Buzza (1979) suggests it occurs naturally and contains the genomes of *B. campestris* and *B. oleracea.*

Originally a source of lamp oil, *B. napus* has developed into a very important source of vegetable oil, in particular with the advent of canola with its low erucic acid and glucosinolate characteristics. The use of *B. napus* as a source of lamp oil was first thought to have occurred in Holland during the seventeenth century (Appleqvist, 1972), and is said to have been introduced into Asia early in the eighteenth century (Downey and Robbelen, 1989). Its use as an oil is reported to have been confined to areas where the olive tree and poppy were unknown (Appleqvist, 1972; Buzza, 1979).

Brassica napus production

Today *B. napus* is grown throughout Canada, Australia, China, India, Poland, Sweden and the European Union (Colton and Sykes, 1992). The production of *B. napus* has increased significantly in Australia since the introduction of the first Canadian varieties in 1969. Colton and Sykes (1992) report that canola production in Australia initially reached 87 000ha in 1971-1972, however, this peak was short lived due to an outbreak of *Leptosphaeria maculans* (blackleg). It was not until the early 1980s that production began to increase to the level it is currently, at approximately 1.6 to 2.4 million tonnes annually (Australian Oilseeds Federation, updated 24 Sept., 2003). The revival of the canola industry in Australia was created from crosses between Canadian varieties and European, Japanese and Chinese varieties all of which provided a wide genetic base leading to the different maturity types in canola varieties today (Mendham *et al.* 1984). Unlike other locations, for example Europe, the *B. napus* which is grown in Australia today contains less than 2% erucic acid and less than 30 micromoles per gram of glucosinolates and forms the Australian standard for canola.

2.2 Physiology of *Brassica napus*

The physiology of any plant species is very important when considering adaptations to particular environments. Manipulation of sowing time can sometimes be advantageous with respect to development and subsequent production, and this is further complicated by water availability. A lack of water at critical times during growth and development can lead to significant reductions in production with water stress being experienced at different stages during the growing season affecting root development and as such above ground plant growth and development in different ways. Therefore, the use of different sowing times, varieties, and the assessment of soil moisture and their effects during growth and development of the plant are vital in developing canola farming systems for low rainfall environments. However, predicting the interaction of these factors is complex because of the extent of their relatedness.

Canola has eight major developmental stages that can be affected by genotypic and phenotypic influences. The lifecycle of canola will be referred to as development in this document, and growth will refer to the increase in dry matter that occurs at each developmental stage and substages within these. For example, the initial developmental stage is emergence and its growth can be described as the expansion of the cotyledons and taproot (Daniels *et al.* 1986; Mendham and Salisbury, 1995). It must, however, be noted that each developmental stage may encompass several substages which can be defined. It is also important to understand that several stages in development may be occurring at the same time. For example, visually the plant may be involved in leaf production, while at the same time it will undergo initiation of the inflorescence and stem elongation.

Emergence: germination, expansion of cotyledons and growth of taproot

Once enough water has been absorbed for germination to begin, emergence is largely influenced by soil temperature. At germination the radicle splits the seed coat, and the hypocotyl pushing through the soil exposes the cotyledons. In the Australian environment, where autumn sowing is prevalent, soil moisture is just as important as soil temperature (Mendham and Salisbury, 1995) in ensuring adequate germination and is the first hurdle to overcome when sowing in low rainfall environments.

Kondra *et al.* (1983) have shown that canola will germinate in a range of temperatures achieving at least ninety percent germination from 2°C to 25°C, with the germination time varying from fourteen days to eleven days respectively. Emergence, as distinct from germination, was observed to take approximately nine days at an average temperature of 15°C (Leterme, 1988a cited in Mendham and Salisbury, 1995). In comparison, Daniels *et al.* (1986) reported that in the United Kingdom, under moist autumn seedbed conditions crop emergence took 4 – 5 days, and that in the spring emergence was delayed up to 10 – 15 days due to colder soil temperatures. Another factor which influences germination and emergence is the maturity of seed at harvest. Leterme (1988a, cited in Mendham and Salisbury, 1995) observed that seed which reached full maturity on the mother plant had a faster radicle emergence than immature seed, and that larger seeds which occurred on the mainstem or upper branches produced larger cotyledons and were more vigorous seedlings. This was also reported by Major (1977) and Mendham *et al.* (1981b) suggesting that the larger seed benefited later crop performance only when the plant size at flowering was limited due to late sowing; this illustrates that vigour early in crop growth would lessen the effect of later sowing, although Major (1977) noted that this had no effect on final plant population or yield.

Leaf production: initiation and appearance

Leaf production commences with the initiation of leaf initials from the apex (growing point). These have a helical arrangement with approximately 130° between each of the leaves (Mendham and Salisbury, 1995). The initiation of the leaf (plastochron) occurs faster than the actual appearance of the leaf (phyllochron), which leads to the accumulation of leaf primordia around the apex. Once initiated, leaf formation is continuous between germination and the onset of reproductive development when the apex begins to initiate the first flower buds of the terminal raceme (Daniels *et al.* 1986).

There are several environmental factors influencing the rate at which initiation, appearance and subsequent growth occurs. Daniels *et al.* (1986) reported that the number of leaves produced between germination and floral initiation was influenced by sowing date, variety and season. Temperature has a direct effect via the number of day-degrees and, therefore, how quickly the plant reaches the initiation and appearance phases in leaf production. Leterme (1988a, cited in Mendham and Salisbury, 1995), reported that, in the cultivar Jet Neuf, leaf initiation could take from twenty to sixty day-degrees, but this was also dependent on nitrogen supply and plant population. Morrison *et al.* (1989) determined the mean growing day-degrees required for leaf production in the cultivar Westar, at a baseline temperature of 5°C, to be two hundred and seventy five. Smith and Scarisbrick (1990) reported for the cultivar Bienvenu sown during autumn in the United Kingdom, the number of day-degrees (as defined by Gallagher (1979), with a base temperature of 0°C), varied across the three years of experiments for both leaf initiation and appearance. This indicates that, although temperature is important, other factors such as genotype, vernalisation requirement, photoperiod, sowing time and seasonal conditions also influence leaf production and subsequent crop development (Daniels *et al.* 1986; Smith and

Scarisbrick, 1990; Mendham and Salisbury, 1995). For example, a trial sown in 1983 on 24th August at Kent in the United Kingdom took forty-five day-degrees to reach leaf initiation, while in 1985 when the plants were sown on 4th September it only took twenty-nine day-degrees to reach leaf initiation (Smith and Scarisbrick, 1990).

Inflorescence initiation

Inflorescence initiation as described by Tittonel *et al.* (1982) and Smith and Scarisbrick (1990) is first identified by the swelling of the axil of one of the leaf primordia at the apex. The development of successive primordia continues from the axillary meristem, eventually becoming the flowers. Once the sympodial flower buds are formed, axillary buds from lower down begin to develop in a basipetal direction into primary branches. While these axillary buds continue to form lower down the plant, floral development continues with the sepals, and peduncles forming. Development of the stamens, petals and gynoecium are referred to as the green-bud stage (Sylvester-Bradley and Makepeace, 1984).

According to Mendham and Salisbury (1995), there are four main factors influencing inflorescence initiation. The first is a predetermined requirement for a minimum number of leaf initials before initiation can begin. This is a genotypically determined trait and can vary significantly (Thurling and Vijendra Das, 1977; Mendham *et al.* 1981a). The second factor is the requirement for a basic temperature response per leaf. For every leaf there are a required number of day-degrees that have to be achieved before floral initiation can occur. The third factor is vernalisation which is required to allow the plant to proceed from the vegetative to the reproductive phase and is thought to be governed by four genes in canola according to Thurling and Vijendra Das (1979a).

The final requirement is for a daylength response which can coincide with vernalisation and which also operates prior to initiation. However, it must be noted that all these factors have to be satisfied for inflorescence initiation to occur. If vernalisation or daylength responses have not been satisfied, then initiation and subsequent flowering would be delayed despite the minimum number of leaf initials being achieved. This leads to delayed flowering, and although detrimental in some cases, the lengthening of the vegetative phase may lead to larger plants, more siliquas and potentially higher yields (Mendham and Salisbury, 1995). However, it must be remembered that in low rainfall environments, lengthening of the vegetative phase may lead to reductions in potential grain yield with increased temperature and moisture stress being experienced during the reproductive phase as a result of a shortened post-anthesis duration (Si and Walton, 2004).

Stem elongation

Elongation of the stem occurs across several developmental stages. It is influenced primarily by daylength and, according to Mendham and Salisbury (1995), may influence final yield of the crop more so than the length of the pre-initiation phase. This has also been reported by Campbell and Kondra (1978) and Thurling and Vijendra Das (1974a) while Jenkins and Leitch (1986) noted that delayed sowing resulted in a significantly reduced overall stem length at maturity. Mendham and Scott (1975) also report there is good evidence that a critical size for a plant to have reached by initiation exists below which yield is diminished proportionately and above which no extra yield is produced because other factors become limiting. Thurling and Vijendra Das (1979b) showed that stem elongation in the cultivar Target could be manipulated by photoperiod and that an increase in seed yield resulted from an increase in the number of siliqua per plant which accompanied progressive extensions in the duration of stem elongation. Thurling and Kaveeta (1992a) also investigated factors affecting the stem elongation phase and determined that a long photoperiod significantly reduced the stem elongation phase. This may suggest that a lengthening of the stem elongation phase in crops grown in low rainfall environments could lead to more siliquas being produced and hence a higher grain yield being achieved, providing no other factors are limiting.

Flowering

Tayo and Morgan (1975), Mendham and Scott (1975) and McGregor (1981) have investigated the pattern of floral development of canola in pot and field situations. According to Tayo and Morgan (1975), the oldest most basal inflorescence yields the first flower after which flowering proceeds acropetally. It was noted that the terminal raceme was the first to flower followed by the axillary inflorescences from nodes one to five approximately three to eight days later. This provides some explanation as to the pattern and contribution of siliquas from particular branches to final yield. The time of flowering was longest on the terminal raceme (taking 26 days) and this declined with every axillary inflorescence to only fourteen days at node five. This allows the cessation of flowering to occur at the same time for all branches. The number of flowers that appeared per plant averaged 439, with the majority appearing on the terminal raceme and the least number of flowers being produced on the lowest axillary branch. This corresponds with the development of siliquas, which begins with the terminal raceme and progresses to the lowest branches suggesting that the terminal raceme and upper branch siliquas contribute significantly to grain yield. This being the case, it may be more advantageous to produce taller plants with fewer primary and secondary branches which, in a low rainfall environment, would allow the plant to achieve its yield potential rather than having a plant with lots of primary and secondary branches with siliquas it cannot fill due to water and nutrient deficits. This has been demonstrated in other indeterminate species such as chickpea where terminal drought led to decreased rates of flower production in both desi and kabuli chickpea (Davies *et al.* 1999).

Pollination, siliqua and seed development

Canola is largely self-pollinating (Downey 1966; Daniels *et al.* 1996) however wind and insect movement also aid pollination in the field. The most efficient method of pollination is through insects (Eisikowitch, 1981) although under field conditions William *et al.* (1987) proved that pollen transfer was improved by the wind mainly within or between flowers as a result of contact between floral parts. Climate also influences the success of pollination and subsequent seed set via several mechanisms. Firstly, bee activity is reduced if it is cold, dull or windy and this reduces the chance of the optimum number of ovules being fertilised. This can cause poor pollination, particularly in hybrid crops relying on insects for pollination. Frost can also cause significant grain yield loss through reducing seed set from the abortion of buds, flowers or siliquas (Mendham and Scott, 1975).

Hocking and Mason (1993) investigated the growth of siliquas and seeds under field conditions in Australia. Siliqua development was observed to commence much earlier than seed development. The development of the siliqua began as early as approximately 4 days after anthesis with rapid growth in length and then weight. Seed growth and development does not occur until 20 days after the commencement of siliqua growth. Siliquas were observed to be almost fully developed in length before the seed began to grow and gain weight. By the time the siliqua has reached its maximum length and weight, the seed had only achieved 35% of its final dry weight (Hocking and Mason, 1993). This has implications for the effects temperature and moisture stress place on siliqua development. Clearly, if there are temperature and water stresses occurring during siliqua development, then there must be significant subsequent effects on seed development after the siliqua has reached its maximum length and weight. Oil content develops in a similar way to seed dry weight and reaches its maximum percentage at approximately 60 days after anthesis, however the total oil content increases further with dry matter accumulation (Mendham and Salisbury, 1995).

The number of siliquas and the number of seeds per siliqua are both influenced by similar factors. Generally there are approximately nine axillary inflorescences in addition to the terminal inflorescence. Of these, only five of the upper most branches produce open flowers and siliquas (Tayo and Morgan, 1975). The remaining branches produce flower buds, however, these abort as development continues due to competition for assimilates and shading from the upper branches, flowers and siliquas. It is also possible for secondary inflorescences to develop from the axillary branches, however, very few of these produce flowers and no siliquas are retained (Mendham and Salisbury, 1995). However, Angadi *et al.* (2003) did note in an experiment in Canada that at very low populations there was a contribution from secondary branching of fertile siliqua.

The major determinant of the likelihood of the siliqua developing and producing seed is the position of the siliqua on the plant. Tayo and Morgan (1975) recorded flowering and siliqua production, determining that successful development of siliquas decreased from 68% on the sympodium to 22% on the fifth branch. Of the siliquas which did reach maturity and contribute to yield, it was estimated that seventy five percent were formed from flowers which opened up to 14 days after the initiation of anthesis. This suggests that the critical time period for siliqua development contributing to yield is the two to three week period after anthesis.

Environmental factors also influence the success of siliqua and seed development. Leterme (1988b, as cited by Mendham and Salisbury, 1995) illustrated that the amount of solar radiation intercepted by the plant per flower could be an indication of the likelihood of the siliqua developing and contributing to yield. Nutrient and water stress will also influence the success of siliqua and seed development. Mendham *et al.* (1981a) investigated the relationship between sowing time, and flower, siliqua and seed production in the field and found that most of the losses which occur do so during the 3-4 week period after full flower and are a result of assimilate and nutrient demands not being met by the plant. Seed production in this same experiment was compared between early and late sowings. The major loss of seed occurred during the same 3-4 week period when the siliqua was growing at its maximum rate and the seed had not begun a rapid increase in dry matter. There were also significant losses noted in the earlier sowing times where the lower canopy was shaded. The later sowing did not show the changes throughout the canopy probably because of less competition between siliquas. This would suggest that moisture and temperature stress during this period would impact significantly on final yield, so that if this is prevented through early sowing or varietal choice potential grain yield could be satisfied. Therefore, although early sowing leads to losses from canopy shading, the advantages of reduced temperature and moisture stress would be critical when determining the optimum time of sowing in low rainfall environments.

2.3 Canola in low rainfall environments of Australia

Low rainfall environments of eastern Australia

Until recently, the production of canola has been restricted to the higher rainfall regions of Australia. It has been successfully grown as an alternative crop to cereals and in particular as a break crop for disease management (Kirkegaard *et al.* 1994; Kirkegaard *et al.* 1997). With the shift to more intensive cropping, the use of canola and its rotational benefits have only recently been recognised by growers in the lower rainfall regions. Little research has been conducted into the production of canola in the low rainfall regions of the eastern wheat belt due to its limited use as a rotational crop in these areas. However, production is increasing as farmers seek alternative enterprises to complement their livestock operations, particularly with the reduction in wool prices in the last 10 years. The lack of canola production in the Condobolin region arises from the low and unpredictable rainfall (Hocking *et al.* 1997), leading to unacceptably low grain yields and oil concentrations. This low yield and poor oil concentrations may be improved with correct sowing time, variety and moisture management; should enable the success of canola in these low rainfall areas and this is the focus of this thesis.

Low rainfall environment at Condobolin

Condobolin represents a typical low rainfall environment in south-eastern Australia. Condobolin (33° 03' 59'' S, 147° 13' 42'' E) is situated in the central west of New South Wales and has an average annual rainfall of 400 – 450 mm. This precipitation falls during all months of the year with approximately 30 mm expected to fall each month. It is the winter rainfall (approximately 200 mm between April and October) which allows cropping to be conducted in this area. Winter cropping is currently dominated by wheat production but as growers change to more intensive cropping systems, canola is becoming increasingly important in the crop rotation. In an average year, approximately 150 mm of rainfall could be expected to fall between December and April. G. Brooke (2002, pers. comm.) states that this is vital for the production of canola as stored moisture in the soil prior to sowing is one of the important factors considered by canola growers prior to sowing and suggests that without 80 cm depth of wet soil prior to sowing, the production of canola may be limited and will certainly be limited if below average rainfall (<200 mm) is predicted or received during the growing season. Therefore, the correct sowing time, variety and soil moisture are vital in producing successful canola crops in this low rainfall region of central western New South Wales. If improvements in these can be achieved, then farm productivity may be increased through better cropping rotations being developed as canola becomes a viable option. Condobolin is also indicative of many regions in south-eastern Australia which receive similar rainfall and produce canola; the Riverina region of southern New South Wales and the higher rainfall regions of the Mallee are examples of other regions which fit into this category.

2.4 Canola sowing times

The correct time of sowing of canola in low rainfall environments is vital to ensure maximum production is achieved. Sowing time impacts on yield and quality (oil and protein concentration and 1000-grain weight) of canola in a range of environments (Scott *et al.* 1973; Hodgson, 1979b; Mendham *et al.* 1981a; Scarisbrick *et al.* 1981; Jenkins and Leitch 1986; Mendham *et al.* 1990; Taylor and Smith 1992; Hocking, 1993; Johnson *et al.* 1995; Robertson *et al.* 1999; Kirkland and Johnson 2000; Hocking and Stapper 2001a; Hopkinson *et al.* 2002; Robertson *et al.* 2004); however, it is particularly important in low rainfall environments where plant growth may be limited by soil moisture and temperature (Richards, 1978; Richards and Thurling 1978a; Richards and Thurling 1978b; Hodgson, 1979a; Mailer and Cornish, 1987; Lewis and Thurling, 1994; Wright *et al.* 1995; Wright *et al.* 1996; Robertson *et al.* 1999a; Angadi *et al.* 2000; Aksouh *et al.* 2001; Hocking and Stapper 2001; Farre *et al.* 2002; Morrison and Stewart, 2002; Niknam *et al.* 2003; Anderson *et al.* 2003; Si and Walton, 2004; Robertson and Holland, 2004). The correct sowing time is essential in low rainfall environments because it determines how growth and development occur throughout the growing season, ultimately impacting on yield and quality of the grain. If the correct sowing time is identified, and grain yield and quality are acceptable, then the production of canola in these low rainfall environments can be successful and provide an efficient alternative to cereal crops.

Sowing time effects on grain yield, yield components, plant growth and water use

The choice of sowing time impacts significantly on the ability of canola to produce its potential grain yield, oil and protein concentration, and 1000-grain weight through maximising plant growth and water use. The earlier the sowing time from the current mid-late April recommendation (McRae *et al.* 2003), the higher the chance of these four parameters reaching their potential in canola grown in lower rainfall environments (MacKinnon and Fettell, 2003 (Appendix 2.1); MacKinnon *et al.* 2004 (Appendix 2.2), as has been demonstrated in other environments (Richards and Thurling, 1978b; Hodgson, 1979b; Mendham, 1981; Scarisbrick *et al.* 1981). The main factor leading to increased grain yield and yield components with early sowing is the maximisation of overall plant growth. With maximised plant growth there is an increase in the vegetative and reproductive phases of growth leading to improved grain quality and yields (Hocking, 2001; Hocking and Stapper, 2001).

The initial increase in plant growth and subsequent root development comes early in the vegetative phase and continues providing larger, leafier plants with more branching. As stem elongation occurs leaf size then declines allowing increased light penetration into the canopy maximising the area of photosynthetically active tissue being exposed to solar radiation, namely the leaf and stem (Daniels *et al.* 1986). These plant parts are then capable of acting as a storage site for carbohydrates providing assimilates during the reproductive phase making them better able to cope with adverse environmental conditions such as lack of moisture, high temperatures and high assimilate demand. The increase in plant growth is not only in relation to dry matter production and leaf area; early sowing times tend to produce taller plants, with more branching and a higher number of heavier main raceme and upper primary branch siliquas. These siliquas also function as temporary storage organs for nutrients such as nitrogen and phosphorus which are then re-distributed to the developing seeds all of which lead to increased grain yields

(Hocking and Mason, 1993). Redistribution of carbon and nitrogen and its subsequent contribution to final grain yield in other indeterminate crop species has also been reported by Davies *et al.* (2000) in chickpea. However, this increase in plant growth would not be achieved without significant increases in root development. Increases in root development with early sowing has been reported by Kirkegaard *et al.* (1997) at Condobolin with canola root reaching depths of 1.8m in contrast to experiments conducted by Gregory (1998) in Western Australia where canola root reached depths of 60 cm – 80 cm.

Vegetative growth in general is increased through the production of a higher leaf area, which leads to increased dry matter production. For maximum growth to occur, Walton *et al.* (1999) stated that a leaf area index of 4.0 is required to intercept 90% of solar radiation. If this is not achieved due, for example, to later sowing times restricting vegetative growth, then there is less chance that the potential yield or yield components may be achieved. The reduced leaf area as a result of later sowing could be caused by several factors, including the production of fewer leaves so total leaf area is reduced because less leaves are available to capture light (Jenkins and Leitch, 1986). Reduced leaf area as a result of later sowing has also been reported by Hocking and Stapper (2001) in experiments conducted in the low rainfall environment of Ariah Park in New South Wales. This would suggest that similar results could be expected in the Condobolin environment. Reduced leaf area may also occur due to reductions in the number of leaves but the leaves are also smaller in size and hence leaf area is reduced even further (Robertson *et al.* 2002b). The loss in leaf number has implications not only for reducing total leaf area but also in determining the number of siliquas. Mendham *et al.* (1981a) suggests that the number of siliquas is closely related to the number of primary leaves which determines the number of primary branches. This also suggests that the later sowing times, producing less leaves and hence less branches, would result in lower yields as the reduced number of siliquas and branches would impact on the potential grain yield which could be achieved (Scarisbrick *et al.* 1981). This may also be associated with plant height, as taller plants have the ability to produce more main raceme siliquas and higher dry weights than shorter plants which have less siliqua on the main raceme (Pechan and Morgan, 1985.) This is because the siliqua are not only closer to the stem which acts as a storage source for assimilates to be re-distributed, but the main raceme siliqua are initiated first and as assimilates are not distributed evenly between developing siliqua (Major and Charnetski, 1976) they act as stronger sinks drawing assimilates away from developing siliqua on the branches (Keiller, 1982). Mendham *et al.* (1981a) demonstrated that plant size at floral initiation may be directly correlated with the number of axillary inflorescences, flowers and ultimately siliquas produced by the crop. This was also reported by Campbell and Kondra (1978), where the numbers of siliquas on the main raceme were major contributors to yield and they suggested that increased leaf area resulted in increased dry matter production and plant height, which impacted significantly on grain yield and subsequent quality.

The leaf area of the plant has a direct influence on dry matter production because with a lower leaf area there is a reduction in the plant's capacity to photosynthesise. Wright *et al.* (1988) suggested that dry matter was strongly related to the amount of incident light intercepted, which was a direct function of the crop's leaf area. Therefore, if there is less leaf area, as could be expected in the later sown crops, then there would be a reduction in dry matter production. As dry matter production determines the ability of the plant to provide assimilates during the reproductive phase and when leaves have senesced, leaf area is the most important factor in increasing dry matter production and ultimately grain yield and quality. However, there may be a need to balance the size of the plant with its ability to provide assimilates. In low rainfall environments it may be more advantageous to have a plant which will have a lower yield potential but a greater ability to reach that potential during grain filling than a large plant which cannot do so, leading to severely reduced grain yield and quality. Clearly, a balance between maximised vegetative growth and the plant's ability to reach its yield potential needs to be achieved so that a large crop is not grown which then fails to fill grain.

Reductions in grain yield and dry matter associated with late sowing have been reported by Hocking *et al.* (1997) at Condobolin and this reinforces the need for early sowing so that dry matter production may be maximised. If late sowing is practised, it could be assumed that the loss in yield and yield components would be substantial and I would suggest that sowing as late as mid-June in a low rainfall environment such as Condobolin could lead to substantial losses. Losses in grain yield have been reported by other researchers, with Hocking and Stapper (2001) reporting losses of up to 58% when sowing was delayed from April until June at Ariah Park.

The losses reported from late sowing, and the advantages of early sowing, also impinge on harvest index. Taylor and Smith (1992) reported a low harvest index with early sowing times and suggested it may have been due to excessive stem growth. Mendham *et al.* (1981a) also reported reductions in harvest index with early sowing, with these plants producing 20% or less of dry matter as usable product. This makes early-sown crops less efficient because, although well grown and producing many siliquas, the siliquas produced few seeds. Conversely, the low harvest indices may occur because the plant is generally inefficient and becomes more so when production is being maximised or environmental variations occur independent of the final dry matter production (Thurling, 1974a). However, Hocking and Stapper (2001) reported reduced harvest index with later sowing at Ariah Park.

Late sowing has the potential to severely impede the reproductive growth of canola, reducing the production of branches, flowers, siliquas and seeds per siliqua which ultimately determine grain yield (Hodgson, 1979b; Scarisbrick *et al.* 1981). Earlier sowing allows reproductive development to occur when temperature and moisture stress are less allowing maximum grain quantity and quality to be achieved (Aksouh *et al.* 2001). This coupled with improved vegetative growth allows for an improved supply of assimilates from flowering onwards when the grain yield and oil concentration of the plant is set (Mendham *et al.* 1981a).

The increased demand for assimilates by the plant also corresponds with the time when leaf area begins to decrease, with the senescence, towards the end of the growing season, of leaves shaded by flowers and then siliquas (Cheema *et al.* 2001; Mendham *et al.* 1981a). This further increases the pressure on the plant's ability to transfer assimilates. If the supply of assimilates is limited, the ability of the plant to support reproductive development is limited. Potential yields are not able to be met, and reductions in siliqua dry weight and seed dry weight are expected to occur

(Tayo and Morgan, 1979). This is not just limited to growth during siliqua and seed development. According to Morgan (1982), siliqua production is affected not only by assimilate supply but by the number of inflorescences, the rate of production and duration of flowering, and the proportion of flower forming siliquas which are retained until maturity. This reinforces the need to maximise both vegetative and reproductive growth. There is no point in sowing too early if the potential for yield is restricted by the plant's ability to provide assimilates to a large number of siliquas, just as there is no point in sowing too late when the siliqua number is satisfactory but the plant cannot provide the assimilates required to support these siliquas. If there are losses due to lack of assimilates, then the sowing time would need to be manipulated to provide a balance between maximum yield potential and optimum production.

Losses may also occur in dense plants as a result of shading similar to that which occurs in the leaves once flowering and siliqua production starts. It may be that reductions in siliqua number and siliqua dry weight occur because siliquas on upper branches shade those on lower branches (Morgan 1982). However, Mendham *et al.* (1981a) reports a different situation where the later sown crops outperformed the earlier sown crops in siliqua dry weight. The later sown crops were able to grow well before the onset of flowering and so support a higher number of seeds per siliqua in the reduced number of siliquas which occurred because of the later flowering time. This suggests that it may be possible to reach an optimum sowing time where siliqua numbers are not at a maximum but grain yield is, because the supply of assimilates is not restrictive.

Early sowing achieves these increases in vegetative and reproductive production by increasing plant development when environmental stresses such as temperature and moisture do not restrict growth (Johnson *et al.* 1995). This is particularly important in low rainfall environments, as temperature and moisture stress from flowering onwards can severely impede development leading to reduced yields and grain quality. If the reproductive phase can be reached prior to high temperature stress, more soil moisture may be available to allow continued growth and, with more vegetative growth being achieved from the earlier sowing, the yield potential of the plant may be reached. Hocking and Stapper (2001) suggested that increased temperature and moisture stress during grain filling was a major cause of reduced oil concentration due to late sowing. They reported an inverse relationship between oil concentration and mean daily temperature during siliqua development, with a decrease of 1.7 percentage points per 1°C increase in mean temperature. If this can be proven through the experiments reported in this thesis, it would be possible to predict the loss in oil concentration as a consequence of sowing on a particular date, providing an additional management tool when deciding on sowing time options, particularly if the sowing time is bordering on being too late (Chapter five). Walton and Trent (1997) also report a reduction in oil concentration with increased moisture and temperature stress during flowering. This would suggest that early sowing would allow reproductive development to occur when temperatures were cooler, reducing the likelihood of reductions in oil concentrations (Hodgson, 1979b).

Accompanying this loss in oil concentration and subsequent increases in protein concentration from late sowing is a reduction in 1000-grain weight as a consequence of temperature and water stress during grain filling (Hocking and Stapper, 2001; Morrison and Stewart, 2002). Not only is there reduced oil concentration associated with later sowing, there is also a reduction in 1000-grain weight which ultimately impacts on grain yield, both of which are closely influenced by the ability of the plants to supply assimilates (Cheema *et al.* 2001). This is also influenced by reduced dry matter production. However, when determining how much earlier to sow than the current recommended sowing time (McRae *et al.* 2003), other environmental factors need to be considered. Although lack of moisture and temperature stress during reproduction and the plant's ability to supply assimilates is important, the chance of a frost occurring and reducing grain yield and quality must also be considered in low rainfall environments as it is also an important factor that canola growers consider (Bernardi and Banks, 1991).

There is also some evidence in European environments that earlier sowing may not lead to increases in grain yield and quality in canola, with Jenkins and Leitch (1986) and Mendham *et al.* (1981a) recording increases in seed yield with delay in sowing in Britain. This was associated with growth patterns which favoured increases in dry matter production during the spring allowing leaf area to be increased prior to flowering. This pattern of growth would not be expected to occur in low rainfall environments in Australia, as reproductive growth is associated with heightening temperatures and increased photoperiod (Mendham *et al.* 1990; Hocking, 2001; Hocking and Stapper, 2001). An increase in vegetative growth, particularly leaf area during flower and siliqua production, would be inhibited due to shading from flowers and siliquas and competition between leaves, flowers and siliquas for assimilates (Mendham *et al.* 1990).

With a loss in oil concentration due to increasing temperatures during reproductive growth comes an increase in protein concentration. This does provide an alternative use for canola as an animal feed; however, in Australia canola is grown for its grain yield and oil concentration and its use as an animal feed is limited. There is an inverse relationship between oil and protein concentration where a loss in protein concentration with early sowing times results in higher oil concentration (Hodgson, 1979b; Brennan *et al.* 2000). However, the increased protein is generally also associated with reduced yields as the later sowing times produce lower yields. Marketing canola in a poor season for animal feed, due to increased protein levels, would probably not suffice, as the yields would also be reduced, so it would be important to assess the price penalties incurred with lower oil concentration against marketing the canola for animal feed.

2.5 Canola varieties

The different maturity types of canola, all of which have particular advantages, vary mainly in differences in time to flowering. As discussed earlier in this chapter, flowering is influenced mainly by photoperiod and temperature, and early maturing varieties are at an advantage as they reduce the risk of flowering occurring when temperatures are hotter and water stress may occur. However, if sowing time can be manipulated, later maturing varieties may also be grown because flowering will occur when temperatures and water stress are minimal. This will allow for the comparison of early, mid and late maturing varieties under conditions which do not limit their growth with regards to temperature and moisture, and provide a wider range of varieties from which to choose when sowing canola. However, although early sowing may be advantageous for the later maturing varieties, the risk of frost damage in the early maturing varieties is increased. As sowing time is delayed, the risk of flowering and siliqua development during hotter temperatures for all varieties is increased but it is in this situation that the early maturing varieties will be at an advantage. Optimising these factors is complex with many management issues requiring consideration.

Variety effects on grain yield, yield components, plant growth and water use

As would be expected, different varieties have recorded differences in grain yield, yield components, plant growth (Thurling, 1974b) and water use (Hodgson, 1979a; Gregory, 1998). There is little research evidence to suggest why varieties perform in different ways. It may be that the flowering time associated with the early, mid and late maturing varieties grown in Australia currently provide the differences in the above components and that this is strongly influenced by sowing time. If it is assumed that sowing is conducted on the same day across all varieties, the early maturing varieties are going to complete their vegetative and reproductive phases faster than the later maturing varieties, illustrating that although their growth patterns are similar, their response to the environment differs. This suggests that differences in variety are associated with the genetically controlled response of the plant to the environment and not fundamental to the plant's make-up, excluding the classifications of early, mid and late maturity which are associated with flowering. This corresponds with Johnson *et al.* (1995) who stated there was little difference in physiological maturity and duration of development. They concluded that differences in grain yield resulted from the later maturing varieties benefiting from the earlier sowing times. This occurs as they are not restricted in their vegetative growth by temperature and moisture stress inducing faster reproductive growth than would normally occur when they are sown later.

As discussed above, leaf area and dry matter production have a major influence on grain yield and quality achieved at the end of the growing season. The development pattern of leaf area is similar across all varieties with an increase to a maximum just prior to flowering and then a decline as leaves senesce as flowering and siliqua production progress (Jenkins and Leitch, 1986). However, the actual values achieved differ between varieties, as reported by Jenkins and Leitch (1986) and Lewis and Thurling (1994), and this has implications for the potential ability of the plant to photosynthesise and produce dry matter. These effects may be due to the different ways in which individual varieties react to the environment or as a result of different genotypes. Robertson *et al.* (2002b) reported differences in leaf area between triazine tolerant and non-triazine tolerant varieties; differences were due to the non-triazine tolerant varieties having bigger leaves. This may be the case in the varietal differences reported by others although there is no evidence of this. Once there are differences in leaf area across varieties, there will be differences in all other aspects of plant growth as leaf area determines dry matter production which provides assimilates and therefore determines the number of flowers, siliquas, and seeds per siliqua and ultimately grain yield and quality.

Generally, the differences in dry matter production are small but become more pronounced as time progresses (Mendham *et al.* 1981a; Mendham *et al.* 1981b). This may result from a combination of different environmental stresses causing varieties to develop differently. It may also be differences in flowering which result in the larger varietal differences observed as time progresses, with later maturing varieties having the ability to grow for longer and hence having increased yields. Lewis and Thurling (1994) reported the importance of the time of elongation, because an erect habit, or taller plant, was very efficient in capturing radiation and therefore had increased flowering and numbers of siliquas. This could mean that varieties having a shorter time for stem elongation do not have the ability to maximise grain yield and quality. Morgan (1982) reported that higher yielding varieties developed fewer lower position axillaries and carried a higher proportion of their yield on the terminal and upper axillaries. This also has implications for differences in plant height. If a particular variety is taller, it may have the ability to produce more siliquas on the main raceme which, due to their proximity to the stem which re-distributes assimilates during the reproductive phase, increases grain yield. However, if there are limited assimilates available to the higher number of siliquas, this may not be the case and a loss in yield and quality may occur.

The number of branches as a result of plant height may also have an effect on grain yield and quality because of shading of siliquas on lower branches. Therefore the variation in branching reported by Scarisbrick *et al.* (1981) could significantly influence the development of the siliqua including its dry weight, seed oil and protein concentration and 1000-grain weight.

Differences in dry matter production and grain yield lead to the development of different harvest indices for the canola varieties, with Zaheer *et al.* (2000) reporting differences in harvest indices between canola genotypes in Western Australia. Niknam *et al.* (2003) suggested that the different harvest indices arise due to some genotypes being better osmotic adjusters (Kumar *et al.* 1984; Kumar *et al.* 1987; Wright *et al.* 1996). This would suggest that the genotypes better at osmotic adjustment are able to adapt to changing environments and can produce better harvest indices (Niknam *et al.* 2003). Osmotic adjustment would be an important area to consider for the selection of canola varieties to be grown in low rainfall environments. This has implications for the time of flowering of varieties because, if some are flowering in hotter, drier conditions, those better osmotic adjusters will be at an advantage and will not incur such severe losses in production. The main advantage in osmotic adjustment is through the ability of plants to continue growing, exploring deeper soils in an effort to continue providing moisture during the reproductive phase. Those which do not have the ability to adjust osmotically and continue growing, risk water stress during reproductive growth and subsequent reductions in grain yield and quality. If varieties with the ability to osmotically adjust can be grown in low rainfall environments, the potential of canola in low rainfall environments would be increased. Little information was available on selection or screening of canola varieties for osmotic adjustment. Kumar and Singh (1998) conducted work on screening *Brassica* species for drought tolerance assessing osmotic adjustment and concluded that there were relationships between grain yield and osmotic adjustment. However, further work was required to identify and manipulate the genes controlling such traits in plant breeding programmes. This is certainly an area which may be investigated further to increase the likelihood of producing efficient varieties for low rainfall environments.

Once flowering has commenced, the development of siliquas is influenced by environmental factors, particularly temperature and moisture. Morrison and Stewart (2002) and Aksouh *et al.* (2001) reported reductions in grain yield when temperature stress occurred from stem elongation until the end of flowering, with short episodes of high temperatures having a more deleterious effect on yield formation than progressive temperature stress. This would suggest that varieties which are better osmotic adjusters may be able to continue growing in these situations. The number and development of siliquas is primarily determined by the flowering conditions and is an area where differences in the development of varieties lead to the subsequent differences in varietal grain yield and quality. If there are environmental stresses during flowering which affect certain varieties more than others, from this stage onwards grain yield and quality begins to differ between varieties.

Oil concentration in canola varieties is under considerable genetic control (Si *et al.* 2003) and is less likely to be influenced by sowing time than grain yield. Little has been reported on the affects of maturity type on oil concentration, although Johnson *et al.* (1995) recorded a lower oil concentration for the earliest maturing varieties compared with later maturing varieties. This may be due to faster growth not allowing early maturing varieties to reach their potential. Alternatively, it may simply be related to genotypic differences due to the inverse relationship between oil and protein concentration. Si *et al.* (2003) reported that in a study in Southern Australia location high verses low rainfall environments had a larger effect on oil and protein concentration than genotype but that within each environment genotypes tended to maintain a consistent ranking for oil and protein concentration. This would therefore suggest that in low rainfall environments, for example, high oil and protein concentrations would depend on the adaptation of the genotypes to low rainfall environments with respect to their phenology and yield and not just their genotypic characteristics.

As with the other quality parameters, 1000-grain weight could be expected to be greater in those varieties where grain-fill occurs under less moisture and temperature stress which would allow a better supply of assimilates to the seed (Tayo and Morgan, 1979). This would also suggest that 1000-grain weight would be influenced by the interaction between sowing time and variety. The early maturing varieties sown later record higher 1000-grain weights than the later maturing varieties because they would have been grain filling under less temperature and moisture stress (Jenkins and Leitch, 1986). It could therefore be assumed that 1000-grain weight is more likely to be influenced by the variety by environment interaction than variety alone, and that all varieties have the ability to achieve similar 1000-grain weights, with the exception of hybrid varieties as previously discussed.

2.6 Canola and supplementary water

The application of supplementary water, water deficit treatment two in this thesis, leads to increases in all facets of plant growth, grain yield, oil and protein concentration and 1000-grain weight. This is through a reduction in water stress during crop growth allowing plants to maximise their growth potential (Clarke and Simpson, 1978; Mailer and Cornish, 1987; Taylor *et al.* 1991; Andersen *et al.* 1996; Poma *et al.* 1999; Aksouh *et al.* 2001; Morrison and Stewart, 2002; Andagi *et al.* 2003). The increases in vegetative growth occur through a higher leaf area and hence more dry matter being produced, as well as a lengthening of the vegetative phase. This allows for better supply of assimilates during reproductive growth. The increase in reproductive growth involves more flowers, siliquas and seeds being produced under less temperature and water stress, leading to higher grain yield and improved grain quality (Clarke and Simpson, 1978; Taylor *et al.* 1991; Aksouh *et al.* 2001; Morrison and Stewart, 2002; Andagi *et al.* 2003).

Supplementary water effects on grain yield, yield components, plant growth and water use

There is limited evidence on supplementation of rainfall in canola; however the irrigation of canola and effects of drought on canola are well documented. The increase in grain yield and yield components from the application of additional water have been reported by Wright *et al.* (1988), Taylor *et al.* (1991) and Gemmelvind *et al.* (1996). The increases are due to a combination of reduced water stress during critical growth phases which lead to increased siliqua production, and an increase in the depth from which water is extracted by the roots with supplemented treatments extracting water to a greater depth allowing them better access to moisture increasing crop growth (Taylor *et al.* 1991). The application of supplementary water during flowering leads to increases in the number of siliquas produced, whereas the application of supplementary water during grain filling has more of an effect on oil and protein concentration and 1000-grain weight (Mailer and Cornish, 1987). The losses in siliquas, which reduce grain yield, are due to siliqua abortion as a result of water stress suffered before and after flowering. If there is water stress before flowering, not only would siliqua development be reduced but also dry matter production, as a consequence of reduced leaf area and root growth, leading to less assimilates being available for the plant to use reducing the plant's ability to supply assimilates during the reproductive phase.

However, it may not be the timing of the stress that is important but rather that a stress had occurred at all. Nielsen (1997) reported that water stress timing did not affect seed yield, but that losses in yield were attributed to fewer branches and siliquas being produced per plant and the siliquas which were produced having smaller seeds. This does suggest that supplementary water would in some way overcome the stresses of moisture to provide a higher grain yield, but the timing of applications would not be as critical. However, Richards and Thurling (1978a) reported that drought applied at any time during reproductive development would reduce grain yield, and that drought from stem elongation or flowering onwards would cause the greatest yield reduction. This suggests that strategic water applications at critical growth stages may reduce the impact of moisture stress on plant growth and subsequent grain yield. Richards and Thurling (1978a) also report that a high yielding genotype would be one with a large plant height and large number of siliquas and branches. This would correspond with the increased yields of early sown crops, so the application of supplementary water and the combination of early sowing time could increase grain yield, yield components and plant growth substantially. This would be even more pronounced when combined with the appropriate variety for that particular sowing time.

The increases in grain yield would come through increased dry matter production allowing for higher yields to be achieved as a consequence of supplementary water or irrigation. Supplementary water allows the development of higher leaf area and more efficient supply of assimilates, and reduced assimilate competition with the retention of leaves on the stem for longer before senescence (Scott *et al.* 1973). However, for the increase in dry matter to be achieved, the supplementary water would have to be applied at a time when dry matter production could be improved. This would be during vegetative growth rather than reproductive growth and would allow increased root growth so that soil moisture could be accessed from deeper within the profile. If it was applied later there may be increases in siliqua number but there may not be enough assimilates to supply the siliquas. The application of water at a later stage in crop growth may lead to increases in oil concentration or 1000-grain weight but not actual siliqua numbers or the plant's ability to carry those siliquas to full maturity and contribute to grain yield.

The improved oil concentration and 1000-grain weight which could be achieved by supplementary water would be through the ability of the plant to better supply assimilates (Clarke and Simpson, 1978). This corresponds with Mailer and Cornish's (1987) comments who stated that stressed plants had low oil concentrations but that the timing of the stress was not significant. So if the stress could be reduced, oil concentrations may increase. However, Andersen *et al.* (1996) suggested that the reduction in oil concentration depended more on the severity of the stress than the time the stress (drought) occurred. This suggests that oil concentration could be affected by a lack of moisture during vegetative growth, which would reduce the plant's ability to supply assimilates during the production of oil later in crop growth. The increases in oil concentration with supplementary water would lead to reductions in protein concentration due to the inverse relationship between the two (Brennan *et al.* 2000). Jensen *et al.* (1996) reported that plants subject to drought or moisture stress during vegetative growth and early flowering had increased protein concentration. This corresponds with the report by Andersen *et al.* (1996) suggesting that even stresses as early as the vegetative phase can reduce oil concentration and as a consequence increase protein concentration.

Reductions in 1000-grain weight which have been reported are also attributed to increases in water stress during post-anthesis growth and in particular during flowering and seed ripening due to a reduction in assimilate supply (Mailer and Cornish, 1987; Taylor *et al.* 1991; Andersen *et al.* 1996; Poma *et al.* 1999; Morrison and Stewart, 2002; Andagi *et al.* 2003). However, reports by Bernardi and Banks (1991) and Andersen *et al.* (1996) do suggest that under severe drought or water stress there is a mechanism whereby seed weight is increased to compensate for the loss in siliqua production, although this does not provide a significant increase in grain yield.

Siliqua dry weight and siliqua number are increased when supplementary water is applied. This occurs through an increase in the number of flowers leading to more siliquas being produced initially, but also, once the siliquas begin to develop, an increase in available water increases the plant's capacity to provide assimilates so more siliquas are produced and maintained. Reductions in siliqua dry weight have been recorded previously at Condobolin, with reductions of up to 39% in siliqua dry weight recorded between stressed and irrigated plants (Bernardi and Banks, 1991). This may be a combination of siliqua loss due to lack of moisture and reduced dry matter production causing less assimilates to be available, which is complicated by the plant having less capacity to provide assimilates because of the lack of moisture.

Reductions in siliqua number arise from lack of moisture from flowering onwards (Andersen *et al.* 1996) causing reductions in the overall number of flowers produced (Tayo and Morgan, 1975). The reduced siliqua numbers have also been correlated to reductions in dry matter production (Wright *et al.* 1995), which corresponds with the number of leaves determining the siliqua number, as reported by Mendham *et al.* (1981a). Other factors affecting siliqua number are branch number and plant height where there may be plants with a higher number of branches carrying more siliquas, and taller plants carrying more siliquas on the main raceme. These branches are closer to the carbon source so the application of supplementary water would continue the growth of these siliquas and provide the plant with the capacity to supply carbon to other siliquas positioned further from the carbon source. Bernardi and Banks (1991) reported taller plants with increased branching with irrigated crops at Condobolin when compared with dryland crops. The increase in the length of the flowering phase led to increases in grain yield and quality (Clarke and Simpson, 1978). Clearly, the application of supplementary water increases all facets of plant growth, both above and below ground, producing higher grain yield and quality, by reducing water stress during critical stages in growth.

2.8 Conclusion

The information concerning canola production in low rainfall environments, and particularly in Australia, is limited. Several areas require consideration and are applicable to low rainfall environments. Selection of canola varieties through screening for osmotic adjustment is an important factor in increasing the efficiency of canola in low rainfall environments and increasing its production in Australia. The effects of drought have been reported, although little agronomic information is provided on how to reduce the severe water stress in practical terms. Sowing time has been extensively reported, however, not in conjunction with the effects of drought. This was considered to be the first important step in increasing canola production in low rainfall environments and will be reported in this thesis. As a result of the research, two field experiments were conducted at Condobolin in NSW, Australia to determine if sowing time could reduce the effects of water stress in low rainfall environments.

The factors underlying optimisation of sowing time and variety choice for canola production in low rainfall environments are complex but depend on known physiological processes. This thesis focuses on this optimisation using physiological approaches to explain some of the complexities and provide production advice to canola growers in low rainfall environments.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

The experiments reported in this thesis had three aims. Firstly, to determine the importance of sowing time, variety and soil moisture on plant growth of canola in low rainfall environments of central western N.S.W. Secondly, to determine the importance of sowing time, variety and soil moisture on grain yield and yield components of canola in low rainfall environments of central western N.S.W., and thirdly, to determine the importance of sowing time, variety and soil moisture on water use of canola in low rainfall environments of central western N.S.W. Two field experiments addressing these aims were conducted, assessing plant growth, grain yield and yield components and water use, at Condobolin in south-eastern Australia.

3.2 Site and climate

Two field experiments were conducted, one in 2002 and the other in 2003, in the south-eastern wheat belt of Australia at Condobolin (33° 03' 59'' S, 147° 13' 42'' E) in New South Wales. The site is situated in the western part of the New South Wales wheat belt and is classified as low rainfall, with an average annual rainfall of approximately 450 mm. Meteorological data were recorded within 2 km of the sites at the meteorological station at Condobolin Agricultural Research and Advisory Station. Long term mean monthly rainfall, actual monthly rainfall, water deficit one moisture applications and water deficit two moisture applications for 2002 and 2003 are presented in Table 3.1. Minimum, maximum and mean monthly temperatures and evaporation for 2002 and 2003 are presented in Figure 3.1. The soils are classified as Sodosols according to Isbell (1996). The experimental site in 2002 had a pH_{Ca} 5.6, nitrate nitrogen 25.4 mg/kg, sulfate sulfur (MCP) 12.0 mg/kg, phosphorus (Colwell) 10.0 mg/kg and was classified as a clay loam (Appendix 3.1). The experimental site in 2003 had a pH_{Ca} 5.0, nitrate nitrogen 36.2 mg/kg, sulfate sulfur (MCP) 12.0 mg/kg, phosphorus (Colwell) 20.0 mg/kg and was classified as a clay loam (Appendix 3.2).

Table 3.1 Monthly actual and long term mean monthly rainfall, water deficit one moisture applications and water deficit two moisture applications for 2002 and 2003 at Condobolin Agricultural Research and Advisory Station.

	2002			2003			
Month	Actual rainfall	Water deficit one	Water deficit two	Actual rainfall	Water deficit one	Water deficit two	Long term Mean
Jan	0.8			26.2			50.9
Feb	172.1			63			41.8
Mar	19.4			25.7	29	29	39.6
Apr	11	18	18	11.2	18	18	33.4
May	22.1	18	18	7.4	20	20	38.6
Jun	4.4			18.5			26.3
Jul	8	14	14	60.9		30	37.6
Aug	6.6		22	71.7			35.9
Sep	45.1			9.8		30	32.2
Oct	0			19.2			52.5
Nov	2.8			16.8			37.1
Dec	14.2			18.3			40.3
Total	**306.5**	**50**	**72**	**348.7**	**67**	**127**	**466.2**

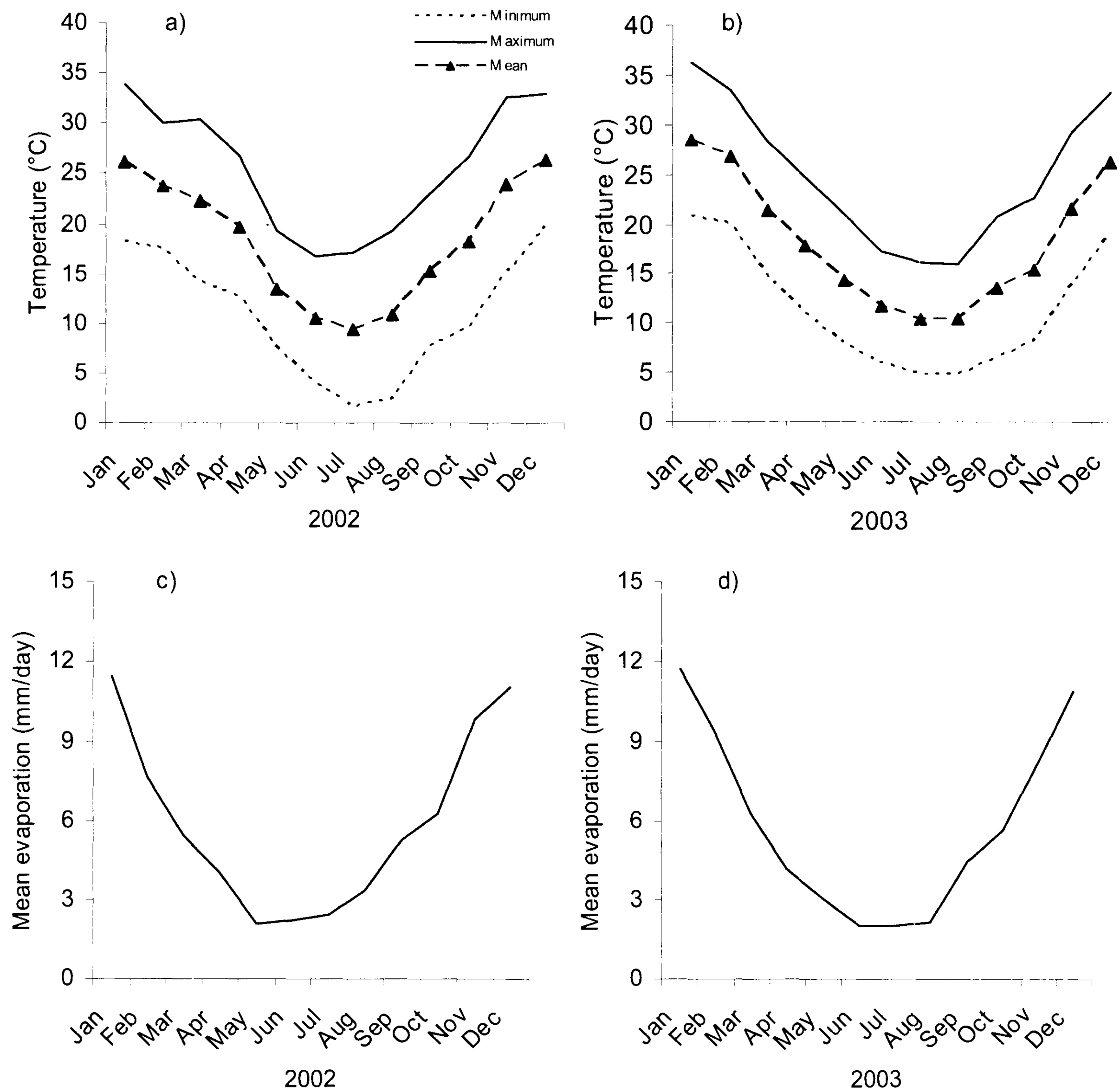

Figure 3.1 Mean monthly maximum, minimum and average temperatures (°C) for 2002 (a) and 2003 (b) and mean monthly evaporation (mm/day) for 2002 (c) and 2003 (d), at Condobolin Agricultural Research and Advisory Station.

3.3 Experimental design and analysis

In 2002 the experiment was based on a 36 row by four column array (Table 3.2). There were three replicates of the factorial treatment design comprising two water treatments (water deficit one and water deficit two), three sowing times (April 22 (T1), May 17 (T2), and June 14 (T3)), and eight canola varieties. The eight canola (*Brassica napus*) varieties used were Ag-Outback, Ag-Emblem, Rivette, Hyola 60, Rainbow, Ripper, Oscar and Dunkeld. Each canola variety was sown at 3.6kg/ha with the exception of Hyola 60, which is 37% heavier and, therefore, an adjustment for this was made and the seed sown at 4.6 kg/ha so that the same plant density could be achieved. These varieties were chosen to provide a range of maturity types and based on current recommendations provided by New South Wales Agriculture for canola varieties which can be grown in NSW (McRae *et al.* 2003). The early maturing canola varieties were Ag-Outback, Rivette and Ag-Emblem and they were chosen for their suitability to the low rainfall regions of eastern Australia. The mid-maturing canola varieties were Hyola 60, Oscar, Rainbow and Ripper and they were chosen for their suitability to the current sowing time recommendations, allowing the plant sufficient time to reach maturity before the sharp increase in temperature and evaporation which occurs in late September/early October (Figure 3.1). The late maturing variety was Dunkeld and this was chosen to illustrate the ability of long season varieties to yield successfully when sown early, allowing for sufficient time to reach maturity prior to the high temperatures and evaporative demands of October conditions.

Water deficit two was applied to the centre two columns of the experiment, although the water treatments were not truly randomised, inferences about the main effects of water could validly be made using the linear mixed model methodology outlines below.

The data were analysed using linear mixed model methodology in ASReml (Gilmour *et al.* 2002), using a randomisation approach. The data for the yield, yield components, water efficiency and plant growth data; main raceme siliqua dry weight, main raceme siliqua number, branch siliqua dry weight, branch siliqua number, branch number and harvest index were based on a single measurement and therefore the base model (Model 1 see appendix 3.3) used in the analysis included fixed terms for water deficit, variety and sowing time and all their interactions. Random terms included in the model reflected the design of the experiment, these were: block, block.column, replicate, replicate.sow_time_row, replicate.sow_time_row.row.block, block.column.replicate.sow_time_row, and block.column.replicate.sow_time_row.row.

The plant growth data was measured up to eight times throughout the growing season. To account for the repeated measurements a longitudinal data analysis was undertaken, using linear mixed model methodology in ASReml (Gilmour *et al.* 2002). The model used in the analysis of the plant growth data (leaf area, dry matter production, siliqua dry weight, siliqua number, plant height) (Model 2 see appendix 3.4) included fixed terms for water deficit, variety, sowing time and a linear trend for sample time and all their interactions. The random terms included the same terms as in Model 1 with the additional terms for curvature of sample time and the lack of fit term for sample time with all the appropriate interactions.

The water use data was measured over time and across soil depths and therefore a longitudinal analysis was required for this data. The model used to analyse the data (Model 3 see appendix 3.5), in ASReml (Gilmour *et al.* 2002), included fixed terms for water deficit, variety, sowing time, sample time and depth and all their interactions. The random terms were the same as those used in Model 1.

All models (Models 1 – 3) fitted an auto-regressive residual correlation structure (of order 1) to test for spatial trends in the field. A significance level of 5% is used throughout the thesis for all inferences about significant effects, standard errors, standard error of differences and least significant differences. The data presented are the predicted values with the exception of the correlations presented in Chapters four, five, six, seven and eight which are based on the raw data and are simple phenotypic (Spearman rank) correlations (r).

Table 3.2 Experimental design in 2002.

Plot	*Buffer*	*Buffer*	*Buffer*	*Buffer*	Rep
1	Ripper_T1	Ripper_T1	Oscar_T1	Oscar_T1	1
2	Outback_T1	Outback_T1	Dunkeld_T1	Dunkeld_T1	1
3	Emblem_T1	Emblem_T1	Rainbow_T1	Rainbow_T1	1
4	Hyola60_T1	Hyola60_T1	Rivette_T1	Rivette_T1	1
	Buffer	*Buffer*	*Buffer*	*Buffer*	
5	Outback_T3	Outback_T3	Ripper_T3	Ripper_T3	1
6	Rivette_T3	Rivette_T3	Rainbow_T3	Rainbow_T3	1
7	Hyola60_T3	Hyola60_T3	Oscar_T3	Oscar_T3	1
8	Dunkeld_T3	Dunkeld_T3	Emblem_T3	Emblem_T3	1
	Buffer	*Buffer*	*Buffer*	*Buffer*	
9	Hyola60_T2	Hyola60_T2	Rainbow_T2	Rainbow_T2	1
10	Rivette_T2	Rivette_T2	Dunkeld_T2	Dunkeld_T2	1
11	Ripper_T2	Ripper_T2	Oscar_T2	Oscar_T2	1
12	Emblem_T2	Emblem_T2	Outback_T2	Outback_T2	1
13	Outback_T2	Outback_T2	Rivette_T2	Rivette_T2	2
14	Oscar_T2	Oscar_T2	Ripper_T2	Ripper_T2	2
15	Rainbow_T2	Rainbow_T2	Hyola60_T2	Hyola60_T2	2
16	Dunkeld_T2	Dunkeld_T2	Emblem_T2	Emblem_T2	2
	Buffer	*Buffer*	*Buffer*	*Buffer*	
17	Emblem_T3	Emblem_T3	Outback_T3	Outback_T3	2
18	Ripper_T3	Ripper_T3	Hyola60_T3	Hyola60_T3	2
19	Dunkeld_T3	Dunkeld_T3	Oscar_T3	Oscar_T3	2
20	Rainbow_T3	Rainbow_T3	Rivette_T3	Rivette_T3	2
	Buffer	*Buffer*	*Buffer*	*Buffer*	
21	Oscar_T1	Oscar_T1	Ripper_T1	Ripper_T1	2
22	Outback_T1	Outback_T1	Rainbow_T1	Rainbow_T1	2
23	Rivette_T1	Rivette_T1	Hyola60_T1	Hyola60_T1	2
24	Emblem_T1	Emblem_T1	Dunkeld_T1	Dunkeld_T1	2
25	Hyola60_T1	Hyola60_T1	Rivette_T1	Rivette_T1	3
26	Ripper_T1	Ripper_T1	Oscar_T1	Oscar_T1	3
27	Dunkeld_T1	Dunkeld_T1	Outback_T1	Outback_T1	3
28	Rainbow_T1	Rainbow_T1	Emblem_T1	Emblem_T1	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	
29	Oscar_T3	Oscar_T3	Emblem_T3	Emblem_T3	3
30	Outback_T3	Outback_T3	Ripper_T3	Ripper_T3	3
31	Rivette_T3	Rivette_T3	Rainbow_T3	Rainbow_T3	3
32	Hyola60_T3	Hyola60_T3	Dunkeld_T3	Dunkeld_T3	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	
33	Hyola60_T2	Hyola60_T2	Ripper_T2	Ripper_T2	3
34	Outback_T2	Outback_T2	Rainbow_T2	Rainbow_T2	3
35	Rivette_T2	Rivette_T2	Oscar_T2	Oscar_T2	3
36	Dunkeld_T2	Dunkeld_T2	Emblem_T2	Emblem_T2	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	

* _T is the sowing time number which corresponds with a sowing date

In 2003 the experiment was based on a 48 row by four column array as presented in Table 3.3. There were three replicates of the three factor factorial treatment design comprising two water treatments (water deficit one and water deficit two), four sowing times (April 2 (T1), April 22 (T2), May 13 (T3) and June 6 (T4)), and six canola varieties. The water treatment was applied to the centre two columns of the experiment as in 2002. There were six canola varieties used in the experiment: Ag-Outback, Hyola 60, Rainbow, Ripper, Oscar and Dunkeld. There were also two Indian Mustard varieties used in this experiment which are not referred to in this thesis. Each canola variety was sown at 3.6kg/ha, with the exception of the variety Hyola 60 which was sown at 4.6kg/ha, as in 2002.

The data were analysed using linear mixed model methodology in ASReml (Gilmour *et al.* 2002), using a randomisation approach. The data for the yield, yield components, water efficiency and plant growth data; main raceme siliqua dry weight, main raceme siliqua number, branch siliqua dry weight, branch siliqua number, branch number and harvest index were based on a single measurement, therefore, the base model (Model 4 see appendix 3.6) used in the analysis included fixed terms for water deficit, variety and sowing time and all their interactions. Random terms included in the model reflected the design of the experiment and these were; block, block.column, replicate, replicate.sow_time_row, replicate.sow_time_row.row.block, block.column.replicate.sow_time_row and block.column.replicate.sow_time_row.row. Plant density was also fitted as a covariate, as a fixed term, along with its interactions with the other fixed terms.

The plant growth data was measured up to nine times throughout the growing season. To account for the repeated measurements a longitudinal data analysis was undertaken, using linear mixed model methodology in ASReml (Gilmour *et al.* 2002). The model used in the analysis of the plant growth data (leaf area, dry matter production, siliqua dry weight, siliqua number, plant height) (Model 2 see appendix 3.4) included fixed terms for water deficit, variety, sowing time and a linear trend for sample time and all their interactions. The random terms included the same terms as in Model 1 (appendix 3.3) with the additional terms for curvature of sample time and the lack of fit term for sample time with all the appropriate interactions.

The water use data was measured over time and across soil depths, and therefore a longitudinal analysis was required for this data. The model used to analyse the data (Model 5 see appendix 3.7), in ASReml (Gilmour *et al.* 2002), included fixed terms for water deficit, variety, sowing time, a linear trend for sample time and a linear trend for depth and all their interactions. The random terms were the same as those used in Model 2, but also included additional terms for curvature of depth and the lack of fit term for depth with all the appropriate interactions. All models for the 2003 data (Models 2, 4 and 5) fitted an auto-regressive residual correlation structure (of order 1) to test for spatial trends in the field. A significance level of 5% was used throughout this thesis for all inferences about significant effects, standard errors, standard error of differences and least significant differences. The data presented are the predicted values with the exception of the correlations presented in Chapters four, five, six, seven and eight are based on the raw data and are simple phenotypic (Spearman rank) correlations (*r*).

Table 3.3 Experimental design in 2003.

Plot	*Buffer*	*Buffer*	*Buffer*	*Buffer*	Rep
1	M887_T2	M887_T2	Hyola60_T2	Hyola60_T2	1
2	Dunkeld_T2	Dunkeld_T2	Oscar_T2	Oscar_T2	1
3	Rainbow_T2	Rainbow_T2	Ripper_T2	Ripper_T2	1
4	Outback_T2	Outback_T2	JN28_T2	JN28_T2	1
	Buffer	*Buffer*	*Buffer*	*Buffer*	
5	JN28_T1	JN28_T1	Oscar_T1	Oscar_T1	1
6	Hyola60_T1	Hyola60_T1	Outback_T1	Outback_T1	1
7	Ripper_T1	Ripper_T1	M887_T1	M887_T1	1
8	Dunkeld_T1	Dunkeld_T1	Rainbow_T1	Rainbow_T1	1
	Buffer	*Buffer*	*Buffer*	*Buffer*	
9	M887_T4	M887_T4	Ripper_T4	Ripper_T4	1
10	Oscar_T4	Oscar_T4	Hyola60_T4	Hyola60_T4	1
11	Outback_T4	Outback_T4	Dunkeld_T4	Dunkeld_T4	1
12	JN28_T4	JN28_T4	Rainbow_T4	Rainbow_T4	1
	Buffer	*Buffer*	*Buffer*	*Buffer*	
13	Rainbow_T3	Rainbow_T3	JN28_T3	JN28_T3	1
14	Outback_T3	Outback_T3	M887_T3	M887_T3	1
15	Oscar_T3	Oscar_T3	Ripper_T3	Ripper_T3	1
16	Dunkeld_T3	Dunkeld_T3	Hyola60_T3	Hyola60_T3	1
17	M887_T3	M887_T3	Hyola60_T3	Hyola60_T3	2
18	Ripper_T3	Ripper_T3	Dunkeld_T3	Dunkeld_T3	2
19	Outback_T3	Outback_T3	Oscar_T3	Oscar_T3	2
20	Rainbow_T3	Rainbow_T3	JN28_T3	JN28_T3	2
	Buffer	*Buffer*	*Buffer*	*Buffer*	
21	M887_T1	M887_T1	Dunkeld_T1	Dunkeld_T1	2
22	Oscar7_T1	Oscar_T1	Ripper_T1	Ripper_T1	2
23	Outback_T1	Outback_T1	JN28_T1	JN28_T1	2
24	Hyola60_T1	Hyola60_T1	Rainbow_T1	Rainbow_T1	2
	Buffer	*Buffer*	*Buffer*	*Buffer*	
25	Dunkeld_T2	Dunkeld_T2	Outback_T2	Outback_T2	2
26	M887_T2	M887_T2	Oscar_T2	Oscar_T2	2
27	Rainbow_T2	Rainbow_T2	Ripper_T2	Ripper_T2	2
28	Hyola60_T2	Hyola60_T2	JN28_T2	JN28_T2	2
	Buffer	*Buffer*	*Buffer*	*Buffer*	
29	JN28_T4	JN28_T4	Oscar_T4	Oscar_T4	2
30	M887_T4	M887_T4	Rainbow_T4	Rainbow_T4	2
31	Outback_T4	Outback_T4	Hyola60_T4	Hyola60_T4	2
32	Dunkeld_T4	Dunkeld_T4	Ripper_T4	Ripper_T4	2
33	Ripper_T4	Ripper_T4	Oscar_T4	Oscar_T4	3
34	Rainbow_T4	Rainbow_T4	M887_T4	M887_T4	3
35	JN28_T4	JN28_T4	Outback_T4	Outback_T4	3
36	Dunkeld_T4	Dunkeld_T4	Hyola60_T4	Hyola60_T4	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	
37	Ripper_T3	Ripper_T3	M887_T3	M887_T3	3
38	Hyola60_T3	Hyola60_T3	Dunkeld_T3	Dunkeld_T3	3
39	Oscar_T3	Oscar_T3	Outback_T3	Outback_T3	3
40	Rainbow_T3	Rainbow_T3	JN28_T3	JN28_T3	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	
41	Oscar_T2	Oscar_T2	Outback_T2	Outback_T2	3
42	JN28_T2	JN28_T2	M887_T2	M887_T2	3
43	Hyola60_T2	Hyola60_T2	Rainbow_T2	Rainbow_T2	3
44	Ripper_T2	Ripper_T2	Dunkeld_T2	Dunkeld_T2	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	
45	Hyola60_T1	Hyola60_T1	M887_T1	M887_T1	3
46	Ripper_T1	Ripper_T1	Outback_T1	Outback_T1	3
47	JN28_T1	JN28_T1	Rainbow_T1	Rainbow_T1	3
48	Oscar_T1	Oscar_T1	Dunkeld_T1	Dunkeld_T1	3
	Buffer	*Buffer*	*Buffer*	*Buffer*	

* _T is the sowing time number which corresponds with a sowing date

3.4 Measurements 2002

In 2002 the three sowing dates were April 22 (sowing time one), May 17 (sowing time two) and June 14 (sowing time three). These were chosen as they represented the spread of sowing dates commonly used for growing canola in the region and they also correspond with current recommendations for south-eastern Australia (McRae *et al.* 2003). Plots (each 19.6 m in length with a row spacing of 0.21 m and a total area of 32.93 m^2) were sown to a depth of 0.03 m using a cone seeder with press wheels to increase seed soil contact and starter fertiliser was applied at the time of sowing below the seed. In 2002 (Appendix 3.1) and 2003 (Appendix 3.2), soil tests indicated that the soil was of adequate fertility for plant growth. Each experiment was sown with fertiliser providing 10 kg/ha of nitrogen, 14 kg/ha of phosphorus and 5 kg/ha of sulfur.

Once sowing was completed, plant counts were conducted for each sowing time when plants were at the four-leaf stage (stage 1,04 on the Sylvester-Bradley and Makepeace, 1984, growth scale). The established plant densities for each individual plot were determined for use in data analysis and ranged from 54 plants/m^2 to 76 plants/m^2. The first plant sampling of canola was conducted approximately 38 days after sowing for each sowing time. Only sowing time one was sampled at the first sampling (May 30), as the other two sowing times had not yet reached the correct sampling stage. After the initial plant sampling, samples were taken approximately every 21 days. The area sampled was four rows, each 0.5 m in length, totally an area of 0.42 m^2.

At each plant sampling green leaf area, dry matter production, and dry matter partitioning into leaf, petiole, stem, siliqua and seed, siliqua number, plant height, and stage of development (Sylvester-Bradley and Makepeace, 1984) were recorded. Leaf area was measured using an electronic planimeter (Paton Industries Pty. Ltd., Australia.) and plant samples were dried at 60°C for 48 hours. The final plant sampling was conducted at maturity and additional measurements were recorded. These were branch number, the number of siliquas and their dry weight for the terminal raceme only, and then for all remaining branches. The corresponding seed weight for the terminal raceme and branch siliquas and the harvest index were also calculated.

Grain was harvested from October 30 onwards as the different sowing times matured with an average harvested area per plot of 31.25 m^2. This was done via direct harvesting by plot header as opposed to windrowing and then harvesting as this is common practise when harvesting canola in this region. Grain was weighed to provide an estimate of yield and samples were analysed to provide measurements of oil and protein concentration and 1000-grain weight.

Neutron probe measurements were conducted throughout the experiment, providing an estimate of water use, coinciding with the plant sampling. They were also recorded before and after the water treatment (water deficit two) was applied. Measurements were recorded to a depth of 1.8 m at 20 cm intervals. The final reading was conducted at maturity.

Volumetric soil moisture content was determined using the calibration equation $[-0.09 + 0.246 * \{1.0977 * (X / 12898) - 0.0352\}]$. Crop water use and water use efficiency for grain yield and dry matter production pre-anthesis and post-anthesis were measured as the sum of change in soil water content and rainfall, specific to the growing period for each sowing time and variety. In this thesis, runoff and run-on were assumed to be negligible due to the flat terrain (approximately 1% slope), infrequent occurrence of high intensity storms during the growing season, and the predominately dry state of the surface soil. Drainage was also assumed to be negligible due to the lack of rainfall and was expected to be small and less than the error of measurement of the overall water balance (O'Connell *et al.* 2002). Ogola *et al.* (2002) also assumed drainage and runoff to be negligible in an experiment conducted on maize in the United Kingdom. Soil evaporation under crop was assumed to be 40% of evapotranspiration as reported by Siddique *et al.* (1990) for wheat in an experiment at Merredin in Western Australia which records a similar in-crop rainfall to Condobolin. This value has also been used by Maccallum *et al.* (2003) for experiments conducted at Condobolin, again in wheat.

Visual observations were conducted at 7-day intervals from stem elongation until maturity detailing flowering and siliqua development.

3.5 Measurements 2003

In 2003 the four sowing dates were April 2 (sowing time one), April 22 (sowing time two), May 13 (sowing time three) and June 6 (sowing time four). The earliest sowing date was included as early season breaks often require canola to be sown outside the recommended sowing window. The plots were sown to a depth of 0.03 m using a cone seeder with press wheels to increase seed soil contact and starter fertiliser was applied at the time of sowing below the seed. The plots were 21.0 m in length with a row spacing of 0.21 m and a total area of 35.28 m^2.

Plant counts were conducted for each sowing time after establishment, as in 2002. Established plant densities were determined for each individual plot and ranged from 40 plants/m^2 to 89 plants/m^2. Plant sampling began approximately 38 days after sowing for each sowing time. The first plant sampling, at the four-leaf stage, was conducted on April 29, with only sowing time one being sampled. The other three sowing times had not yet reached the correct sampling stage. After the initial plant sampling, samples were taken approximately every 21 days with the same measurements being conducted and recorded as in 2002. Grain harvest began on October 29 and continued until the final sowing time matured with an average harvested area per plot of 33.60 m^2. Once harvest was completed, grain was weighed to provide an estimate of yield and samples were analysed to allow measurements of oil and protein concentration, and 1000-grain weight as in 2002. Neutron probe measurements were also conducted throughout the experiment as in 2002 coinciding with plant growth measurements. Crop water use and water use efficiencies for grain yield and dry matter production pre-anthesis and post-anthesis were measured as in 2002. Visual observations were also conducted at 7-day intervals from stem elongation until maturity detailing flowering and siliqua development.

3.6 Management 2002

Two water treatments were planned; they were water deficit one and water deficit two. Water deficit two was intended to increase water deficit one (which it was hoped would represent an average year) to 25% above an average year. However, due to below average rainfall, extreme temperatures and high evaporative demands arising from the drought, three supplementary water applications totalling 50 mm were applied to the whole experiment (water deficit one) to increase the 97.2 mm of in-crop rainfall in 2002. This still did not represent what was considered average rainfall (200 mm) in the growing season (April – October). Water deficit two was given an additional 22 mm of water on August 15 using a hard hose single boom sprinkler irrigator, bringing the total in-crop rainfall for that treatment to 169.2 mm, still below average for the growing season.

3.7 Management 2003

In 2003 three supplementary water applications totalling 67 mm were applied to the whole experiment (water deficit one) prior to sowing on the April 2, April 22 and May 13, to allow sowing to commence following a lack of pre-season rainfall (132 mm between November 2002 and April 2003). However due to increased in-crop rainfall, water deficit one received 265.7 mm during the growing season which would be considered above average (33% above the average), with water deficit two receiving an additional 60 mm of water in 2 applications on July 15 and September 8, using the same irrigation system as in 2002, bringing the total in-crop rainfall for water deficit two to 325.7 mm, well above the long-term average for in-crop rainfall (63% above the average).

CHAPTER FOUR: PLANT GROWTH

4.1 Introduction

Production of canola in the low rainfall region of the south-eastern wheat belt of Australia is limited largely by the low and unpredictable nature of rainfall which is received in the area (Hocking *et al.* 1997). To increase the production of canola it was necessary to explore the factors preventing canola from being grown successfully. The main constraints identified included a lack of moisture throughout the growing season and an increase in temperature and moisture stress towards the end of the growing season. Both of these factors severely impede the ability of canola to yield successfully in low rainfall environments.

To investigate this, two experiments were established at Condobolin (33° 03' 59'' S, 147° 13' 42'' E) in central western New South Wales in 2002 and 2003 to determine the best sowing time and variety appropriate to the individual sowing time to reduce the water deficit and limit the amount of moisture and temperature stress which is experienced when the canola crop is maturing. Accompanying this, two water treatments (water deficit one and water deficit two) were established to assess the effects of increased moisture on the major parameters measured. The two water treatments were water deficit one, which represented the season rainfall plus additional irrigation required to ensure the viability of the trial, and water deficit two, which should have represented a year 25% above the average annual in-crop rainfall (200 mm), but as discussed in Chapter three this was unattainable.

To understand how the plant responds to these environmental factors, three different sowing times were established in 2002 involving eight canola varieties chosen for their suitability to the low rainfall environment represented by Condobolin and to provide a range of different maturity types (McRae *et al.* 2003). Plant growth measurements were taken as detailed in Chapter three throughout the growing season until maturity. In 2003 a similar experiment was established using six canola varieties, however, an additional earlier sowing time (April 2) was added which represented a sowing time which farmers in the region were actively practising in response to early season breaks. Plant architecture was also investigated as detailed in Chapter three. This was to determine if it was better to have bigger plants with lots of branching to achieve higher grain yield or if there was a level at which plant growth was too high leading to reduced grain yield because of the plant's inability to supply assimilates and moisture. The investigation of a wide range of plant growth parameters was important in determining which were significant in contributing to canola yield and yield components in low rainfall environments.

4.2 Results

4.2.1 Phenology

The development of the four canola varieties (Dunkeld, Ag-Outback, Hyola 60 and Ripper) throughout the season, for each sowing time in 2002, is presented in Table 4.1. There was no difference in the developmental pattern between the water deficit one and water deficit two water treatments and, therefore, the average growth stage is presented. Table 4.2 presents the development of three canola varieties (Ag-Outback, Hyola 60 and Ripper) across the four sowing times in 2003 with the restricted water supply of the water deficit one treatment increasing the rate of development in a number of the sowing time and variety combinations. In this year there were differences in development between the water deficit one and water deficit two water treatments mainly as a lengthening of some growth stages and these have been presented. The plant growth stage was determined using the code for stages of development in oilseed rape by Sylvester-Bradley and Makepeace (1984). The code describes the life cycle of oilseed rape and is divided into seven principal stages: germination and emergence, leaf production, stem extension, flower bud development, flowering, siliqua development and seed development. These stages are also divided into secondary stages with a further three principal stages detailing the senescence of leaves, stems and siliquas (Sylvester-Bradley and Makepeace, 1984).

Table 4.1 Plant growth stage (Sylvester-Bradley and Makepeace, 1984) of four canola varieties sown over three sowing times at Condobolin in 2002.

Date	Variety	Sowing time	Growth stage	Date	Variety	Sowing time	Growth stage
30-May	Dunkeld	April 22	1,4	30-May	Ag-Outback	April 22	1,5
24-Jun			1,8	24-Jun			1,8
16-Jul			2,4	16-Jul			2,4
6-Aug			4,2	6-Aug			4,2
28-Aug			4,8	28-Aug			4,8
16-Sep			5,9	16-Sep			5,9
7-Oct			6,1	7-Oct			6,1
30-Oct			6,9	30-Oct			6,9
24-Jun		May 17	1,4	24-Jun		May 17	1,4
16-Jul			1,8	16-Jul			1,8
6-Aug			2,4	6-Aug			2,4
28-Aug			4,2	28-Aug			4,2
16-Sep			5,5	16-Sep			5,5
7-Oct			5,9	7-Oct			5,9
30-Oct			6,9	30-Oct			6,9
6-Aug		June 14	1,5	6-Aug		June 14	1,5
28-Aug			2,4	28-Aug			2,4
16-Sep			4,8	16-Sep			4,8
7-Oct			5,5	7-Oct			5,5
30-Oct			6,9	30-Oct			6,9
30-May	Hyola 60	April 22	1,4	30-May	Ripper	April 22	1,5
24-Jun			1,8	24-Jun			1,8
16-Jul			2,4	16-Jul			2,4
6-Aug			4,2	6-Aug			4,2
28-Aug			4,8	28-Aug			4,8
16-Sep			5,9	16-Sep			5,9
7-Oct			6,1	7-Oct			6,1
30-Oct			6,9	30-Oct			6,9
24-Jun		May 17	1,4	24-Jun		May 17	1,4
16-Jul			1,8	16-Jul			1,7
6-Aug			2,4	6-Aug			2,4
28-Aug			4,2	28-Aug			4,2
16-Sep			5,5	16-Sep			5,5
7-Oct			5,9	7-Oct			5,9
30-Oct			6,9	30-Oct			6,1
6-Aug		June 14	1,5	6-Aug		June 14	1,5
28-Aug			2,4	28-Aug			2,4
16-Sep			4,8	16-Sep			4,8
7-Oct			5,5	7-Oct			5,5
30-Oct			6,1	30-Oct			6,9

Table 4.2 Plant growth stage (Sylvester-Bradley and Makepeace, 1984) of three canola varieties sown over four sowing times at Condobolin in 2003.

Date	Variety	Sowing time	W1^	W2^^	Date	Variety	Sowing time	W1	W2	Date	Variety	Sowing time	W1	W2
29-Apr	Hyola 60	April 2	1,4	*	29-Apr	Ag-Outback	April 2	1,4	*	29-Apr	Ripper	April 2	1,4	*
20-May			1,8	*	20-May			1,8	*	20-May			1,8	*
10-Jun			2,3	*	10-Jun			2,1	*	10-Jun			2,2	*
1-Jul			3,7	*	1-Jul			4,2	*	1-Jul			3,1	*
22-Jul			4,2	*	22-Jul			4,7	*	22-Jul			4,2	*
12-Aug			4,5	4,7	12-Aug			5,1	5,2	12-Aug			4,5	4,3
2-Sep			5,8	5,7	2-Sep			5,8	6,3	2-Sep			5,7	5,8
23-Sep			6,3	5,9	23-Sep			6,3	6,9	23-Sep			6,3	6,3
14-Oct			6,9	6,3	14-Oct			6,9	6,9	14-Oct			6,9	6,9
30-Oct			6,9	6,9	30-Oct			6,9	*	30-Oct			6,9	6,9
20-May		April 22	1,4	*	20-May		April 22	1,4	*	20-May		April 22	1,4	*
10-Jun			1,7	*	10-Jun			1,8	*	10-Jun			1,7	*
1-Jul			2,2	*	1-Jul			2,1	*	1-Jul			2,1	*
22-Jul			3,1	*	22-Jul			3,3	*	22-Jul			3,1	*
12-Aug			4,5	4,3	12-Aug			4,8	5,1	12-Aug			4,1	4,3
2-Sep			5,4	5,2	2-Sep			5,3	5,7	2-Sep			5,2	5,2
23-Sep			6,3	5,8	23-Sep			5,8	5,8	23-Sep			6,2	5,7
14-Oct			6,9	6,3	14-Oct			6,9	6,9	14-Oct			6,9	6,3
30-Oct			6,9	6,9	30-Oct			6,9	6,9	30-Oct			6,9	6,9
1-Jul		May 17	1,6	*	1-Jul		May 17	1,7	*	1-Jul		May 17	1,6	*
22-Jul			2,2	*	22-Jul			2,1	*	22-Jul			2,1	*
12-Aug			3,6	3,6	12-Aug			4,4	4,2	12-Aug			3,1	3,1
2-Sep			5,1	5,1	2-Sep			5,1	5,1	2-Sep			4,5	4,5
23-Sep			6,1	5,6	23-Sep			6,1	6,1	23-Sep			5,6	5,5
14-Oct			6,3	6,3	14-Oct			6,3	6,3	14-Oct			6,3	6,3
30-Oct			6,9	6,9	30-Oct			6,9	6,9	30-Oct			6,9	6,9
12-Aug		June 6	3,1	3,1	12-Aug		June 6	3,1	3,3	12-Aug		June 6	3,1	3,0
2-Sep			4,1	4,1	2-Sep			4,1	4,1	2-Sep			3,6	3,3
23-Sep			5,5	5,2	23-Sep			5,7	5,1	23-Sep			5,1	5,1
14-Oct			6,3	6,3	14-Oct			6,3	6,3	14-Oct			6,3	6,3
30-Oct			6,9	6,9	30-Oct			6,9	6,9	30-Oct			6,9	6,9

^W1:water deficit one ^^W2: water deficit two * no measurement

4.2.2 Leaf area

There was a significant interaction (P=0.008) between water deficit, variety, sowing time and the number of days after sowing for leaf area index (m^2 m^{-2}) of canola sown at Condobolin in 2002 (Figure 4.1). The April 22 sowing time recorded a significantly higher leaf area index than the May 17 sowing time which was significantly higher than the June 14 sowing time for Ripper water deficit one, Ag-Outback water deficit one, Hyola 60 water deficit one and Dunked water deficit one. There were a reduced number of significant differences for all varieties sown for water deficit two with Ripper and Hyola 60 sown on April 22 recording significantly higher leaf area index after peak leaf area index was achieved than Dunkeld and Ag-Outback.

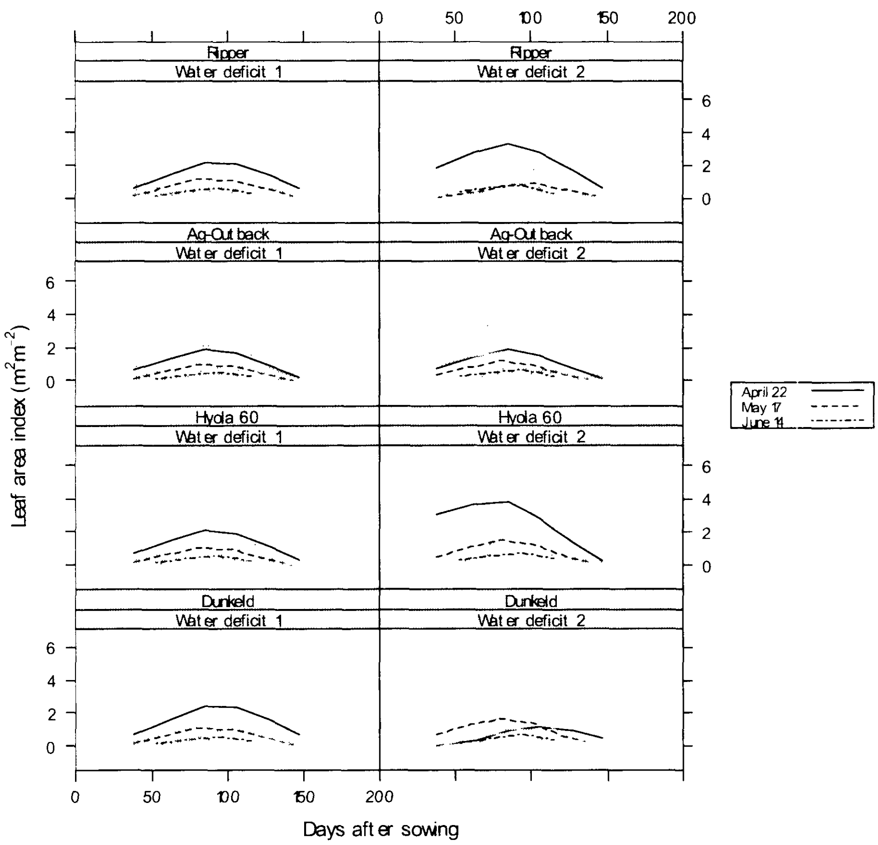

Figure 4.1 The effects of sowing time, variety, water deficit and days after sowing on leaf area index (m^2 m^{-2}) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

There was a significant interaction (P=0.024) between water deficit, variety, sowing time and the number of days after sowing for leaf area index of canola sown at Condobolin in 2003. Figure

4.2 presents the predicted values for these interactions; there were significant differences in leaf area index throughout the growing season however, these were only single point differences and they did not produce an overall trend.

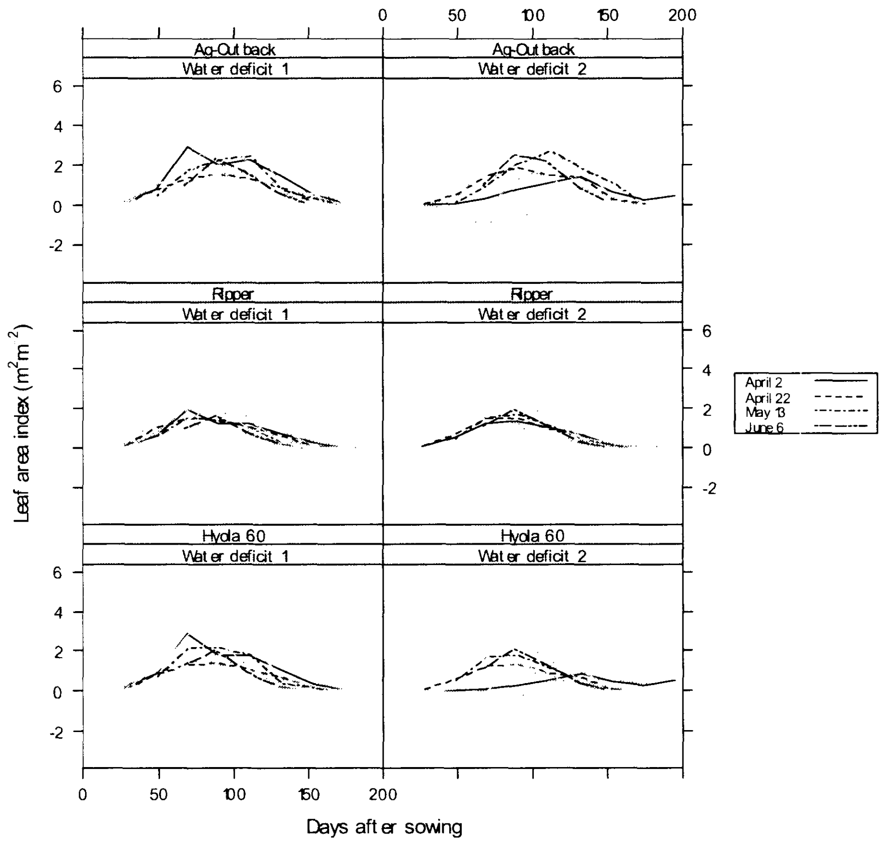

Figure 4.2 The effects of sowing time, variety, water deficit and days after sowing on leaf area index (m^2 m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

4.2.3 Dry matter production

There was a significant interaction between sowing time and days after sowing (P=0.004), water deficit and days after sowing (P<0.001) and variety and sowing time (P=0.036) for dry matter production (g m^{-2}) of canola at Condobolin in 2002. Figure 4.3a presents the predicted values for the effects of sowing time on dry matter production throughout the growing season, with the April 22 sowing time recording a significantly higher dry matter production than the May 17 sowing time which was significantly higher than the June 14 sowing time. The predicted values for the effects of water deficit on dry matter production throughout the season in 2002 are presented in Figure 4.3b. Water deficit two recorded a significantly higher dry matter production until approximately 147 days after sowing when there were no further significant differences between water deficit one and water deficit two. Figure 4.4 presents the predicted values for dry matter production of canola at Condobolin in 2002 for the interaction between sowing time and variety. The June 14 sowing time recorded a significantly higher dry matter production than the April 22 and May 17 sowing times for Ag-Outback, Ripper and Hyola 60. The May 17 sowing time recorded a significantly lower dry matter production than the April 22 and June 14 sowing times for Dunkeld. Hyola 60 sown on June 14 recorded a significantly higher dry matter production than all other treatments and Dunkeld sown on May 17 recorded a significantly lower dry matter production than all other treatments.

a) b)

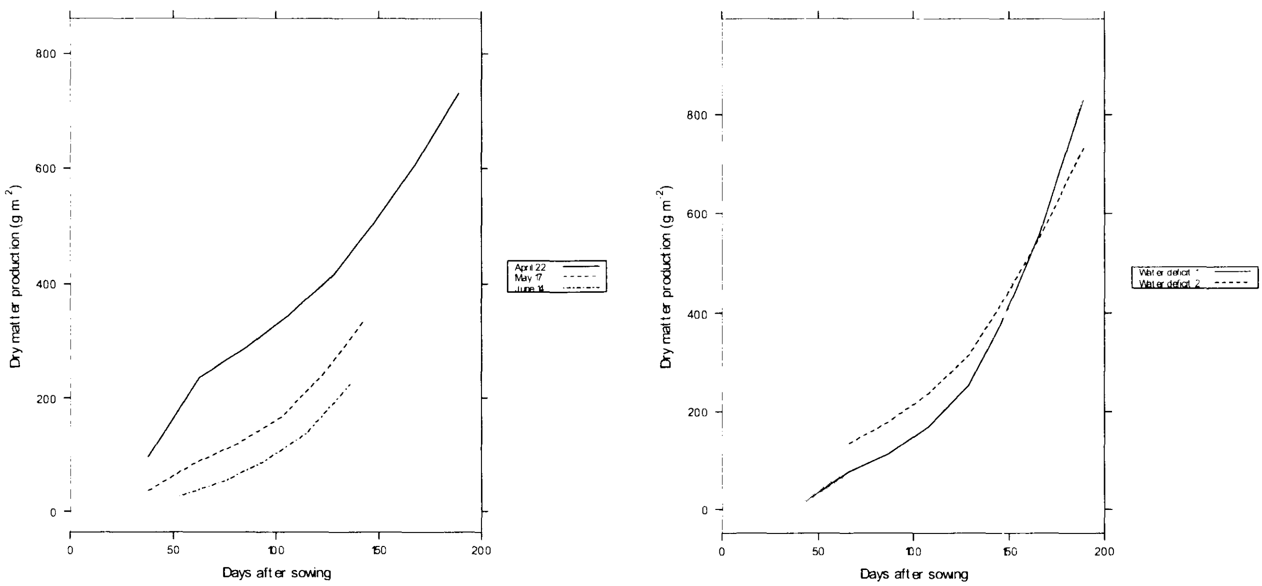

Figure 4.3 The effects of sowing time and days after sowing (a) and water deficit and days after sowing (b) on dry matter production (g m^{-2}) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

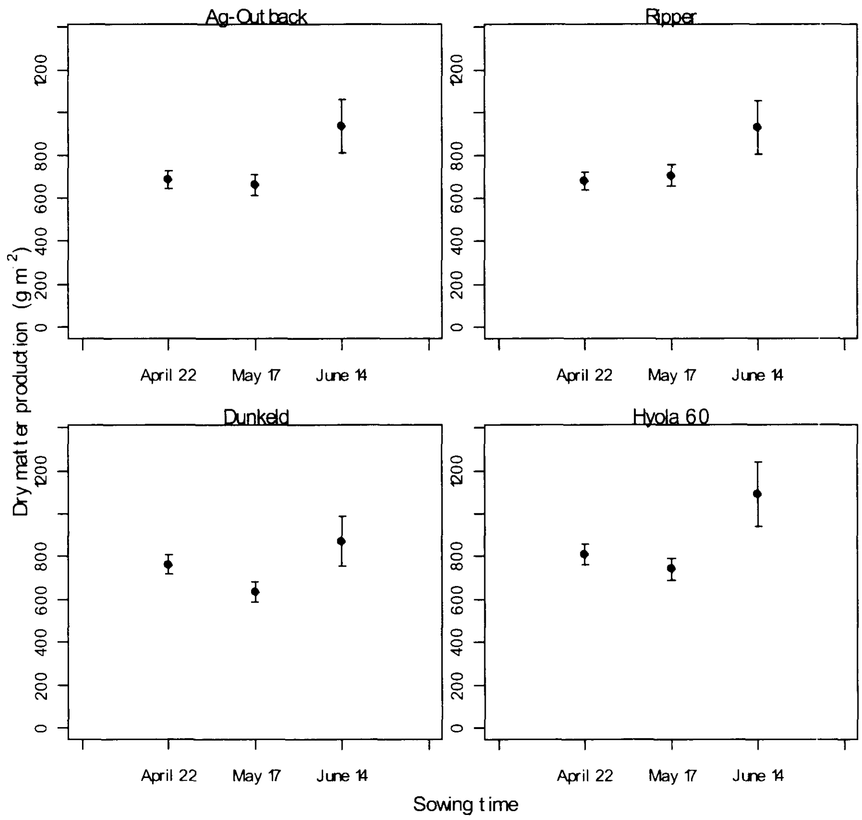

Figure 4.4 The effects of sowing time and variety on dry matter production (g m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

There was a significant interaction (P=0.024) between variety, sowing time and days after sowing for dry matter production of canola at Condobolin in 2003. Figure 4.5 presents the predicted values for the effects of sowing time, variety and days after sowing on dry matter production. Ag-Outback and Ripper sown on April 2 recorded a significantly higher dry matter production than the April 22, May 13 and June 6 sowing times. The April 22 sowing time recorded a significantly higher dry matter production than the June 6 sowing time for all three canola varieties. The May 13 sowing time also recorded a significantly higher dry matter production than the June 6 sowing time. Hyola 60 sown on April 2 recorded a significantly higher dry matter production than the May 13 and June 6 sowing times. Hyola 60 sown on April 2 and May 13 recorded a significantly higher dry matter production during the growing season until 132 and 154 days after sowing respectively than the other canola varieties. There were no significant differences between varieties sown on April 22 or June 6. The interaction of water deficit and days after sowing also had a significant effect (P<0.001) on dry matter production in 2003 and is presented in Figure 4.6, with water deficit two recording a significantly higher dry matter production than water deficit one from 150 days after sowing until final harvest.

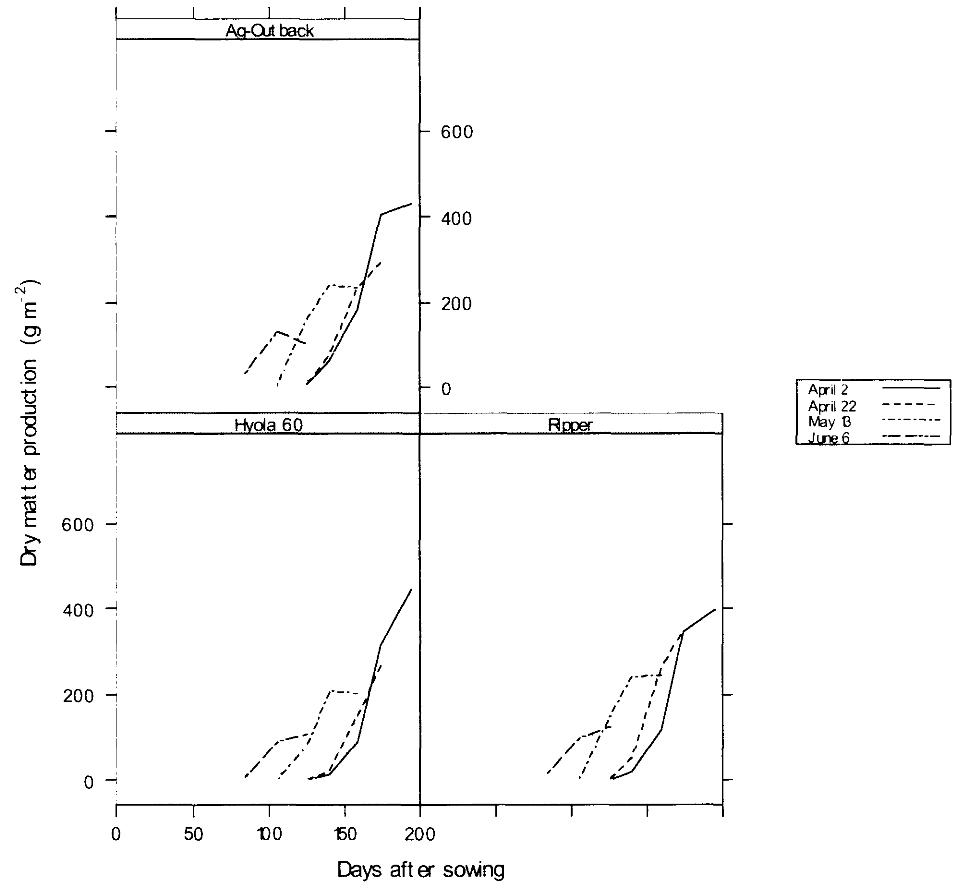

Figure 4.5 The effects of sowing time, variety and days after sowing on dry matter production (g m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

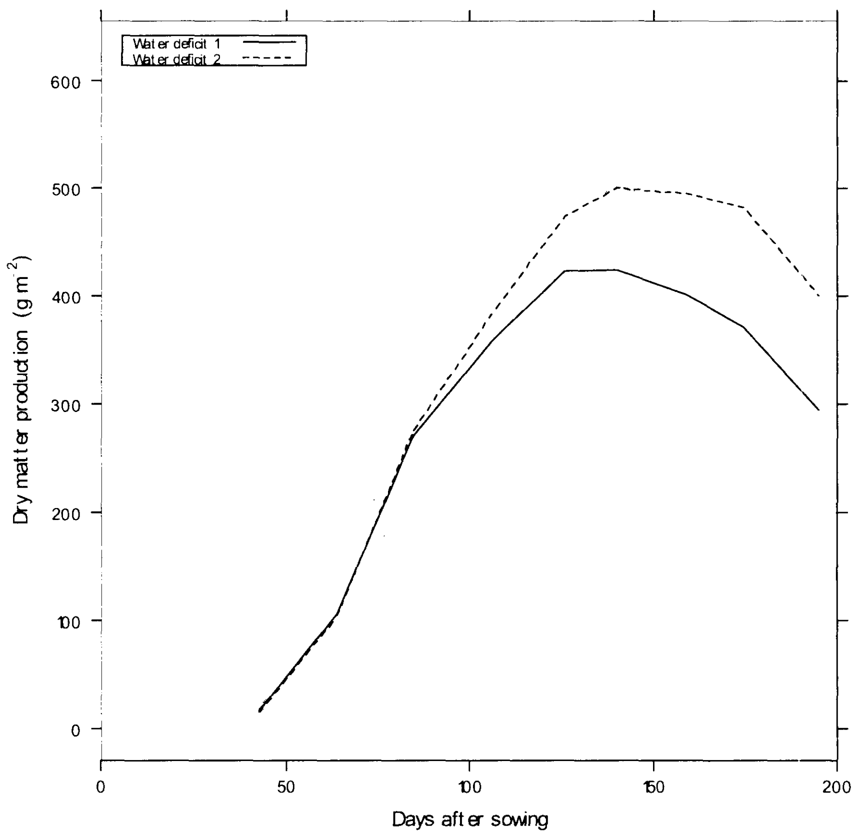

Figure 4.6 The effects of water deficit and days after sowing on dry matter production (g m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

4.2.4 Siliqua dry weight

There were significant interactions between variety and days after sowing (P=0.026) (Figure 4.7a) and variety and sowing time (P=0.011) (Figure 4.8) for siliqua dry weight (g m^{-2}) of canola sown at Condobolin in 2002. Water deficit also had a significant effect (P=0.002) on siliqua dry weight (Figure 4.7b) with water deficit two recording a significantly higher siliqua dry weight than water deficit one. The predicted values for the interaction between variety and days after sowing are presented in Figure 4.7a. Ag-Outback recorded a significantly higher siliqua dry weight than Ripper and Dunkeld 106 and 128 days after sowing. Hyola 60 recorded a significantly higher siliqua dry weight than Dunkeld 128 days after sowing while Ag-Outback and Hyola 60 recorded a significantly higher siliqua dry weight than Dunkeld 117 days after sowing. There were no significant differences in siliqua dry weight 168 and 189 days after sowing. The April 22 sowing time recorded a significantly higher siliqua dry weight than the May 17 sowing time which recorded a significantly higher siliqua dry weight than the June 14 sowing time for Dunkeld, Hyola 60 and Ag-Outback (Figure 4.8). Ripper sown on June 14 recorded a significantly lower siliqua dry weight than the April 22 and May 17 sowing times.

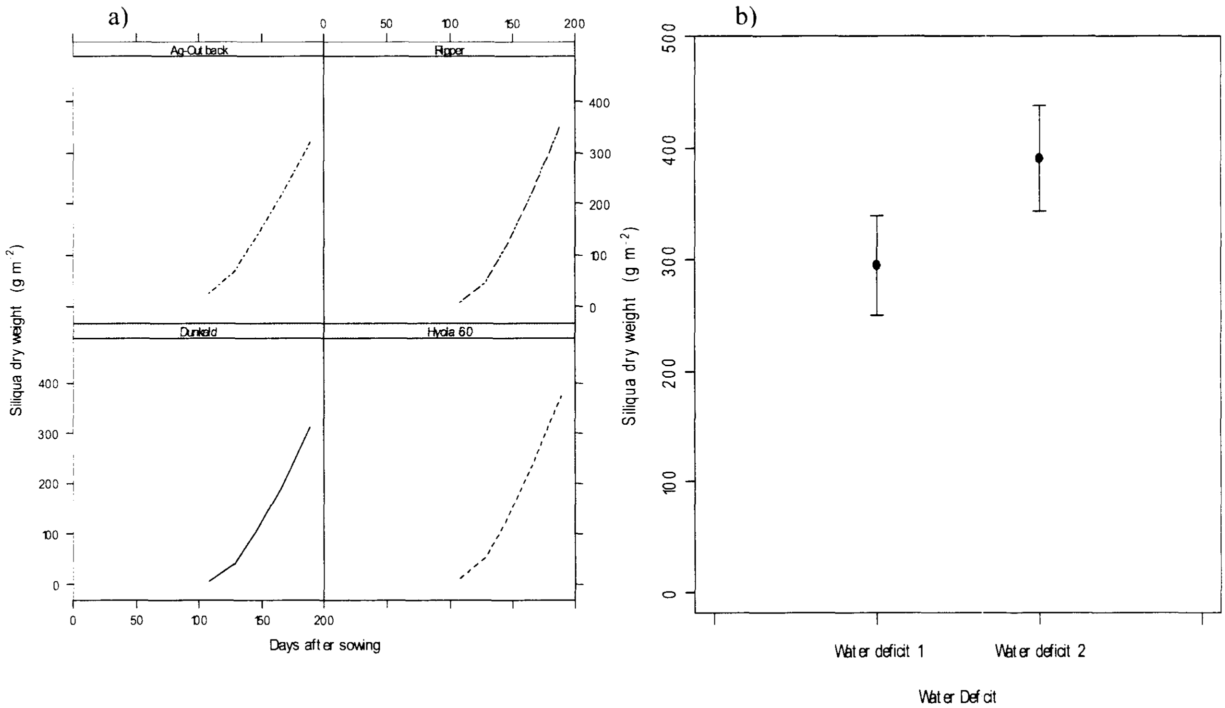

Figure 4.7 The effects of variety and days after sowing (a) and water deficit (b) on siliqua dry weight (g m^{-2}) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

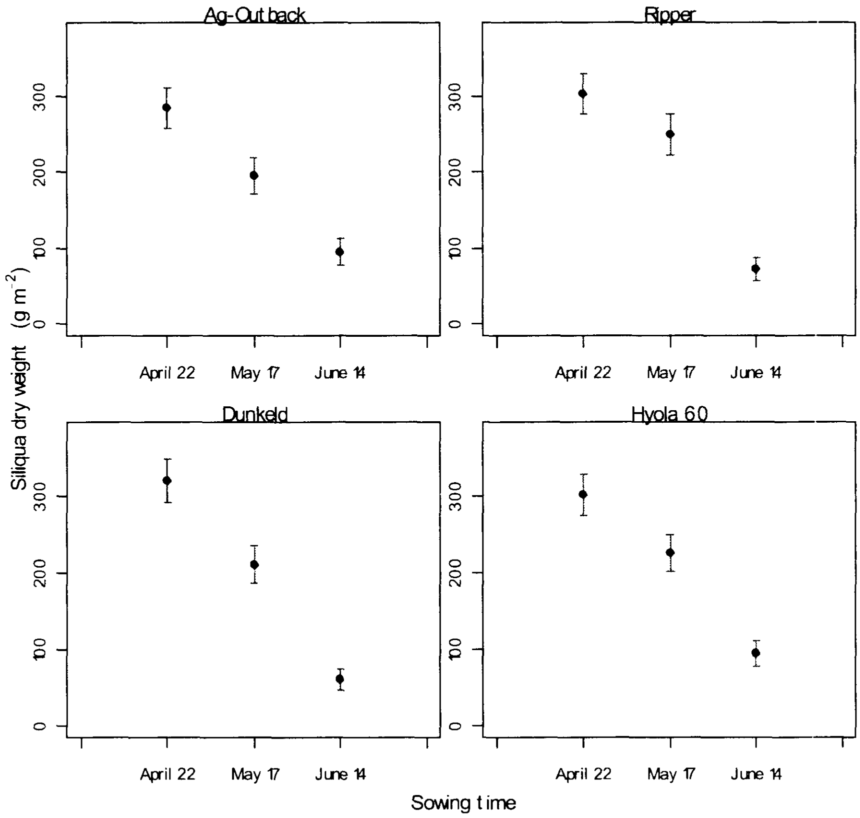

Figure 4.8 The effects of sowing time and variety on siliqua dry weight (g m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

There was a significant interaction (P=0.009) between variety, sowing time and days after sowing for siliqua dry weight of canola sown at Condobolin in 2003 (Figure 4.9). Hyola 60 sown on April 2 recorded a significantly higher siliqua dry weight than the June 6 sowing time throughout the growing season. The April 22 and May 13 sowing times also recorded significantly higher siliqua dry weight than the June 6 sowing time. This was also the case for Ag-Outback however the April 2 sowing time recorded a significantly higher siliqua dry weight than the April 22, May 13 and June 6 sowing times throughout the growing season. Ripper sown on April 2 recorded a significantly higher siliqua dry weight than the April 22, May 13 and June 6 sowing times throughout the growing season. The April 22 sowing time recorded a significantly higher siliqua dry weight than the May 13 and June 6 sowing times and the May 13 sowing time recorded a significantly higher siliqua dry weight than the June 6 sowing time.

There were no significant differences in siliqua dry weight between varieties in any of the four sowing times throughout the growing season.

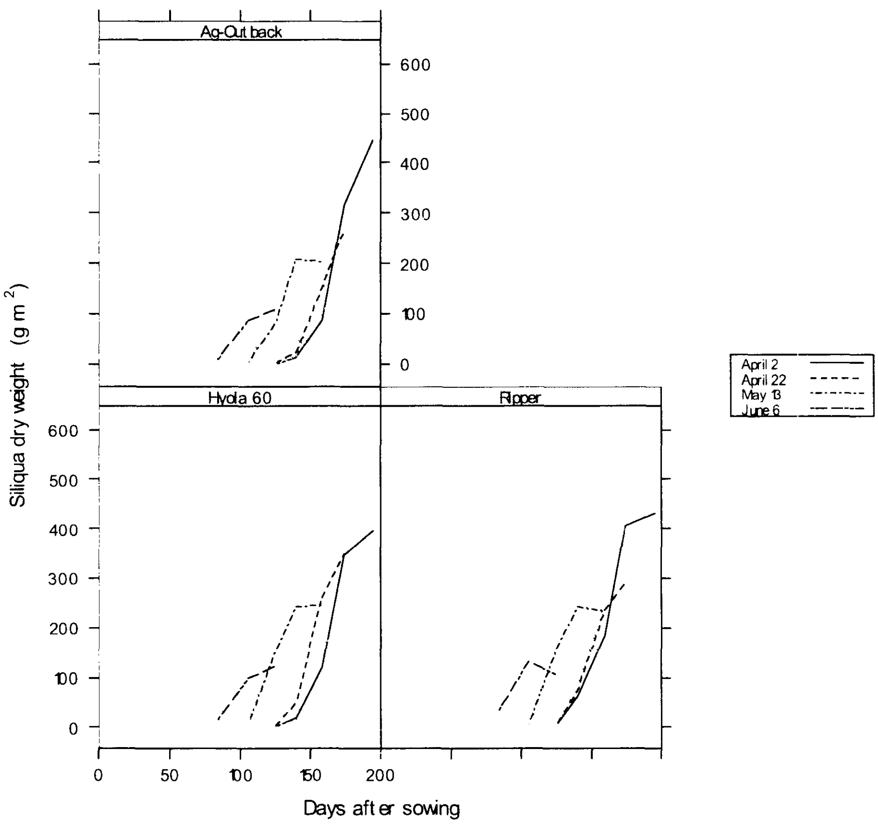

Figure 4.9 The effects of sowing time, variety and days after sowing on siliqua dry weight (g m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

4.2.5 Siliqua number

There was a significant interaction between water deficit, variety, sowing time and the number of days after sowing (P=0.039) for siliqua number (m^{-2}) of canola sown at Condobolin in 2002 Figure 4.10). There was no significant difference in siliqua number between water deficit one and water deficit two 189 days after sowing for Dunkeld sown on April 22 and 136 days after sowing for the June 14 sowing time, however, water deficit two recorded a significantly higher siliqua number than water deficit one 164 days after sowing for Dunkeld sown on May 17. There was no significant difference between water deficit one and water deficit two for siliqua number of Ripper and Hyola 60 sown on April 22, 189 days after sowing, May 17, 164 days after sowing, and June 14, 136 days after sowing. Whilst Ag-Outback water deficit two recorded a significantly higher siliqua number than water deficit one, 136 days after sowing, when sown on June 14, there were no such significant difference for the April 22 and May 17 sowing times.

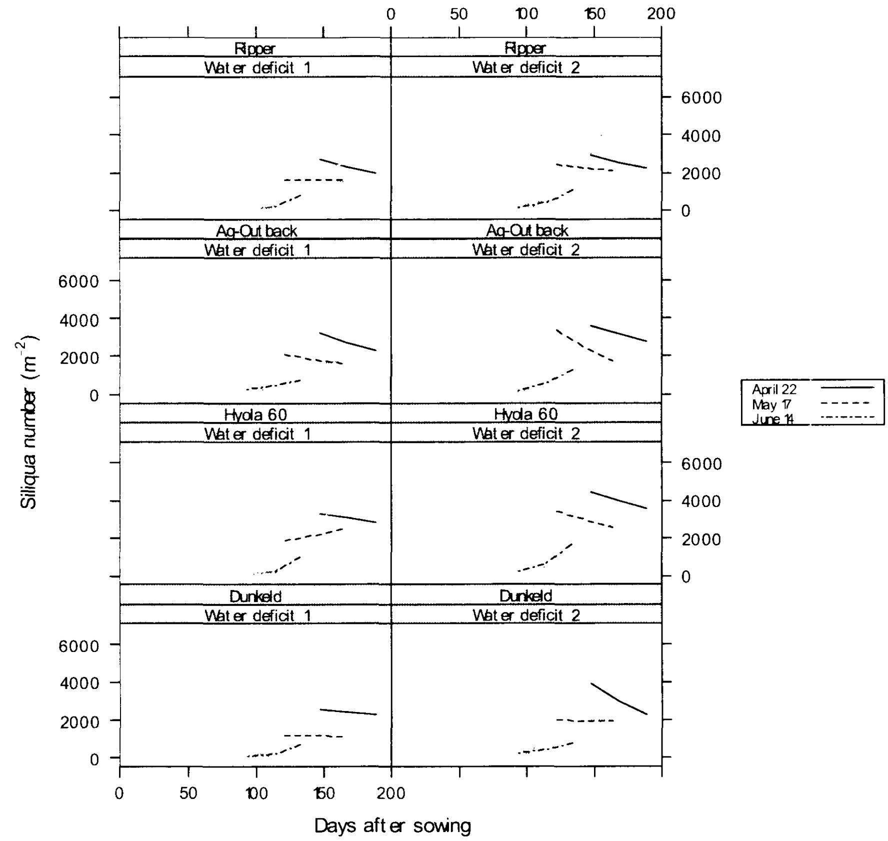

Figure 4.10 The effects of sowing time, variety, water deficit and days after sowing on siliqua number (m^{-2}) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

Water deficit, sowing time and variety interactions with days after sowing all had significant effects on siliqua number of canola sown at Condobolin in 2003. Figure 4.11 presents the effect of water deficit and days after sowing (P=0.04) on siliqua number. There were no significant differences in siliqua number between water deficit one and water deficit two at the same stages throughout the growing season. However, there were significant differences in siliqua number individually for both water deficit one and water deficit two during the growing season; significantly higher siliqua number were recorded as days after sowing increased after 132 days from sowing. The effects of variety and days after sowing (P=0.021) on siliqua number are presented in Figure 4.12. There was a significant difference in siliqua number throughout the growing season for Hyola 60, Ripper and Ag-Outback with the exception of 111 and 132 days after sowing when there were no significant differences in siliqua number. Figure 4.13 presents the effect of sowing time and days after sowing (P=0.003) on siliqua number. The April 2 sowing time recorded a significantly higher siliqua number than the May 13 and June 6 sowing times at the end of the growing season. The April 22 sowing time recorded a significantly higher siliqua number than the May 13 and June 6 sowing time and the May 13 sowing time recorded a significantly higher siliqua number than the June 6 sowing time at harvest. There were no significant differences in siliqua number for the April 2 sowing time until 117 days after sowing. There was no significant difference in siliqua number for the April 22 sowing time until 154 days after sowing. Compared with the June 6 sowing time there were no significant differences throughout the growing season for the May 13 sowing time except after 131 days from sowing.

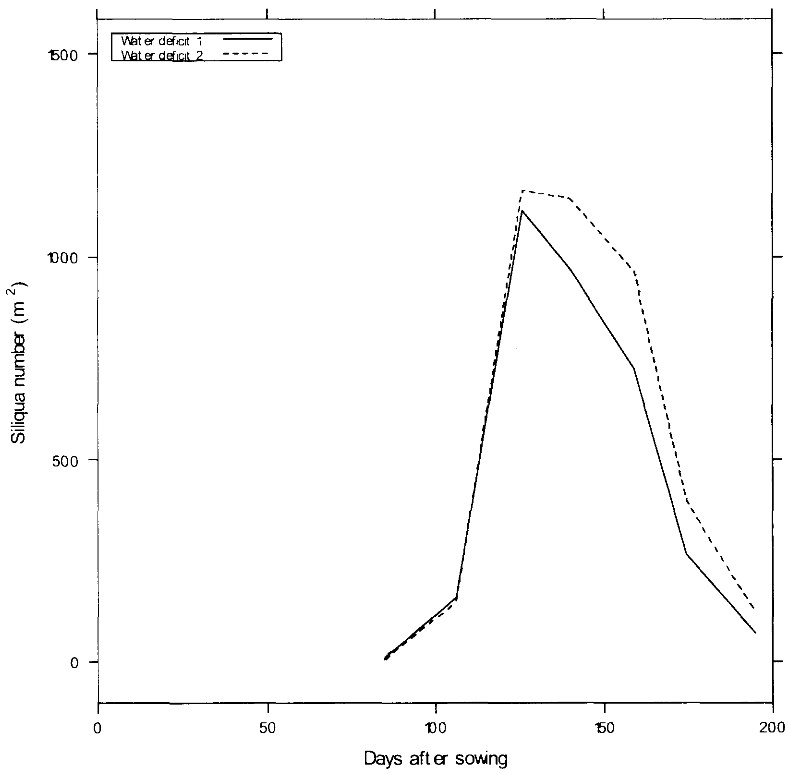

Figure 4.11 The effects of water deficit and days after sowing on siliqua number (m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

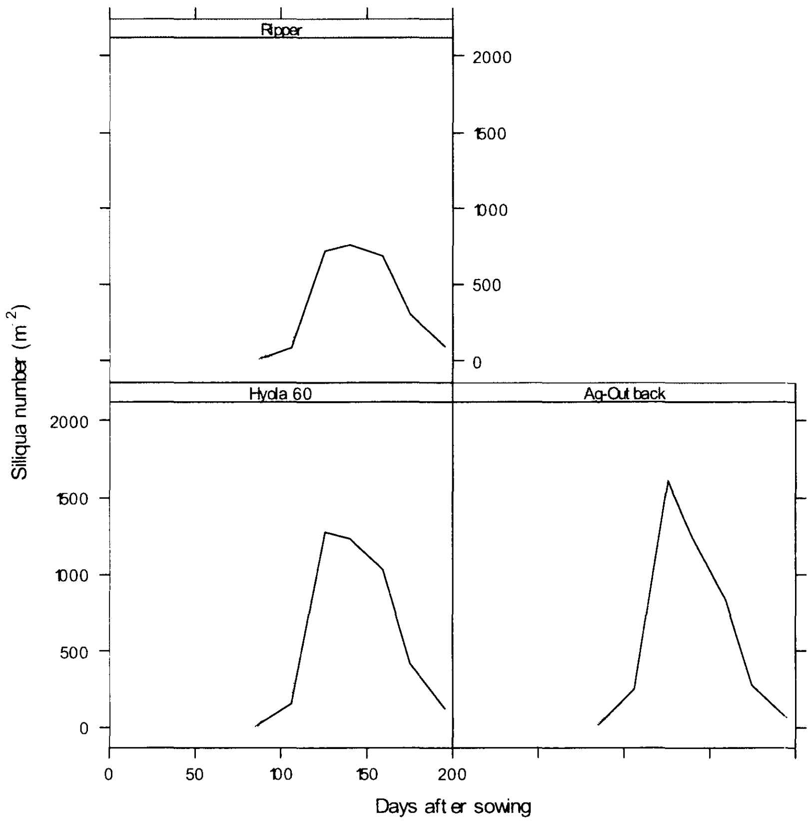

Figure 4.12 The effects of variety and days after sowing on siliqua number (m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

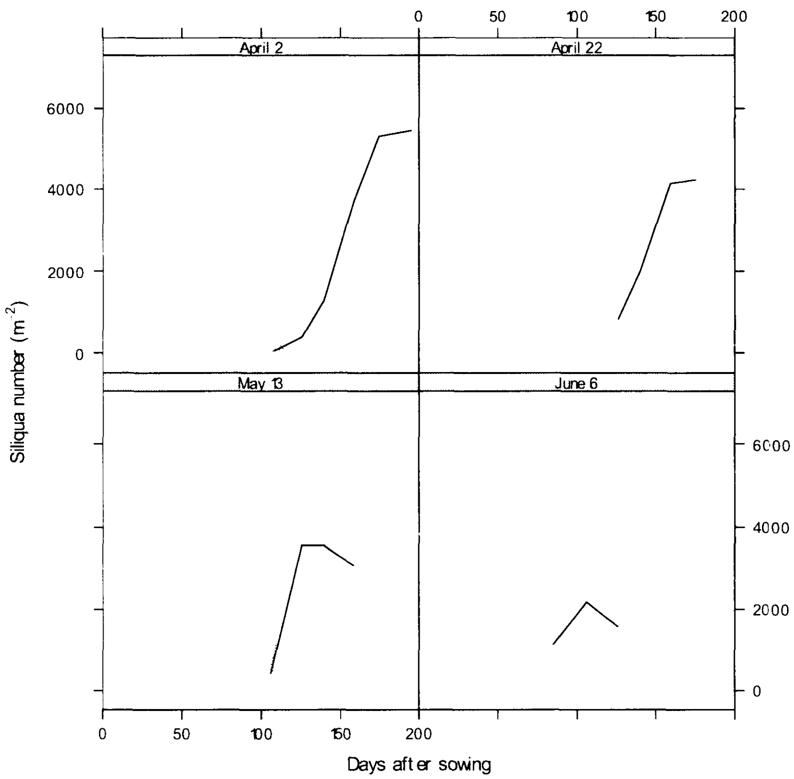

Figure 4.13 The effects of sowing time and days after sowing on siliqua number (m^{-2}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

4.2.6 Main raceme siliqua dry weight

The interaction of variety and sowing time had significant effects (P=0.019) on main raceme siliqua dry weight (g m^{-2}) of canola sown at Condobolin in 2002 (Figure 4.15). Water deficit also had a significant effect (P=0.002) on main raceme siliqua dry weight with water deficit two recording a significantly higher main raceme siliqua dry weight than water deficit one (Figure 4.14). Ripper and Dunkeld sown on June 14 recorded a significantly lower main raceme siliqua dry weight than the April 22 and May 17 sowing times. Hyola 60 sown on April 22 recorded a significantly higher main raceme siliqua dry weight than the May 17 and June 14 sowing times. There was no significant difference in main raceme siliqua dry weight of Ag-Outback sown on April 22, May 17 and June 14. However, Ag-Outback recorded a significantly lower main raceme siliqua dry weight than Ripper, Hyola 60 and Dunkeld sown on April 22. Ripper and Dunkeld recorded a significantly higher main raceme siliqua dry weight than Ag-Outback and

Hyola 60 sown on May 17 while there were no significant differences in main raceme siliqua dry weight of the four varieties sown on June 14.

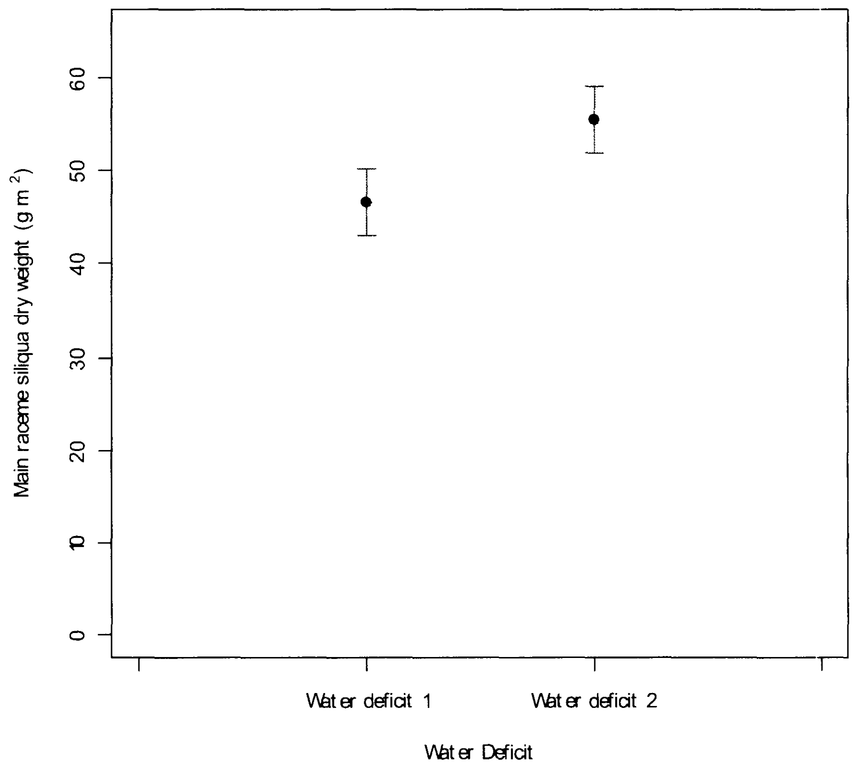

Figure 4.14 The effects of water deficit on main raceme siliqua dry weight (g m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

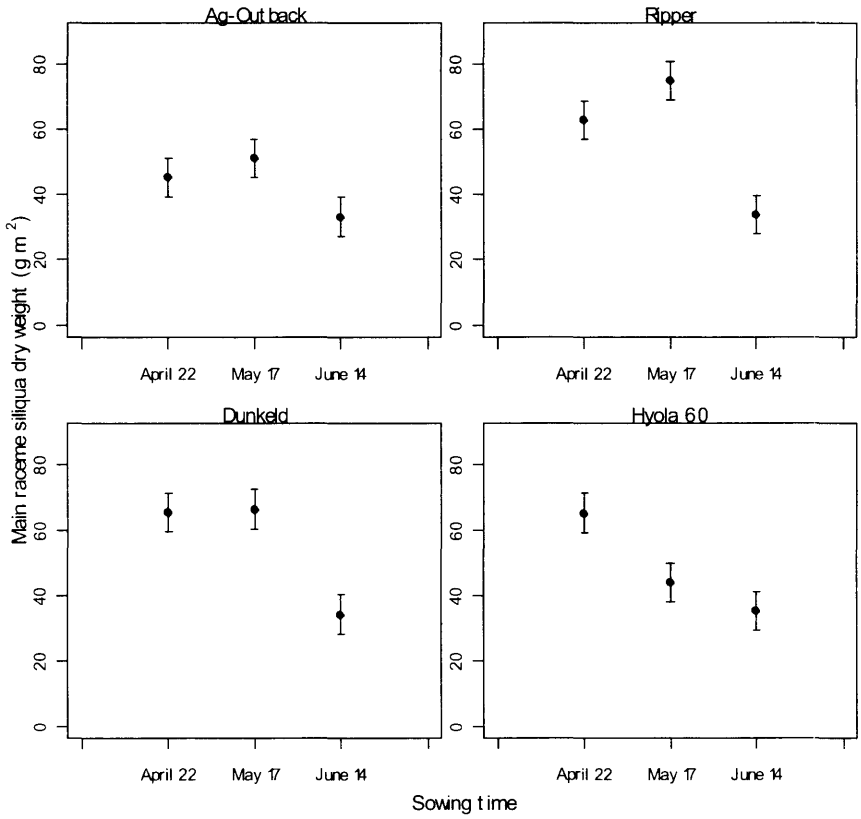

Figure 4.15 The effects of sowing time and variety on main raceme siliqua dry weight (g m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The interaction of variety and sowing time ($P<0.001$) and water deficit and sowing time ($P=0.03$) had significant effects on main raceme siliqua dry weight of canola sown at Condobolin in 2003. Figure 4.16 presents the effects of variety and sowing time on main raceme siliqua dry weight. Ag-Outback sown on April 22 and May 13 recorded a significantly higher main raceme siliqua dry weight than when sown on April 2 and June 6. Ripper sown on June 6 recorded a significantly lower main raceme siliqua dry weight than the April 2, April 22 and May 13 sowing times. Hyola 60 sown on April 22 and May 13 recorded a significantly higher main raceme siliqua dry weight than when sown on April 2 and June 6. Ripper recorded a significantly higher main raceme siliqua dry weight than Hyola 60 which was significantly higher than Ag-Outback when sown on April 2. Ripper and Hyola 60 recorded a significantly higher main raceme siliqua dry weight than Ag-Outback when sown on April 22. There were no significant differences in main raceme siliqua dry weight of varieties sown on May 13 and June 6. Figure 4.17 presents the effects of water deficit and sowing time on main raceme siliqua dry weight. The April 22 and May 13 sowing times recorded significantly higher main raceme siliqua dry weight than the April 2 and June 6 sowing times for water deficit one. For water deficit two the April 22 and May 13 sowing times recorded a significantly higher main raceme siliqua dry weight than the April 2 and June 6 sowing times. Water deficit two recorded a significantly higher main raceme siliqua dry weight than water deficit one for the May 13 and June 6 sowing times although there was no significant difference between water deficit one and water deficit two for the April 2 and April 22 sowing times.

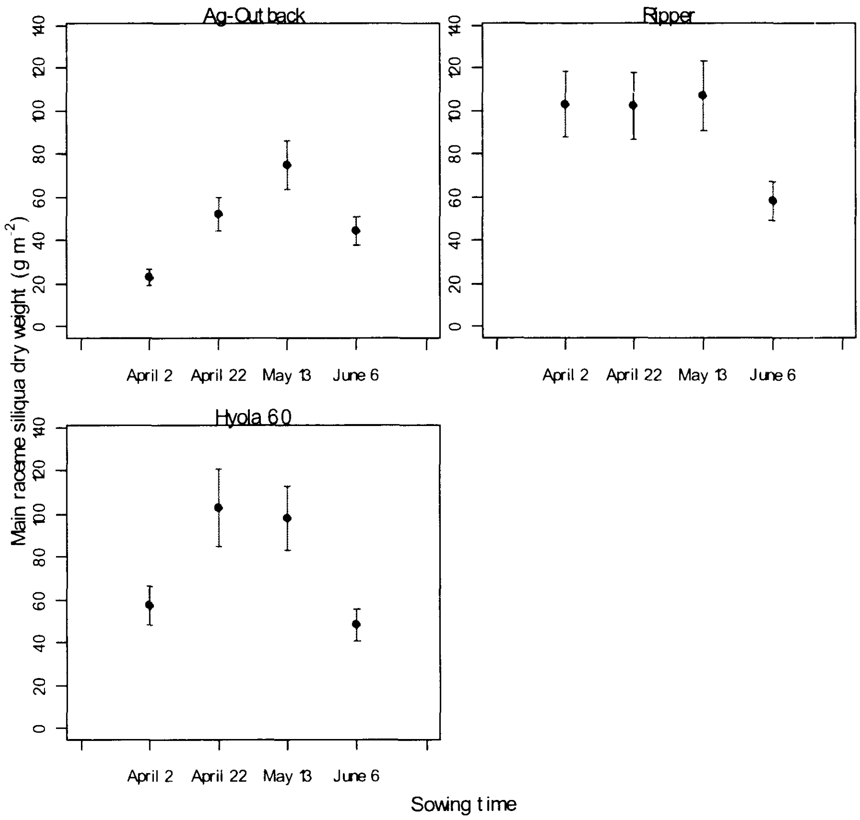

Figure 4.16 The effects of sowing time and variety on main raceme siliqua dry weight (g m^{-2}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

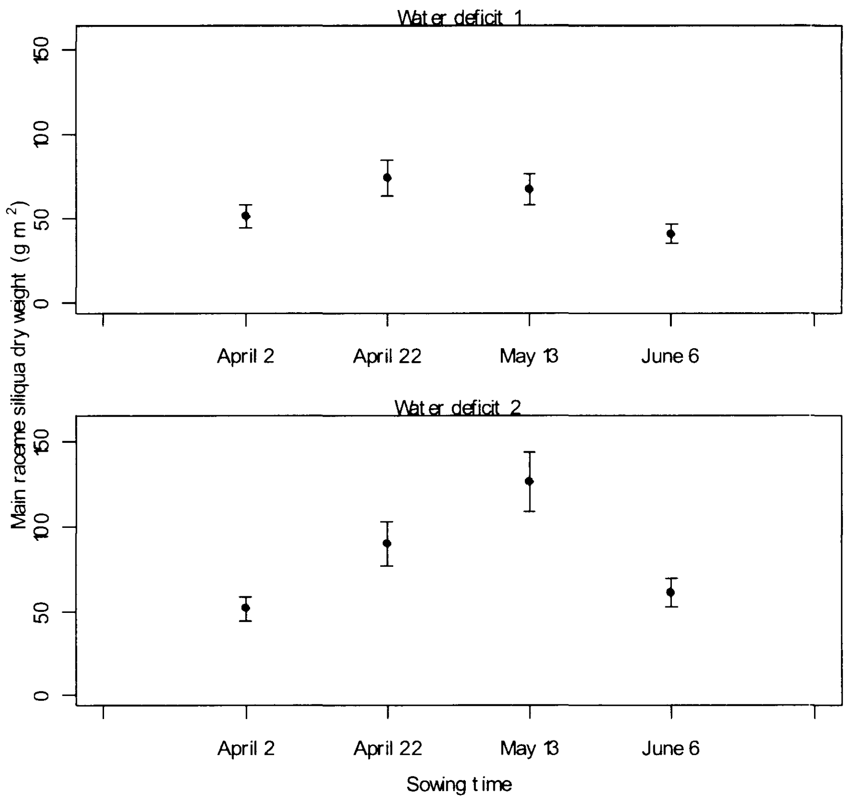

Figure 4.17 The effects of sowing time and water on main raceme siliqua dry weight (g m^{-2}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

4.2.7 Branch siliqua dry weight

The interaction between water deficit, variety and sowing time had a significant effect (P=0.004) on branch siliqua dry weight (g m^{-2}) of canola sown at Condobolin in 2002 (Figure 4.18). Dunkeld sown on June 14, water deficit two, recorded a significantly lower branch siliqua dry weight than Ripper, Hyola 60 and Ag-Outback for that water deficit. There were no other significant differences between varieties sown on each sowing time across both water deficits. The April 22 sowing time recorded a significantly higher branch siliqua dry weight than the May 17 sowing time which recorded a significantly higher branch siliqua dry weight than the June 14 sowing time for all varieties across water deficit one and water deficit two with the exception of Ripper water deficit one which recorded no significant difference in branch siliqua dry weight between the April 22 and May 17 sowing time however, they were significantly higher than the June 14 sowing time.

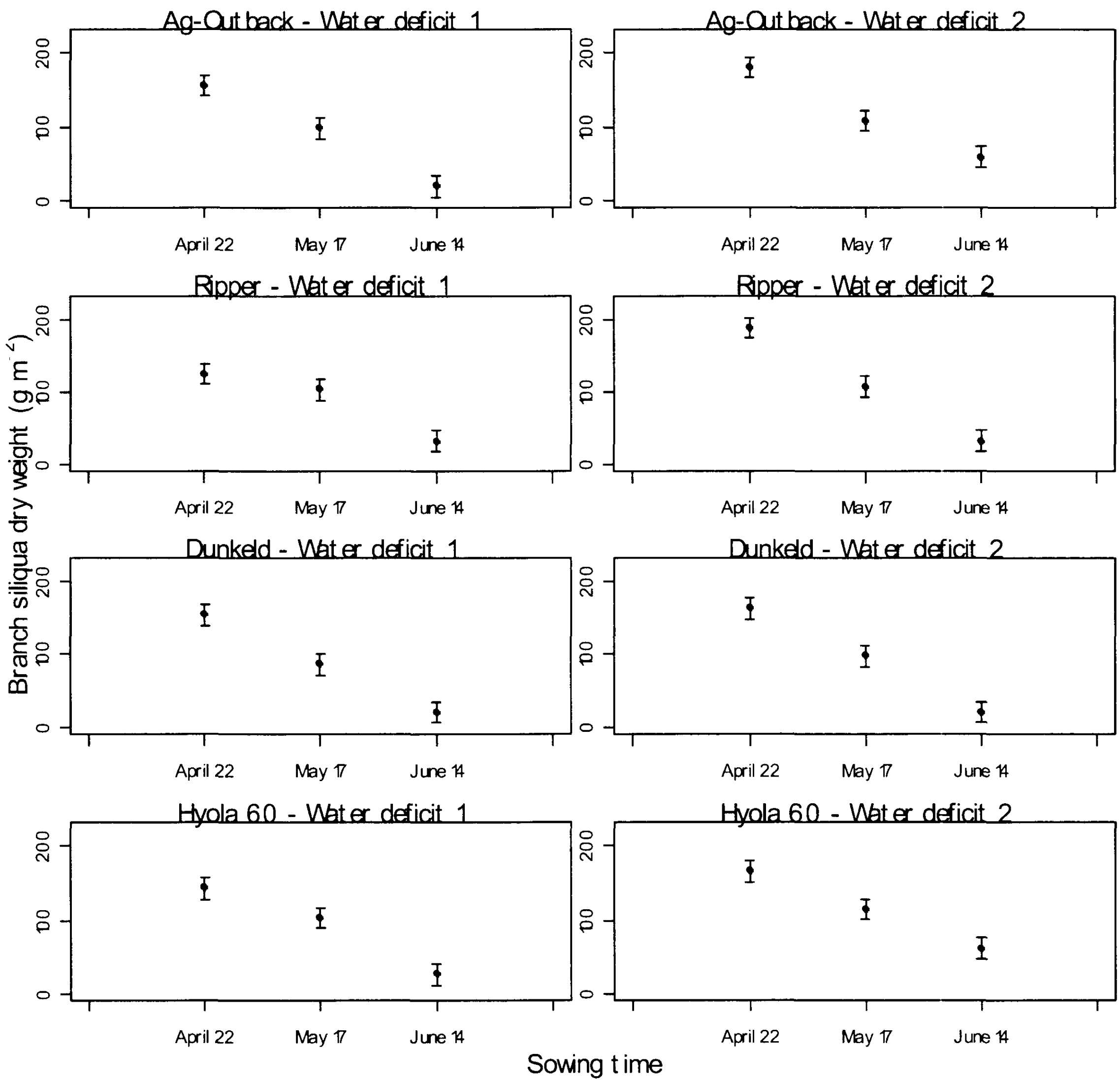

Figure 4.18 The effects of sowing time, variety and water deficit on branch siliqua dry weight (g m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

Sowing time, variety and water deficit all had significant effects ($P<0.001$) on branch siliqua dry weight of canola sown at Condobolin in 2003. Figure 4.19a presents the effects of variety on branch siliqua dry weight. Ag-Outback and Hyola 60 recorded a significantly higher branch siliqua dry weight than Ripper. Figure 4.19b presents the effects of sowing time on branch siliqua dry weight with delayed sowing after April 2 recording a progressive significant decline in branch siliqua dry weight through to the June 6 sowing time. The effects of water deficit on branch siliqua dry weight are presented in Figure 4.19c with water deficit two recording a significantly higher branch siliqua dry weight than water deficit one.

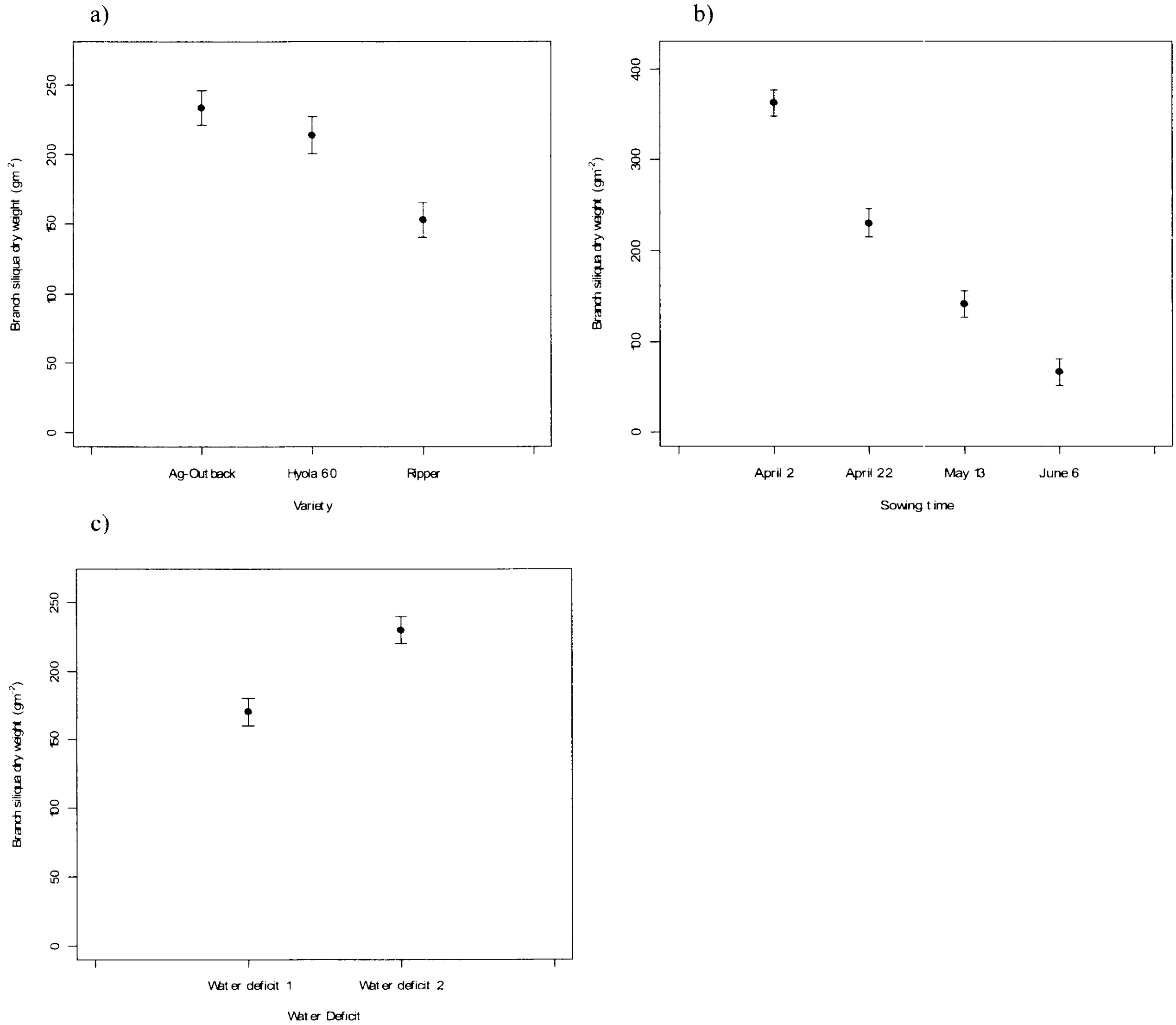

Figure 4.19 The effects of variety (a), sowing time (b) and water deficit (c) on branch siliqua dry weight (g m^{-2}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

4.2.8 Main raceme siliqua number

Sowing time ($P<0.001$), variety ($P=0.008$) and water deficit ($P=0.003$) all had individual significant effects on main raceme siliqua number (m^{-2}) of canola sown at Condobolin in 2002. Hyola 60 recorded a significantly higher main raceme siliqua number than Ripper, Dunkeld and Ag-Outback (Figure 4.20a). Water deficit two recorded a significantly higher main raceme siliqua number than water deficit one (Figure 4.20b). The effect of sowing time on main raceme siliqua number is presented in Figure 4.20c. The June 14 sowing time recorded a significantly lower main raceme siliqua number than the April 22 and May 17 sowing times. There were no significant effects on main raceme siliqua number of canola sown at Condobolin in 2003.

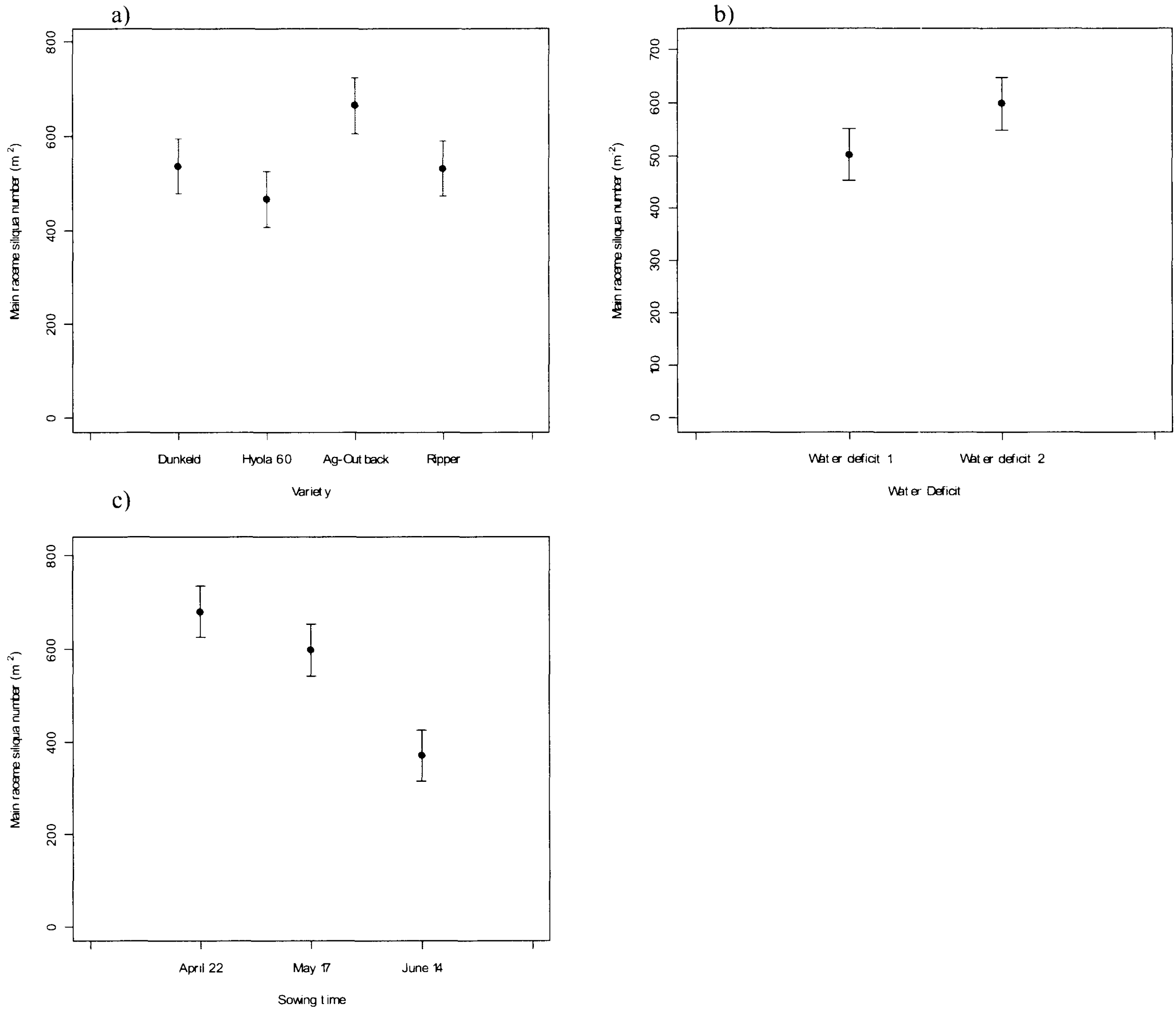

Figure 4.20 The effects of variety (a), water deficit (b) and sowing time (c) on main raceme siliqua number (m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

4.2.9 Branch siliqua number

Sowing time ($P<0.001$), variety ($P<0.001$) and water deficit ($P=0.006$) had significant effects on branch siliqua number (m^{-2}) of canola sown at Condobolin in 2002. Hyola 60 recorded a significantly higher branch siliqua number than Ag-Outback, Dunkeld and Ripper (Figure

4.21a). The effects of water deficit are presented in Figure 4.21b; water deficit two recorded a significantly higher branch siliqua number than water deficit one. Figure 4.21c presents the effects of sowing time on branch siliqua number. There was a significant difference between all three sowing times with the April 22 sowing time recording a significantly higher branch siliqua number and the June 14 sowing time recording a significantly lower branch siliqua number.

Variety ($P<0.001$) and the interaction of water deficit and sowing time ($P=0.035$) had significant effects on branch siliqua number of canola sown at Condobolin in 2003. The effects of variety are presented in Figure 4.21d. Ag-Outback and Hyola 60 recorded a significantly higher branch siliqua number than Ripper. For both water deficits the April 2 sowing time recorded a significantly higher branch siliqua number than the April 22 sowing time which was significantly higher than the May 13 sowing time which was significantly higher than the June 6 sowing time (Figure 4.22). Water deficit two also recorded a significantly higher branch siliqua number than water deficit one when sown on May 13. There were no significant differences between water deficit one and water deficit two for the April 2, April 22 and June 6 sowing times.

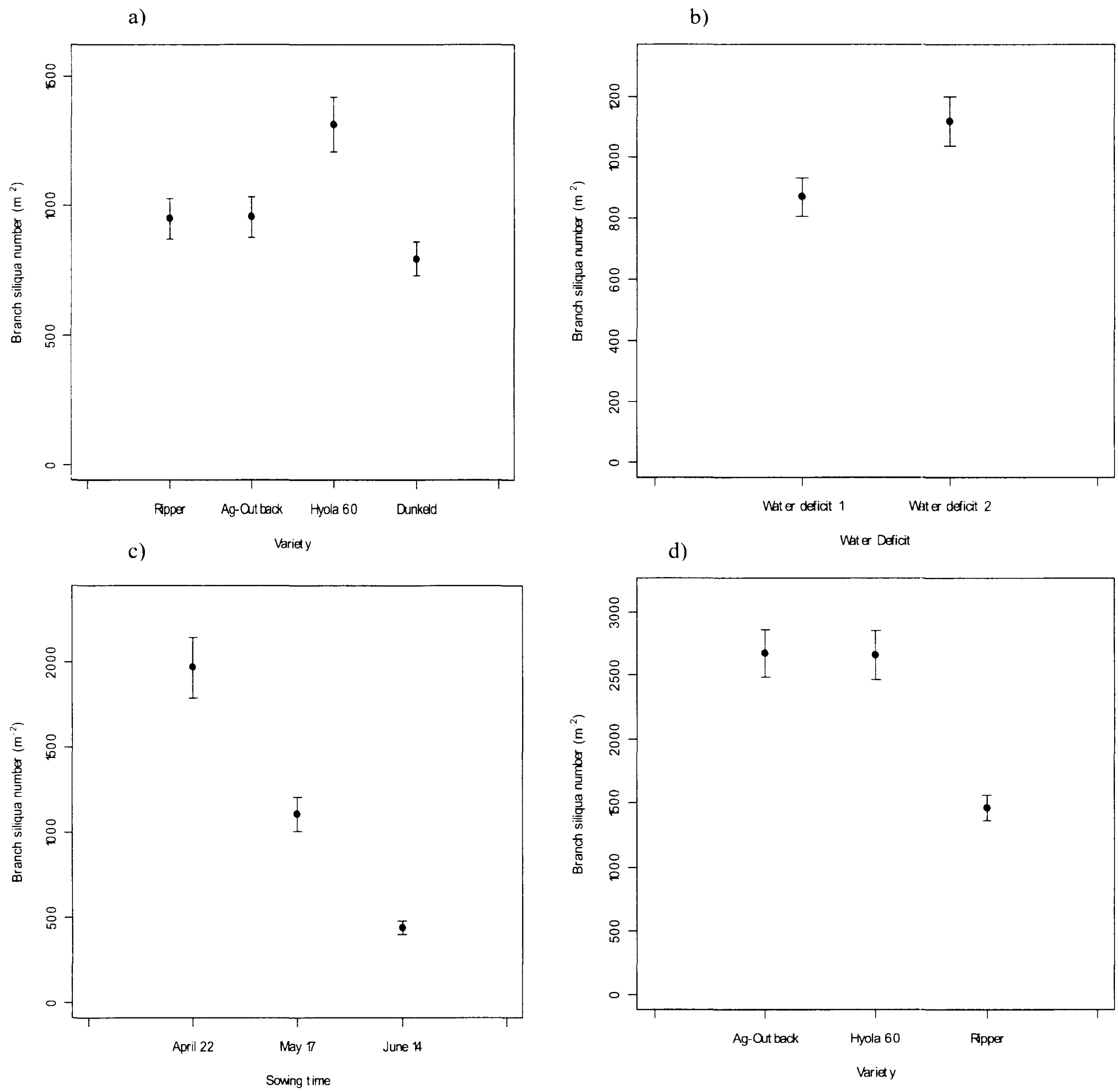

Figure 4.21 The effects of variety (a), water deficit (b) and sowing time (c) of canola at Condobolin in 2002 and variety (d) of canola at Condobolin in 2003 on branch siliqua number (m^{-2}). Error bars represent +/- one standard error at the 5% significance level.

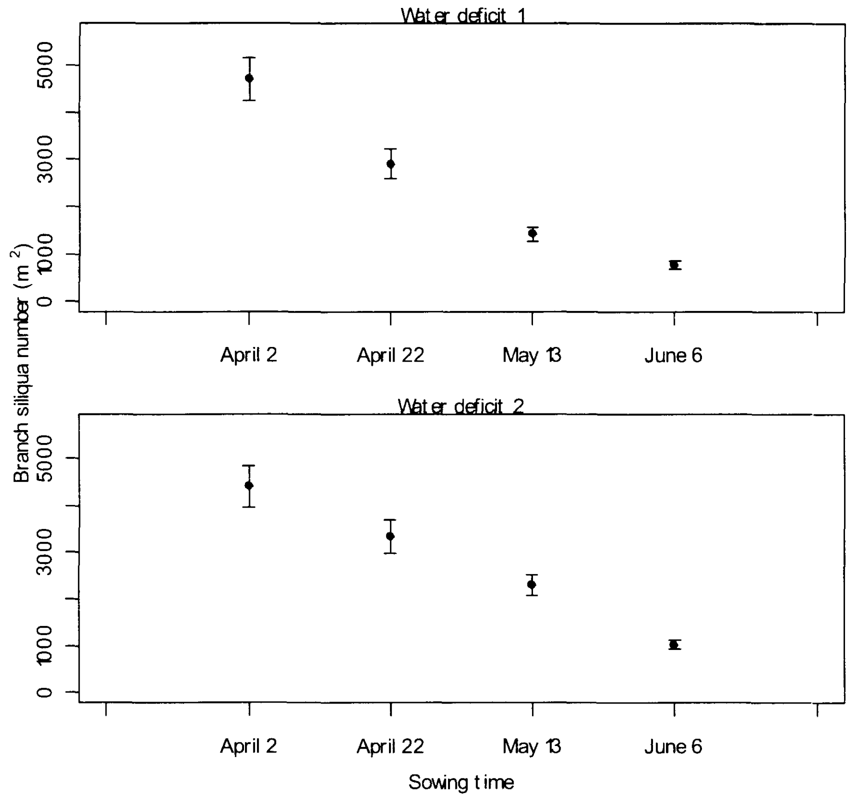

Figure 4.22 The effects of sowing time and water deficit on branch siliqua number (m^{-2}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

4.2.10 Plant height

The interactions of sowing time and variety (P=0.012), variety and days after sowing (P<0.001) and sowing time, water deficit and days after sowing (P=0.009) all had significant effects on plant height (m) of canola sown at Condobolin in 2002. The predicted values for the effects of sowing time and variety on plant height are presented in Figure 4.23. Ag-Outback recorded a significantly lower plant height than Hyola 60, Dunkeld and Ripper for the April 22 sowing time. Dunkeld recorded a significantly lower plant height than Hyola 60, Ag-Outback and Ripper for the May 17 and June 14 sowing times. The April 22 sowing time recorded a significantly higher plant height than the May 17 sowing time which recorded a significantly higher plant height than the June 14 sowing time for all four canola varieties. Figure 4.24 presents the effect of variety on plant growth throughout the growing season. There were no significant differences between varieties in plant height 85 days after sowing. At 106 days after sowing Hyola 60 recorded a significantly higher plant height than Ripper and Dunkeld whilst recording a significantly higher plant height than Ripper, Ag-Outback and Dunkeld 128 days after sowing. There were no significant differences in plant height at 147, 168 and 189 days after sowing. Figure 4.25 presents the significant effects of water deficit and days after sowing on plant height; water deficit two recorded a significantly higher plant height than water deficit one throughout the growing season for the April 22, May 17 and June 14 sowing times with the exception of the final reading for the June 14 sowing time 136 days after sowing, when there was no significant difference recorded between water deficit one and water deficit two.

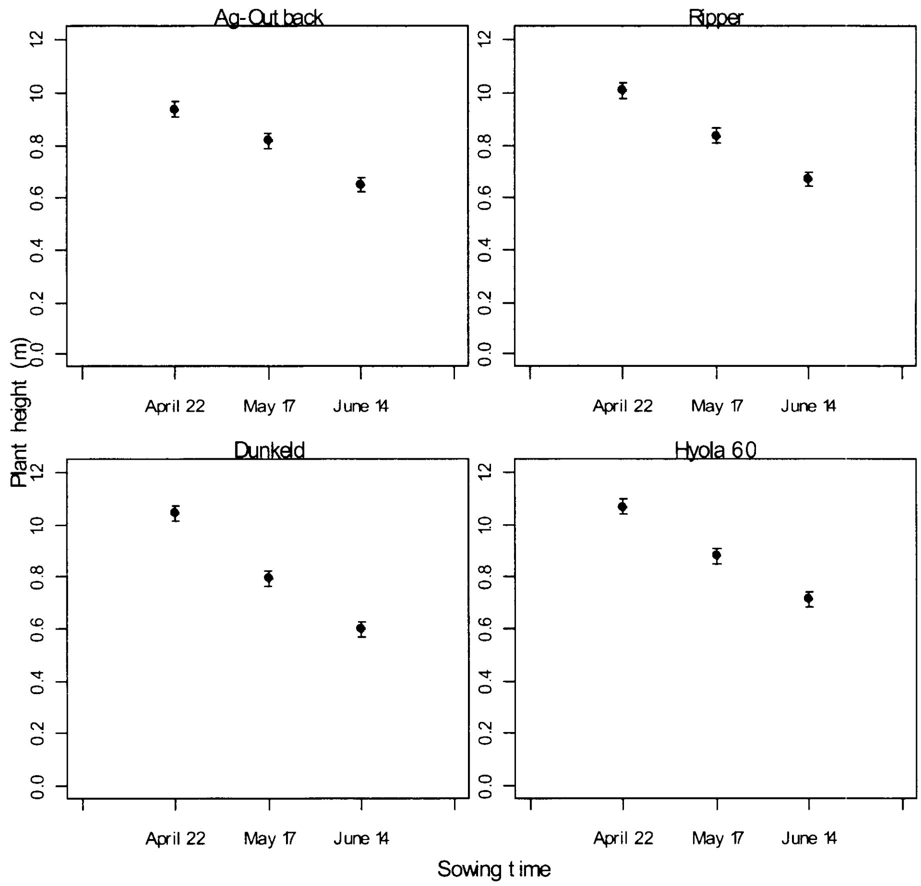

Figure 4.23 The effects of sowing time and variety on plant height (m) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

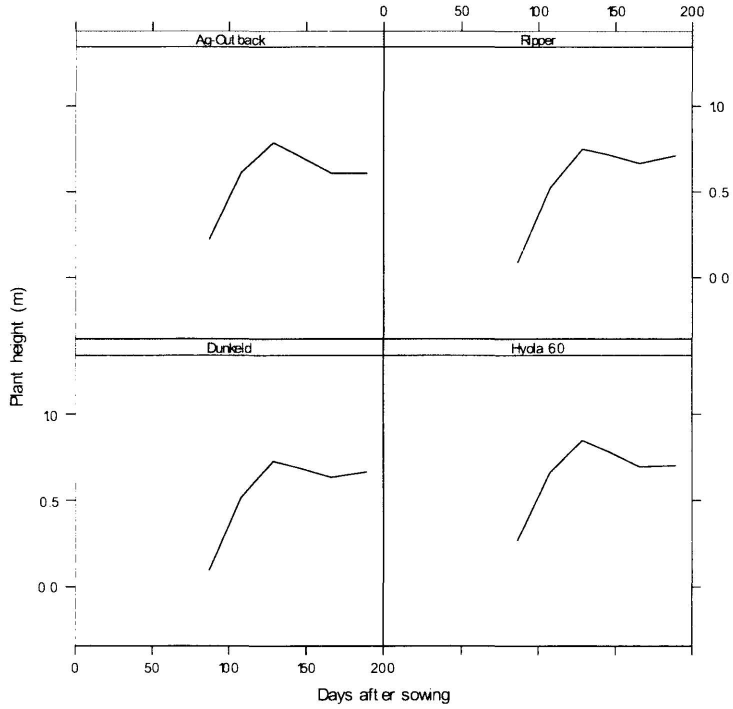

Figure 4.24 The effects of variety and days after sowing on plant height (m) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

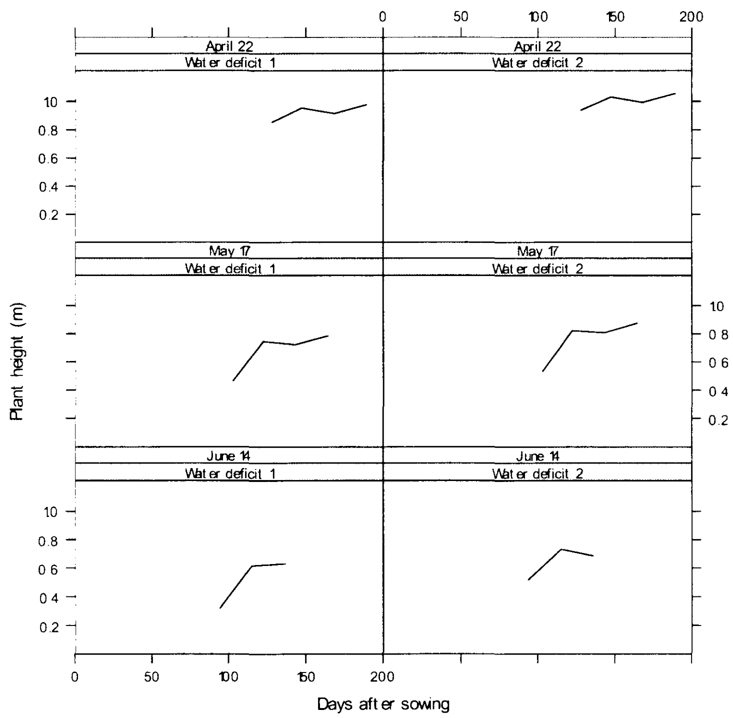

Figure 4.25 The effects of sowing time, water deficit and days after sowing on plant height (m) of canola at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

The interaction of sowing time and water deficit had a significant effect (P=0.014) on plant height of canola sown at Condobolin in 2003 (Figure 4.26). There were no significant differences for water deficit one or water deficit two sown on any of the four sowing times or between the four sowing times for water deficit one or water deficit two. There was however, a significant difference in plant height between water deficit two sown on June 6 and water deficit one sown on May 13. The June 6 sowing time recorded a significantly higher plant height than the other three sowing times for both water deficit one and water deficit two. Figure 4.27 presents the effects of variety and days after sowing (P=0.004) on plant height; Hyola 60 recorded a significantly higher plant height than Ripper and Ag-Outback from 69 days after sowing until 132 days after sowing after which Hyola 60 recorded a significantly higher plant height than Ag-Outback until 153 days after sowing. There was no significant difference at final harvest 174 days after sowing.

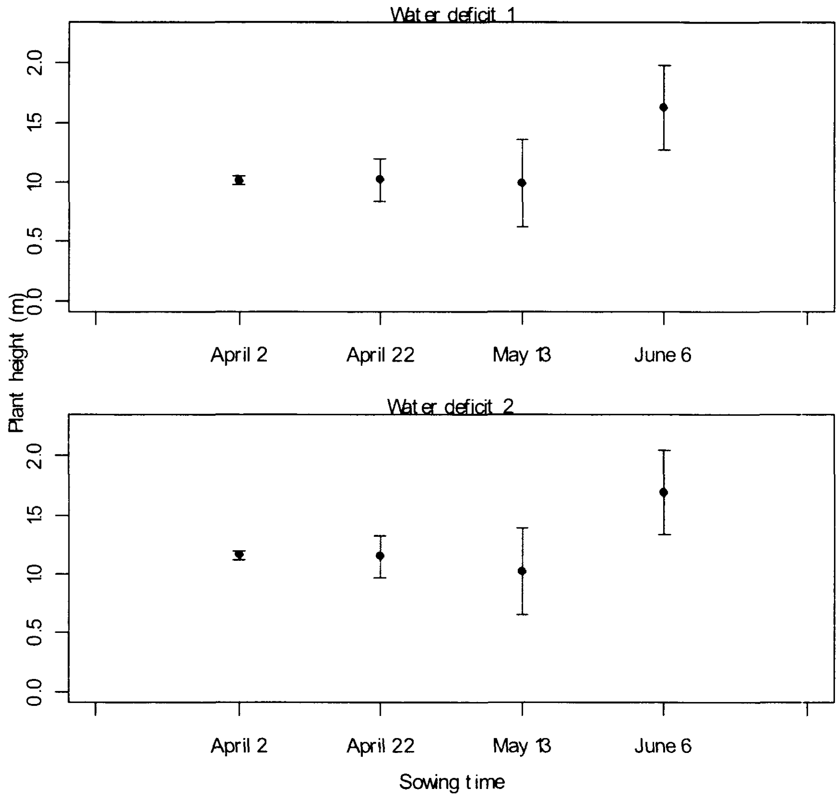

Figure 4.26 The effects of sowing time and water deficit on plant height (m) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

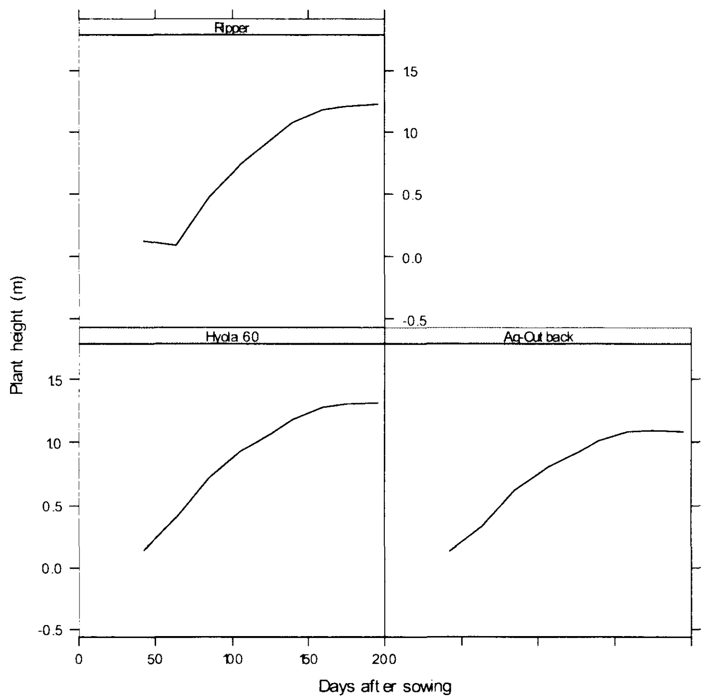

Figure 4.27 The effects of variety and days after sowing on plant height (m) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

4.2.11 Branch number

The interaction between water deficit, variety and sowing time had a significant effect (P=0.013) on branch number (m^{-2}) of canola sown at Condobolin in 2002 (Figure 4.28). The April 22 sowing time recorded a significantly higher branch number than the May 17 sowing time which recorded a significantly higher branch number than the June 14 sowing time for Ag-Outback water deficit two, Hyola 60 water deficit one and Dunkeld water deficit one. The April 22 sowing time recorded a significantly higher branch number than the May 17 and June 14 sowing times for Ag-Outback water deficit one and Ripper water deficit two. The June 14 sowing time recorded a significantly lower branch number than the April 22 and May 17 sowing times for Ripper water deficit one and Dunkeld water deficit two. There were no significant differences in branch number between the three sowing times for Hyola 60 water deficit two. Hyola 60 and Ag-Outback recorded a significantly higher branch number than Ripper and Dunkeld when sown on June 14 under water deficit two. There were no other significant differences between varieties sown across the three sowing times under the two water deficits.

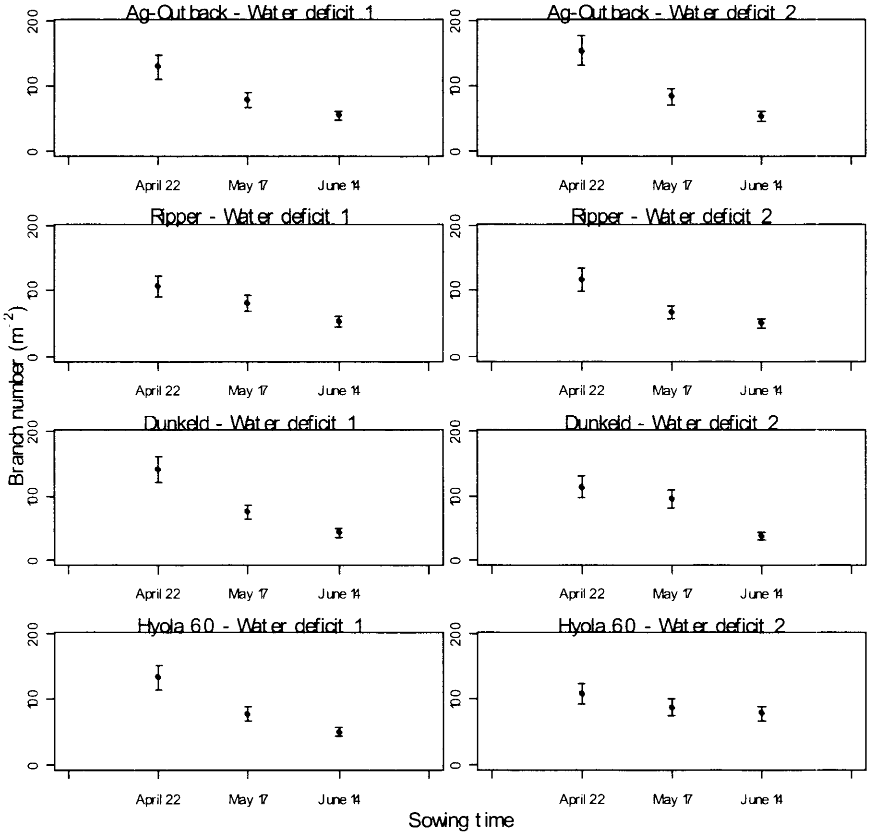

Figure 4.28 The effects of sowing time, variety and water deficit on branch number (m^{-2}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The interaction between water deficit, variety and sowing time had a significant effect (P=0.026) on branch number of canola sown at Condobolin in 2003 (Figure 4.29). The April 2 sowing time recorded a significantly higher branch number than the April 22 sowing time which was significantly higher than the May 13 and June 6 sowing times for Ag-Outback water deficit one. The June 6 sowing time recorded a significantly lower branch number than the April 2, April 22 and May 13 sowing times for Ag-Outback water deficit two and Hyola 60 water deficit two. Ag-Outback recorded a significantly higher branch number than Hyola 60 and Ripper for water deficit one sown on April 2 and April 22 and water deficit two sown on April 2 and May 13. Ripper recorded a significantly lower branch number than Hyola 60 and Ag-Outback sown on April 22 for water deficit two.

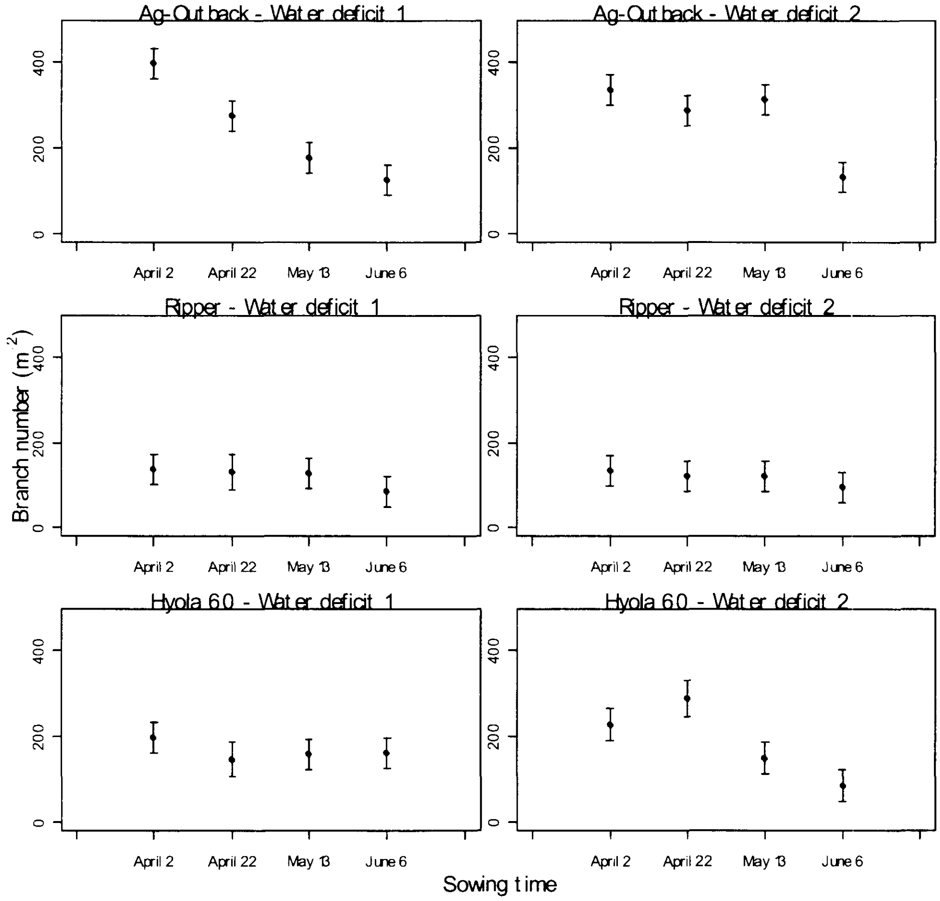

Figure 4.29 The effects of sowing time, variety and water deficit on branch number (m^{-2}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

4.2.12 Harvest index

The interaction of variety and sowing time had a significant effect (P=0.011) on harvest index of canola sown at Condobolin in 2002 (Figure 4.30). The June 14 sowing time recorded significantly lower harvest index than the April 22 and May 17 sowing times for Dunkeld and Ripper. There were no significant differences between sowing times for harvest index of Ag-Outback and Hyola 60. Ag-Outback and Hyola 60 recorded significantly higher harvest indices than Ripper and Dunkeld when sown on June 14.

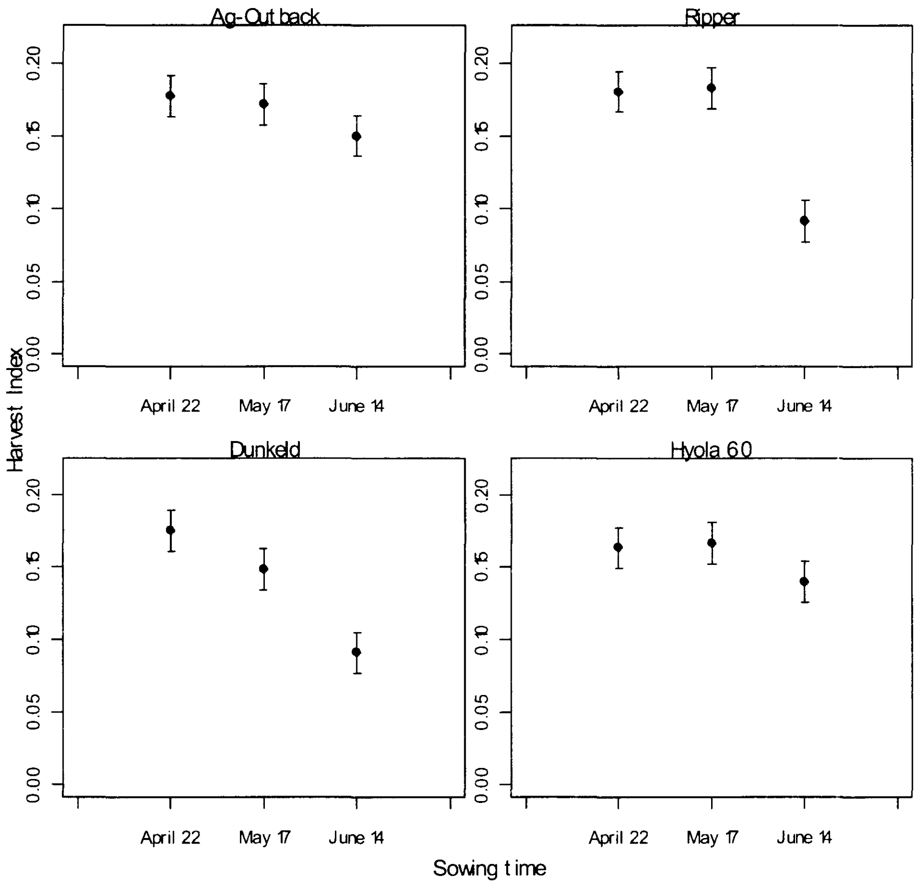

Figure 4.30 The effects of sowing time and variety on harvest index of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The main effects of sowing time and variety were significant (P<0.001) on harvest index of canola sown at Condobolin in 2003. The effects of sowing time are presented in Figure 4.31a. The April 2 sowing time recorded a significantly higher harvest index than the May 13 and June 6 sowing time and the April 22 sowing time recorded a significantly higher harvest index than the June 6 sowing time. Hyola 60 recorded a significantly lower harvest index than Ag-Outback and Ripper (Figure 4.31b).

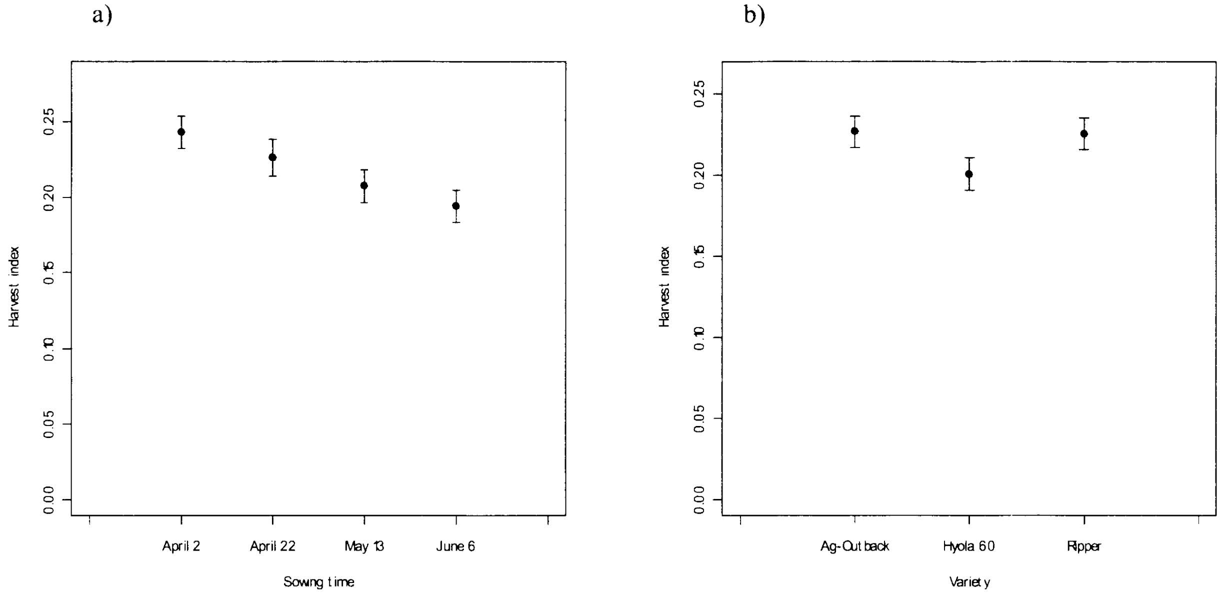

Figure 4.31 The effects of sowing time (a) and variety (b) on harvest index of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

4.3 Discussion

4.3.1 Leaf area

In these experiments, in the low rainfall region of south-eastern Australia, canola sown earlier than currently recommended by McRae *et al.* (2003) showed increased leaf area. A reduction in cumulative leaf area was observed in both years when sowing was delayed. The leaf area indices (LAI) achieved in 2002 for the April 22 sowing time and in 2003 for the April 2 sowing time correspond with the mean LAI reported by Thurling (1974a), Robertson *et al.* (2002b) and Cheema *et al.* (2001), but they were lower than those reported by Mendham *et al.* (1990) and the simulated value predicted by the APSIM model in Farre *et al.* (2002). The LAI achieved in both years did not reach a level that would provide maximum light interception according to Walton *et al.* (1999) who report that a LAI of 4.0 is required to intercept 90% of solar radiation. This may be one of the factors influencing the low grain yields reported in Chapter five.

There was a sharp reduction in LAI as sowing time was delayed and this was especially evident in 2002. This rapid loss with delay in sowing time is attributed to the onset of the reproductive phase restricting further vegetative development, in particular leaf number and hence leaf area as reported by Scott *et al.* (1973). This also corresponds with reductions in dry matter production, reported later in this chapter, and grain yield (Chapter five) with delay in sowing time. There was a high positive phenotypic correlation in 2002 between maximum leaf area index and dry matter production (r = + 0.62) at maturity (Figure 4.32a), although there was a low positive phenotypic correlation between maximum leaf area index and grain yield (r = + 0.26) (Figure 4.33a). However, in 2003 there were moderate to high negative phenotypic correlations for both maximum leaf area index and dry matter production (r = - 0.54) at maturity (Figure 4.32b) and grain yield (r = - 0.67) (Figure 4.33b). The reasons for these differences between years is unclear and it would be advisable to conduct further experiments to determine if these negative correlations in 2003 were due to seasonal variation or occurred frequently and then could be investigated if they were not uncommon. Reductions in LAI due to later sowing have been observed by Jenkins and Leitch (1986), Mendham *et al.* (1981a) and Mendham *et al.* (1981b).

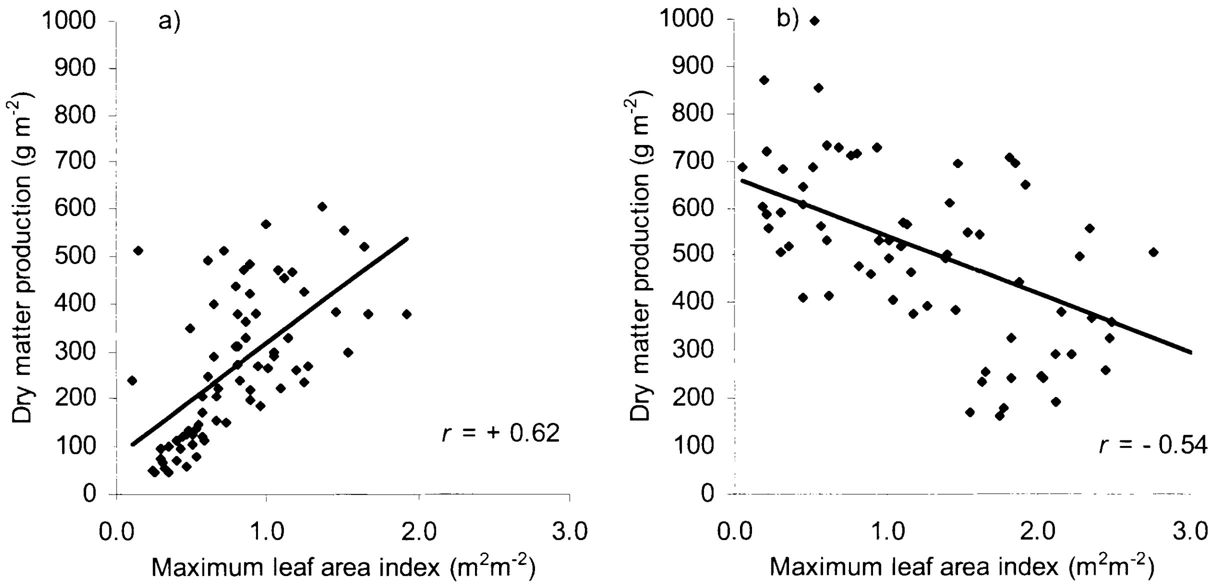

Figure 4.32 Phenotypic correlation between maximum leaf area index (m^2 m^{-2}) and dry matter production (g m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

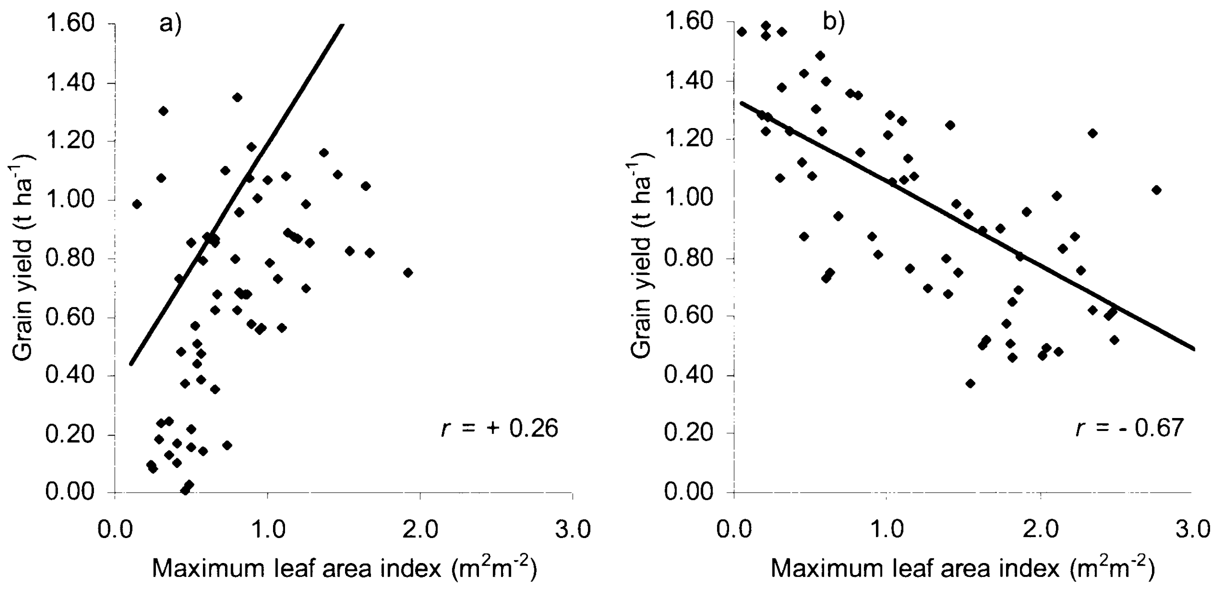

Figure 4.33 Phenotypic correlation between maximum leaf area index (m^2 m^{-2}) and grain yield (t ha^{-1}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

The decline in LAI after maximum leaf area index was recorded across all sowing times in both years and was attributed to the senescence of leaves due to shading from flowers and siliquas as plant growth progresses from the vegetative to the reproductive phase, as observed by Mendham *et al.* (1981a), Mendham *et al.* (1981b), Jenkins and Leitch, (1986) and Cheema *et al.* (2001). Differences in leaf area index were recorded between varieties in both years (Jenkins and Leitch, 1986), however these were unable to be distinguished due to the interaction of water deficit, sowing time and days after sowing with variety. Varietal response to LAI in *Brassica* species have been reported by Lewis and Thurling (1994) and Robertson *et al.* (2002b) who reported the differences to be due to variation in leaf size.

The effect of the water treatment on leaf area index was also difficult to assess due to the combined interaction of variety, water deficit, sowing time and days after sowing. However, in 2002 and 2003 the maximum LAI was achieved close to flowering in the later sowing times, while maximum LAI for the earlier sowing times was achieved up to five weeks before flowering. This would suggest that the application of additional water, in the water deficit two water treatment, in 2002 and 2003 was made at a time when leaf area would not have been influenced by additional water applications, since in both years additional water was applied after maximum leaf area index was achieved.

4.3.2 Dry matter production

Early sowing increases dry matter production of canola in low rainfall environments (Taylor and Smith, 1992). This is consistent with the findings of Hocking *et al.* (1997) who reported that sowing late at Condobolin reduced the biomass of canola and linola. Hocking and Stapper (2001) also reported reductions in dry matter production, of up to 58%, of canola sown at Ariah Park when sowing was delayed from April until June. In 2002, in the presented data, when sowing was delayed from April 22 until June 14, there was a reduction in dry matter production of 68%, and in 2003, when sowing was delayed from April 22 until June 6, there was a loss in dry matter production of 58%. These reductions in dry matter production with the later sowing times are reflected in the reduced siliqua dry weight, plant height, and branch number reported in this chapter and the grain yields reported in Chapter five.

Reductions in dry matter production with delayed sowing have been reported by Mendham *et al.* (1981a), Mendham *et al.* (1981b), Jenkins and Leitch (1986) and Gunasekera *et al.* (2001). Wright *et al.* (1988) reported similar dry matter production to that recorded for April 22 and April 2 sowing times in 2002 and 2003, and suggested that dry matter production was strongly related to the amount of incident light intercepted, which was calculated as a direct function of the crop's LAI. This being the case, the reduction in dry matter production with delayed sowing can be directly correlated with the reduced leaf area (Hocking and Stapper, 1993; Hocking and Stapper, 2001) reported previously in this chapter.

The loss in dry matter production in the later sowing times may also be attributed to the reduced length of the flowering period experienced by crops sown in the later sowing times (Table 4.1 and Table 4.2). The April 22 sowing time in 2002 flowered for 14 days longer than the June 14 sowing time, greatly reducing the potential to increase dry matter production through increased siliqua numbers and siliqua dry weight. Similar trends were observed in 2003 with the April 2 sowing time reaching peak flowering 126 days after sowing while the June 6 sowing time reached peak flowering only 88 days after sowing. This would suggest that the reduction in dry matter with delay in sowing time may also be due to a reduction in the length of the vegetative and reproductive phases, which has been reported by Thurling (1974a), Hocking (2001) and Hocking and Stapper (2001). This reduction in dry matter production led to reduced grain yield, oil concentration, and 1000-grain weight (Chapter five) and was attributed to reduced assimilate availability and increased temperature and moisture stress during critical growth periods (Aksouh *et al.* 2001).

Varietal effects presented for 2002 and 2003 were consistent with those reported by Mendham *et al.* (1981a), Mendham *et al.* (1981b) and Jenkins and Leitch (1986), who observed that differences in dry matter production between cultivars were generally quite small early in the season with larger differences becoming apparent, although not significant, later in the season. Conversely, Zaheer *et al.* (2000) reported that total dry matter production varied significantly among genotypes. This was observed in Hyola 60 sown on June 14 in 2002, which recorded higher dry matter production. This has been attributed to its high leaf area, siliqua dry weight and plant height which led to its high grain yield reported in Chapter five.

The increased dry matter production recorded for water deficit two is consistent with the increases in siliqua dry weight, siliqua number and plant height all of which contribute to dry matter production. The increase in dry matter production with increased water application has also been reported by Bernardi and Banks (1991) at Condobolin who reported increases in dry matter production of up to 33% when canola was provided with additional moisture applications.

4.3.3 Siliqua dry weight

Siliqua dry weight declined with delay in sowing time in both years, as did main raceme siliqua dry weight and branch siliqua dry weight. This has also been reported by Mendham and Scott (1975) and according to Morgan (1982), siliqua production is affected by the number of inflorescences, number of flowers (rate of production and duration of flowering), and the proportion of flowers forming siliquas that are retained until maturity. The reductions in siliqua dry weight with delay in sowing time were attributed to the restricted period of time the later sowings had to fill siliquas. The June 14 sowing time in 2002 recorded 20 days less (Table 4.1) for grain fill to occur, and the June 6 sowing time in 2003 recorded 25 less (Table 4.2) in which grain fill occurred as compared with the April 22 and April 2 sowing times, respectively. Individual siliqua dry weight also decreased with delay in sowing time, however, the June sowing times in both years recorded individual siliqua dry weights similar to the April sowing times.

Tayo and Morgan (1979) reported the importance of the supply of carbon assimilates from before, until well after, anthesis in regulating the weights attained by individual siliquas and their constituents. Tommey and Evans (1992) also reported that reductions in siliqua dry weight were due to overall reductions in biomass. The presented results support these findings with phenotypic correlations of leaf area and dry matter production with siliqua dry weight in 2002 indicating a high positive correlation with $r = + 0.68$ for leaf area (Figure 4.34a) and $r = + 0.77$ (Figure 4.35a) for dry matter production. However, in 2003 a high negative correlation between leaf area and siliqua dry weight was recorded ($r = - 0.71$) (Figure 4.34b) but a high positive correlation between dry matter production and siliqua dry weight was recorded ($r = + 0.74$) (Figure 4.35b). These differences between 2002 and 2003 may be due to seasonal variations associated with both years similar to those which caused the poor correlations in Figures 4.32 and 4.33.

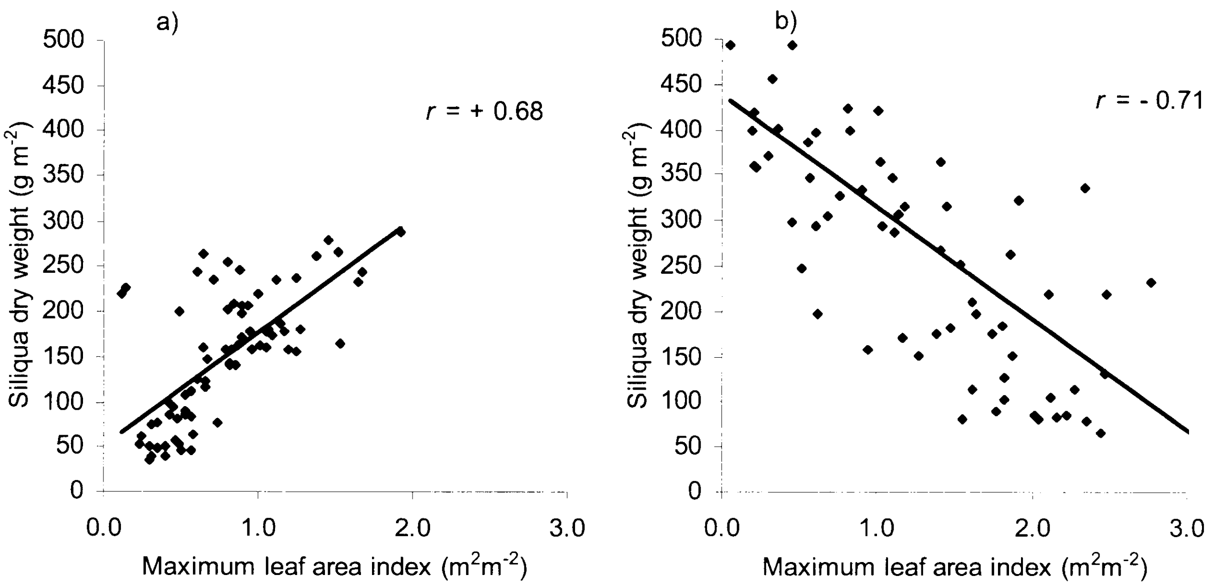

Figure 4.34 Phenotypic correlation between siliqua dry weight (g m^{-2}) and maximum leaf area index (m^2 m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

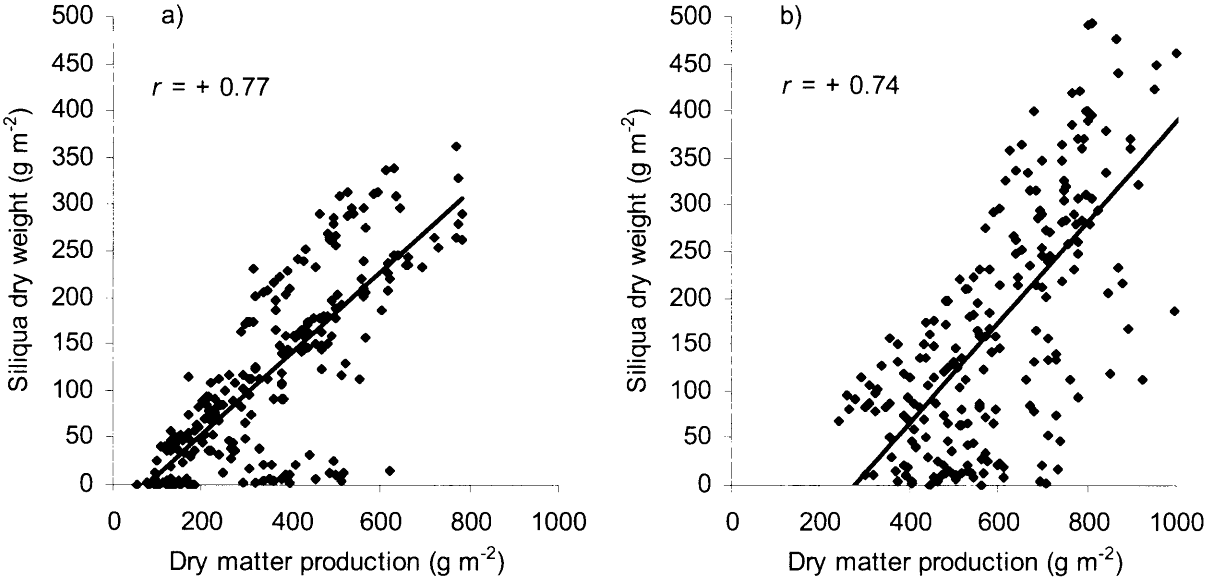

Figure 4.35 Phenotypic correlation between siliqua dry weight (g m^{-2}) and dry matter production (g m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

In 2003 there were losses in siliqua dry weight at maturity particularly in the later sowing times of May and June. Reductions in siliqua dry weight at maturity have been reported by Tayo and Morgan (1979), Pechan and Morgan (1985), McGregor (1987) and Wright *et al.* (1996), all of whom report the importance of the supply of photosynthates and assimilates for siliqua production. The reduced siliqua dry weight at maturity may also be due to shading by flowers and siliquas as reported by Mendham and Scott (1975), Morgan (1982), Chapman *et al.* (1983) and Daniels *et al.* (1986).

Varietal differences were observed for siliqua dry weight, main raceme siliqua dry weight, and branch siliqua dry weight in 2002 and 2003. In 2003 Ag-Outback recorded a significantly higher branch siliqua dry weight than Hyola 60 and Ripper. This also occurred in 2003 for the April 22 and May 13 sowing times for main raceme siliqua dry weight. This was attributed to the moderate positive phenotypic correlation between plant height and siliqua dry weight recorded in 2002 (r = + 0.56); however, this correlation was low in 2003 (r = + 0.23) (Figure 4.36) and does not correspond with the results recorded for plant height with Hyola 60 recording a higher plant height in 2003. Mendham *et al.* (1981a) demonstrated that plant size at initiation could be directly correlated with the number of axillary inflorescences, flowers and ultimately siliquas produced by the crop.

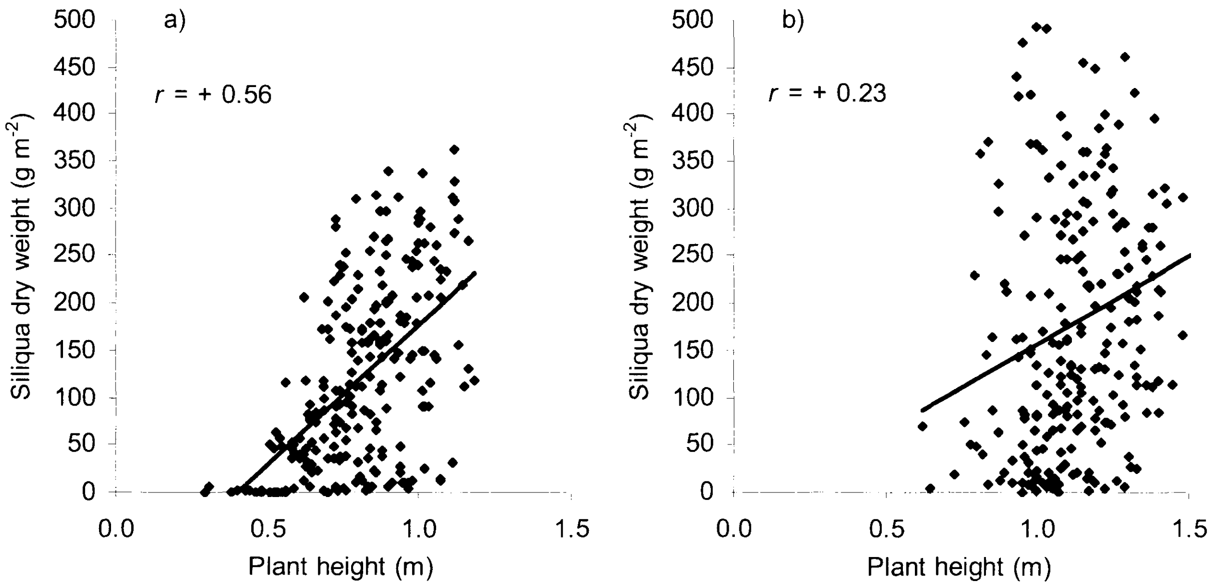

Figure 4.36 Phenotypic correlation between siliqua dry weight (g m^{-2}) and plant height (m) of canola sown at Condobolin in 2002 (a) and 2003 (b).

The increased siliqua dry weight, branch siliqua dry weight and main raceme siliqua dry weight recorded for water deficit two has also been reported by Bernardi and Banks (1991) at Condobolin with an increase in pod dry matter of 38% when additional water was applied.

4.3.4 Siliqua number

Sowing early increased the number of siliquas, main raceme siliqua number, and branch siliqua number. The reduction in siliqua number with delayed sowing was attributed to the earlier sowing times providing more assimilates during siliqua production. This was achieved through increased vegetative growth indicated by high dry matter production, greater leaf area, more branching, and taller plants, as reported in this chapter, and through reproductive growth occurring when temperature and moisture stress were reduced. This is also reflected in the higher grain yield and 1000-grain weight reported for earlier sowing times in Chapter five. Mendham (1981) reported that siliqua number always declines with later sowing and related this to the reduced primary leaf and branch number of later sown plants. This corresponds with results from both years with high positive phenotypic correlations between branch number and siliqua number of $r = +0.72$ in 2002 and $r = +0.62$ in 2003 (Figure 4.37). Mendham (1981) also noted that early sowings appear to carry too many siliquas, and this may suggest that plants were unable to support the amount of siliquas that were initially produced leading to the loss in siliqua number recorded at maturity in 2002 and 2003.

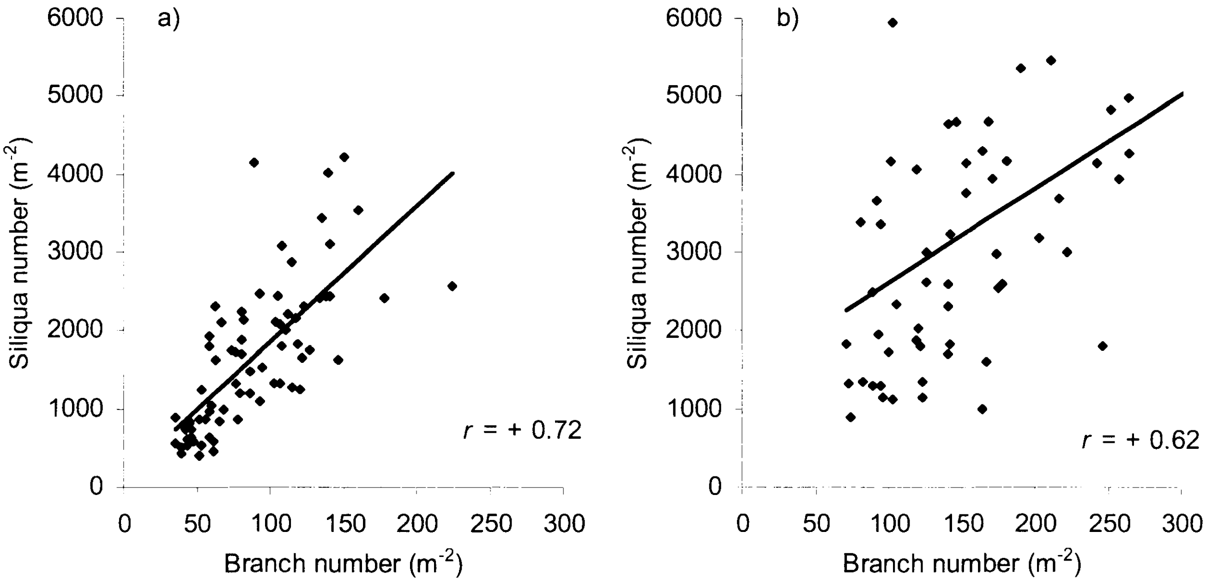

Figure 4.37 Phenotypic correlation between branch number (m^{-2}) and siliqua number (m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

Thurling (1974a), Mendham and Scott (1975), and Tayo and Morgan (1975) reported a reduction in siliqua number with delayed sowing and suggested that the loss in siliqua number may be due to fewer flowers being produced. The reduction in siliqua number reported for the later sowing times in 2002 and 2003 correspond with these reports, where later sowing times had reduced flowering periods (Table 4.1 and Table 4.2).

Jenkins and Leitch (1986) also associate loss in siliqua number with autumn growth and plant size. Mendham *et al.* (1981a) also demonstrated that plant size at initiation could be directly correlated with the number of axillary inflorescences, flowers, and ultimately siliquas produced by the crop. This corresponds with the results reported in this thesis with an r value of + 0.77 recorded for plant height at maturity and siliqua number in 2002 (Figure 4.38a). However there was only a low positive phenotypic correlation recorded in 2003 with r = + 0.19 (Figure 4.38b). Taylor and Smith (1992) reported that the length of the stem elongation period was proportionate to the number of siliquas produced. This may suggest that the plants in the later sowing times were smaller at inflorescence initiation due to a reduction in the stem elongation phase (Table 4.1 and Table 4.2) which resulted in a reduction in the number of axillary inflorescences.

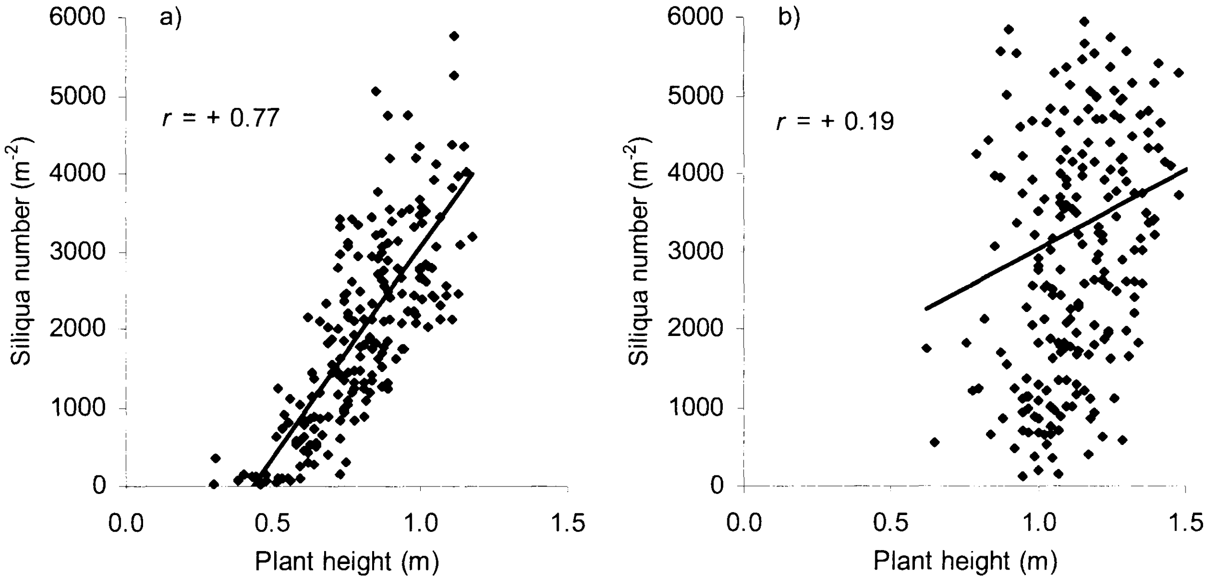

Figure 4.38 Phenotypic correlation between plant height (m) and siliqua number (m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

Reductions in siliqua number at maturity were recorded in 2002 and 2003 across all sowing times. This was attributed to the lack of assimilates available for the siliquas and shading from late flowers and early formed siliquas as discussed earlier in this chapter. Tayo and Morgan (1979) and Habekotte (1993) also reported that this may be due to a decrease in the supply of carbon assimilates to the developing inflorescences. This would suggest that the later sowing times may have had less available assimilates indicated by their reduced dry matter production and did not have the capacity to maintain the number of siliquas.

This reduction in siliqua number at maturity has also been reported by Mendham *et al.* (1981a), Mendham *et al.* (1981b) and Daniels *et al.* (1986) who suggested that a loss in siliqua number was a result of shading. Mendham and Scott (1975) reported that at most only half the potential yield bearing siliquas contributed to final yield and in some cases the siliquas only represented 30% of the potential. This suggests that a canola plant with the largest number of siliquas does not necessarily lead to the highest grain yield. Mendham *et al.* (1981a) suggested that the highest yielding crop may be one which makes good growth before flowering, but produces only a small number of siliquas, each with many seeds. This would be particularly beneficial in low rainfall environments where competition for soil moisture and assimilates may be high, and suggests that there is a balance which needs to be achieved between potential production and maximum yield. Mendham (1981) also reported heavy seed abortion in the earliest siliquas to set seed in the lower parts of the canopy, as they were shaded by flowers and siliquas and as a large number of siliquas were competing for assimilates. Therefore, there may be some advantage in taller plants producing more main raceme siliquas, which are closer to the carbon source (main raceme). Johnson *et al.* (1995) associated loss in siliqua numbers with hot and dry conditions during the reproductive phase of development. This would suggest that the loss in siliqua number with later sowing is due to the increased temperature and moisture stress experienced during reproductive growth compared with the earlier sowing times where reproductive growth occurs under cooler temperatures and less moisture stress.

There were no significant varietal differences in siliqua number in 2002 from the interaction of water deficit, sowing time, variety and days after sowing and this is supported by the findings of Johnson *et al.* (1995 and Lewis and Thurling (1994). However, Hyola 60 recorded higher main raceme siliqua number and branch siliqua number and this was attributed to its greater plant height and branch number, which are reported in this chapter. The importance of the main raceme siliqua number is highlighted by Campbell and Kondra (1978), who reported that the numbers of siliquas on the main raceme are major contributors to yield. In 2003 there were some varietal differences in siliqua number, which have also been reported by Scott *et al.* (1973), Thurling (1974b), Hodgson (1979b), Morgan (1982), Jenkins and Leitch (1986), Mendham *et al.* (1990), Taylor and Smith (1992) and Thurling and Kaveeta (1992b). Ag-Outback recorded higher overall siliqua number than the other varieties, and this corresponds with results reported in this chapter for plant height and branch number with Ag-Outback recording a high branch number. There was a loss in siliqua number at the end of the growing season and this may suggest that its high number of branches caused shading of siliquas and subsequent loss of siliquas as reported by Mendham *et al.* (1981a); Mendham *et al.* (1981b); Morgan, (1982) and Daniels *et al.* (1986).

The application of additional water representing water deficit two significantly increased siliqua number, main raceme siliqua number and branch siliqua number in both years. Clarke and Simpson (1978) reported that a high irrigation level caused an increase in the number of branches per plant and hence an increase in siliqua number. This corresponds with the high positive phenotypic correlation between branch number and siliqua number in 2002 (r = + 0.72) and 2003 (r = + 0.62) (Figure 4.37). This may also be attributed to a lengthening of the flowering period and reductions in water stress increasing assimilate supply (Clarke and Simpson, 1978; Wright *et al.* 1988). The flowering period was lengthened for the water deficit two, water treatment in 2003 by 14 days (Table 4.2).

4.3.5 Plant height

Plant height decreased with delay in sowing time in 2002; however, this did not occur in 2003 with the June 6 sowing time recording the highest plant height. The reduction in plant height with delayed sowing was attributed to reduced leaf area and dry matter due to shortening of the vegetative and reproductive growth phases as reported by Hocking (2001) and Hocking and Stapper (2001). This reduced plant height with delayed sowing may have influenced branch number and subsequent siliqua numbers and dry weights resulting in the lower grain yields and 1000-grain weights reported in Chapter five for the later sowing times. High positive phenotypic correlations were recorded between plant height and branch number (r = + 0.78) (Figure 4.39a), and plant height and dry matter production in 2002 (r = + 0.86) (Figure 4.40a). However, in 2003 low negative phenotypic correlations were recorded with r values of - 0.04 for plant height and branch number (Figure 4.39b), and r = + 0.35 for plant height and dry matter production (Figure 4.40b). The high positive phenotypic correlations are consistent with the findings of Mendham *et al.* (1981a), Jenkins and Leitch (1986) and Johnson *et al.* (1995). Conversely, Hodgson (1979b) reported, in an experiment in northern New South Wales, no significant differences in plant height when sowing was earlier or later than July 12. This corresponds with the results recorded in 2003 where sowing time did not affect plant height, with the exceptions of the June 6 sowing time.

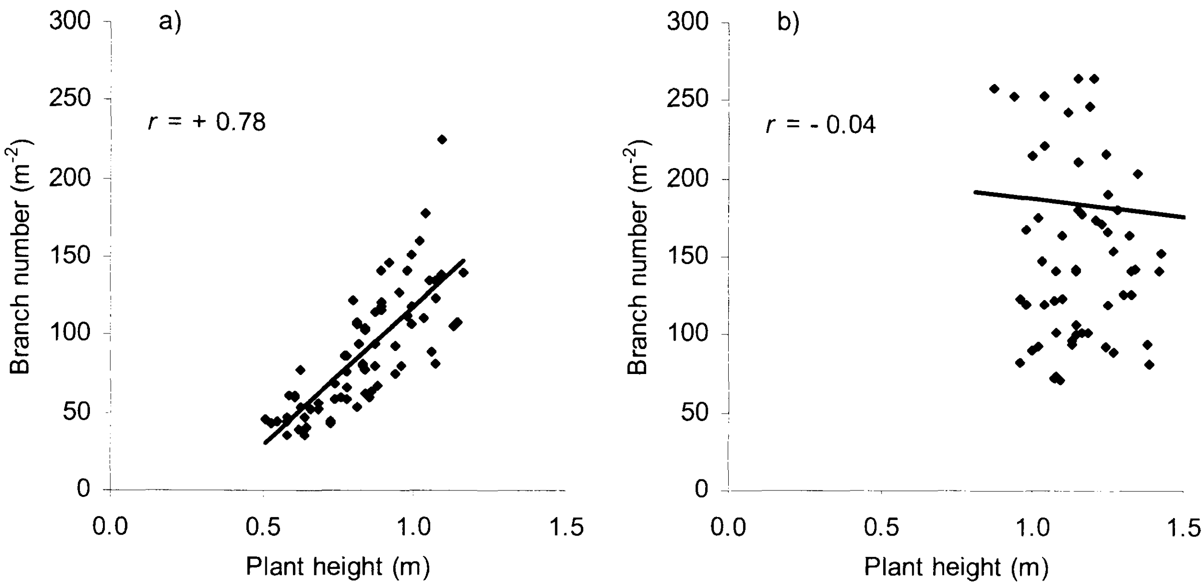

Figure 4.39 Phenotypic correlation between plant height (m) and branch number (m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

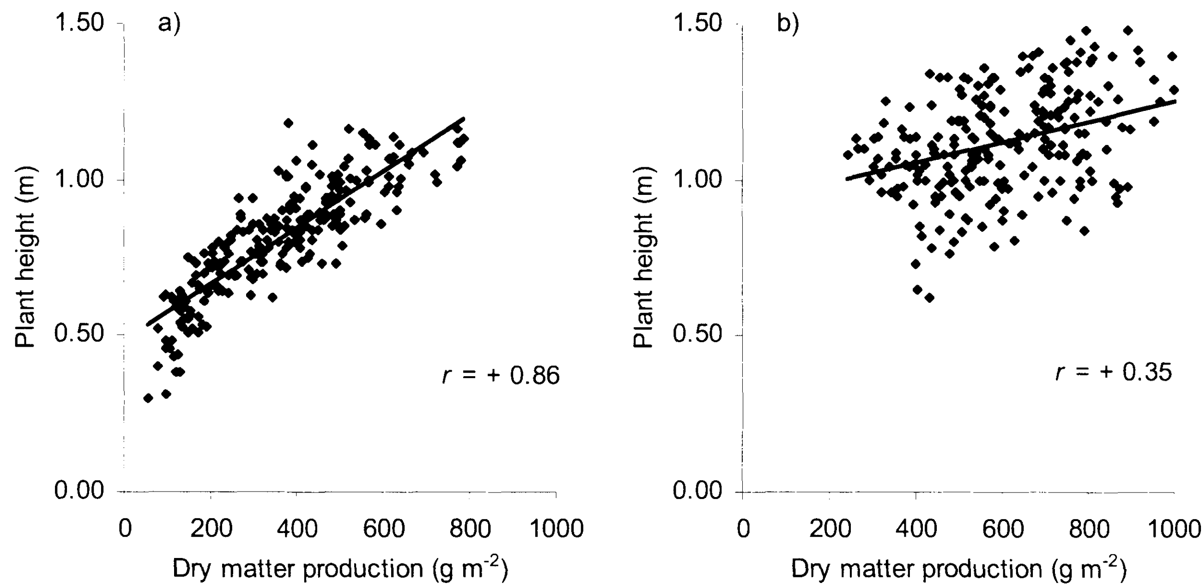

Figure 4.40 Phenotypic correlation between dry matter production (g m^{-2}) and plant height (m) of canola sown at Condobolin in 2002 (a) and 2003 (b).

There were some varietal differences recorded for plant height in 2002 and 2003 during the season although there was no significant difference in plant height at final harvest. The high plant height recorded by Hyola 60, which contributed to the higher main raceme siliqua number reported earlier in this chapter, was attributed to its consistently high leaf area and dry matter production with high positive phenotypic correlations reported previously in this chapter. This is supported by the findings of Hodgson (1979b) who reported that cultivar differences were significant for plant height in experiments conducted in northern New South Wales, and Jenkins and Leitch (1986) who reported differences in plant height for four canola varieties grown in Britain.

The significantly higher plant height recorded for water deficit two in 2002 is consistent with the findings of Bernardi and Banks (1991) who reported in an irrigation experiment conducted at Condobolin that plant height increased by up to 12% when compared with non irrigated water treatments.

4.3.6 Branch number

A reduction in branch number was recorded with delay in sowing time in both years. The reduction in branch number with delayed sowing was attributed to reduced dry matter production and plant height reported earlier in this chapter. Reductions in branch number with delay in sowing time have also been reported by Scarisbrick *et al.* (1981) and Johnson *et al.* (1995).

There were no significant individual differences in branch number recorded between canola varieties in 2002 and 2003, however there were combined differences in varieties associated with other interactions. Hyola 60 and Ag-Outback recorded a significantly higher branch number in water deficit two in 2002 and Ag-Outback recorded a higher branch number in 2003. Hyola 60's increased branch number may be attributed to increased dry matter production and plant height reported earlier in this chapter. Ag-Outback's higher branch number does not correspond with results recorded for dry matter production or plant height. Varietal differences in branching have been recorded by Richards and Thurling (1978b), Scarisbrick *et al.* (1981) and Morgan (1982).

In some cases in both 2002 and 2003 water deficit two recorded a higher branch number than water deficit one. This can be attributed to an increase in leaf area index, dry matter production and plant height as discussed earlier in this chapter. Clarke and Simpson (1978) reported an increase in branch number with the application of additional water, such as in water deficit two, and speculated that it was due to a lengthening of the flowering period which is consistent with the findings of this thesis where the flowering period was lengthened for the water deficit two, water treatment in 2003 by 14 days.

4.3.7 Harvest index

Early sowing of canola increased harvest indices in both 2002 and 2003. This was attributed, in part, to early sowing increasing dry matter production, reported previously in this chapter, and grain yield, reported in Chapter five. The increased harvest indices also suggest that the earlier sowing times were more efficient in converting dry matter to grain yield. This is very important when considering that canola production in low rainfall environments needs to be more efficient to allow successful production in water limited environments. The harvest indices reported in this thesis are similar to those reported by Cheema *et al.* (2001) who recorded harvest indices of 0.14 for canola grown in Pakistan. Reductions in harvest index with delay in sowing have been reported by Hocking and Stapper (2001) at Ariah Park where dry matter harvest indices for canola decreased between April and June sowings. Richards and Thurling (1978a and 1978b) also report reductions in harvest index with delay in sowing time in Western Australia, recording values similar to those in my experiments. Conversely, Thurling (1974a) reported increases in harvest index with delay in sowing time stating that harvest index is particularly responsive to environmental variation, which is clearly independent of the final dry weight of the plant. Mendham *et al.* (1981a), Taylor and Smith (1992) and Johnson *et al.* (1995) all reported lower harvest indices with early sowing times and attributed these to excessive stem growth and inefficient transfer of biomass to grain yield, while Hocking *et al.* (1997) reported that sowing time had little effect on the harvest index of canola, which is contrary to the findings in this thesis but may be associated with higher rainfall environments causing excessive stem growth which is less likely to occur in the lower rainfall regions such as at Condobolin.

There were varietal differences in harvest index recorded in both years. Hyola 60 and Ag-Outback recorded the highest harvest indices in 2002. However, in 2003 Hyola 60 recorded a significantly lower harvest index than the other varieties. The reason for this is unexplained. Zaheer *et al.* (2000) recorded significant variation among harvest indices of canola genotypes in Western Australia, as did Richards (1978), Campbell and Kondra (1978) and Taylor and Smith (1992). Hodgson (1979b) recorded variations in harvest index between varieties within the same sowing time. Niknam *et al.* (2003) suggests that the differences in varietal harvest index are due to osmotic adjustment with osmotic adjusting genotypes recording higher harvest indices than poor adjusting genotypes. This may have been the case, however, osmotic adjustment was not measured in these experiments. Conversely, Thurling and Kaveeta (1992a) recorded little differences in the harvest index of canola varieties in Western Australia.

4.4 Conclusions

Clearly, the effect of sowing time on plant growth is significant and greatly influences the growth parameters presented in this chapter which contribute directly to grain yield. When considering the low rainfall environment, it is important to maximise leaf area and dry matter production as these influence the yield determining components, namely, siliqua number and siliqua dry weight. Plant height and branch number also have significant roles to play and the balance between dry matter production and grain yield may be achieved through manipulating these components in the future. The work in this thesis shows that the most important determinants of plant growth in low rainfall environments are sowing time and variety. To achieve maximum yield in this low rainfall environment, increasing leaf area and dry matter production while achieving a balance between siliqua number and grain yield will lead to the production of successful canola crops. The increase in plant growth associated with water deficit two is also important although not as significant as sowing time and variety but demonstrates that increases in plant growth could be expected when increased rainfall does occur in these low rainfall environments illustrating the plant's capacity to respond and use moisture to increase production.

CHAPTER FIVE: YIELD AND YIELD COMPONENTS

5.1 Introduction

The use of canola as an alternative crop to cereals in higher rainfall regions, and in particular as a break crop for disease management (Kirkegaard *et al.* 1994; Kirkegaard *et al.* 1997), coupled with significant increases in its commodity price has seen production of canola in NSW grow from 56 000 hectares in 1900/1991 to 280 000 hectares in 2004/2005 (ABARE, 1996; ABARE, 2005). The use of canola and its rotational benefits have only recently been recognised by growers in the lower rainfall regions where there is a shift to more intensive cropping. However, little research has been conducted into the production of canola in the low rainfall regions of the south-eastern wheat belt of Australia due to canola's limited use as a rotational crop in these areas. For example, in the Condobolin region in 2001 growers planted 305 000 hectares of wheat compared to only 9 000 hectares of canola (Fitzsimmons, 2001).

The limited use of canola is due to the region's low and unpredictable rainfall (Hocking *et al.* 1997), leading to unacceptably low grain yields and oil concentrations. Current recommendations provided by New South Wales Department of Primary Industries report optimum sowing times from mid to late April (McRae *et al.* 2003). It is suggested that these sowing times are too late, and experiments were established at Condobolin in central western NSW to determine the optimum sowing time for successful canola production in these low rainfall regions. In 2002 there were three sowing times (April 22, May 17 and June 14) and in 2003 there were four sowing times (April 2, April 22, May 13 and June 6).

Having assessed the plant growth factors influencing canola growth in Chapter four, this chapter examines the effects of sowing time, variety, and water deficit on grain yield, oil concentration, protein concentration, and 1000-grain weight.

5.2 Results

5.2.1 Grain yield

There was a significant interaction ($P<0.001$) between sowing time, variety and water deficit for the grain yield (t ha^{-1}) of canola sown at Condobolin in 2002 (Figure 5.1). All eight canola varieties recorded significantly higher grain yield for the April 22 sowing time with the May 17 sowing time recording a significantly higher grain yield than the June 14 sowing time. Rivette recorded a significantly higher grain yield than all the other varieties with the exception of Rainbow when sown on April 22. Hyola 60 recorded a significantly higher grain yield than all other varieties with the exception of Rivette when sown on May 17. Hyola 60 also recorded a significantly higher grain yield than all other varieties when sown on June 14 with the exception of Ag-Outback.

Figure 5.2 presents the predicted values for the effects of sowing time and variety with water deficit two on grain yield. Rivette, Emblem, Hyola 60, Dunkeld and Ag-Outback recorded significantly higher grain yield for the April 22 sowing time compared with the May 17 sowing time recording a significantly higher grain yield than the June 14 sowing time. However, Oscar, Rainbow and Ripper recorded a significantly lower grain yield for the June 14 sowing time with no significant difference between the April 22 and May 17 sowing times. Hyola 60 recorded a significantly higher grain yield than all varieties when sown on April 22 with the exception of Ag-Outback and Rivette. Emblem and Dunkeld recorded a significantly lower grain yield than all other varieties when sown on May 17. Hyola 60 recorded a significantly higher grain yield than all other varieties when sown on June 14.

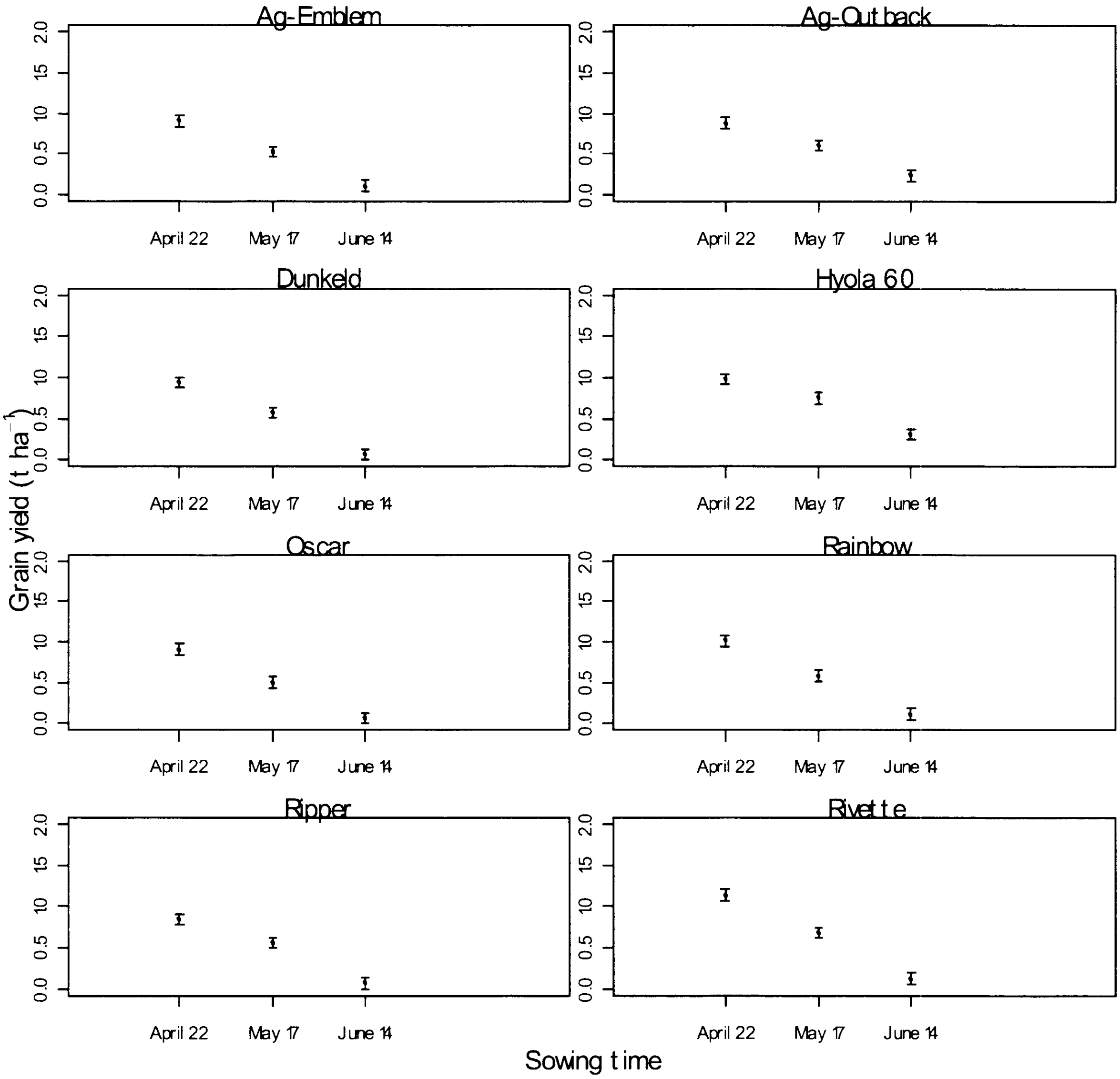

Figure 5.1 The effects of sowing time and variety with water deficit one on grain yield (t ha^{-1}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

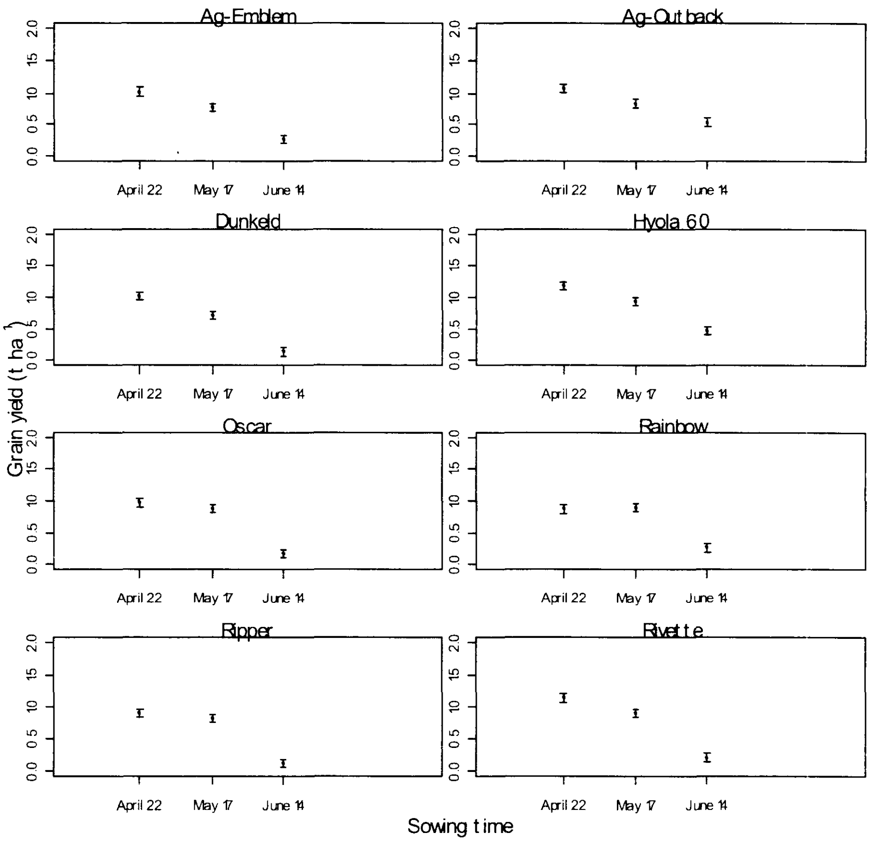

Figure 5.2 The effects of sowing time and variety with water deficit two on grain yield (t ha^{-1}) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

There was a significant interaction between sowing time and water deficit (P=0.008), variety and water deficit (P=0.002) and variety and sowing time (P=0.001) for grain yield of canola sown at Condobolin in 2003. Figure 5.3 presents the predicted values for the effects of sowing time and water deficit on grain yield. Water deficit two recorded a significantly higher grain yield for all four sowing times than water deficit one. The April 2 sowing time recorded a significantly higher grain yield than the April 22 sowing time which was significantly higher than the May 13 sowing time which was significantly higher than the June 6 sowing time in both water deficit one and water deficit two. Figure 5.4 presents the predicted values for the effects of variety and water deficit on grain yield. Water deficit two recorded a significantly higher grain yield than water deficit one for all varieties. Rainbow and Oscar recorded significantly higher grain yield than all other varieties for water deficit two. There was no significant difference between varieties for water deficit one. Figure 5.5 presents the predicted values for the effects of sowing time and variety on grain yield. The April 2 sowing time recorded a significantly higher grain yield than the April 22 sowing time for all six canola varieties. The May 13 sowing time recorded a significantly higher grain yield than the June 6 sowing time for all six varieties. The April 22 sowing time recorded a significantly higher grain yield than the May 13 sowing time for Hyola 60, Oscar and Rainbow; however, any such differences were not significant for Ag-Outback, Dunkeld and Ripper.

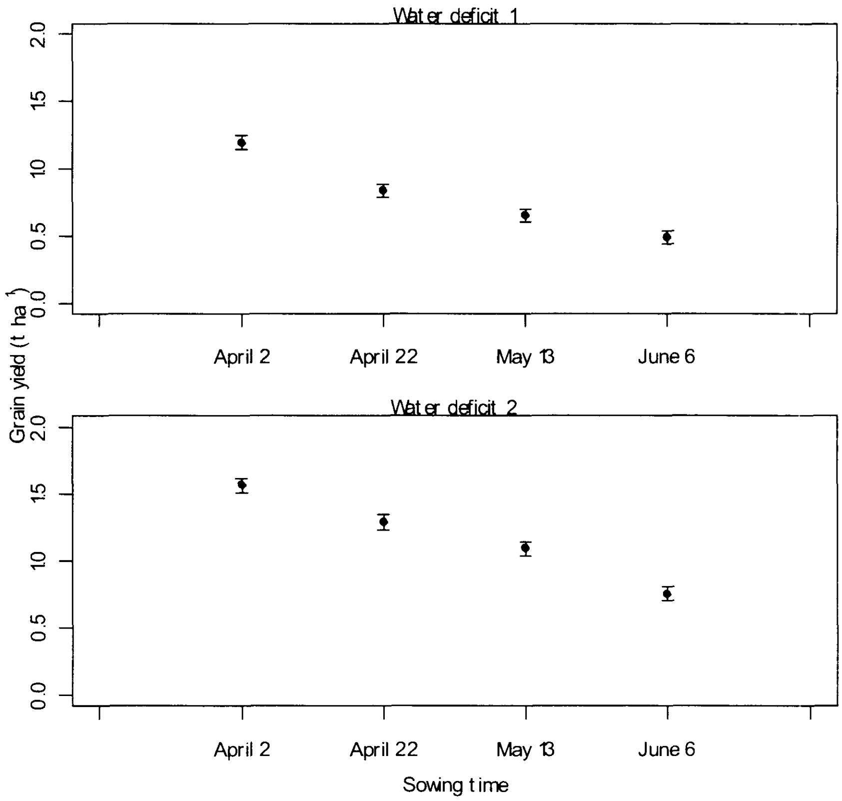

Figure 5.3 The effects of sowing time and water deficit on grain yield (t ha^{-1}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

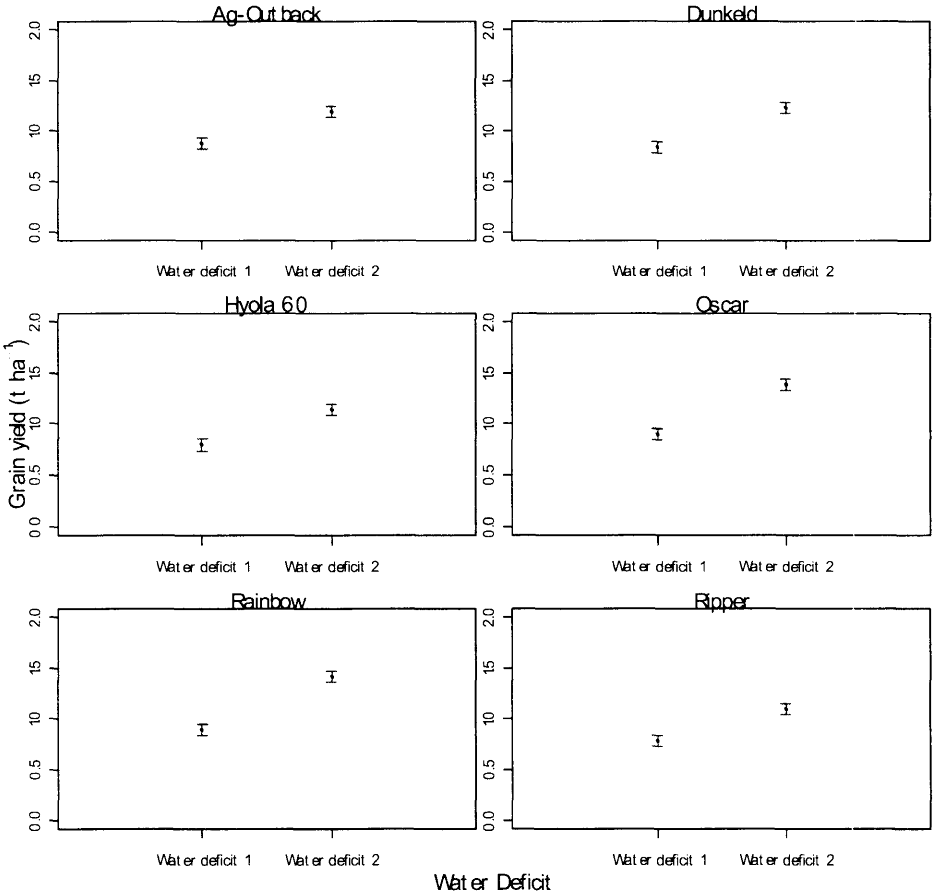

Figure 5.4 The effects of variety and water deficit on grain yield (t ha^{-1}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

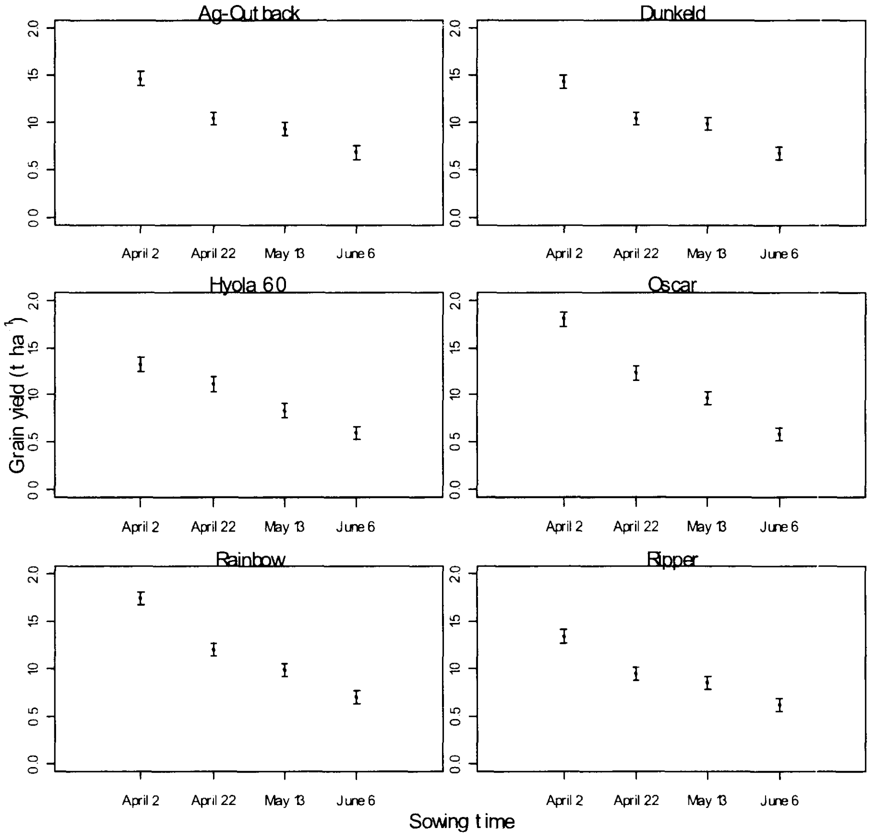

Figure 5.5 The effects of sowing time and variety on grain yield (t ha^{-1}) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

5.2.2 Oil concentration

The main effects of variety and sowing time had significant effects ($P<0.001$) on oil concentration (%) of canola sown at Condobolin in 2002. Figure 5.6a presents the predicted values for the effects of variety on oil concentration with Oscar recording a significantly lower oil concentration than all other varieties. Ripper, Hyola 60 and Rivette recorded a significantly higher oil concentration than all other varieties. Dunkeld recorded a significantly higher oil concentration than Emblem, Ag-Outback, Rainbow and Oscar. Figure 5.6b presents the effect of sowing time on oil concentration of canola at Condobolin in 2002. There was no significant difference in oil concentration of the April 22 and May 17 sowing time however they were both significantly higher than the June 14 sowing time.

The main effect of variety had a significant effect ($P<0.001$) on oil concentration as did the interaction between sowing time and water deficit ($P<0.001$) of canola sown at Condobolin in

2003. Figure 5.6c presents the effects of variety on oil concentration. Ripper recorded a significantly higher oil concentration than Hyola 60 with significant progressive reductions in oil concentration in the order of Dunkeld followed by Rainbow which was followed by Oscar. There was no significant difference in oil concentration between Oscar and Ag-Outback. Figure 5.7 presents the effects of the interaction between sowing time and water deficit on canola. Water deficit two recorded a significantly higher on oil concentration for the April 2, April 22 and May 13 sowing time however there was no significant difference between water deficit one and water deficit two for the June 6 sowing time. The April 2 sowing time recorded a significantly higher oil concentration than the other three sowing times for water deficit one. The April 2 sowing time also recorded a significantly higher oil concentration with significant progressive reductions in oil concentration with each delay in sowing time for water deficit two.

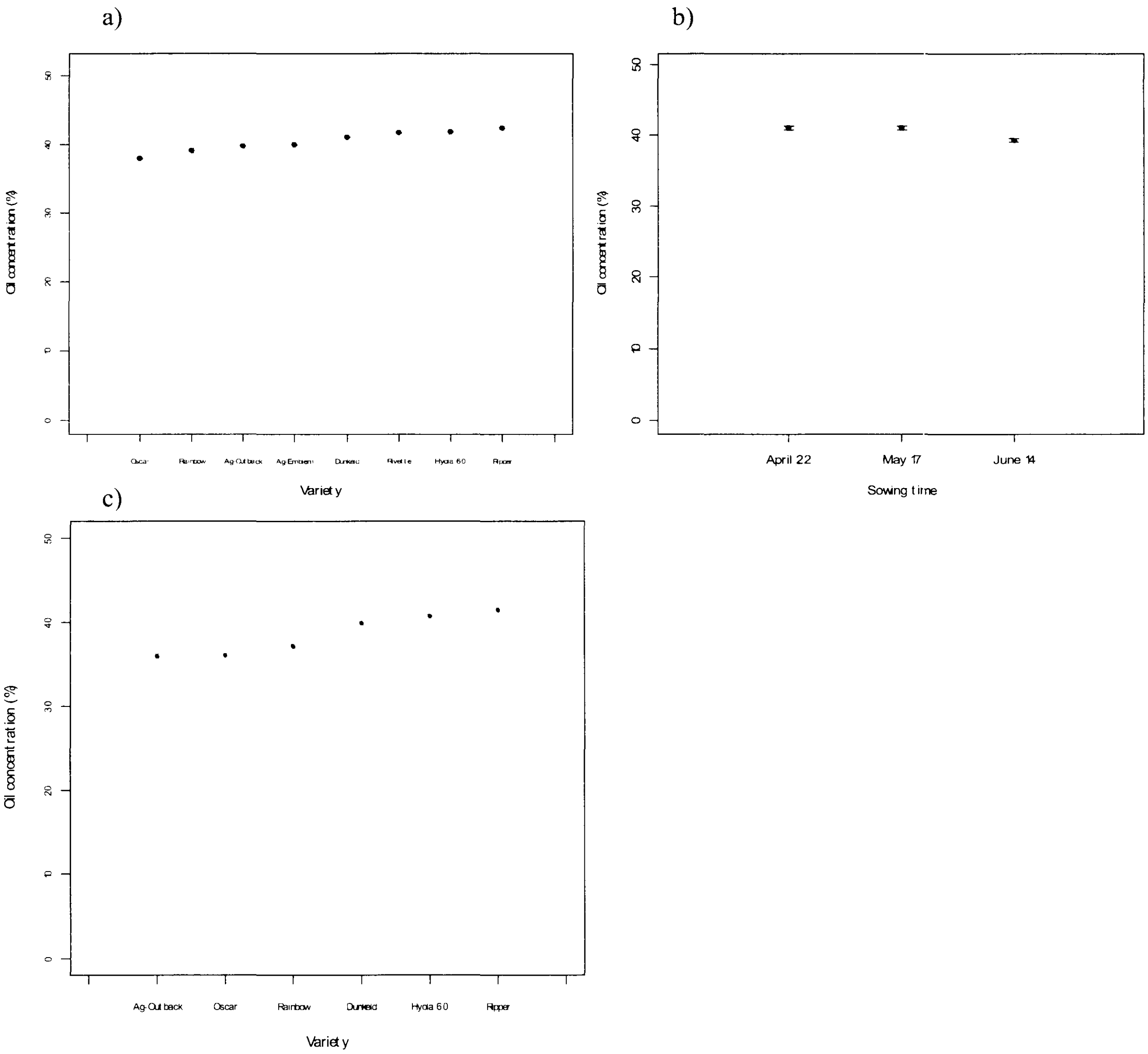

Figure 5.6 The effects of variety (a) and sowing time (b) of canola at Condobolin in 2002, and variety (c) of canola at Condobolin in 2003 on oil concentration (%). Error bars represent +/- one standard error at the 5% significance level.

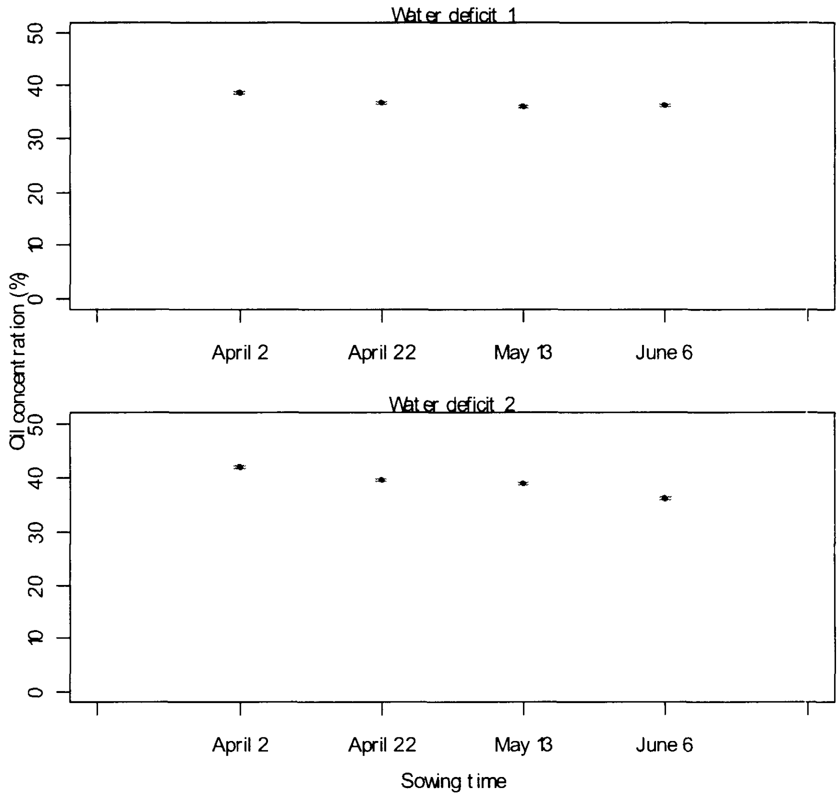

Figure 5.7 The effects of sowing time and water deficit on oil concentration (%) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

5.2.3 Protein concentration

Variety and sowing time had a significant effect (P<0.001) on the protein concentration (%) of canola sown at Condobolin in 2002. Figure 5.8a presents the effects of variety on protein concentration with Oscar and Hyola 60 recorded significantly higher protein concentration than all other canola varieties. Figure 5.8b presents the effects of sowing time on protein concentration with the June 14 sowing time recording a significantly higher protein concentration than the April 22 and May 17 sowing times. There was no significant difference between the April 22 and May 17 sowing times.

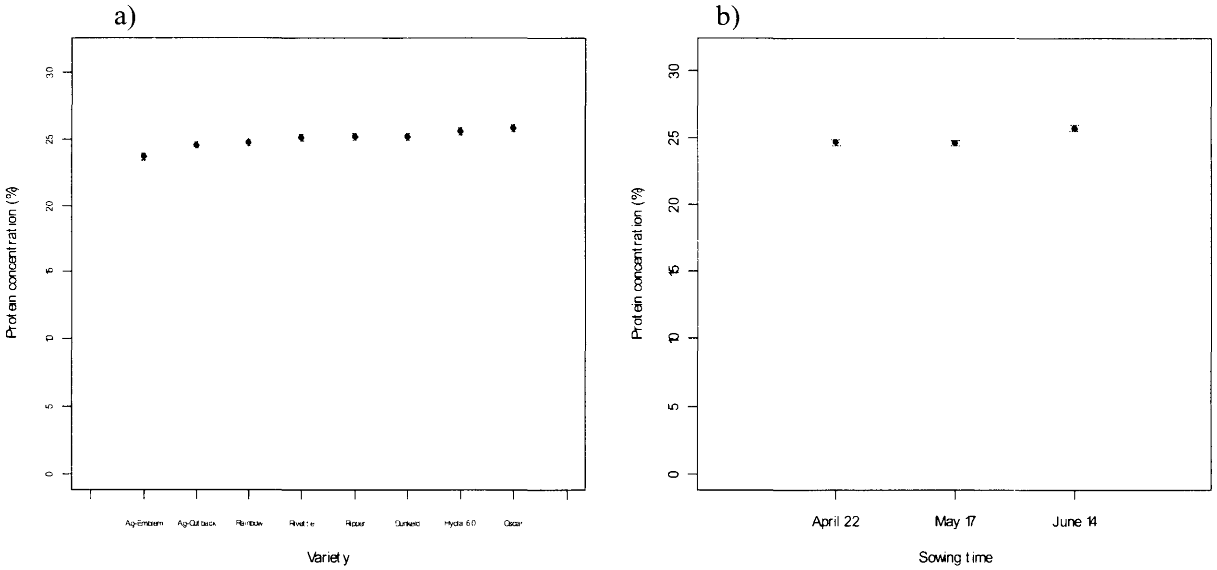

Figure 5.8 The effects of variety (a) and sowing time (b) on protein concentration (%) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The interactions of sowing time and water deficit ($P<0.001$) and sowing time and variety ($P=0.001$) had significant effects on the protein concentration of canola sown at Condobolin in 2003. Figure 5.9 presents the effects of sowing time and water deficit on protein concentration. Water deficit one recorded a significantly higher protein concentration than water deficit two for the April 2, April 22 and May 13 sowing times however there was no significant difference between the May 13 and June 6 sowing time. The June 6 sowing time recorded a significantly higher protein concentration with significant progressive reductions in protein concentration with each earlier sowing time for water deficit two. There was no significant difference in protein concentration between the June 6 and May 13 sowing times however these were significantly higher than the April 22 sowing time which recorded a significantly higher protein concentration than the April 2 sowing time for water deficit one. Figure 5.10 presents the predicted values for the effects of variety and sowing time on protein concentration. The June 6 sowing time recorded a significantly higher protein concentration than the May 13 sowing time which was significantly higher than the April 22 sowing time which was significantly higher than the April 2 sowing time for Ag-Outback, Dunkeld, Rainbow and Ripper. There was no significant difference in protein concentration (%) for the June 6 and May 13 sowing times for Hyola 60 and Oscar however they recorded a significantly higher protein concentration than the April 22 sowing time which recorded a significantly higher protein concentration than the April 2 sowing time. For the June 6 sowing time Hyola 60 recorded a significantly lower protein concentration than all other varieties. Oscar, Ripper and Hyola 60 recorded a significantly higher protein concentration than Dunkeld, Rainbow and Ag-Outback when sown on May 13. Dunkeld recorded a significantly lower protein concentration than all other varieties when sown on April 22 and Ag-Outback, Oscar and Hyola 60 recorded significantly higher protein concentration than Dunkeld, Rainbow and Ripper when sown on April 2.

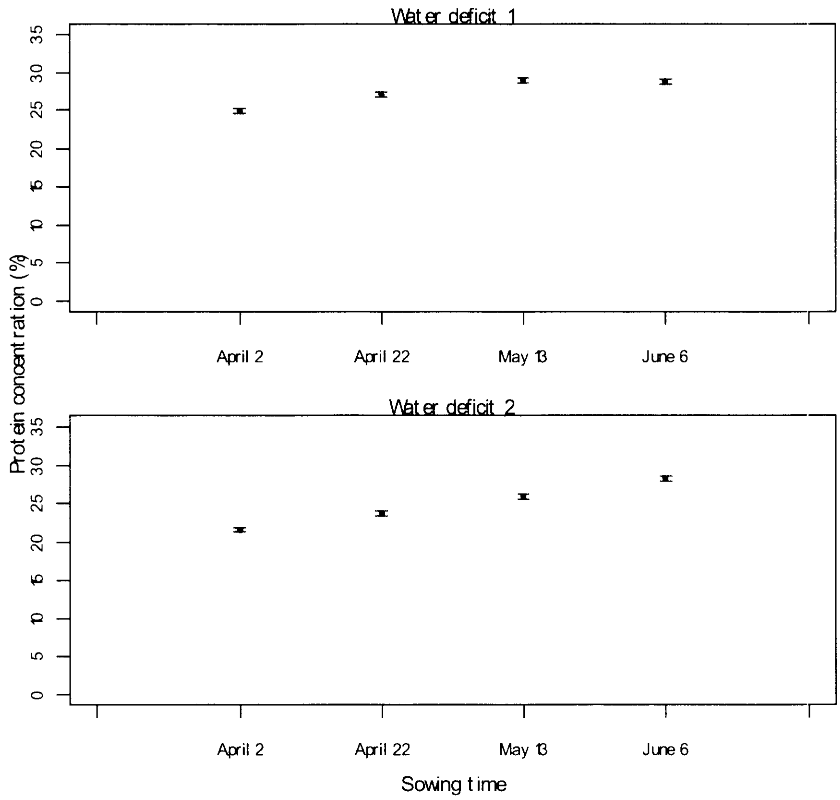

Figure 5.9 The effects of sowing time and water deficit on protein concentration (%) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

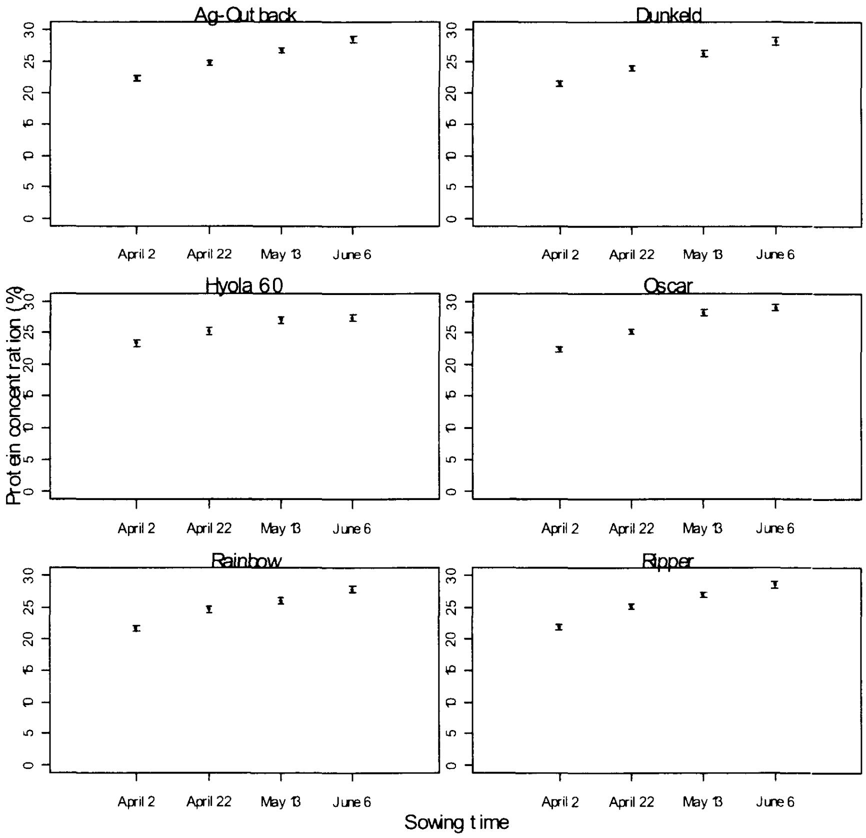

Figure 5.10 The effects of sowing time and variety on protein concentration (%) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

5.2.4 1000 grain weight

There was a significant interaction (P<0.001) between sowing time and variety for 1000 grain weight (g) of canola sown at Condobolin in 2002 (Figure 5.11). There was a progressive significant decline in 1000 grain weight from the April 22 sowing time, May 17 sowing time and June 14 sowing time for Ag-Outback, Rivette and Dunkeld. Emblem, Rainbow and Ripper recorded no significant difference in 1000 grain weight between the April 22 and May 17 sowing times however the June 4 sowing time recorded a significantly lower 1000 grain weight. There was no significant difference in 1000 grain weight recorded for Oscar across sowing times and the April 22 sowing time recorded a significantly higher 1000 grain weight for Hyola 60 however there was no significant difference between the May 17 and June 14 sowing times.

Ag-Outback, Hyola 60, Rivette and Dunkeld recorded a significantly higher 1000 grain weight for April 22 and May 17 sowing times than Ripper, Emblem, Oscar and Rainbow. However, Hyola 60 recorded a significantly higher 1000 grain weight than all other varieties and Emblem and Ripper recorded a significantly lower 1000 grain weight than all other varieties when sown on June 14.

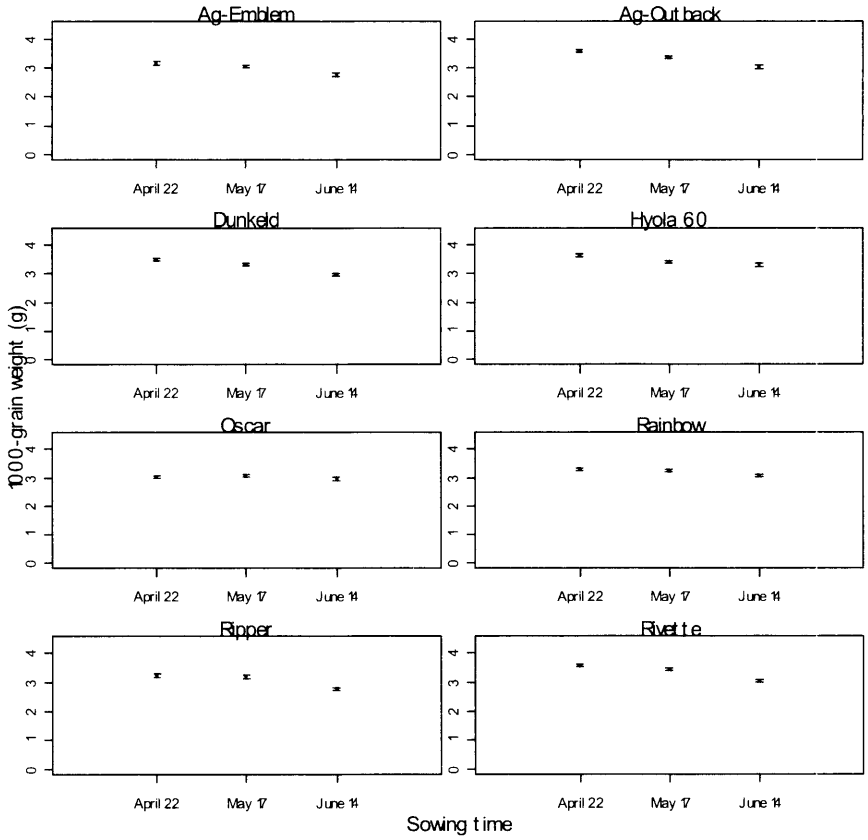

Figure 5.11 The effects of sowing time and variety on 1000 grain weight (g) of canola at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

There was a significant interaction (P=0.005) between variety and sowing time for 1000 grain weight of canola sown at Condobolin in 2003 (Figure 5.12). Ag-Outback and Hyola 60 recorded a significantly higher 1000 grain weight for the April 2 and May 13 sowing times. Oscar and Rainbow recorded a significantly lower 1000 grain weight for the April 22 sowing time. Dunkeld recorded a significantly lower 1000 grain weight for the May 13 sowing time and there was no significant difference in 1000 grain weight recorded for Ripper across sowing times. For the April 2 sowing time Dunkeld, Ag-Outback and Hyola 60 recorded a significantly higher 1000 grain weight than the other varieties. When sown on April 22 Hyola 60 and Dunkeld recorded a significantly higher 1000 grain weight than the other varieties. Hyola 60 and Ag-Outback recorded a significantly higher 1000 grain weight than all other varieties when sown on May 13 and Ag-Outback recorded a significantly lower 1000 grain weight than all other varieties when sown on June 6.

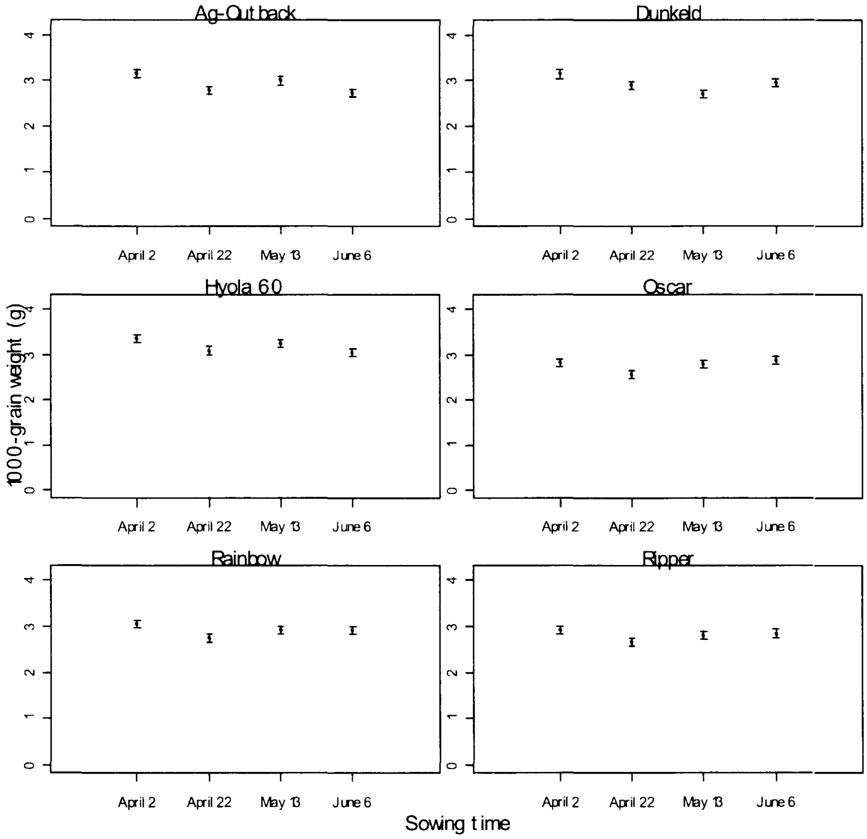

Figure 5.12 The effects of sowing time and variety on 1000 grain weight (g) of canola at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

5.3 Discussion

5.3.1 Grain yield

Sowing canola earlier than the recommended sowing time of mid-late April (McRae *et al.* 2003) increases grain yield in low rainfall regions of the south-eastern wheat belt of Australia. Reductions in grain yield were recorded when sowing was delayed beyond April 22 in 2002, and April 2 in 2003. Losses in grain yield due to delayed sowing have also been reported by Hodgson (1979a), Mendham (1981), Johnson *et al.* (1995) and Farre *et al.* (2002). Thurling (1974a), Thurling and Vijendra Das (1979b) and Si *et al.* (2002) reported a reduction in grain yield with delay in sowing time with a positive correlation between yield and the time to 50% anthesis. The longer the duration to 50% anthesis the higher the potential grain yield. This corresponds with the current experiments where the later sowing times recorded a reduction in time to anthesis of up to fourteen days when sowing was delayed beyond April 22 in 2002 and April 2 in 2003 (see Tables 4.1 and 4.2, Chapter four). A reduction in the time to anthesis of approximately one day for every five days sowing was delayed, was recorded.

Hocking (2001), Hocking and Stapper (2001) and Si and Walton (2004) attributed the reduction in grain yield with later sowing to a shortening in the amount of time available for both the vegetative and reproductive phases of crop growth as a result of water and heat stress. Reductions in the time available for both growth phases were recorded in the present experiments in 2002 and 2003 (Table 4.1 and Table 4.2, Chapter four). The reduction in reproductive growth was attributed to increased water and heat stress during flowering, siliqua production and grain fill, as temperatures were hotter and evaporative demands greater for the later sowing times compared to the earlier sowing times (Chapter three). For every one day delay in sowing from April 2 to April 22, there was a delay in flowering of approximately 1.25 days. The delay in flowering from April 2 to May 17 was approximately 0.55 days for every one day delay in sowing, and when sowing was delayed from April 2 to June 14 there was a delay in flowering of approximately 0.65 days for every one day delay in sowing (Tables 4.1 and Table 4.2, Chapter four). It is therefore clear that later sowing restricts the amount of time available for both the vegetative and reproductive growth phases. However, it is important to balance the risk of frost damage against the earlier flowering times achieved with earlier sowing time (Bernardi and Banks, 1991). I was unable to test this in the 2002 and 2003 seasons as there were no significant frost events, however, it is important to consider the risk of frost damage when determining how early to sow canola.

The risk of frost occurring during the end of flowering and early grain fill is of considerable importance in canola (Colton and Sykes, 1992) in Australia. In this thesis, frost thresholds were defined at -2°C measured in the screen, based on simulated data; there are however, no well-defined frost thresholds for canola in Australia (Robertson *et al.* 2001). Cumulative probabilities were determined in 14 day periods from July 1 until September 6 over forty six years (1957 – 2003) to determine the likelihood of frost events when the early sowing times (early April) are at the end of flowering and early grain fill. From July 1 until July 14 there was a 12% chance that a frost event may occur (Figure 5.13). From July 14 until July 28 there was an 8% chance that a frost event may occur (Figure 5.14) and from July 28 until August 11 a 5% chance (Figure 5.15). Therefore, based on these graphs for the Condobolin area, with the end of flowering and early grain fill occurring from July 1 onwards, the likelihood of frost damage occurring is, at most, only 12 %. This level is one that current canola growers in the low rainfall environments would be prepared to take as the increase in grain yield outweighs the potential risk associated with a frost event; however, on average, one year in every ten years could result in serious frost damage.

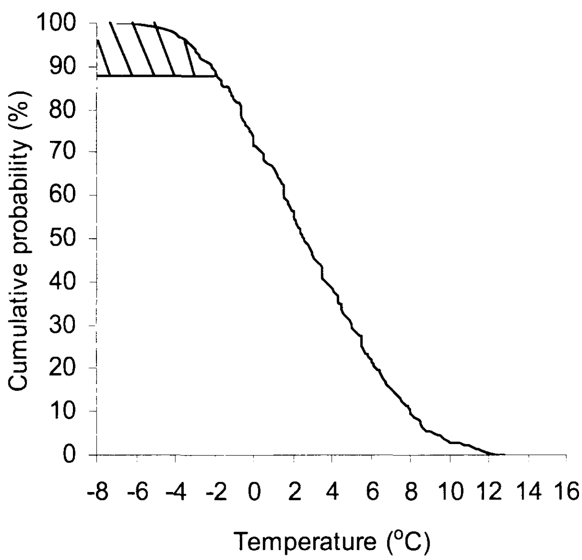

Figure 5.13 Cumulative probability (%) of frost damage (-2°C) occurring from July 1 until July 14 at Condobolin, over the last forty six years to 2003.

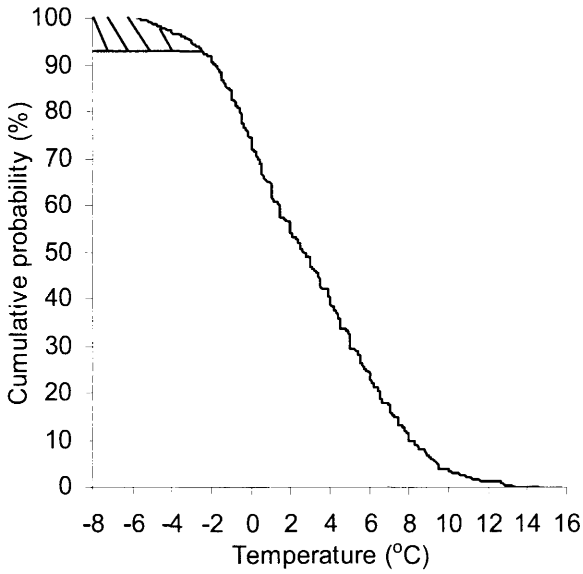

Figure 5.14 Cumulative probability (%) of frost damage (-2°C) occurring from July 14 until July 28 at Condobolin, over the last forty six years to 2003.

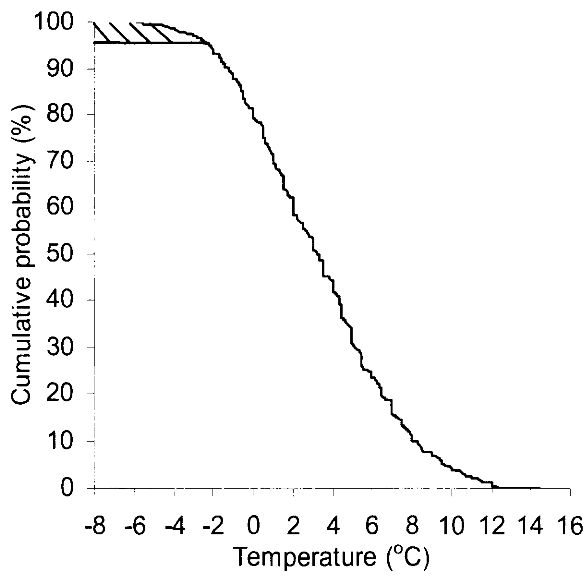

Figure 5.15 Cumulative probability (%) of frost damage (-2°C) occurring from July 28 until August 11 at Condobolin, over the last forty six years to 2003.

A number of authors have reported reductions in grain yield with delay in sowing and correlated these with plant growth parameters. Moderate to high positive phenotypic correlations were recorded in the current experiments, with grain yield and siliqua number (Figure 5.16) recording r = + 0.39 in 2002 and r = + 0.79 in 2003 (Scott *et al.* 1973; Richards and Thurling, 1978b; Hodgson, 1979b; Mendham *et al.* 1990; Taylor and Smith, 1992). Dry matter production and grain yield recorded a moderate positive phenotypic correlation in 2002 of r = + 0.41 and a very high positive phenotypic correlation in 2003 of r = + 0.80 (Figure 5.17). These have also been reported by Thurling (1974b) and Richards and Thurling (1978b). There was a low positive correlation between grain yield and 1000-grain weight in 2002 (r = + 0.25) but a moderate positive correlation in 2003 (r = + 0.36) (Figure 5.18) (Mendham *et al.* 1990). Mendham and Scott (1975) reported plant height to have an effect on grain yield and this corresponds with the moderate positive correlation in 2002 (r = + 0.41), however, in 2003 there was a very low positive correlation of r = + 0.07, with taller plants producing more grain yield (Figure 5.19). In 2002 there was a low positive correlation between leaf area and grain yield (r = + 0.26), however, there was a high negative correlation recorded in 2003 (r = - 0.67) (Figure 5.20) (Scott *et al.* 1973). Moderate positive correlations were recorded in 2002 and 2003 for branch number and grain yield (r = + 0.30 in 2002 and r = + 0.50 in 2003) (Figure 5.21) and this was also reported by Scarisbrick *et al.* (1981) and was attributed to reduced reproductive growth by Hocking (2001) and Hocking and Stapper (2001).

Conversely, Jenkins and Leitch (1986) recorded increases in seed yield with delay in sowing time, and suggested that the later sowing resulted in patterns of growth and development which increased the efficiency with which dry matter was partitioned to the seed. Mendham *et al.* (1981a) also reported higher yields in late sown crops, but only in certain exceptional seasons and associated this with an increase in leaf area prior to flowering as a result of spring regrowth. This is unlikely to occur in the low rainfall regions of south-eastern Australia due to the restriction on spring growth by increases in heat and moisture stress preventing dry matter being partitioned efficiently to the seed and the loss of leaf area due to shading from flowers and siliquas.

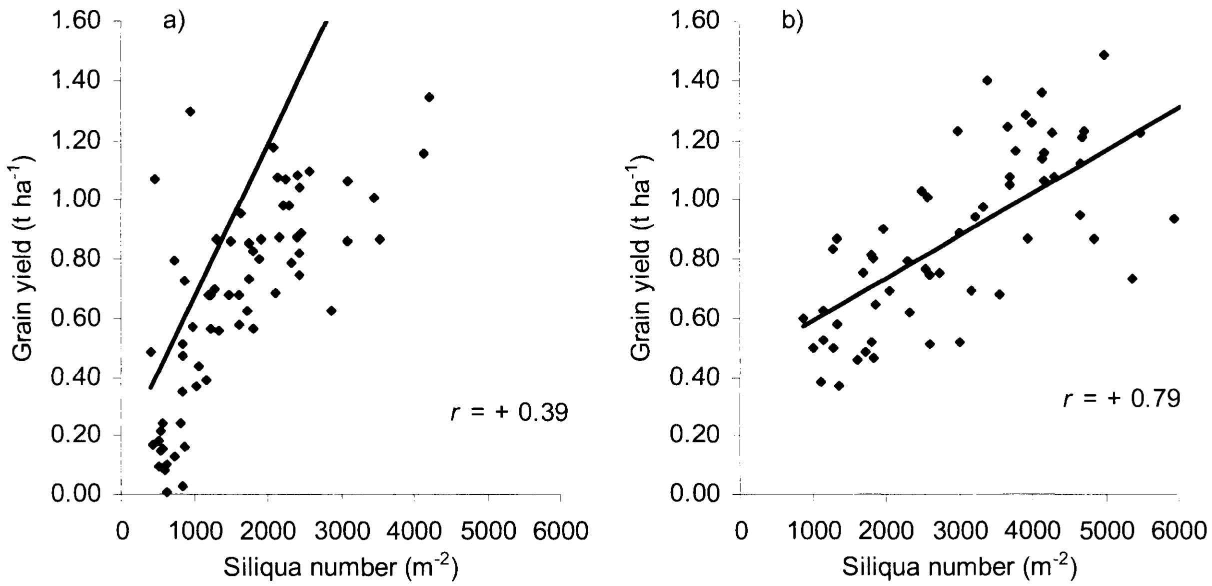

Figure 5.16 Phenotypic correlation between grain yield (t ha^{-1}) and siliqua number (m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

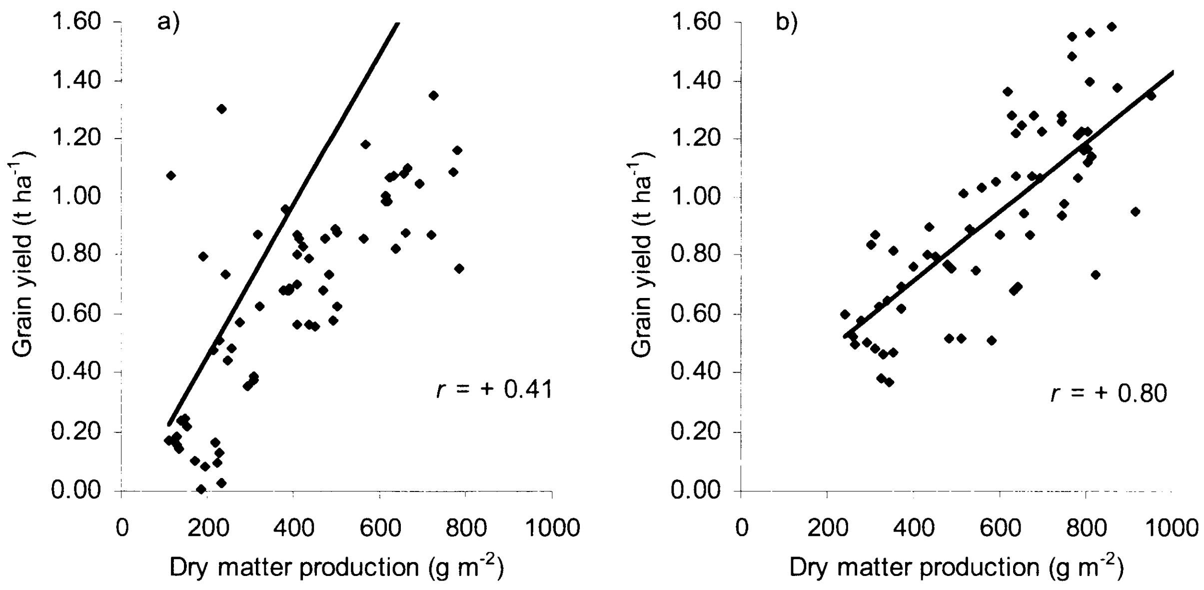

Figure 5.17 Phenotypic correlation between grain yield (t ha^{-1}) and dry matter production (g m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

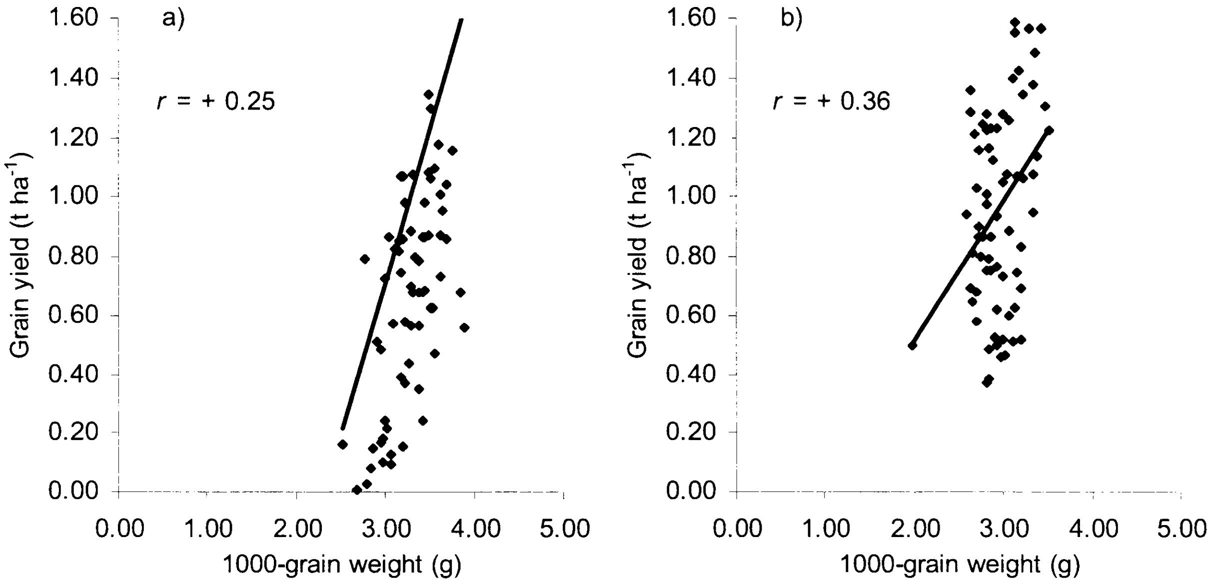

Figure 5.18 Phenotypic correlation between grain yield (t ha^{-1}) and 1000-grain weight (g) of canola sown at Condobolin in 2002 (a) and 2003 (b).

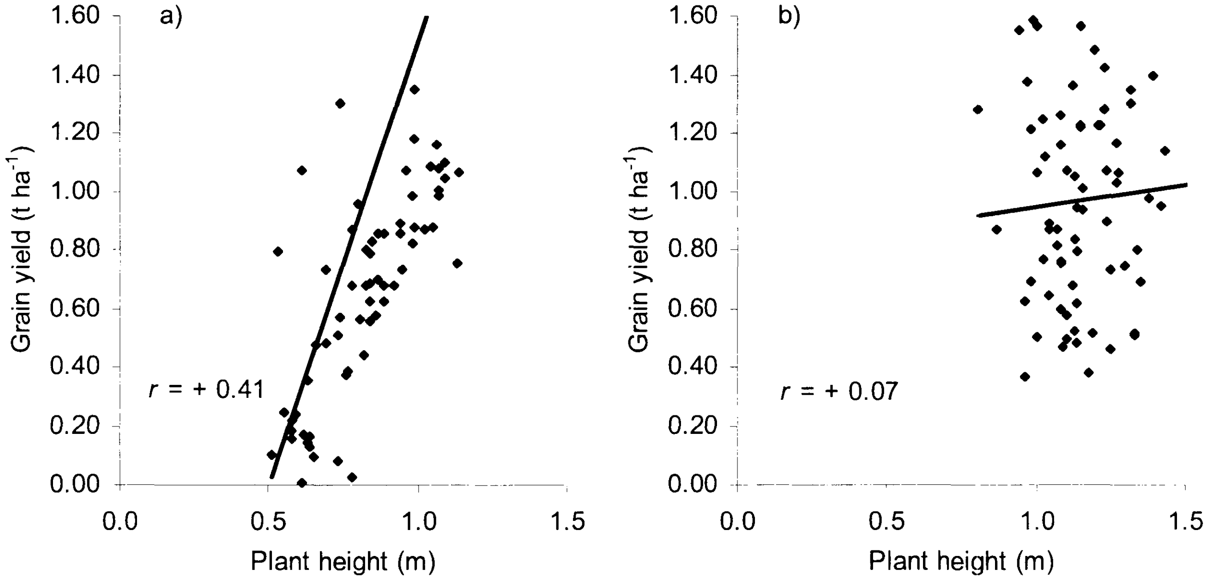

Figure 5.19 Phenotypic correlation between grain yield (t ha^{-1}) and plant height (m) of canola sown at Condobolin in 2002 (a) and 2003 (b).

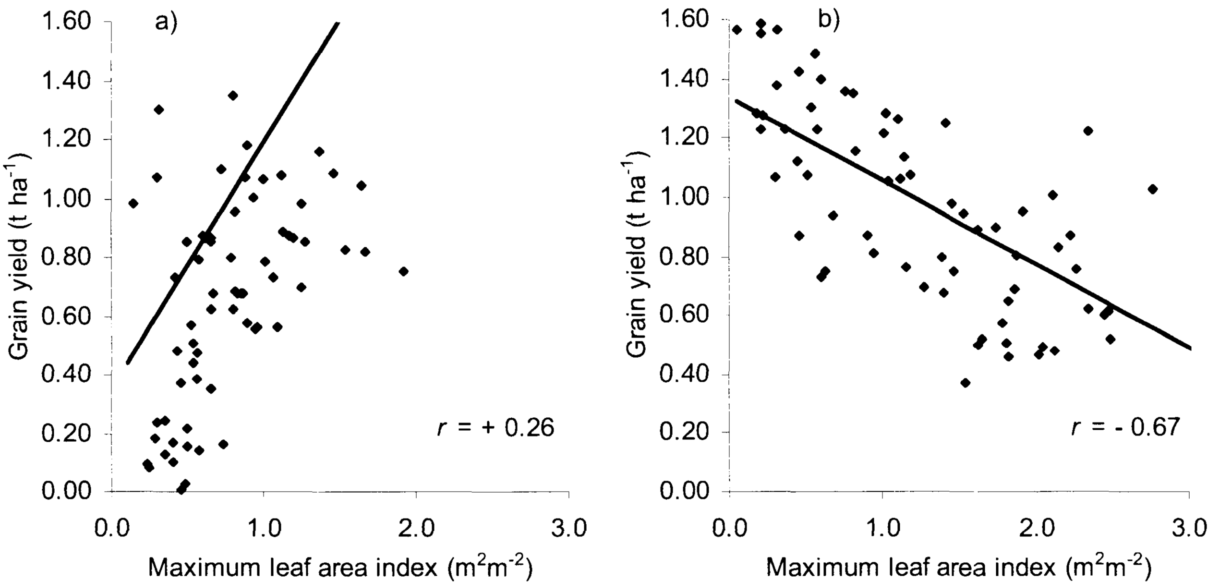

Figure 5.20 Phenotypic correlation between grain yield (t ha^{-1}) and leaf area index (m^2 m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

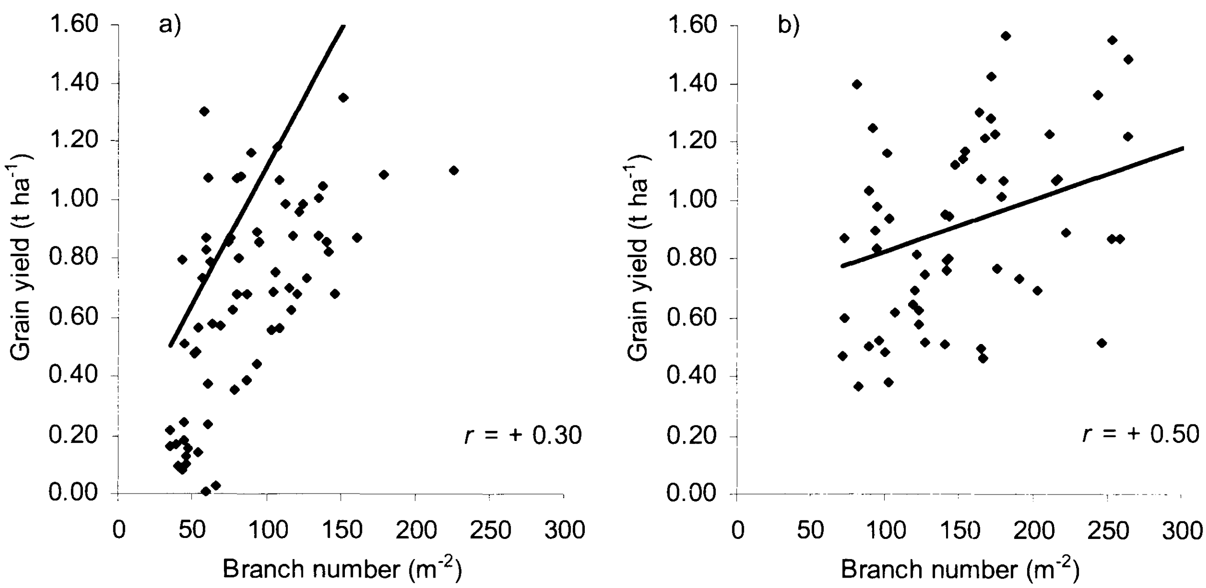

Figure 5.21 Phenotypic correlation between grain yield (t ha^{-1}) and branch number (m^{-2}) of canola sown at Condobolin in 2002 (a) and 2003 (b).

The percentage difference in grain yield between the highest and lowest yielding varieties in 2002 was between 22% for the April 22 sowing time and 76% for the June 14 sowing time. In 2003 the percentage differences in grain yield between the highest and lowest yielding varieties was between 14% for the May 13 sowing time and 26% for the April 2 sowing time. These differences in yield between canola varieties are consistent with those observed by others in a range of environments (Scott *et al.* 1973; Thurling, 1974b; Richards and Thurling, 1978b, Hodgson, 1979a; Scarisbrick *et al.* 1981; Jenkins and Leitch, (1986); Mendham *et al.* 1990; Thurling and Kaveeta, 1992b). The differences in grain yield of varieties reported above do not, however, indicate why these differences arise and their likely causes. The varieties used in this study are of different maturity types and have growing seasons of different lengths which may account for some of the variation in grain yield.

Thurling (1974a) reported differences in grain yield for three *B. napus* cultivars, which varied greatly in their patterns of response to delays in sowing time. This may be the case in the experiments reported in this thesis. The early maturing varieties Rivette and Ag-Outback, and mid-maturing variety Hyola 60 yielded well across all sowing times in 2002. This was attributed to their earlier flowering times, the plants at this stage being less subject to water and heat stress. However, it must be acknowledged that the performance of Hyola 60 as a hybrid variety expressing hybrid vigour would also account for increased grain yield (Parker *et al.* 2002). These varieties flowered between 7 and 14 days earlier than the later maturing varieties of Oscar, Dunkeld, Rainbow, Ag-Emblem and Ripper (Table 4.1 and Table 4.2, Chapter four). I would suggest that the later maturing varieties may be affected by water and heat stress at flowering and grain-fill, leading to reduced overall grain yield because flowering and grain-fill are occurring later in the season when moisture and heat stress are greater. This was observed across all sowing times in 2002 as these varieties mature later, flower later and hence the environmental conditions impact significantly on their ability to yield.

Morrison and Stewart (2002) reported that the accumulation of daily air temperatures greater than 29.5°C from stem elongation to the end of flowering significantly reduced yield. In 2002 temperatures reached 31.6°C and 34.6°C on September 24 and 25 respectively, and in 2003, temperatures reached 35.4°C on September 22, a time when the later maturing varieties in the May and June sowing times were in full flower. This could be expected to severely impact on their ability to reach their full yield potential. Similarly, Aksouh *et al.* (2001) recorded reductions of up to 89% in grain yield with heat stress, reporting that canola is susceptible to heat stress, even in short episodes, during seed development with abrupt heat stress having a more deleterious effect on yield formation than stepped heat stress. This would suggest that the severe temperatures during September 2002 and 2003 would have severely reduced the yield-forming capacity of the plants, particularly for the later sowing times and later maturing varieties. Angadi *et al.* (2000) also reported reduction in yield with a temperature of 35/15°C for 1 week during early flowering. Si *et al.* (2002) reported that post-anthesis rainfall and temperature had a strong influence on seed yield. This corresponds with my results where grain yield was reduced in the later sowing times which experienced higher temperatures during siliqua and seed development, compared with earlier sowing times and the water deficit two water treatment which recorded higher grain yield.

However, the longer maturing varieties, in particular Rainbow and Oscar, yielded higher in 2003 at the earlier sowing times, than the earlier maturing varieties. This is thought to be due to the longer growing season provided by the April 2 and April 22 sowing time reducing water stress at critical times, but does not account for the better performance of longer maturing varieties in the later sowing times. This may have been due to the increased in-crop rainfall and the timing of these events (Chapter three), which allowed the longer maturing varieties a greater opportunity to reach their yield potential. Si *et al.* (2002) reported that an earlier date of flowering would lengthen post-anthesis duration, increasing the chance of post-anthesis rainfall, and the likelihood of lower post-anthesis temperature, leading to increased grain yields. This is the opposite effect to what would presumably occur with the later sowing times, as reported by Hocking (2001) and Hocking and Stapper (2001), and, therefore, does not account for the better performance of the longer maturing varieties in the later sowing times. Johnson *et al.* (1995) in North Dakota recorded differences in grain yield with the later maturing cultivars Westar and Topas benefiting from the earlier sowing times. This corresponds with the performance of the later maturing varieties in the present experiments for the early sowing times but not the later sowing times.

As previously suggested, it may be that the differences recorded in my experiments are due to the rainfall received during July and August, totalling 132.6 mm (Chapter three), a time when the later maturing varieties, of the April 2, April 22 and May 13 sowing times, were in full flower. The early maturing varieties were finishing flowering at the end of August, while the longer maturing varieties were able to reach their full potential by producing more flowers under less water and heat stress, as compared with 2002. It may also be that the early maturing varieties such as Ag-Outback, where flowering began on July 14 and ended on August 14, were subjected to more days of temperatures below zero degrees Celsius, compared with the longer maturing varieties such as Ripper which began flowering on August 6 and finished on August 31.

Meteorological data from the Condobolin Agricultural Research and Advisory Station Meteorological Station recorded 15 days of a terrestrial minimum of zero degrees Celsius or lower for Ag-Outback compared with only 12 days for the longer maturing variety, Ripper. Accompanying this, the early maturing variety Ag-Outback commenced grain-fill up to 14 days earlier than the later maturing Ripper, increasing its exposure to these lower temperatures during grain filling by six days. This corresponds with reports by Colton and Sykes (1992) that frost damage occurring during early and late grain fill will reduce grain yields. However, another reason concerning why the later maturing varieties in 2003 and the early maturing varieties in 2002 did well, may be that maturity type is not as important as first thought, and that the variation is due to the differing response of the varieties to the environment. It is, however, important to consider that, if sowing late, the early maturing varieties may be a better option as their faster growth will ensure the major growth stages occur before the onset of water and heat stress.

The water deficit two water treatment, as expected, led to increases in grain yield across all sowing times (Wright *et al.* 1988; Taylor *et al.* 1991; Gemmelvind *et al.* 1996). This increase in grain yield was attributed to a reduction in water stress during the reproductive growth phase, leading to increased siliqua production and grain yield. The largest increase in grain yield was observed for the May 17 sowing time in 2002 and the April 22 and May 13 sowing times in 2003. This was attributed to 100% flowering occurring up to two weeks after the water application, reducing water stress when compared to water deficit one allowing the plants to produce flowers to their full potential under less limited soil moisture conditions (Clarke and Simpson, 1978). The April 2 and June 6 sowing times flowered too early and too late respectively to achieve sufficient increases in flowering which could then be converted to siliquas and therefore grain yield.

Poma *et al.* (1999) in Italy reported a reduction in grain yield when soil moisture was reduced from field capacity with the stressed treatments recording reductions of up to 52% in yield. This was thought to have resulted from a decrease in the number of seeds/siliquae and a lowering of the 1000 grain weight. This trend of reduced grain yield with reduced soil moisture corresponds with the present results with moderate positive phenotypic correlations between grain yield and

1000 grain weight reported earlier in this chapter. Nielsen (1997) reported that water stress timing did not significantly affect seed yield, but that the lowest yield occurred when water stress was applied during the grain-filling period and attributed the loss in yield to the production of fewer branches per plant, siliquas per plant and smaller seeds. This corresponds with the present data showing moderate to high positive phenotypic correlations between grain yield and branch number, siliqua number and 1000 grain weight.

Richards and Thurling (1978a) also reported that a high yielding genotype under drought conditions would be one that has a large plant weight and large number of siliquas and branches. This corresponds with the current data with moderate to high positive phenotypic correlations between these components detailed earlier in this chapter. Niknam *et al.* (2003) reported differences in grain yield and varietal response to irrigation in a Western Australian low rainfall environment similar to Condobolin, with up to 39% reduction in grain yield when under rainfed conditions. This correlates with the results reported in this thesis where a reduction in grain yield of 40% was recorded for the May 13 sowing time in 2003, with differences in grain yield also recorded for the canola varieties in my experiments in 2002 and 2003. Wright *et al.* (1995) reported that reduced water availability severely reduced dry matter production and seed yield. Again, this is similar to the results reported in this thesis, with correlations of $r = + 0.41$ reported in 2002 and $r = + 0.80$ in 2003 for dry matter production and grain yield (Figure 5.17).

It is important to note, that in 2002, a year where rainfall was 35% below the long term mean (Chapter three), sowing on April 22 produced a grain yield of 0.95 t ha^{-1}. Further, in 2002 the water deficit two treatment which created a year which was 15% below the long term mean (Chapter three), a yield of 1.00 t ha^{-1} could be achieved. This is important as it illustrates that it is possible to grow canola in the low rainfall regions of south-eastern Australia even under below average rainfall and still receive what is considered to be an acceptable yield.

5.3.2 Oil concentration

Sowing canola early is essential to achieve high oil concentration in low rainfall regions of south-eastern Australia. A delay in sowing time led to reduced oil concentrations in 2002 and 2003 for all varieties. Reductions in oil concentration from late sowing have also been reported by Scott *et al.* (1973), Mendham and Scott (1975), Scarisbrick *et al.* (1981), Sang *et al.* (1986), Taylor and Smith (1992), Wright *et al.* (1995) and Walton and Trent (1997), reinforcing the need for early sowing to achieve the best possible oil concentration. Hocking and Stapper (2001) reported a reduction in canola oil concentration of approximately three percentage points for each month delay in sowing time at Ariah Park in central New South Wales. Si and Walton (2004) also reported a reduction in oil concentration of 1.1 percentage points for every two week delay in sowing suggesting that this was associated significantly with post-anthesis duration, but not pre-anthesis duration; this corresponds with the results reported in this thesis where later sowing times recorded reduced post-anthesis duration (Chapter four). Johnson *et al.* (1995) reported a reduction in oil concentration of up to 1% when sowing was delayed from May 1 until May 31 in North Dakota. In the current experiments, there was a reduction in oil concentration of 0.03 percentage points for every one day delay in sowing beyond April 22 in 2002 and 0.06 percentage points for every one day delay in sowing beyond April 2 in 2003. This suggests that sowing later than April 2 will lead to reductions in oil concentration.

This has ramifications for Australian canola growers in low rainfall regions, with reductions in price received of 1% for every percent decrease in oil concentration below 42% (Parker *et al.* 2002). With this in mind, in 2002 a penalty would have been incurred for all three sowing times and all varieties with the exception of Ripper, and in 2003 there would have been penalties incurred for all sowing times and varieties. This, coupled with the loss that would have been incurred due to the reduction in yield associated with delayed sowing, would have lead to an unsuccessful crop. The level of losses which would have been incurred in 2002 may suggest that for longer term successful canola production in the low rainfall regions, variety selection specifically for high oil concentrations under water stressed conditions may be justified.

The reduction in oil concentration with late sowing has been attributed to increased water and heat stress experienced by the later sown crops during grain fill (Aksouh *et al.* 2001). This has also been reported by Hocking and Stapper (2001) who suggested it was likely that increased temperature and heat stress during grain filling was a major cause of reduced oil concentration associated with late sowing. They went on to report an inverse relationship between oil concentration and mean daily temperature during siliqua development, with a decrease of 1.7 percentage points per 1°C increase in mean temperature. Losses in oil concentration with increases in temperature have also been reported by Hocking *et al.* (1997) at Condobolin, Hodgson (1979b) and Walton *et al.* (1999). In the present experiments the loss in oil concentration in 2002 was 0.47 percentage points per 1°C increase in mean temperature and in 2003 it was 0.78 percentage points per 1°C increase in mean temperature. These are lower than those reported above, but still reinforce the need for early sowing to allow the crop to mature under conditions where temperature and heat stress are minimised.

However, Jenkins and Leitch (1986) report conflicting results, with inconsistent variation in oil content associated with sowing time and significant increases in oil content in the later sowing times. While Mendham *et al.* (1990) reported no clear relationship between oil content and sowing time, the highest oil contents were generally in early sowings, which is consistent with the results from the current experiment in 2002. Woods (2000) reported that an increase in seed size in many cases seemed to be associated with reduced oil content. Although seed size was not measured in my experiments, 1000 grain weights were and these reports correspond with this finding with low positive phenotypic correlations between oil concentration and 1000 grain weight of $r = +0.09$ in 2002 and $r = +0.30$ in 2003, illustrating that high 1000 grain weight was associated with high oil concentration (Figure 5.22).

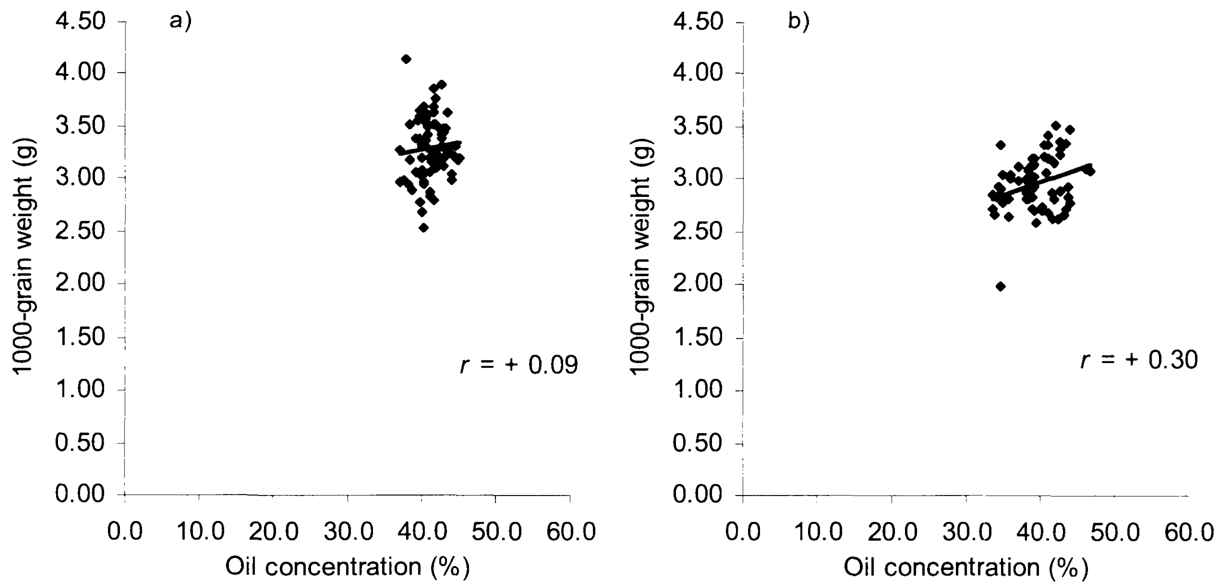

Figure 5.22 Phenotypic correlation between oil concentration (%, at 8.5% moisture) and 1000-grain weight (g) of canola sown at Condobolin in 2002 (a) and 2003 (b).

Despite the loss in oil concentration from a delay in sowing time, there is a positive benefit with an increase in protein concentration. Hodgson (1979b) reported that early plantings tended to favour high oil and low protein levels whereas late planting tended to favour high protein and low oil levels. This inverse relationship between oil and protein content has been reported by Holmes and Ainsley (1979), Smith *et al.* (1988), Taylor *et al.* (1991), Zhao *et al.* (1993), Hocking (1995), Hocking *et al.* (1997), Brennan *et al.* (2000) and Si *et al.* (2003). The high oil content recorded in the early sowing times reported by Hodgson (1979b) was attributed to oil production being favoured by cooler conditions. This is consistent with the current findings of this thesis where the reduction in oil concentration for the later sowing times corresponds with increases in temperature experienced in the later sowing times during seed development. Despite the loss in oil concentration from later sowing, the increase in protein concentration does allow Australian canola growers to seek other marketing opportunities such as through providing feed for animals, if the oil concentration is not adequate. However, it must be remembered that canola is grown for its grain yield and oil concentration, and protein concentration takes a secondary role in marketing of canola.

A range of oil concentrations were recorded across varieties in both experiments in 2002 and 2003. Differences in oil concentration of varieties have also been reported by Hodgson (1979b), Scarisbrick *et al.* (1981), Mendham *et al.* (1990), Taylor and Smith (1992) and Johnson *et al.* (1995). The effects of variety on oil concentration are significantly influenced by genetic control (Si *et al.* 2003; Si and Walton, 2004) and the current results correspond with those from NSW Agriculture variety experiments (McRae *et al.* 2003), with the high oil varieties reported by NSW Agriculture recording high oil concentration in both 2002 and 2003. The results illustrate that high grain yield and high oil concentration are not mutually exclusive characteristics, with Rivette and Hyola 60 recording high yields and high oil concentrations in 2002. However, this was not the case in 2003 with the higher yielding varieties Oscar and Rainbow not achieving high oil concentrations; this reinforces the importance of genetic control over oil concentration reported by Si *et al.* (2003).

In 2002, the application of additional water (water deficit two) did not increase oil concentration. This was attributed to the lack of additional water that was applied to the experiment, which was unable to compensate for the severity of the water stress in 2002 (Chapter three). However, in 2003 the application of additional water (water deficit two) increased oil concentration across all sowing times with the exception of the June 6 sowing time. The reason for a lack of response by the June 6 sowing time to water deficit two is unclear; however it may be speculated that higher temperatures at grain filling may have contributed although there is no reported evidence of this in other experiments. Increases in oil concentration with increased water applications have been reported by Mailer and Cornish (1987), Smith *et al.* (1988), Taylor *et al.* (1991) and Nielsen (1998), however, when the stress occurred within the lifecycle of the plant was not significant.

Niknam *et al.* (2003) recorded increases in seed oil concentration of 6 – 11 % for watered treatments when compared with rainfed treatments in Western Australia. However, the increase in oil concentration for the water deficit two water treatment in 2003 ranged from only 2.2% to 3.2%, with the largest difference recorded for the April 2 sowing time. Andersen *et al.* (1996) also reported oil concentration was significantly decreased by drought, but the reduction depended more on the severity than the time when the drought occurred. This may provide some insight into the low oil concentrations recorded in 2002 and 2003 with drought experienced throughout the growing seasons in both years.

5.3.3 Protein concentration

Sowing canola early decreases protein concentration in low rainfall environments of south-eastern Australia. Delaying sowing time in 2002 and 2003 led to increases in protein concentrations. There was a low negative phenotypic correlation recorded between protein concentration (%) and oil concentration (%) in 2002 (r = - 0.28) however, in 2003 there was a moderate negative phenotypic correlation with protein concentration decreasing as oil concentration increased (r = - 0.57, Figure 5.23). The inverse relationship between protein and oil concentration has been well documented by Holmes and Ainsley (1979), Smith *et al.* (1988), Taylor *et al.* (1991), Zhao *et al.* (1993), Hocking (1995), Hocking *et al.* (1997), Brennan *et al.* (2000) and Si *et al.* (2003). The high protein concentration observed in the later sowing times, and as a consequence low oil concentration, was attributed to water and heat stresses during grain fill (Aksouh *et al.* 2001; Hodgson, 1979b).

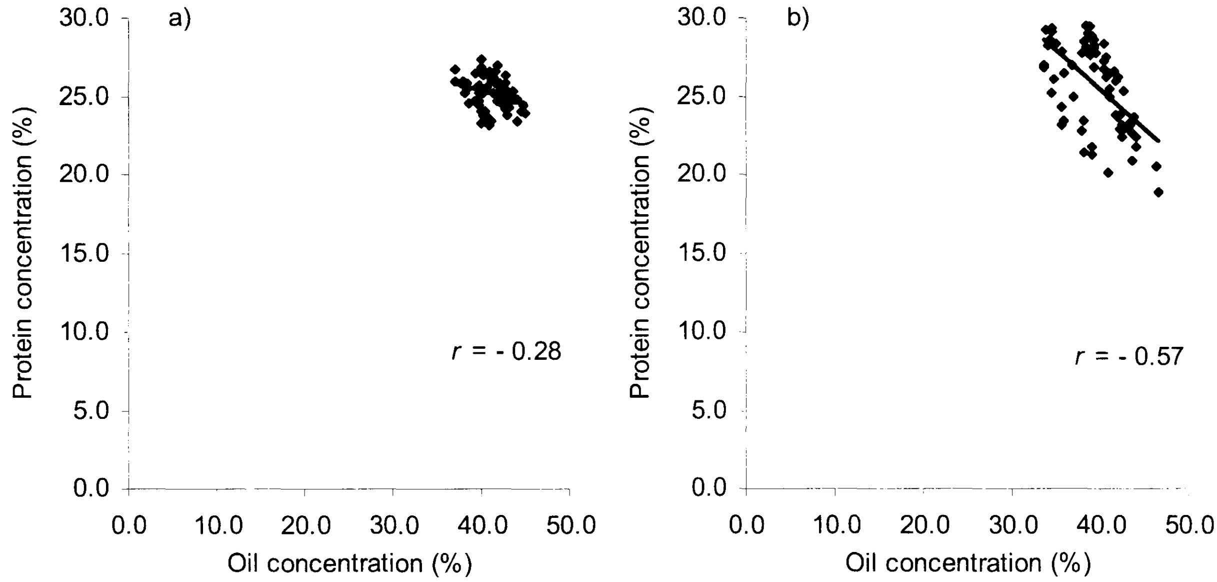

Figure 5.23 Phenotypic correlation between protein concentration (% whole grain, at 8.5% moisture) and oil concentration (%, at 8.5% moisture) of canola sown at Condobolin in 2002 (a) and 2003 (b).

Although protein concentration is not considered initially when canola is marketed, it is important to note alternative uses for canola produced in low rainfall environments with unpredictable seasons. The increased protein concentration that accompanies late sown crops does provide an alternative for canola growers who may wish to market their canola for use in animal feed. However, the grain yield and oil concentration of canola is most important to canola growers in Australia, with its use as an animal feed providing a second option if the standard of canola is not sufficiently high. Conversely, if a poor season is experienced with canola recording poor oil concentration but adequate protein concentration, it may be that, that particular season is one where animal feed is required and would mean farmers did not have to buy in feed, and still achieved the added benefit of the disease break from growing canola.

The provision of high oil concentration is more important than protein production when selecting canola varieties. Despite this, protein concentration is of importance when considering other marketing options. The results show general agreement with the protein concentrations described by NSW Agriculture variety experiments (McRae *et al.* 2003). These illustrate that there is some genetic control of protein concentration (Si *et al.* 2003) with low oil varieties such as Oscar achieving high protein concentrations. However, Oscar's high protein concentration recorded in 2002 and 2003 does not correspond with the NSW Agriculture variety experiments (McRae *et al.* 2003). Hyola 60 recorded high protein concentrations in both 2002 and 2003, and this is contrary to what would be expected as it produces a high oil concentration. The high protein concentration recorded by Hyola 60 may be attributed to Hyola 60 seed being approximately 37% heavier than the other canola varieties in the experiment, and as a consequence may have higher protein concentration.

The application of additional water in water deficit two led to an increase in protein concentration in 2003, although the reason for this is unclear. Initially it was thought to be associated with an increase in seed size (1000 grain weight). However, this does not correspond with the low to moderate negative phenotypic correlations in Figure 5.4, nor does it correspond with reports by Jensen *et al.* (1996) Aksouh *et al.* (2001) and Wright *et al.* (1995) who report increases in protein concentration in canola plants subjected to drought.

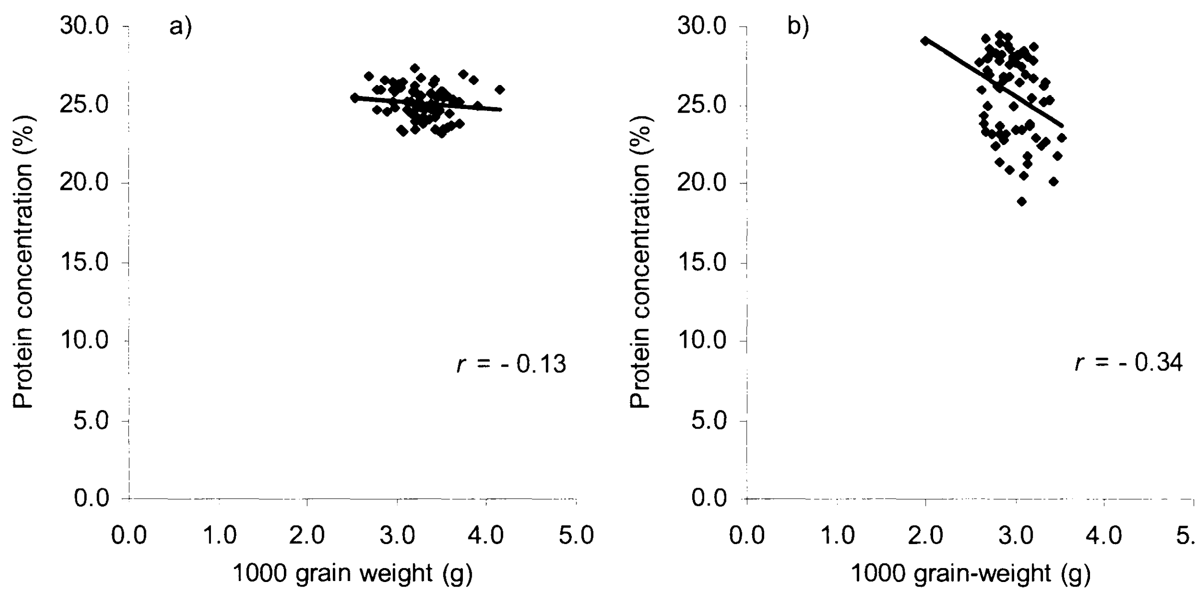

Figure 5.24 Phenotypic correlation between protein concentration (% whole grain, at 8.5% moisture) and 1000 grain weight (g) of canola sown at Condobolin in 2002 (a) and 2003 (b).

5.3.4 1000 grain weight

Sowing canola early increases 1000-grain weight in low rainfall environments of the south-eastern wheat belt of Australia. In the current experiments, a delay in sowing time beyond April 22 in 2002 and April 2 in 2003 led to a reduction in 1000 grain weight. This reduction in 1000-grain weight with delayed sowing has also been observed by Scott *et al.* (1973), Mendham and Scott (1975), Richards and Thurling (1978b), Hodgson (1979b), Chay and Thurling (1989) and Mendham *et al.* (1990), and has been attributed to heat and water stress during grain filling by Hocking and Stapper (2001). Morrison and Stewart (2002) reported reductions in 1000-grain weight when heat stress was applied at flowering. This correlates with the present data where the April 2 sown crop in 2003 was flowering in August whilst the June 6 sown crop flowered in September; mean maximum temperatures were up to four degrees Celsius higher for the June 6 sowing time, and extreme temperatures in late September in 2002 and 2003 were recorded when the later sowing time crops were flowering.

Scott *et al.* (1973) and Cheema *et al.* (2001) reported that the differences in mean seed weight are generally related to the length of period between anthesis and maturity. They suggest that the supply of assimilates to the seed plays a crucial role in seed development, and plants supplied with more nutrients are probably at an advantage over those supplied with less. This corresponds with the current results, which recorded a reduction in time from anthesis to maturity of 29 days in 2002 when sowing was delayed from April 22 until June 14, and 26 days in 2003 when sowing was delayed from April 2 until June 6. There may have been a lack in supply of assimilates and this could be correlated to the lower dry matter production achieved by the later sowing times in the present experiments. Moderate positive correlations between dry matter production and 1000 grain weight were recorded in 2002 (r = + 0.55) and 2003 (r = + 0.48) (Figure 5.25).

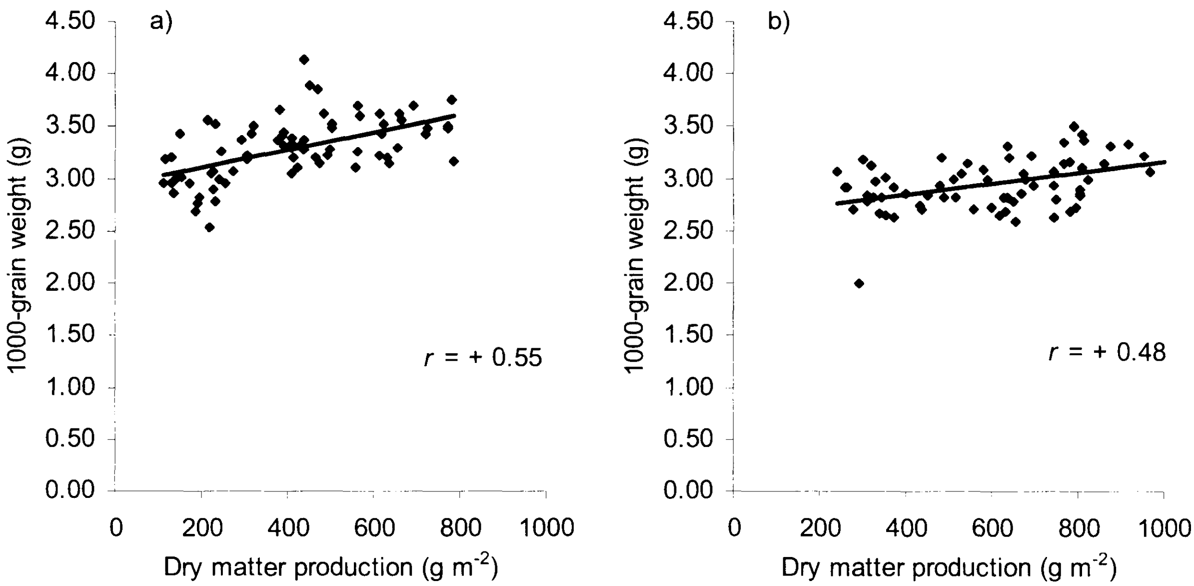

Figure 5.25 Phenotypic correlation between dry matter production (g m^{-2}) and 1000 grain weight (g) of canola sown at Condobolin in 2002 (a) and 2003 (b).

However, in 2003 there were poor correlations between delays in sowing time and decreases in 1000 grain weight for all sowing times. A decrease in 1000 grain weight was recorded when sowing was delayed beyond April 2 in 2003, although this decrease was not continued for each delay in sowing time. These differences may be attributed to differences between the environments under which seed development occurred. The rainfall received in July and August in 2003 (Chapter three) may have provided the canola with extra moisture sufficient to prevent the loss in 1000 grain weight as was recorded in 2002.

Differences in 1000 grain weight were recorded between varieties in 2002 and 2003. Hodgson (1979b), Munir and McNeilly (1986), Thurling and Kaveeta (1992b) and Lewis and Thurling (1994) have reported differences in 1000-grain weight of canola varieties across a range of environments. In the experiments reported in this thesis, early maturing varieties in 2002 and 2003 recorded the largest 1000 grain weights. This suggests they were under less water and heat stress during grain filling, and they may have had the ability to transfer assimilates due to their more productive vegetative phase, allowing for extra storage of assimilates (Tayo and Morgan 1979).

Hyola 60 recorded high 1000 grain weights across all sowing times and this was attributed to the seed being 37% heavier (as a result of hybrid vigour, Parker *et al.* 2002), than the other canola varieties used in the experiments and this must be considered when assessing the results. The greater seed weight may also contribute to Hyola 60 yielding well, providing it with an advantage over the other varieties.

Jenkins and Leitch (1986) reported reductions in 1000-grain weight with delays in sowing and differences between cultivars, and also a significant interaction between cultivars and sowing date. This reduction was also recorded in the current experiments, with Ag-Outback recording a reduction in 1000-grain weight of 16% when sowing was delayed while Oscar recorded a reduction of only 2%. The large difference in 1000 grain weight between varieties is difficult to explain but it may be due to the varieties response to delayed sowing time as a result of the differing maturity types with Ag-Outback being an early maturing variety and Oscar a mid-maturing variety.

There was no difference in 1000 grain weight between water deficit one and water deficit two in 2002 and 2003 and this corresponds with reports by Wright *et al.* (1988) and Wright *et al.* (1995). Richards and Thurling (1978b), Mailer and Cornish (1987), Taylor *et al.* (1991) and Andersen *et al.* (1996) reported a decrease in seed weight when severe drought occurred during the grain filling phase as well as in unirrigated treatments, which would suggest that the later sowing times under more moisture and heat stress would record lower 1000 grain weight than the earlier sowing times.

5.4 Conclusions

The results from these experiments confirm the need to sow canola earlier than the recommended sowing time (mid-late April) to increase grain yield, oil concentration and 1000 grain weight though this does result in reduced protein concentration. This is likely to arise from a reduction in temperature and moisture stress during critical stages in the reproductive growth phase. Increases in production from early sowing are also due to a lengthening of the vegetative and reproductive growth phases, providing the plant with an improved ability to supply assimilates and maximise plant functions towards maturity. However, how early is too early is still unclear. The possible loss in production from frost must be considered when deciding how early to sow. The choice of which canola variety to sow depends largely on the time of sowing and the quality characteristics of available varieties. The application of additional water led to increases in grain yield and oil and protein concentration and illustrates, as in Chapter four, the ability of the canola plant to respond to additional moisture throughout the growing season.

CHAPTER SIX: WATER USE AND WATER USE EFFICIENCY

6.1 Introduction

The plant's ability to access and use available soil moisture and the availability of soil moisture to the plant are crucial factors in the production of canola in low rainfall environments. The characteristically unpredictable and limited rainfall which is received in low rainfall environments, and in particular in central western New South Wales, has limited the production of canola in these regions (Hocking *et al.* 1997). Knowledge of the pattern of water use by canola in low rainfall environments is important to enable growers to maximise water use through manipulating sowing times and varietal choices so that canola may be grown under these adverse conditions whilst optimising plant growth and maximising yield. There is limited evidence available on the effects of variety and sowing time on water use of canola; however, there is evidence to suggest that different canola varieties do have different water use efficiencies. Lewis and Thurling (1994) reported differences in water use efficiency between the canola varieties Eureka and Wesbrook of 4.3% for water use efficiency of growing season dry matter production, 13% for pre-anthesis dry matter production and 8% for post-anthesis dry matter production.

In this thesis, the water use and water use efficiency of two canola varieties, Ag-Outback and Ripper, sown over different dates and under two water regimes (water deficit one and water deficit two) were investigated in 2002 and 2003. These two varieties were chosen to represent the early and mid-maturing varieties used in the experiment. Total water use, pre-anthesis and post-anthesis water use and water use efficiencies for grain yield, total dry matter production, pre-anthesis dry matter production, and post-anthesis dry matter production were measured to determine the optimum sowing time and variety to gain the most efficient use of water under the two water regimes of water deficit one and water deficit two.

6.2 Results

6.2.1 Crop water use – volumetric soil moisture content

There was a significant interaction ($P<0.001$) between water deficit, depth, variety, sowing time and sampling date on volumetric moisture content (mm mm^{-1}) of canola sown at Condobolin in 2002. Figures 6.1 and 6.2 present the effects of water deficit, depth, variety, sowing time and sampling date on volumetric moisture content at the beginning (June 4) and the end (November 12) of the growing season. The individual changes at each sampling throughout the growing season (June 25, July 17, August 7, August 16, August 28, September 19 and October 10) have not been presented due to the small changes between each sampling date they illustrate; however, they do show similar trends to those presented in Figures 6.1 and 6.2. For Ripper and Ag-Outback sown on April 22 water deficit one, the June 4 start of season sampling date recorded a significantly higher volumetric moisture content than the November 12 sampling date at final harvest for all depths. This also occurred for the May 17 sowing time with the exception of the depths 1.5m and 1.7m, where the November 12 sampling date recorded a significantly higher volumetric moisture content, than the June 4 sampling date. For Ripper sown on June 14 water deficit one, the June 4 sampling date recorded a significantly higher volumetric moisture content than the final harvest sampling on November 12 from 0.1m to 0.9m only and for Ag-Outback sown on June 14 water deficit one, the June 4 sampling date recorded a significantly higher volumetric moisture content than the November 12 sampling date from 0.1m to 0.7m.

For Ripper sown on April 22, May 17 and June 14 for water deficit two, the November 12 final harvest sampling date recorded a significantly higher volumetric moisture content than the June 4 sampling date from 1.3m to 1.7m, with the June 4 sampling date recording a significantly higher volumetric moisture content, than the November 12 sampling date from 0.1m to 1.1m. For Ag-Outback water deficit two sown on April 22, the June 4 sampling date recorded a significantly higher volumetric moisture content than the November 12 sampling date from 0.1m to 1.3m, with the November 12 sampling date recording a significantly higher volumetric moisture content for the remaining depths to 1.7m. For Ag-Outback water deficit two sown on

May 17 and June 14 the November 12 sampling date recorded a significantly higher volumetric moisture content than the June 4 sampling date from 1.3m to 1.7m with the June 4 sampling date recording a significantly higher volumetric moisture content, than the November 12 sampling date from 0.1m to 1.1m.

On June 4 (Figure 6.1) water deficit two recorded a significantly higher volumetric moisture content than water deficit one for Ag-Outback sown on April 22 and May 17 at depths of 0.7m to 1.7m. However, the opposite occurred for Ripper sown on April 22 and May 17 from 1.1m to 1.7m with water deficit one recording significantly higher volumetric moisture content, than water deficit two. Ripper recorded a significantly higher volumetric moisture content than Ag-Outback at 0.5m on April 22 water deficit one and 0.3m on May 17 water deficit one. Ag-Outback recorded a significantly higher volumetric moisture content than Ripper on May 17 for water deficit one at 0.3m, on April 22 for water deficit two at 1.7m and on May 17 for water deficit two at 1.5m and 1.7m.

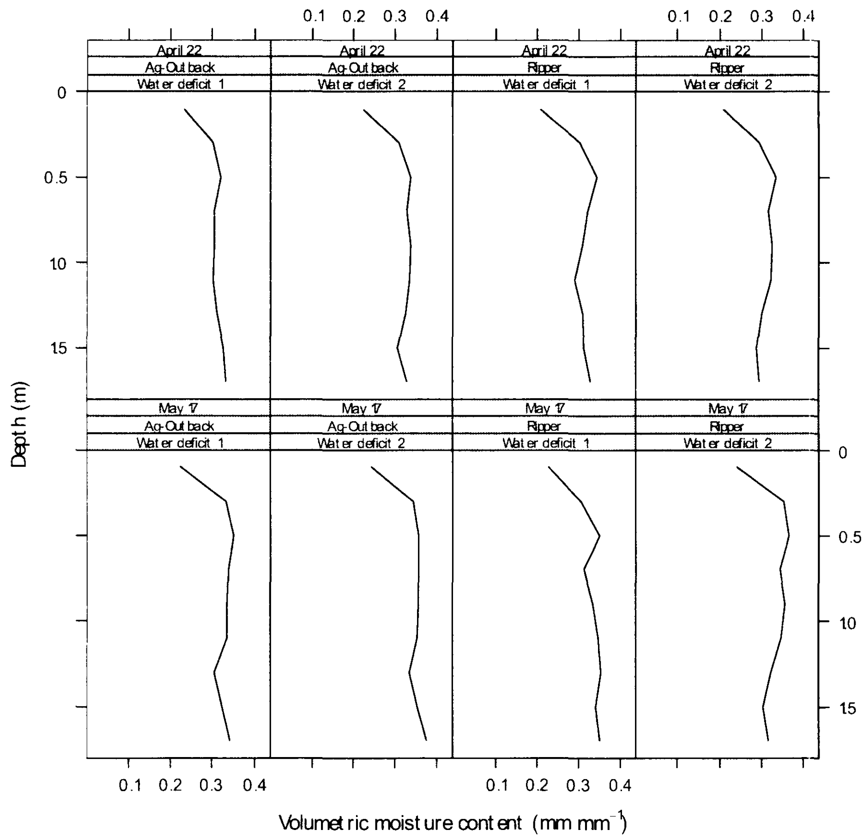

Figure 6.1 The effects of water deficit, depth, variety and sowing time on volumetric moisture content (mm mm^{-1}) of canola measured on June 4, at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

On November 12 (Figure 6.2) Ag-Outback water deficit one recorded a significantly higher volumetric moisture content than Ripper for April 22 at 0.1m and the May 17 sowing time at 0.3m and 0.7m. Ripper water deficit one recorded a significantly higher volumetric moisture content than Ag-Outback for the May 17 sowing time at 1.3m. Ag-Outback water deficit two recorded significantly higher volumetric moisture content than Ripper for the May 17 sowing time at 1.7m and 1.5m. Water deficit two recorded a significantly higher volumetric moisture content than water deficit one for Ag-Outback sown on April 22 at 0.9m, 1.1m and 1.3m, May 17 at 1.5m and 1.7m and June 14 at 1.5m and Ripper sown on April 22 at 0.9m and May 17 at 0.3m, 0.7m and 0.9m. Water deficit one recorded a significantly higher volumetric moisture content than water deficit two for Ag-Outback sown on June 14 at 0.3m.

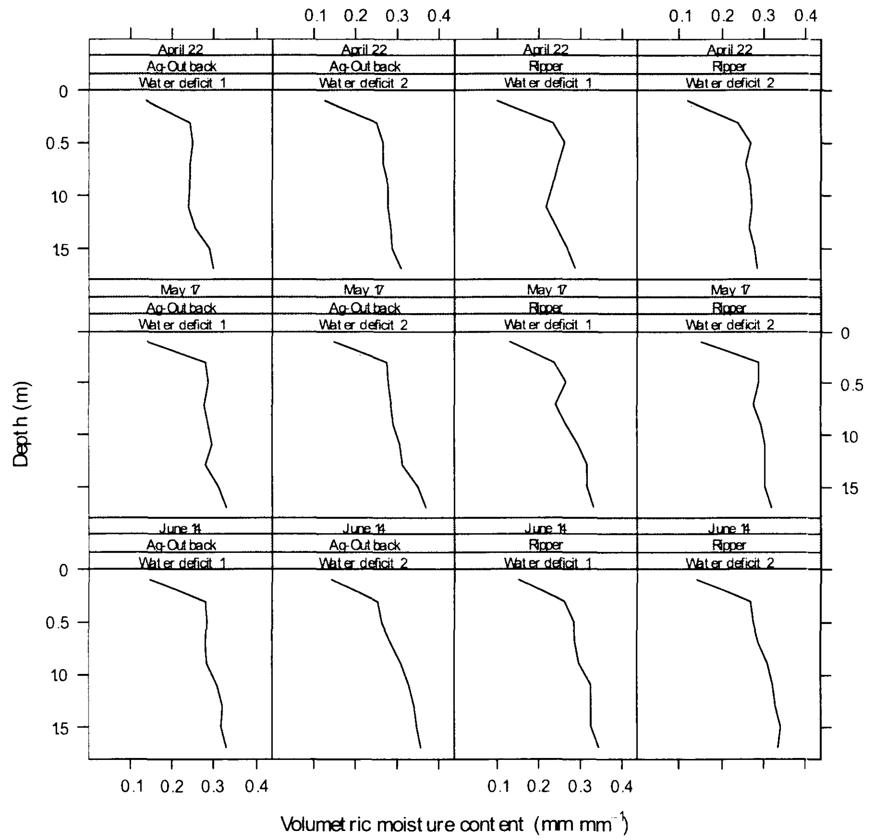

Figure 6.2 The effects of water deficit, depth, variety and sowing time on volumetric moisture content (mm mm^{-1}) of canola measured on November 12, at Condobolin in 2002. Grey lines represent +/- one standard error at the 5% significance level.

There were significant interactions (P<0.001) between water deficit, depth, variety and sowing time; sowing time, depth and sampling date; and water deficit, depth and sampling date on volumetric moisture content of canola sown at Condobolin in 2003. Figure 6.3 presents the effects of water deficit, depth, variety and sowing time on volumetric moisture content of canola sown at Condobolin in 2003. Ag-Outback water deficit one recorded a significantly higher volumetric moisture content than Ripper for April 2 at 1.3m, 1.5m and 1.7m and June 6 at 0.1m, 0.3m and 0.5m. Ag-Outback water deficit two recorded a significantly higher volumetric moisture content than Ripper for May 13 at 1.1m, 1.3m, 1.5m and 1.7m. Water deficit two recorded a significantly higher volumetric moisture content than water deficit one for Ag-Outback sown on April 2 at 0.3m, 0.5m and 0.7m and May 13 at 0.1m and 0.3m and for Ripper sown on April 2 at 0.7m, 0.9m, 1.1m and 1.3m, April 22 at 0.1m and June 6 at 0.1m, 0.3m, 0.5m, 0.7m and 0.9m. Water deficit one recorded a significantly higher volumetric moisture content than water deficit two for Ag-Outback sown on April 22 at 1.3m, 1.5 and 1.7m.

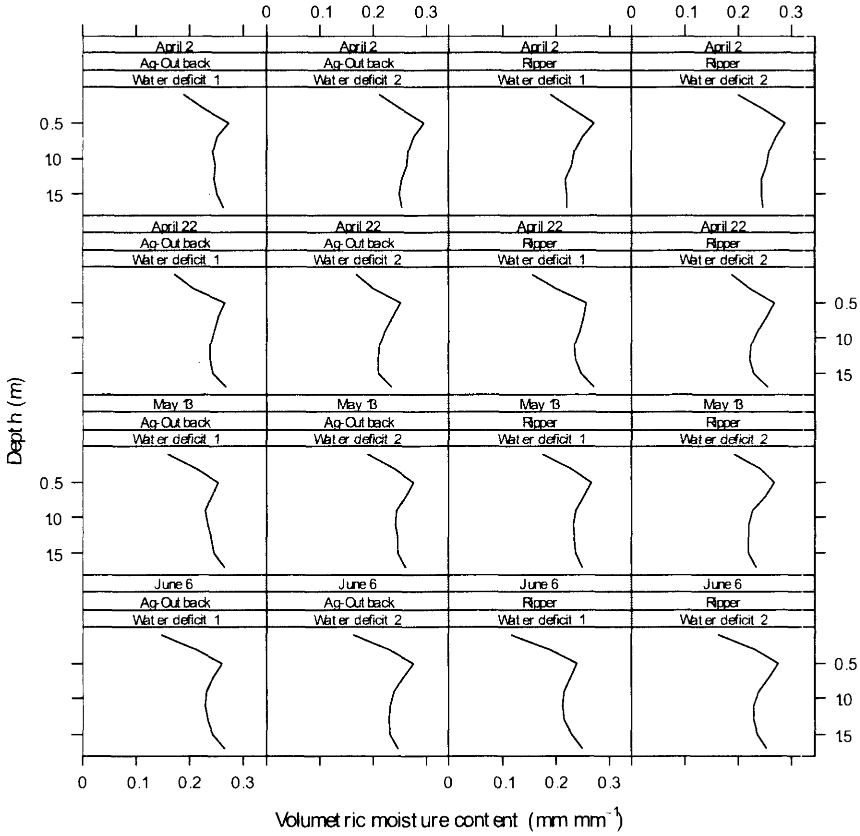

Figure 6.3 The effects of water deficit, depth, variety and sowing time on volumetric moisture content (mm mm^{-1}) of canola at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

Figures 6.4 – 6.7 present the effects of sowing time, depth and sampling date on volumetric moisture content of canola sown at Condobolin in 2003. At the final harvest, sampling date of October 30 the April 2 sowing time recorded a significantly higher volumetric moisture content than the April 22 sowing time at 0.1m, 0.3m, 0.5m, 1.3m and 1.5m, and than the May 13 sowing time at 0.1m and the June 6 sowing time at 0.1m and 0.3m. The April 22 sowing time recorded a significantly higher volumetric moisture content than the June 6 sowing time at 0.1m.

For the April 2 sowing time (Figure 6.4), the April 4 sampling date at sowing recorded a significantly higher volumetric moisture content than the October 30 sampling date at final harvest from 0.1m to 0.9m, the October 15 sampling date from 0.1m to 0.7m and the September

22 sampling date from 0.1m to 0.5m. There was no significant difference in volumetric moisture content for any of the other sampling dates.

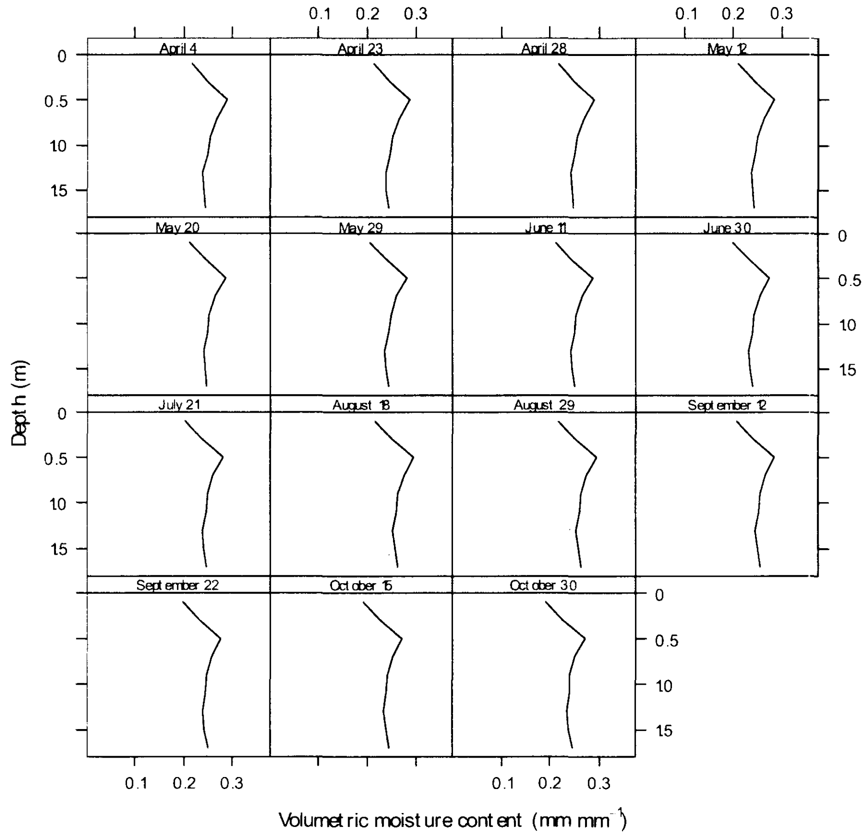

Figure 6.4 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola sown on April 2 at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

For the April 22 sowing time (Figure 6.5), the May 20 sampling date recorded a significantly higher volumetric moisture content than the October 30 sampling date at final harvest from 0.1m to 0.9m, the October 15 sampling date from 0.1m to 0.9m, the September 22 sampling date from 0.1m to 0.9m, the September 12 sampling date from 0.1m to 0.5m and the August 28 and August 16 sampling dates for 0.1m.

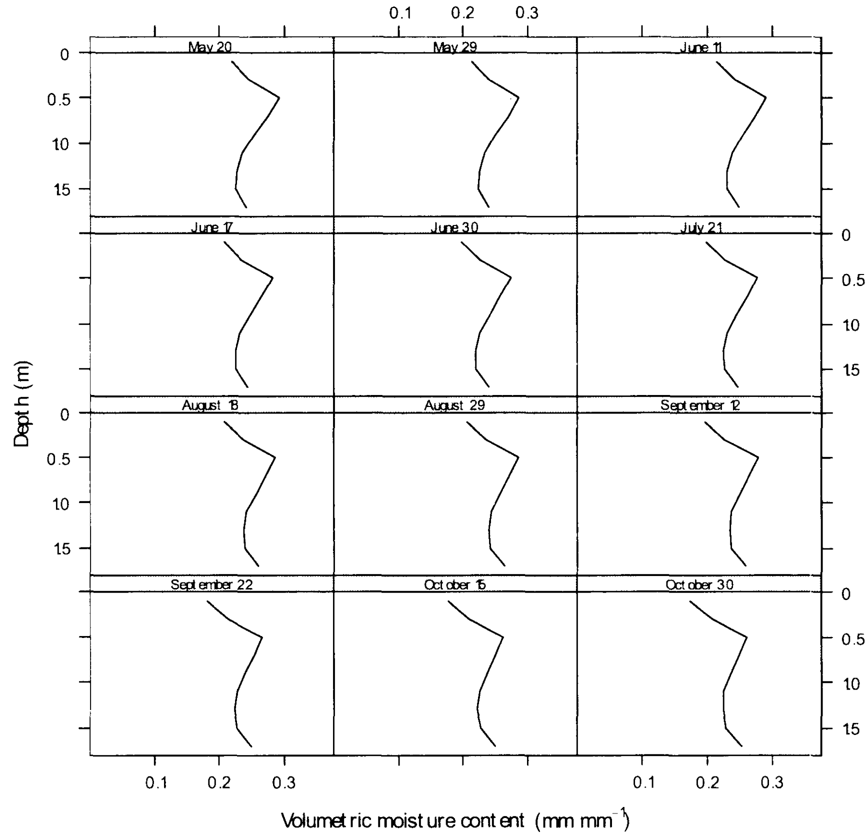

Figure 6.5 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola sown on April 22 at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

For the May 13 sowing time (Figure 6.6), the May 20 sampling date recorded a significantly higher volumetric moisture content than the October 30 sampling date at final harvest from 0.1m to 0.9m, the October 15 sampling date from 0.1m to 0.9m, the September 22 sampling date from 0.1m to 0.7m, the September 12 sampling date from 0.1m to 0.5m and the August 28 sampling date for 0.1m.

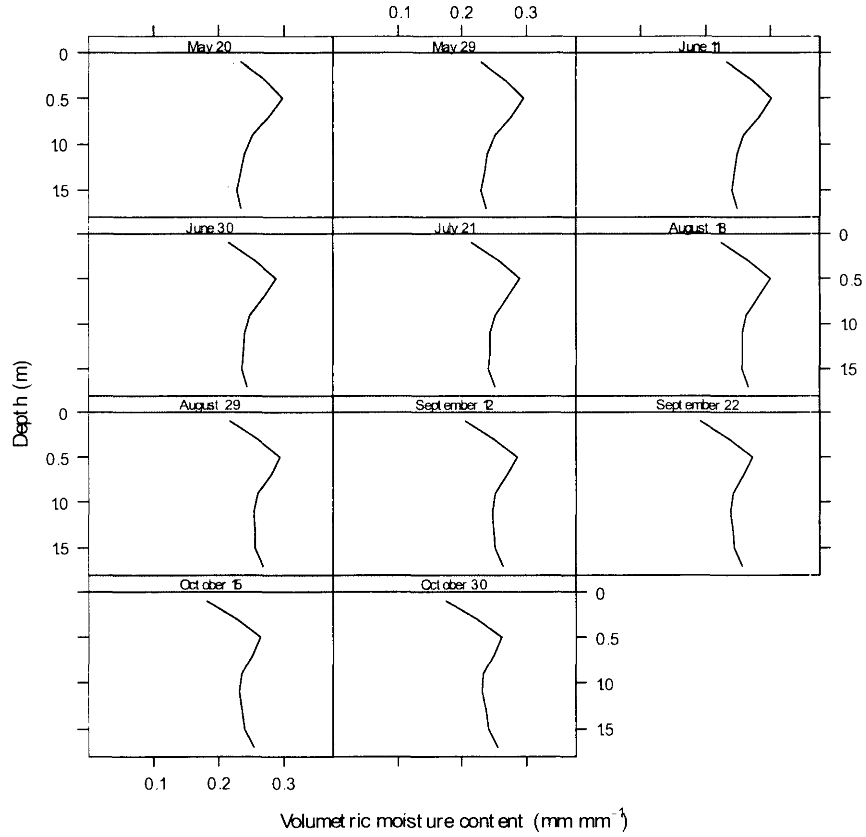

Figure 6.6 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola sown on May 13 at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

For the June 6 sowing time (Figure 6.7), the June 17 sampling date recorded a significantly higher volumetric moisture content than the October 30 sampling date at final harvest from 0.1m to 0.9m, the October 15 sampling date from 0.1m to 0.9m, the September 22 sampling date from 0.1m to 0.7m and the September 12 sampling date from 0.1m to 0.3m.

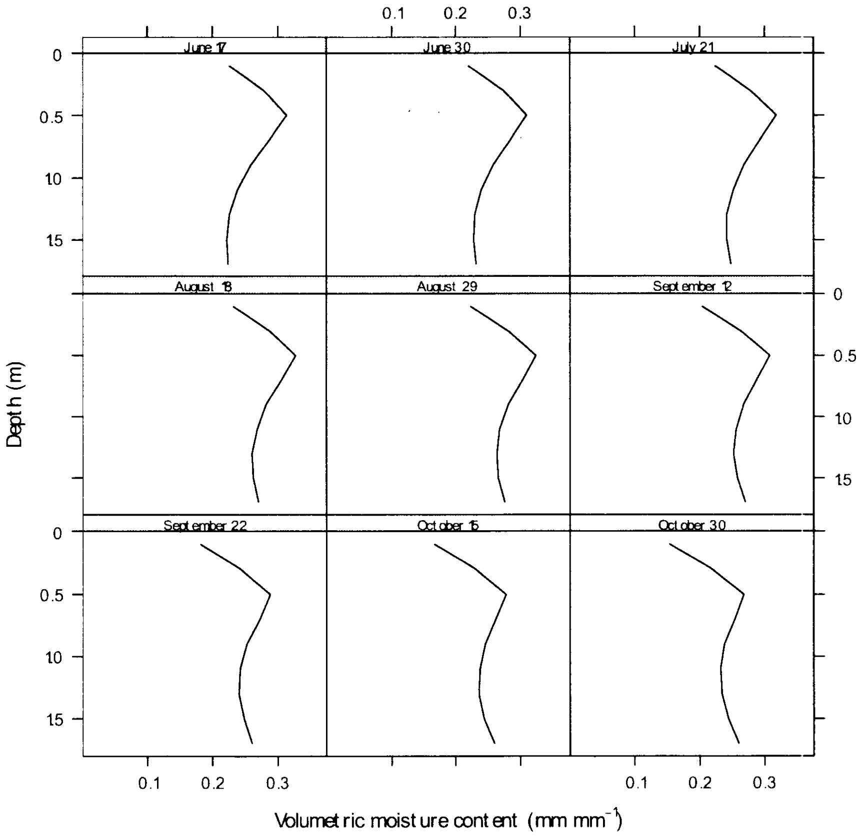

Figure 6.7 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola sown on June 6 at Condobolin in 2003. Grey lines represent +/- one standard error at the 5% significance level.

Figure 6.8 and Figure 6.9 present the effects of water deficit, depth and sampling date on volumetric moisture content of canola sown at Condobolin in 2003. Water deficit two recorded a significantly higher volumetric moisture content than water deficit one at the final harvest sampling on October 30 from 0.1m – 0.9m after which there was no significant difference. For water deficit one the April 4 start of season sampling date recorded a significantly higher volumetric moisture content than the October 30 final harvest sampling from 0.1m to 0.5m and from 0.1m to 0.3m for water deficit two. The October 30 final harvest sampling date recorded a significantly higher volumetric moisture content than April 4 start of season sampling date from 1.1m to 1.7m for water deficit one and 0.9m to 1.7m for water deficit two.

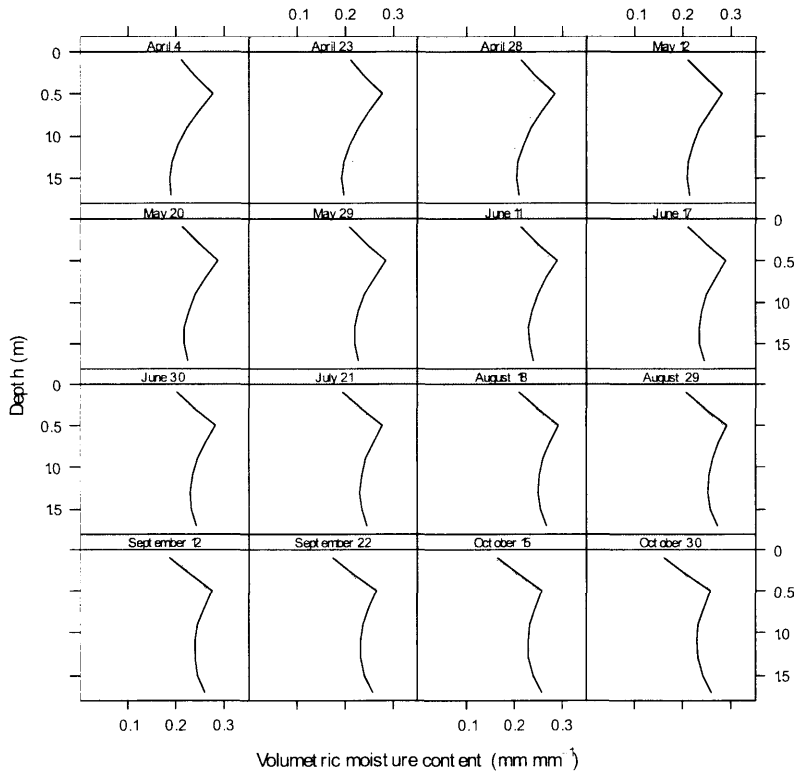

Figure 6.8 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola at Condobolin in 2003 for water deficit one. Grey lines represent +/- one standard error at the 5% significance level.

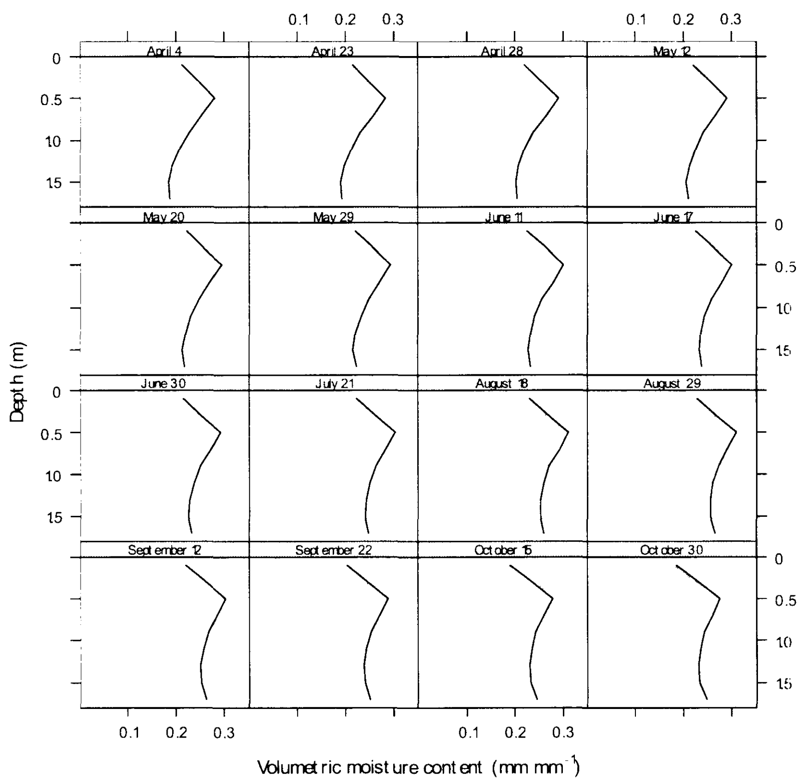

Figure 6.9 The effects of depth and sampling date on volumetric moisture content (mm mm^{-1}) of canola at Condobolin in 2003 for water deficit two. Grey lines represent +/- one standard error at the 5% significance level.

6.2.2 *Crop total water use*

The interactions of variety and water deficit (P=0.006) and sowing time and water deficit (P=0.045) had significant effects on total water use (mm) of canola sown at Condobolin in 2002 (Figure 6.10). Ag-Outback water deficit two recorded a significantly higher total water use than water deficit one. Ag-Outback water deficit one recorded a significantly lower total water use than the other three treatments. There was no significant difference between water deficit one and water deficit two for Ripper. Figure 6.11 presents the effects of sowing time and water deficit on total water use of canola at Condobolin in 2002. There was no significant difference in total water use of water deficit one and water deficit two with the exception of the June 14 sowing time where water deficit two recorded a significantly higher total water use than water deficit one. The June 14 sowing time water deficit one and water deficit two recorded a significantly lower total water use than all other treatments.

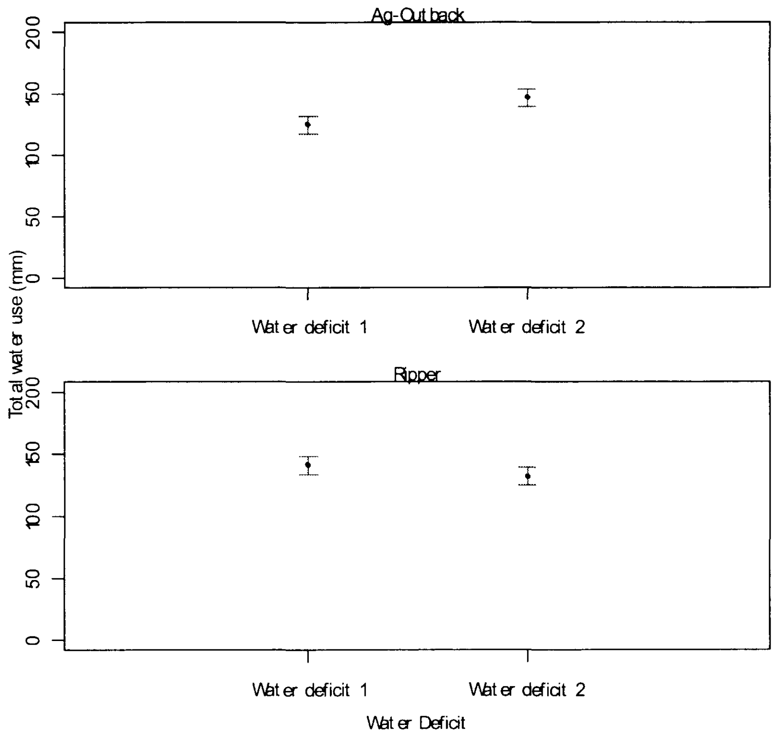

Figure 6.10 The effects of variety and water deficit on total water use (mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

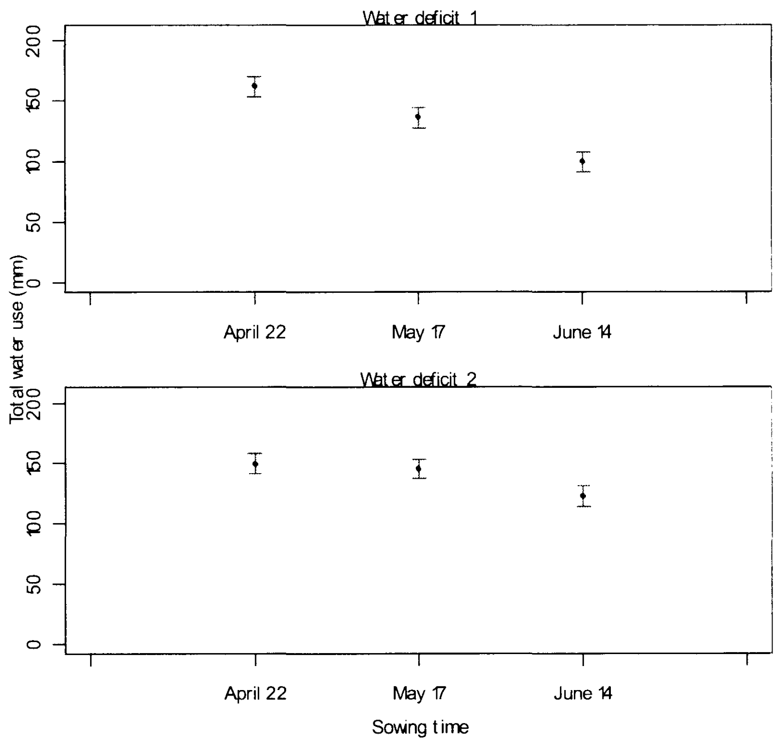

Figure 6.11 The effects of sowing time and water deficit on total water use (mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The interaction of variety and water deficit had a significant effect (P=0.033) on total water use of canola sown at Condobolin in 2003 as did sowing time. Figure 6.12 presents the effects of variety and water deficit on total water use of canola at Condobolin in 2003. Ag-Outback water deficit two recorded a significantly higher total water use than Ripper with water deficit two. There were no significant differences in total water use between Ag-Outback water deficit one and water deficit two and Ripper water deficit one and water deficit two. Figure 6.13 presents the effect of sowing time (P=0.024) on total water use of canola sown at Condobolin in 2003. The April 2 sowing time recorded a significantly higher total water use than the April 22 and May 13 sowing times.

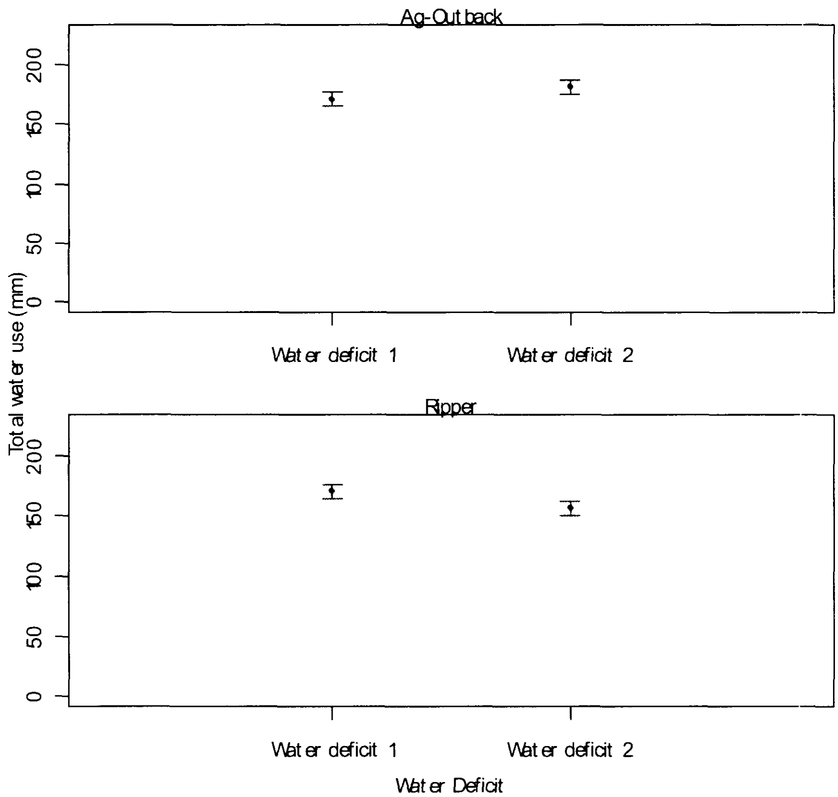

Figure 6.12 The effects of variety and water deficit on total water use (mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

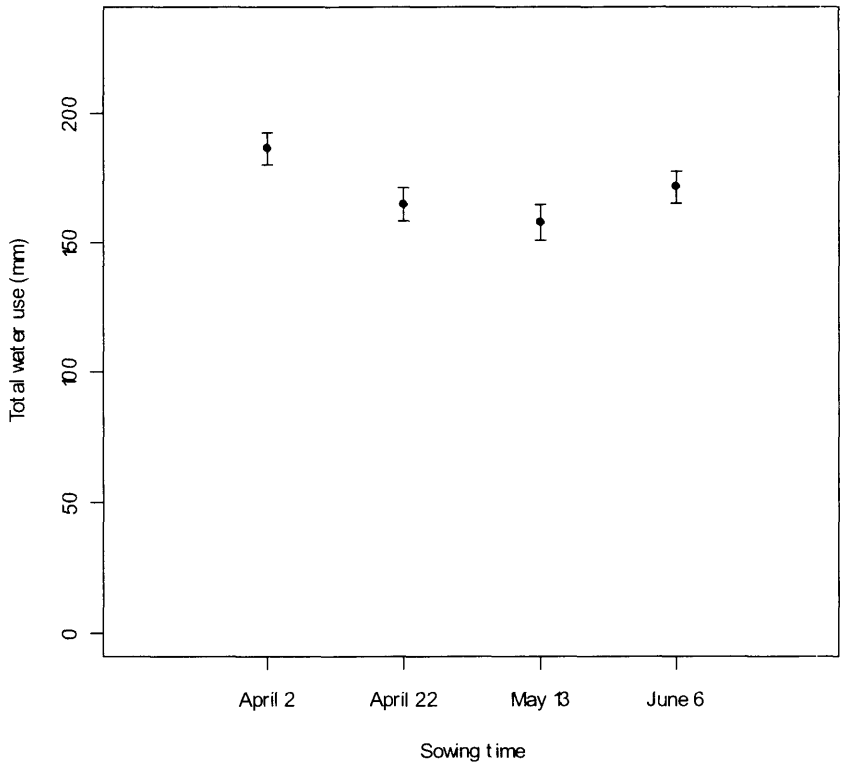

Figure 6.13 The effect of sowing time on total water use (mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

6.2.3 Pre-anthesis water use

The interactions of variety and water deficit and sowing time and water deficit had significant effects ($P<0.001$) on pre-anthesis water use (mm) of canola sown at Condobolin in 2002. Figure 6.14 presents the effects of variety and water deficit on pre-anthesis water use of canola sown at Condobolin in 2002. Ag-Outback water deficit two recorded a significantly higher pre-anthesis water use than water deficit one. Ripper water deficit one recorded a significantly higher pre-anthesis water use than water deficit two. Ripper water deficit one recorded a significantly higher pre-anthesis water use than Ripper water deficit two and Ag-Outback water deficit one. Figure 6.15 presents the effects of sowing time and water deficit on pre-anthesis water use of canola sown at Condobolin in 2002. The April 22 sowing time water deficit one recorded a significantly higher pre-anthesis water use than all other treatments while the June 14 sowing time water deficit one recorded a significantly lower pre-anthesis water use than all other treatments. The

April 22 sowing time water deficit one recorded a significantly higher pre-anthesis water use than water deficit two while the June 14 sowing time water deficit two recorded a significantly higher pre-anthesis water use than water deficit one. There was no significant difference in pre-anthesis water use for the May 17 sowing time.

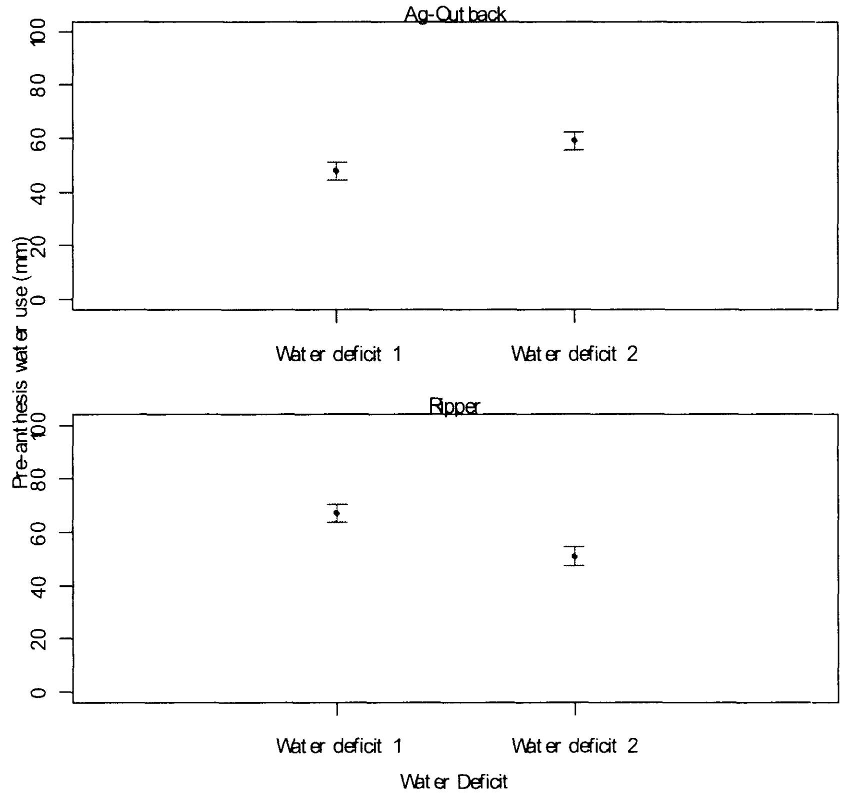

Figure 6.14 The effects of variety and water deficit on pre-anthesis water use (mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

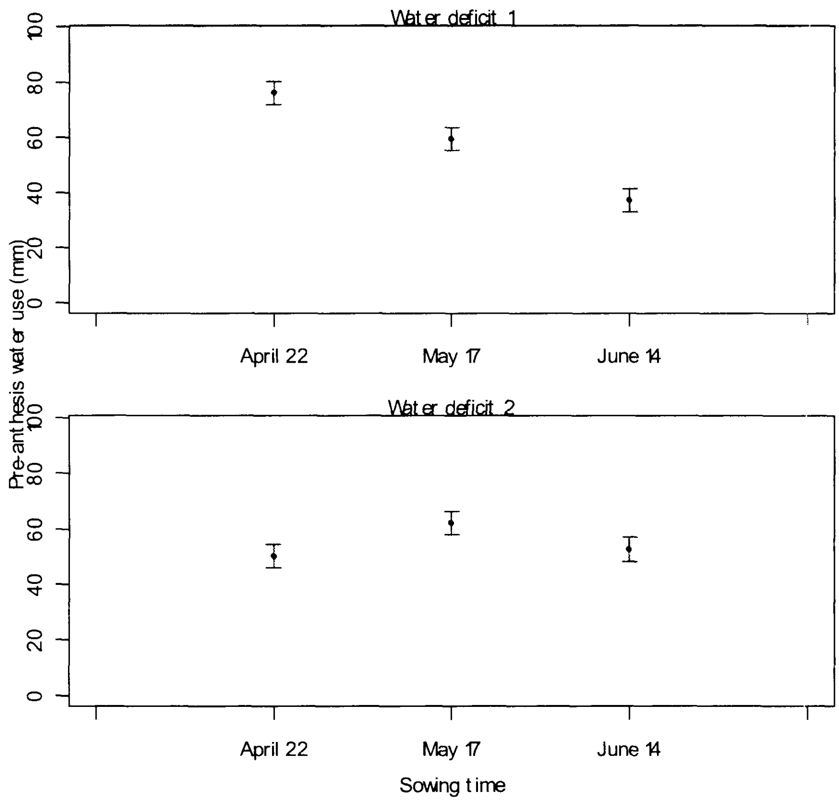

Figure 6.15 The effects of sowing time and water deficit on pre-anthesis water use (mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

Sowing time had a significant effect (P=0.008) on pre-anthesis water use of canola sown at Condobolin in 2003 (Figure 6.16). The April two sowing time recorded a significantly higher pre-anthesis water use than the other three sowing times. There was no significant difference in pre-anthesis water use between the April 22, May 13 and June 6 sowing times.

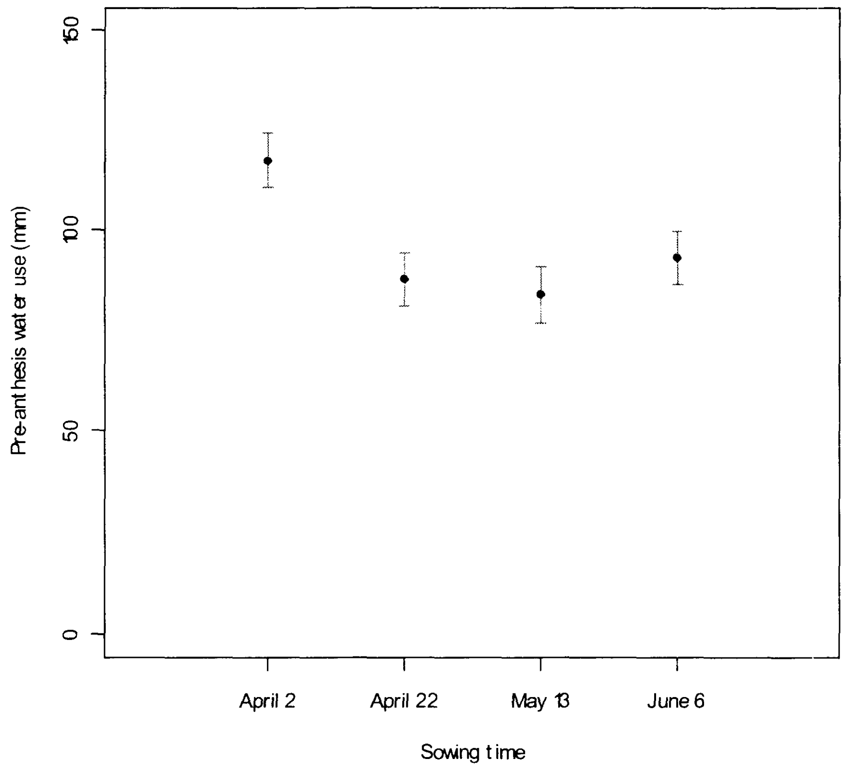

Figure 6.16 The effect of sowing time on pre-anthesis water use (mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

6.2.4 Post-anthesis water use

Sowing time had a significant effect (P<0.001) on post-anthesis water use (mm) of canola sown at Condobolin in 2002. There were no significant effects on post-anthesis water use of canola sown at Condobolin in 2003. Figure 6.17 presents the effects of sowing time on post-anthesis water use (mm) of canola sown at Condobolin in 2002. The April 22 sowing time recorded a significantly higher post-anthesis water use than the May 17 sowing time which recorded a significantly higher post-anthesis water use than the June 14 sowing time.

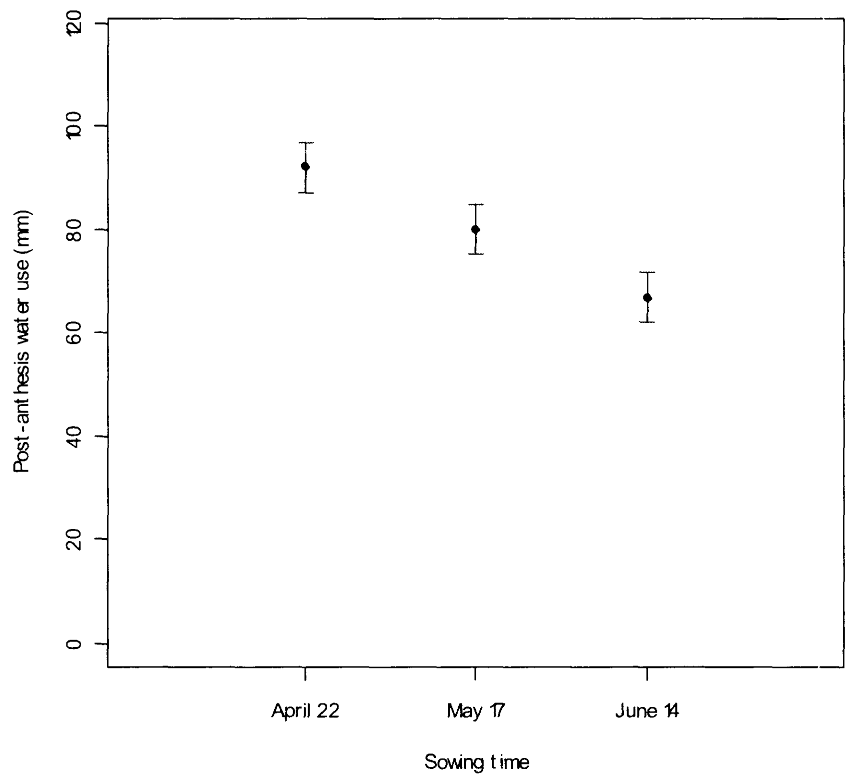

Figure 6.17 The effect of sowing time on post-anthesis water use (mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

6.2.5 Grain water use efficiency

Sowing time, water deficit and variety all has significant effects (P<0.001) on grain water use efficiency (kg ha^{-1}.mm) of canola sown at Condobolin in 2002. Figure 6.18a presents the effect of sowing time on grain water use efficiency of canola sown at Condobolin in 2002. The June 14 sowing time recorded a significantly lower grain water use efficiency than the April 22 and May 17 sowing times. Figure 6.18b presents the effect of variety on grain water use efficiency of canola sown at Condobolin in 2002. Ag-Outback recorded a significantly higher grain water use efficiency than Ripper. Figure 6.18c presents the effect of water deficit on grain water use efficiency of canola sown at Condobolin in 2002. Water deficit two recorded a significantly higher grain water use efficiency than water deficit one.

Sowing time had a significant effect (P<0.001) on grain water use efficiency of canola sown at Condobolin in 2003 (Figure 6.18d). The April 2 sowing time recorded a significantly higher grain water use efficiency than the April 22 sowing time. The June 6 sowing time recorded a significantly lower grain water use efficiency than the April 2, April 22 and May 13 sowing times.

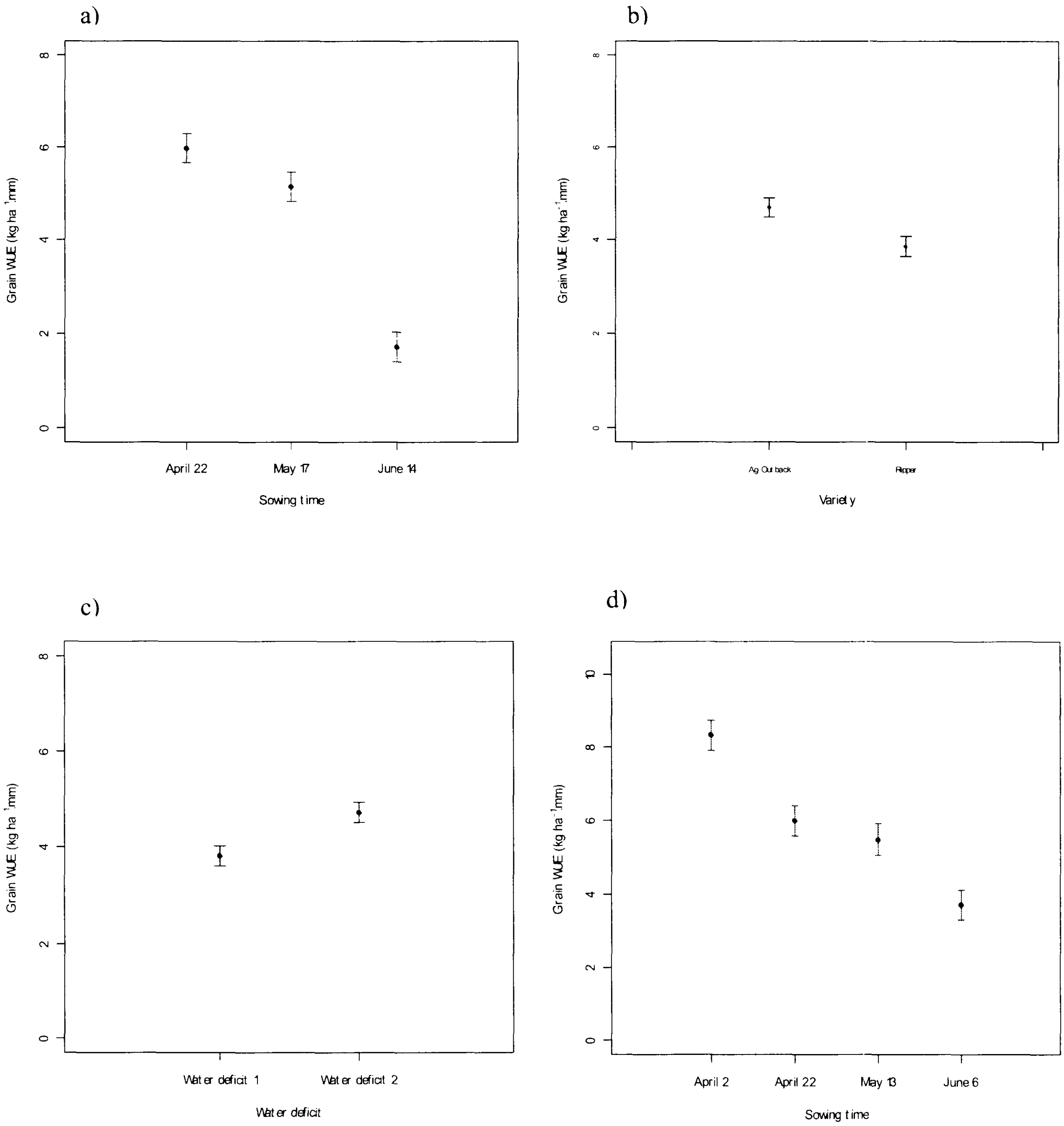

Figure 6.18 The effect of sowing time (a), variety (b) and water deficit (c) of canola sown at Condobolin in 2002 and sowing time (d) of canola sown at Condobolin in 2003 on grain water use efficiency (kg ha^{-1}.mm). Error bars represent +/- one standard error at the 5% significance level.

6.2.6 Dry matter water use efficiency

The interaction between sowing time and water deficit had a significant effect (P=0.015) on dry matter water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2002 (Figure 6.19). The April 22 sowing time water deficit two recorded a significantly higher dry matter water use efficiency than all other treatments. The June 14 sowing time water deficit one and two recorded a significantly lower dry matter water use efficiency than all other treatments.

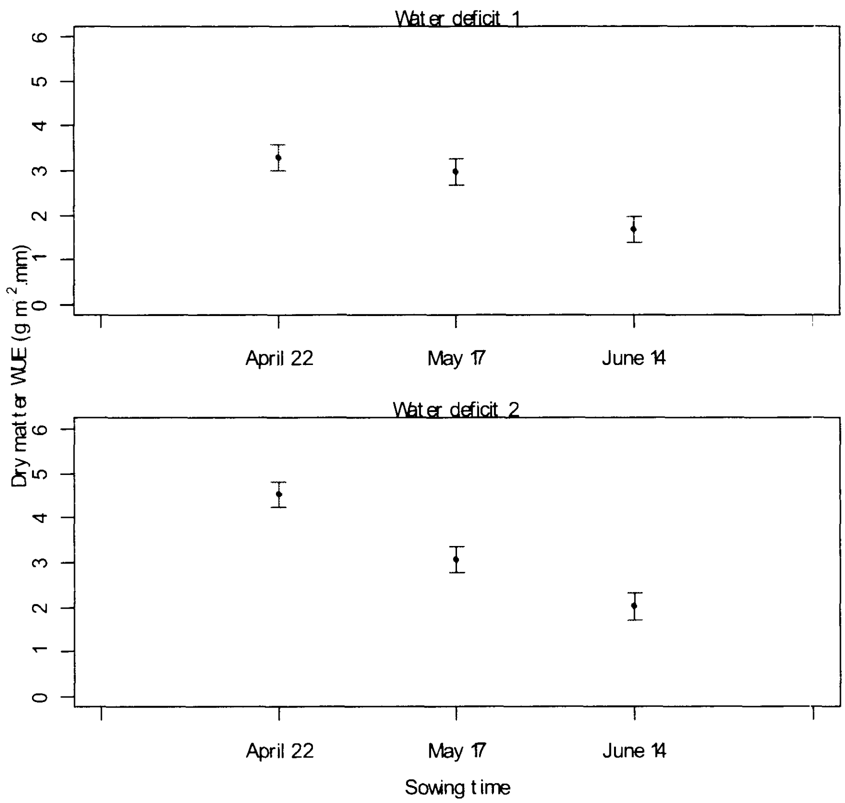

Figure 6.19 The effects of sowing time and water deficit on dry matter water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

The interaction between sowing time and water deficit had a significant effect (P=0.015) on dry matter water use efficiency of canola sown at Condobolin in 2003 (Figure 6.20). The May 13 sowing time water deficit two recorded a significantly higher dry matter water use efficiency than water deficit one. The June 6 sowing time water deficit one and two and the May 13 sowing time water deficit one recorded significantly lower dry matter water use efficiencies than all other treatments.

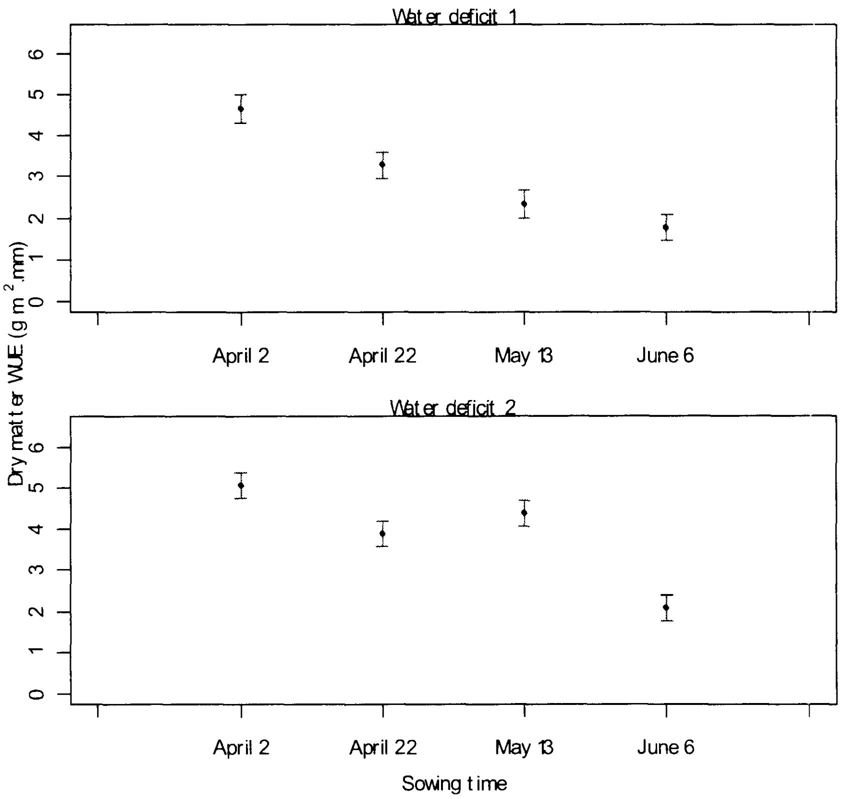

Figure 6.20 The effects of sowing time and water deficit on dry matter water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

6.2.7 Pre-anthesis water use efficiency

The interactions of variety and water deficit (P=0.002) and sowing time and water deficit (P=0.007) had significant effects on pre-anthesis water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2002. Figure 6.21 presents the effects of variety and water deficit on pre-anthesis water use efficiency of canola sown at Condobolin in 2002. Ripper water deficit two recorded a significantly higher pre-anthesis water use efficiency than all other treatments while Ripper water deficit one recorded a significantly lower pre-anthesis water use efficiency than all other treatments. There was no significant difference in pre-anthesis water use efficiency between Ag-Outback water deficit one and water deficit two.

Figure 6.22 presents the effects of sowing time and water deficit on pre-anthesis water use efficiency of canola sown at Condobolin in 2002. The April 22 sowing time water deficit one and water deficit two recorded significantly higher pre-anthesis water use efficiency than all other treatments. The April 22 sowing time water deficit two recorded a significantly higher pre-anthesis water use efficiency than water deficit one.

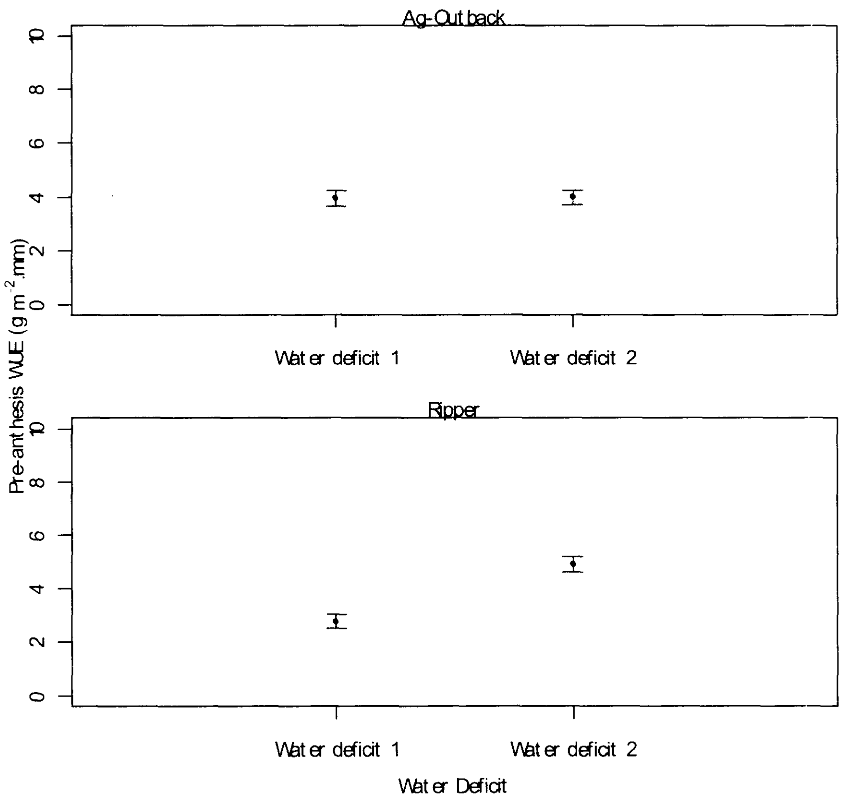

Figure 6.21 The effects of variety and water deficit on pre-anthesis water use efficiency ($g\ m^{-2}.mm$) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

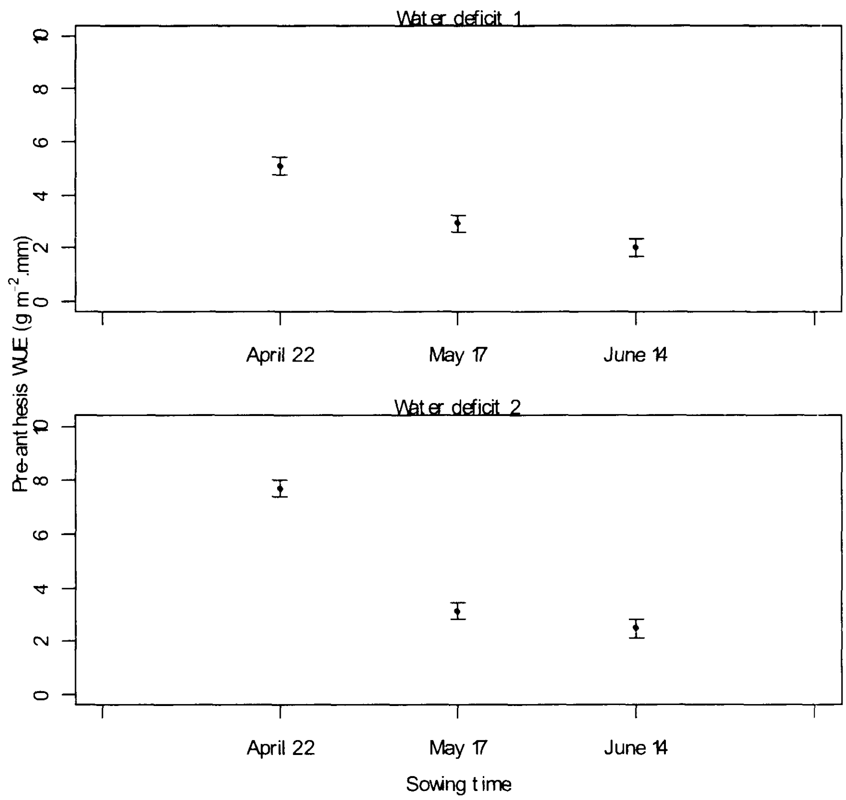

Figure 6.22 The effects of sowing time and water deficit on pre-anthesis water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2002. Error bars represent +/- one standard error at the 5% significance level.

Sowing time had a significant effect (P=0.002) on pre-anthesis water use efficiency of canola sown at Condobolin in 2003 (Figure 6.23). The June 6 sowing time recorded a significantly lower pre-anthesis water use efficiency than the April 22 and May 13 sowing times. There was no significant difference between the April 2, April 22 and May 13 sowing times.

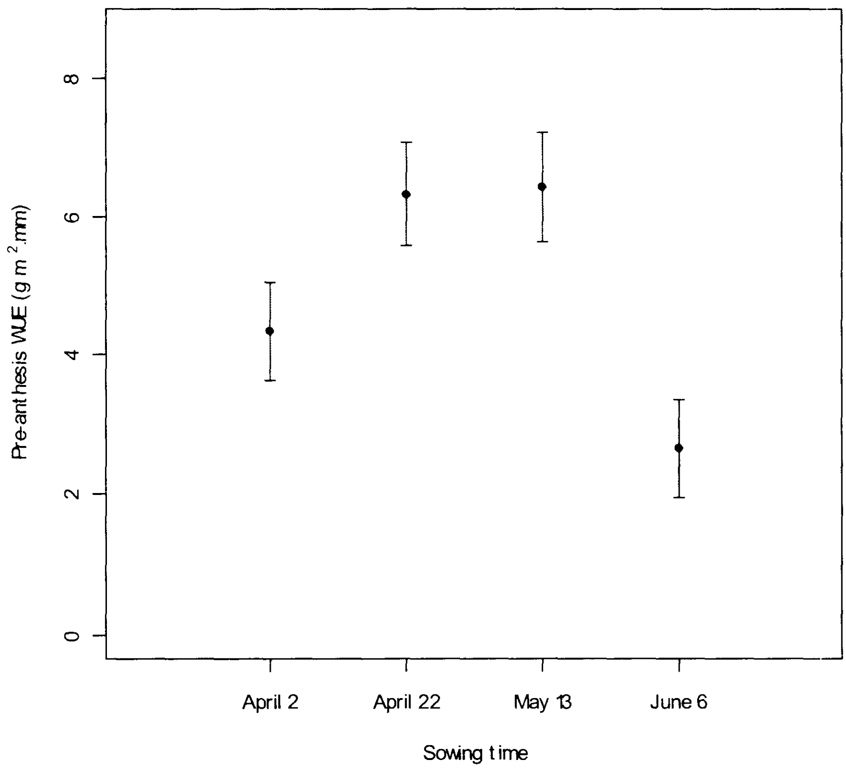

Figure 6.23 The effect of sowing time on pre-anthesis water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

6.2.8 Post-anthesis water use efficiency

There were no significant effects ($P<0.05$) on post-anthesis water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2002. Sowing time ($P<0.001$) and variety ($P=0.013$) had significant effects ($P<0.05$) on post-anthesis water use efficiency of canola sown at Condobolin in 2003. The effects of sowing time on post-anthesis water use efficiency of canola sown at Condobolin in 2003 are presented in Figure 6.24a. The April 2 sowing time recorded a significantly higher post-anthesis water use efficiency than the April 22, May 13 and June 6 sowing times. There was no significant difference in post-anthesis water use efficiency between the April 22, May 13 and June 6 sowing times. Figure 6.24b presents the effects of variety on post-anthesis water use efficiency of canola sown at Condobolin in 2003. Ag-Outback recorded a significantly higher post-anthesis water use efficiency than Ripper.

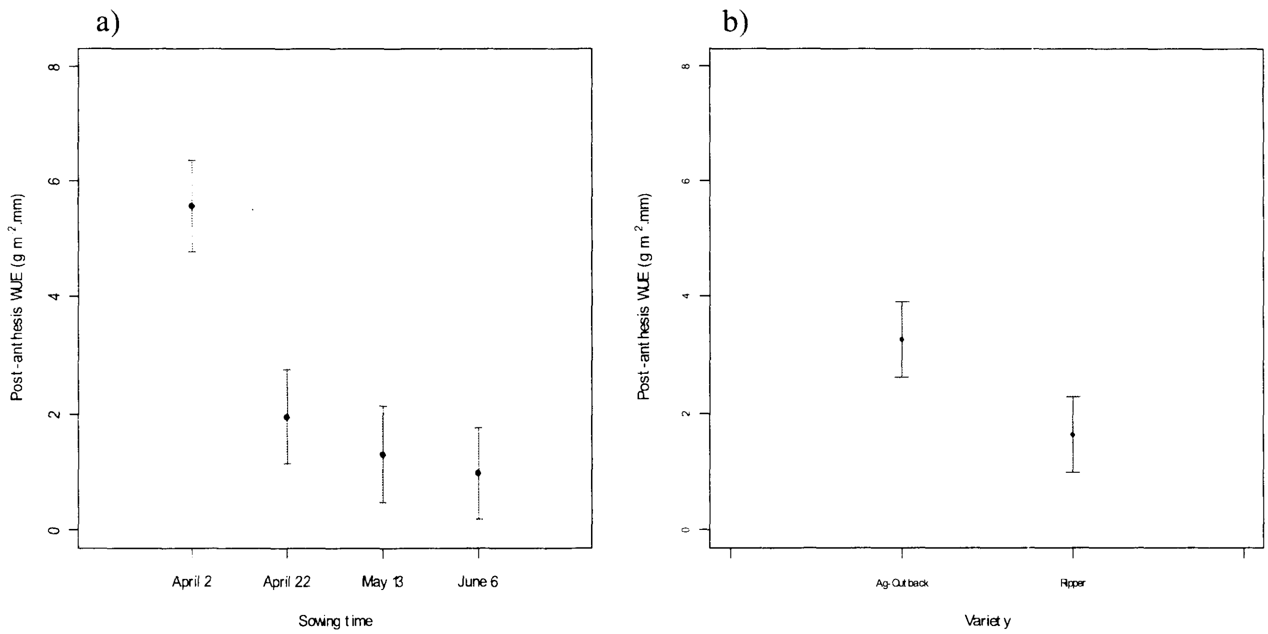

Figure 6.24 The effect of sowing time (a) and variety (b) on post-anthesis water use efficiency (g m^{-2}.mm) of canola sown at Condobolin in 2003. Error bars represent +/- one standard error at the 5% significance level.

6.3 Discussion

6.3.1 Crop water use and water use efficiency

Early sowing of canola in the low rainfall environment at Condobolin increased total water use and water use efficiency in 2002 and 2003. This was attributed to the longer growing season, which led to increases in total water use enabling the crop to reach full maturity unrestricted by water availability. Total water use ranged from approximately 160 mm for the April 22 sowing time to 100 mm for the June 14 sowing time in 2002, and approximately 185 mm for the April 2 sowing time and 160 mm for the June 6 sowing time in 2003. These are similar to those recorded by Washmann *et al.* (2003) for canola sown in Western Victoria, and Lewis and Thurling (1994) who reported water use of 157 mm – 180 mm for canola varieties sown in a similar environment in Western Australia on June 6.

The higher water usage observed in the early sowing times may be attributed to the ability of the plants to access water from deeper down in the soil profile due to greater root growth and the longer growing season (Chapter four). For example, in 2002, crops sown on April 22 extracted water to a depth of 160 - 180 cm while the June 14 sowing time extracted water to a depth of only 110 - 120 cm. This is reflected in the increased grain yields for the early sowing times for both Ripper and Ag-Outback (Chapter five).

These increased grain yields were attributed to increases in total water use leading to higher leaf area and consequently dry matter production (Chapter four). In 2002 moderate positive phenotypic correlations of total water use with maximum leaf area index ($r = +0.39$) (Figure 6.25a), grain yield ($r = +0.34$) (Figure 6.26a) and dry matter production ($r = +0.39$) (Figure 6.27a) were recorded. However, in 2003 the phenotypic correlations were inconsistent with a low positive correlation between total water use and maximum leaf area index of $r = +0.14$ (Figure 6.25b), a low positive correlation between total water use and dry matter production of $r = +0.25$ (Figure 6.27b) and a low negative correlation between total water use and grain yield of $r = -0.08$ (Figure 6.26b). Phenotypic correlations of pre-anthesis and post-anthesis water use in 2002 also suggest that increases in grain yield may be attributed to these effects. There was a low positive phenotypic correlation between grain yield and pre-anthesis water use of $r = +0.28$ (Figure 6.28a) and $r = +0.25$ for post-anthesis water use (Figure 6.28b). However, in 2003 pre-anthesis water use recorded a low positive phenotypic correlation with grain yield of $r = +0.21$ (Figure 6.28c) with post-anthesis water use recording a low negative phenotypic correlation of $r = -0.03$ (Figure 6.28d). This may be due to environmental factors such as high temperatures during flowering and siliqua fill causing the plants to be less efficient at converting available soil moisture into grain yield. This may suggest that total water use and pre-anthesis water use are the most critical factors in the production of canola in low rainfall environments although this is contrary to the finding of Anderson (1992) who reported that increased water use after first open flower was the major factor associated with improved yield in wheat in the central wheat-belt of Western Australia. O'Connell *et al.* (2002) has also reported the importance of post-flowering water use in the contribution to grain production in canola.

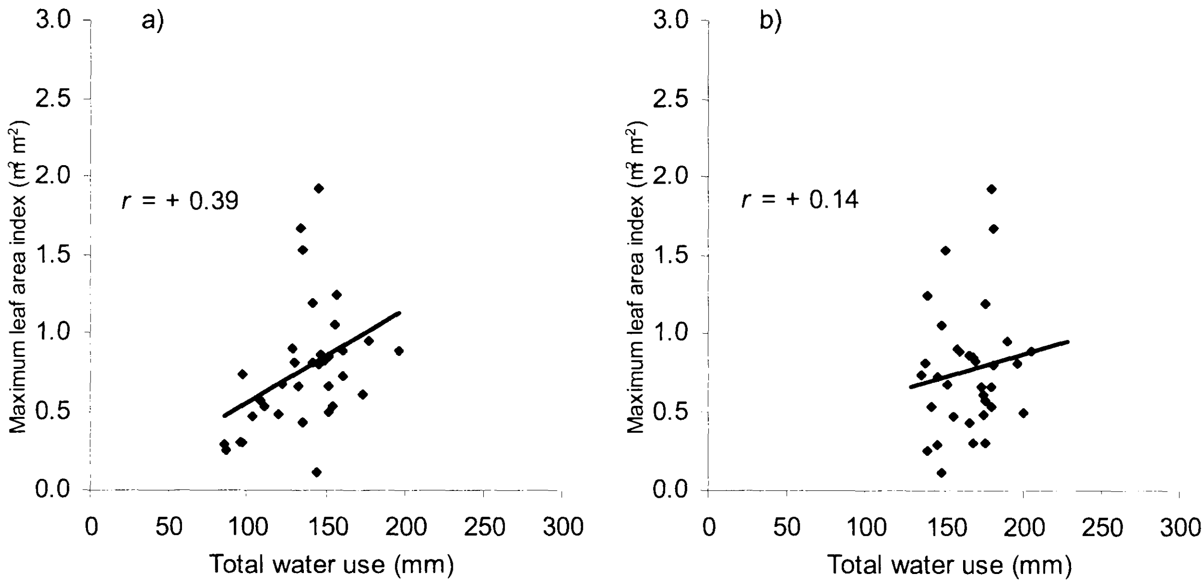

Figure 6.25 Phenotypic correlation between maximum leaf area index (m^2 m^{-2}) and total water use (mm) of canola sown at Condobolin in 2002 (a) and 2003 (b).

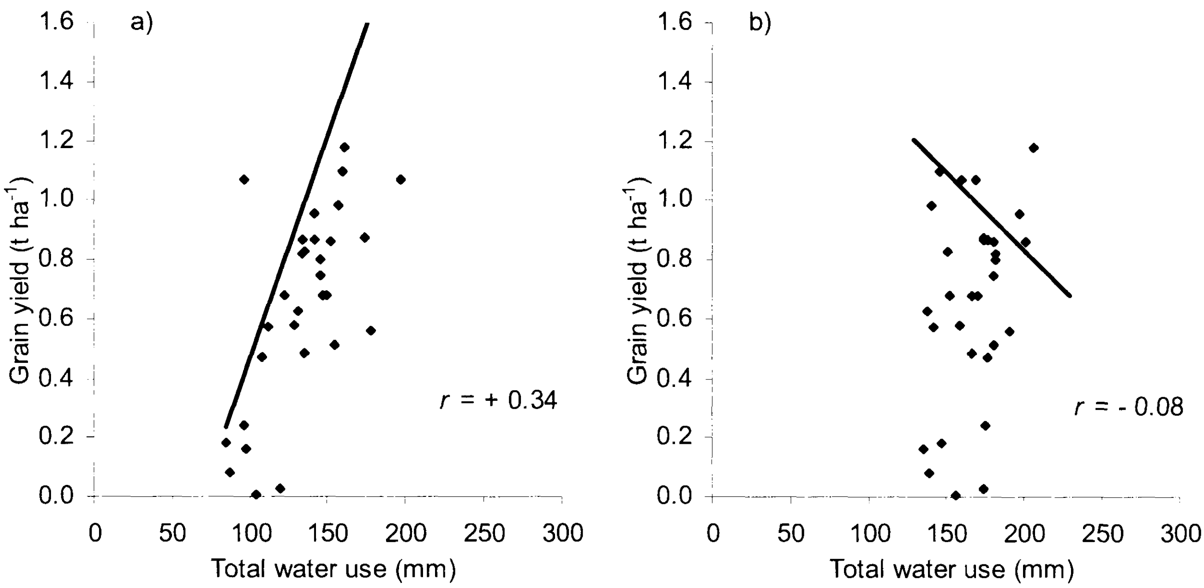

Figure 6.26 Phenotypic correlation between grain yield (t ha^{-1}) and total water use (mm) of canola sown at Condobolin in 2002 (a) and 2003 (b).

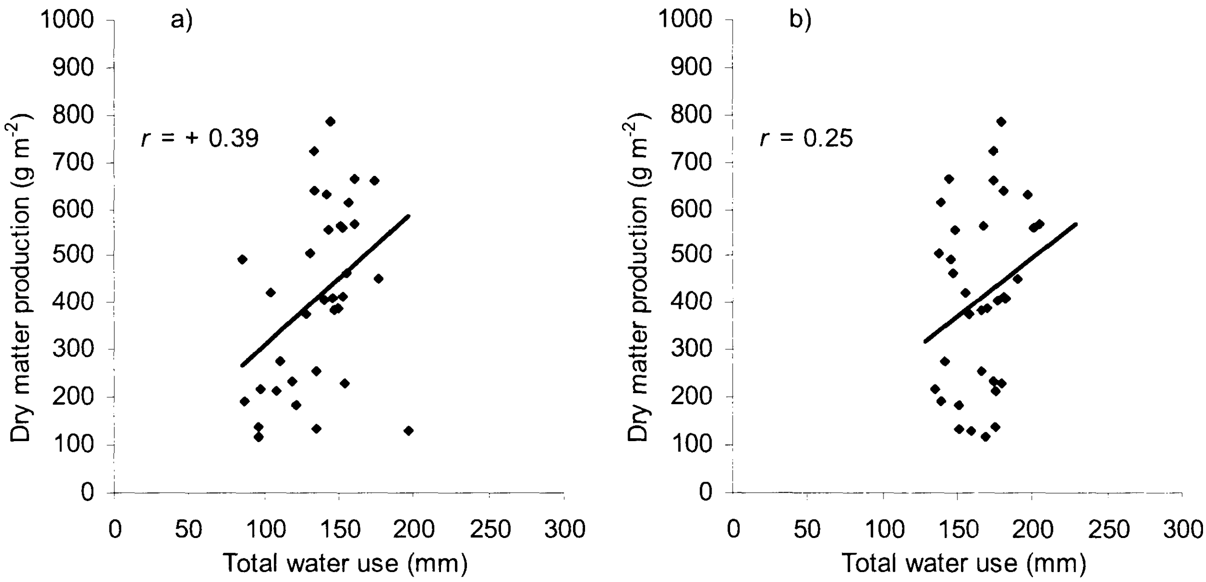

Figure 6.27 Phenotypic correlation between dry matter production (g m^{-2}) and total water use (mm) of canola sown at Condobolin in 2002 (a) and 2003 (b).

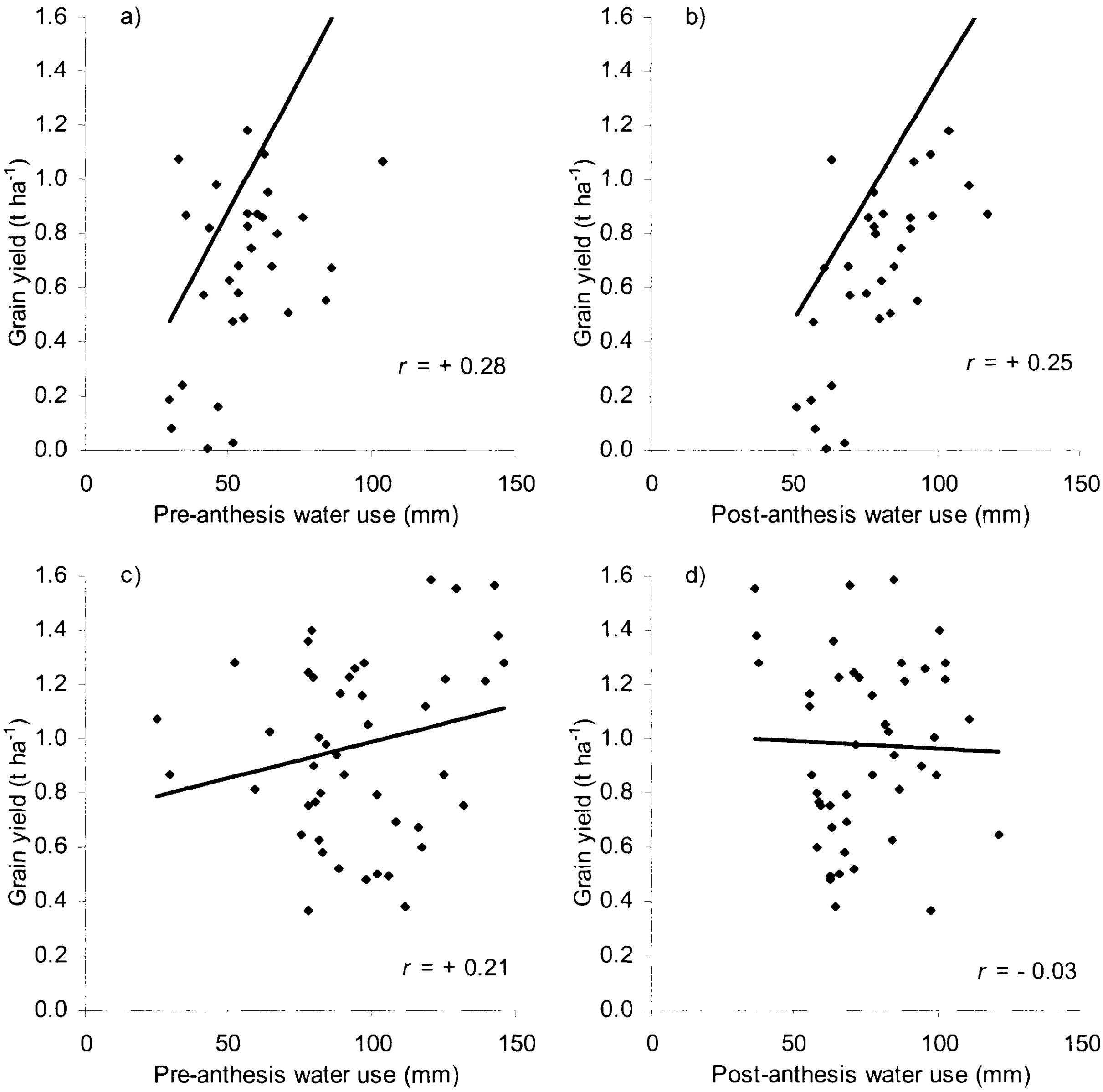

Figure 6.28 Phenotypic correlation between grain yield (t ha^{-1}) and pre-anthesis water use (mm) (a) and post-anthesis water use (mm) (b) in 2002, and pre-anthesis water use (mm) (c) and post-anthesis water use (mm) (d) in 2003, of canola sown at Condobolin.

Nielsen (1997) reported that greater leaf area index was probably the result of greater available soil water at planting. However, this was not the case in the present experiments with no significant differences recorded in 2002 or 2003 of volumetric moisture content at sowing between the different sowing times. Gregory (1998), using a range of crops, reported that differences in water use were associated with differences in the size of the crops, with larger crops using more water from the subsoil. This was observed in 2002 and 2003 with the early sown crops having higher water use and greater dry matter production (Chapter four). However, this was also the case when comparing varieties, with Ripper recording a higher plant height than Ag-Outback but a lower total water use. This also contradicts reports by Gregory (1998) who suggested that increases in water use were due to differences in maturity type with later maturing varieties recording higher water use than early maturing varieties. However, in 2002 Ag-Outback, an earlier maturing variety recorded a higher total water use than Ripper, a mid-maturing variety. It would appear that the increases in water use reported by Gregory (1998) in a non-water limited environment do not reflect the same situation as that in this thesis, namely a water limited environment and as such varieties could be expected to perform differently.

In both years there were sharp increases in volumetric moisture content at specific times and these have been attributed to rainfall. Forty five mm of rain was recorded in September in 2002, and 132 mm between July and August in 2003. Overall water use was greatest in 2003 across all sowing times for both canola varieties, and this was attributed to the increased in-crop rainfall received in the 2003 season compared with the 2002 season allowing more water to be available for use by the plants. (Chapter three).

Grain water use efficiencies ranged from 5.98 kg ha^{-1}.mm for the April 22 sowing time to 1.71 kg ha^{-1}.mm for the June 14 sowing time in 2002, and from 8.3 kg ha^{-1}.mm for the April 2 sowing time to 3.71 kg ha^{-1}.mm for the June 6 sowing time in 2003 (Figure 6.18). Decreased grain and dry matter water use efficiency with delayed sowing time is attributed to a decline in the efficiency of converting moisture to grain yield. This may have been due to moisture and heat stress associated with the later sowing times rendering the plant less able to convert moisture to grain yield and the reduced plant growth recorded by later sowing times (Chapter four) which would have attributed to a reduced supply of assimilates and therefore an ability to produce siliqua and hence grain yield and dry matter.

Varietal differences in pre-anthesis and post-anthesis water use efficiency were inconsistent with Ag-Outback recording higher pre-anthesis water use efficiency than Ripper in 2002 under a more water stressed environment (water deficit one); however under water deficit two Ripper recorded a higher pre-anthesis water use efficiency. It is interesting to note the pre-anthesis water use efficiency for both varieties in 2003 was higher for the later sowing times with the earlier sown crops recording lower pre-anthesis water use efficiency. The reason for this is unclear; however it may be attributed to the large rainfall events in July and August which later maturing varieties were better able to utilise than the earlier maturing varieties. However, reduced dry matter production (Chapter four) due to a lack of assimilates and the plants being unable to increase biomass through siliqua production which was reduced through the senescence of leaves would also have contributed to the reduced grain yields reported in Chapter five for the later sowing times and reinforces the importance of post-flowering water use in the production of grain (O'Connell *et al.* 2002). In 2002, post-anthesis water use efficiency was higher than pre-anthesis water use efficiency; however post-anthesis water use efficiency in 2003 was lower than pre-anthesis water use and this may also have impacted negatively on grain water use efficiency with Anderson (1992) reporting that increased water use after first open flower was the major factor associated with improved yield in wheat in the central wheat-belt of Western Australia and O'Connell *et al.* (2002) who reported the importance of post-flowering water use in the contribution to grain production in canola.

Water use efficiencies were greater in 2003 than 2002, which is contrary to the findings of O'Connell *et al.* (2002), who reported high water use efficiency as typical of dry seasons that have low soil evaporation. This was not the case in the current experiments, with water use efficiencies lower in 2002 than in 2003 for the common April 22 sowing time. This has been attributed to the below average rainfall received in 2002 compared with 2003 and the timing of rainfall events in the two years (Chapter three), and in particular the 130mm received in July and August 2003.

Low water use efficiencies have also been reported by O'Connell *et al.* (2002), who recorded an average water use efficiency of 1.2 kg ha^{-1}.mm for mustard grown in the Victoria Mallee, and Anderson *et al.* (2003), who reported water use efficiency of 4.5 kg ha^{-1}.mm for canola grown in the northern great plains of the United States. The higher water use efficiencies recorded for earlier sowing times have been reported by Taylor *et al.* (1991), who recorded a water use efficiency of canola sown at Tatura in Victoria of 7.6 kg ha^{-1}.mm and Bernardi and Banks (1991), who reported a water use efficiency of 6.43 kg ha^{-1}.mm for canola grown at Condobolin. Hocking *et al.* (2003) also reported water use efficiencies of canola at Harden and Ardlethan to be 6.8 kg ha^{-1}.mm and 9.6 kg ha^{-1}.mm respectively, which correspond with those reported in my experiments.

However, these are still well below reports by Grey (1998) of 18 kg ha^{-1}.mm for canola grown in a high rainfall experiment in Victoria, and French and Shultz (1984) who suggested that canola water use efficiency is approximately 60% of wheat water use efficiency, with an estimated value of 12 kg ha^{-1}.mm. Robertson and Holland (2004) reported predicted water use efficiencies by APSIM of 12 kg ha^{-1}.mm similar to that of Hocking *et al.* (1997) for experiments conducted at Junee and Condobolin. This value appears too high when compared to the results reported in this thesis and by others and that this is due to the use of the estimated soil evaporation value for wheat of 110 mm. If this estimate had been used in this thesis, it would have accounted for between 56 % and 88 % of the water use in 2002 for Ag-Outback, increasing water use efficiencies to 12 kg ha^{-1}.mm for the April 22 sowing time and 27 kg ha^{-1}.mm for the June 14 sowing time which is clearly unrealistic.

The higher water use recorded by Ripper coincided with water being accessed at greater depths, with Ripper accessing water from deeper within the soil profile for the May 17 (160 – 180 cm) and June 14 (120 – 140 cm) sowing times in 2002 and the April 2 and April 22 (160 – 180 cm) sowing times in 2003. This did not, however, lead to increased grain yield or water use efficiency, with Ag-Outback recording a higher grain water use efficiency than Ripper in 2002 and a higher post-anthesis than Ripper in 2003. This suggests that Ripper has the ability to explore and access water from deeper layers, which is an important characteristic in low rainfall environments, but its lower water use efficiency is a disadvantage. Increases in water supply through greater rooting depth have been reported by Kumar and Singh (1998) who reported that continued root growth led to greater exploration of soil volume and an enhanced water supply to the plant. The soil extraction depths reported in this thesis correspond with those of Nielsen (1997) who recorded water extraction to depths of 160cm by canola in north-eastern Colorado. However, Gregory (1998) reported rooting depth of 60-80 cm for canola grown on a shallow duplex soil in Western Australia; this contrasts to depths recorded in this experiment and also those reported by Kirkegaard *et al.* (1997).

The increase in depth of extraction with delay in sowing time recorded for Ripper in 2003 is in contrast to the results of Ag-Outback and those recorded by both varieties in 2002. This may be due to the higher amount of in-crop rainfall received in 2003 compared with 2002 (Chapter three). The higher in-crop rainfall may have reduced the need of the early sown crops to explore deeper into the soil profile to retrieve moisture later in the season in contrast with the later sown crops. The timing of rainfall events in 2003, as detailed previously in this chapter, may also have influenced the crop's need to explore greater soil depths to retrieve water.

Taylor *et al.* (1991) reported depths of extraction of canola sown at Tatura in Victoria to be 130 cm, lower than those reported in the current work. However, Hocking *et al.* (2003) reported extractions depths of between 60 cm and 100 cm in experiments conducted in southern New South Wales. It may also be speculated that in 2002 there was more stored moisture in the soil due to increased summer rainfall (Chapter three) and less in-crop rainfall. This may have caused the plants to explore the deeper soil layers to retrieve moisture. However, in 2003 there was very little stored moisture and so the early sowing times had to survive on in-crop rainfall as there was no moisture to seek at depth. Therefore, the responses which are detailed will vary with summer rainfall conditions and their effects on soil water at sowing. It may also be noted that sub-soil constraints may also prejudice the plant's ability to seek moisture or the soil's ability to retain moisture, although these were not investigated.

6.4 Conclusions

Water use and water use efficiency have significant influences on plant growth and grain yield. Increases in water use and water use efficiency associated with early sowing led to increased leaf area, dry matter production, and subsequent grain yield (Chapters four and five). The increased water use efficiency with early sowing indicates the importance of early sowing to optimise growth in order to maximise grain yield. Early maturing varieties, when compared with later maturing varieties, although having lower total water use, have higher grain water use efficiencies. This suggests that in a low rainfall environment it is important to have a variety that has higher grain water use efficiency than higher total water use. The higher total water use does not necessarily mean higher yields. The effects of pre-anthesis and post-anthesis water use efficiency in low rainfall environments are still unclear and further investigation is required to determine the relative significance of these parameters. Clearly, early sowing increases water use and water use efficiency while early maturing varieties have higher water use efficiency than later maturing varieties in low rainfall environments. However, as discussed in Chapter five this does not indicate the effect frost may have on plant performance.

CHAPTER SEVEN: GENERAL DISCUSSION AND CONCLUSIONS

7.1 Introduction

The principal aim of this research was to determine if canola could be grown efficiently in low rainfall environments of Australia, in particular in central western New South Wales. Within this question, three important aspects of production were identified and outlined in Chapter three. Essentially, they were to determine the importance of sowing time, variety and soil moisture on plant growth, grain yield and yield components and water use. The two main factors were sowing time and variety, with the application of additional moisture being used to allow for comparisons between different levels of water deficit. Sowing time was identified as the most critical factor in improving the efficiency of canola production in low rainfall environments. Sowing earlier than the recommended sowing time of mid-late April (McRae *et al.* 2003) increased plant growth, grain yield and yield components, and water use efficiency. The phenotypic correlations presented in this chapter represent both water deficits and years due to the importance of illustrating the relationships involved in efficient canola production as would be experienced under 'farmer grown' conditions at varying water deficits from year to year. In this final chapter the implications of the study and its results will be discussed and conclusions and recommendations for further study explored.

7.2 Discussion

7.2.1 Sowing time and canola production

Early sowing time is the most critical factor when growing canola in low rainfall environments. Reductions in grain yield, oil concentration, and 1000-grain weight were recorded when sowing was delayed. This was attributed to increased temperature and heat stress with delayed sowing time being experienced by the plants during flowering, siliqua production and grain-fill (Chapter five). Later sowing induced not only lower grain yields but yield components were also reduced, with the loss in oil concentration, a major consideration for Australian growers when marketing and selling canola.

The reductions reported in grain yield and yield components arise directly from a reduction in overall plant growth, with dry matter production being a strong determinant and a critical factor in the resultant grain yield. This is illustrated by the moderate positive phenotypic correlation of $r = +0.36$ shown in Figure 8.1. All areas of plant growth were reduced as sowing time was delayed, which led to reductions in dry matter production. The reduction in plant growth and subsequent dry matter production with delayed sowing has been attributed to a shortening of the vegetative and reproductive phases of development (Hocking and Stapper 2001), with the plant being unable to reach its full growth potential (Chapter five). However, a balance needs to be achieved between optimising plant growth and achieving maximum yield. Figure 8.2 illustrates that dry matter production is driving key growth parameters which determine grain yield. Moderate to high positive phenotypic correlations between dry matter production and leaf area index (Figure 8.2a), dry matter production and plant height (Figure 8.2b), dry matter production and branch number (Figure 8.2c) and dry matter production and siliqua number (Figure 8.2d) illustrate the importance of plant growth in determining the efficiency of canola production.

Despite these positive phenotypic correlations it is important to consider the likely effects that frost may have on canola production. Given that frost thresholds were defined at -2°C in Chapter five, the likelihood of frost occurring is approximately one in every ten years. The level of loss that would be incurred with regards to grain yield is difficult to determine; however, with losses in grain yield of 80% when sowing was delayed from April 22 to June 14 in 2002 and 55% and 42% when sowing was delayed from April 2 and April 22, respectively to June 6 in 2003 (Chapter five), I would suggest that current canola growers would deem the chance of considerable frost damage occurring to be an acceptable risk when compared with the annual loss in grain yield from late sowing. This is further strengthened by the extended flowering period which allows canola to continue producing flowers over a period of up to six weeks. Unless there were a sustained number of frosts across the flowering and siliqua filling window from the six week period from July 1 until August 11, when early sowing times are at peak reproductive production, it is unlikely that canola growers would incur the loss in grain yield reported from delayed sowing.

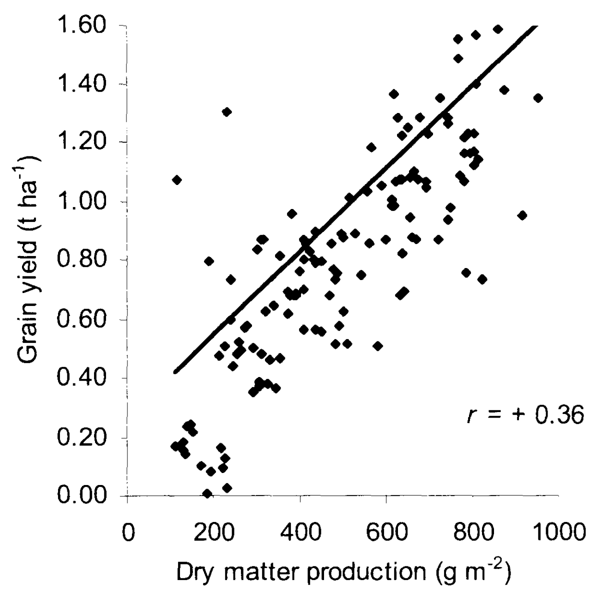

Figure 7.1 Phenotypic correlation between grain yield (t ha^{-1}) and dry matter production (g m^{-2}) of canola grown at Condobolin, in 2002 and 2003 for all varieties, sowing times and water deficits.

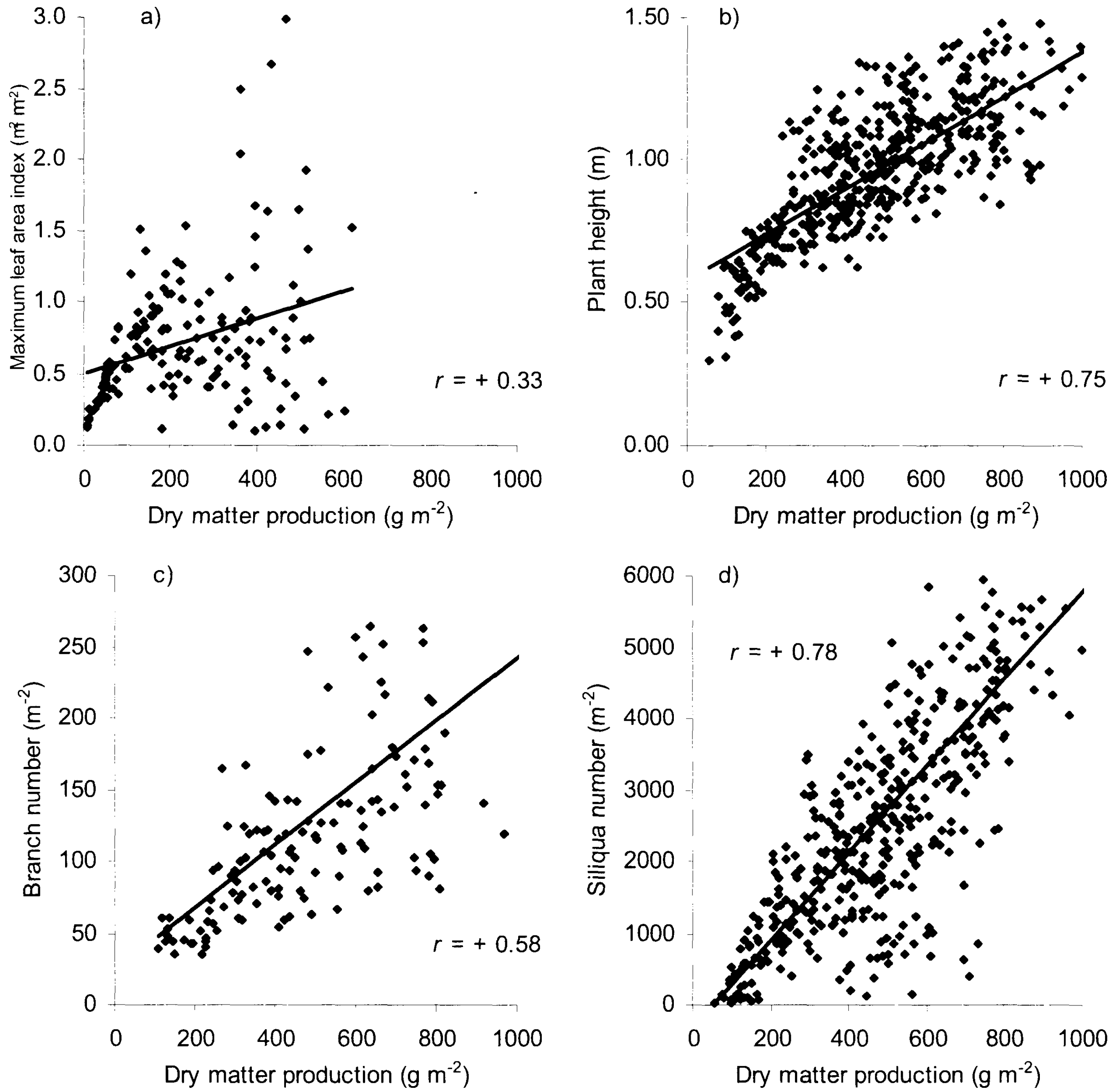

Figure 7.2 Phenotypic correlations between dry matter production (g m^{-2}) and maximum leaf area index (m^{2} m^{-2}) (a), plant height (m) (b), branch number (m^{-2}) (c) and siliqua number (m^{-2}) (d) of canola grown at Condobolin, in 2002 and 2003 for all varieties, sowing time and water deficits.

7.2.2 Water use and canola production

The reductions in plant growth and subsequent grain yield and yield components are also due to a reduction in the amount of water available and subsequent water use efficiency in the later sowings. The early sown crops used an increasing amount of water and this was attributed to the longer growing season and the plant's ability to explore greater soil depths (Chapter six). Phenotypic correlations between total water use and leaf area index, dry matter production, grain yield and harvest index are presented in Figure 8.3. The early sowing times were also the most water efficient and this arose from an ability to increase plant growth through increasing dry matter production and subsequently grain yield as detailed above. The increased water use efficiency with early sowing indicates the importance of early sowing to obtain efficient growth in order to achieve maximum dry matter production and therefore grain yield. Without maximum dry matter production, water use efficiency cannot be maximised and therefore potential grain yield cannot be achieved. There were moderate to high positive phenotypic correlations identified between water use efficiency and dry matter production (Figure 8.4b), water use efficiency and grain yield (Figure 8.4c) and water use efficiency and harvest index (Figure 8.4d). However, this was not the reflected in the phenotypic correlation between water use efficiency and maximum leaf area index, with a low negative phenotypic correlation of r = - 0.13 being recorded (Figure 8.4a). The strongest correlation was between dry matter production and water use efficiency with a high dry matter of 700 g m^{-2} being associated with a water use efficiency of 8.11 kg ha^{-1}.mm. Both these production parameters were associated with early sowing and in a water limited environment, both of these management criteria are highly important for successful crop production systems.

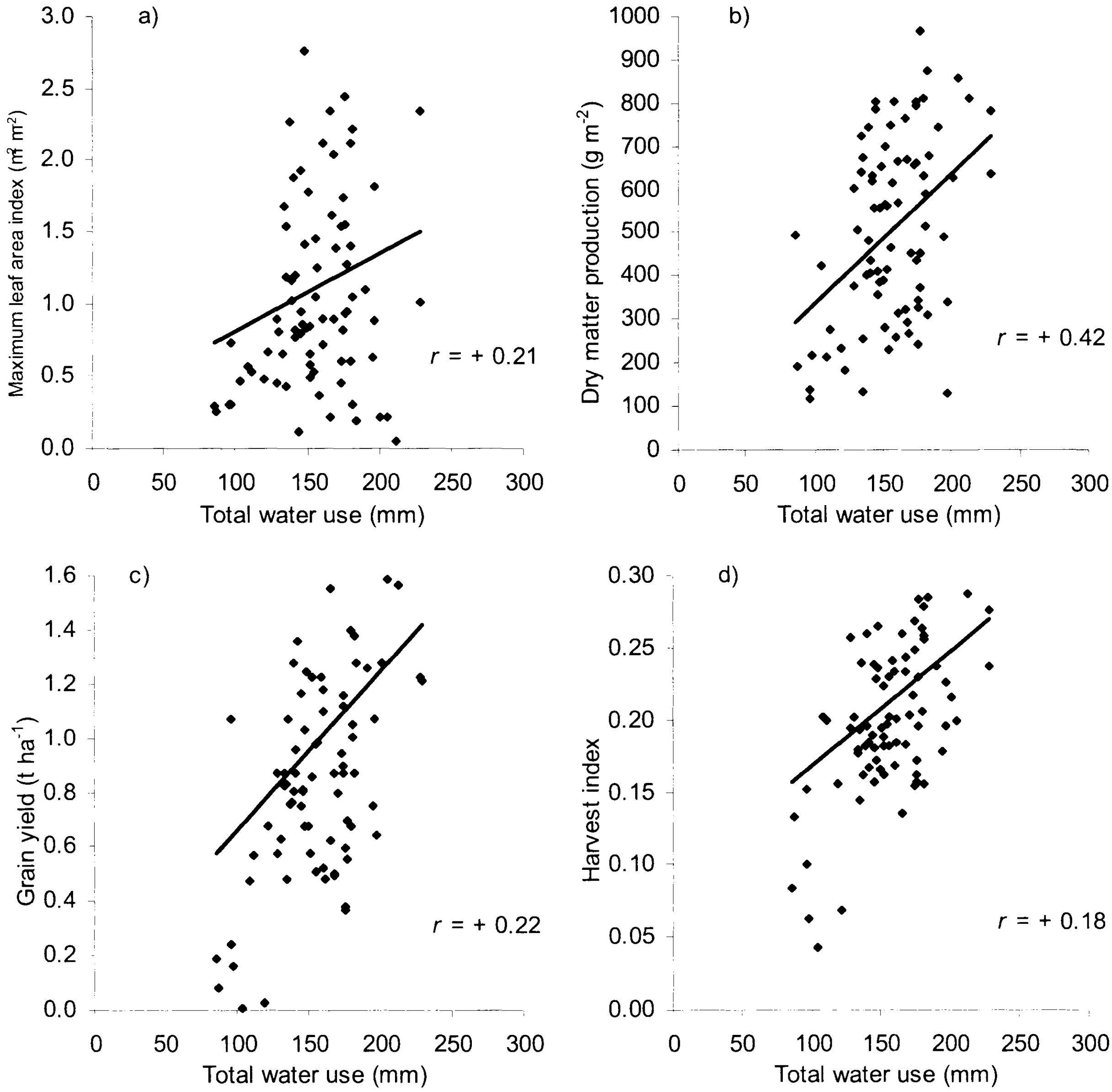

Figure 7.3 Phenotypic correlation between total water use (mm) and maximum leaf area index (m^2 m^{-2}) (a), dry matter production (g m^{-2}) (b), grain yield (t ha^{-1}) (c) and harvest index (d) of canola grown at Condobolin, in 2002 and 2003 for all varieties, sowing times and water deficits.

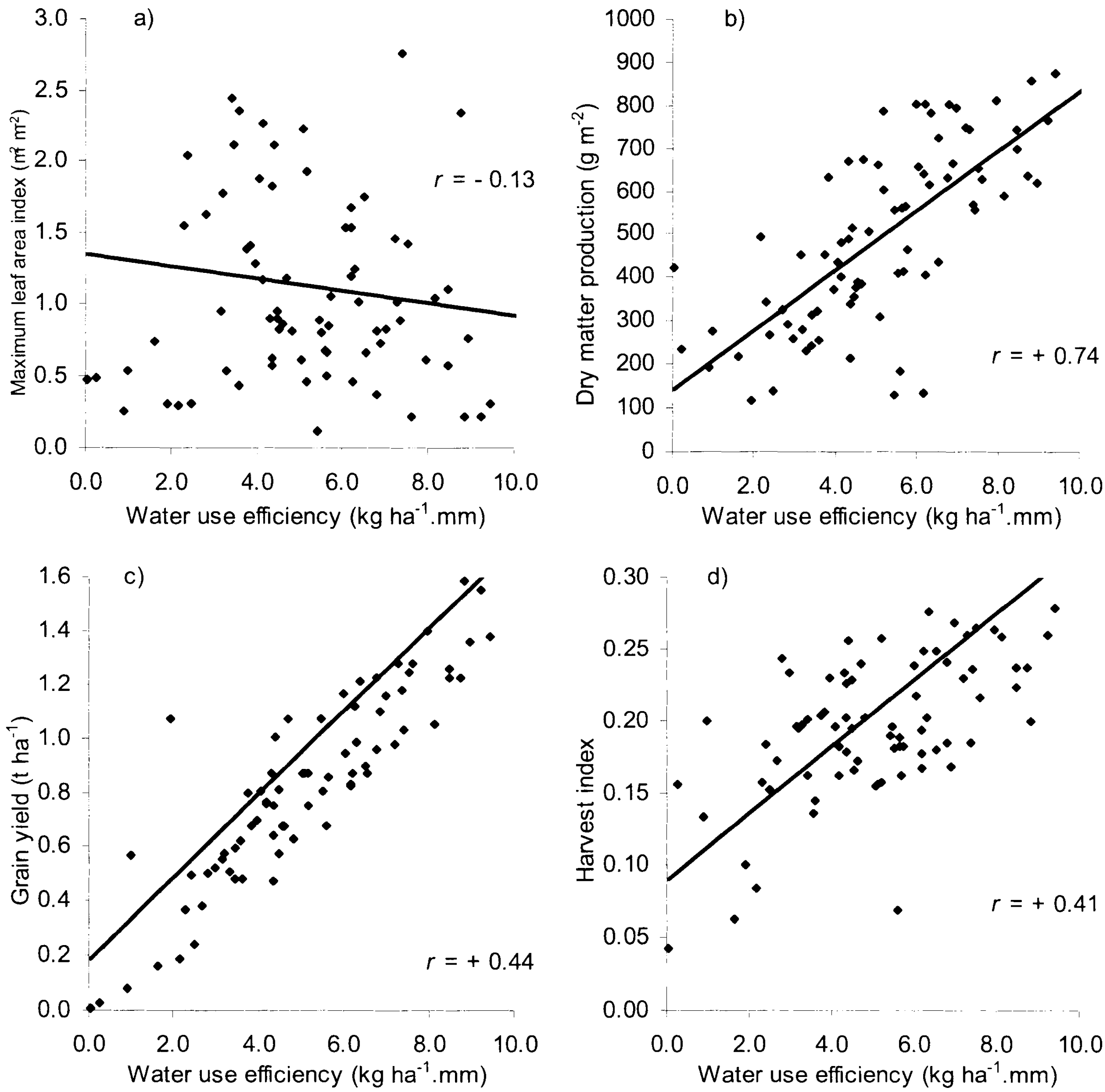

Figure 7.4 Phenotypic correlation between water use efficiency (kg ha^{-1}.mm) and maximum leaf area index (m^2 m^{-2}) (a), dry matter production (g m^{-2}) (b), grain yield (t ha^{-1}) (c) and harvest index (d) of canola grown at Condobolin, in 2002 and 2003 for all varieties, sowing time and water deficits.

7.2.3 Canola varieties and efficient production

Despite the obvious dominance of sowing time, it was hoped that the investigation of different canola varieties and water treatments would have led to more conclusive statements regarding the variety of canola to grow in this low rainfall environment. Unfortunately this was not the case. All the canola varieties performed differently with no single variety dominating. The choice of which variety to sow depends largely on the time of sowing and quality characteristics of the varieties available. The performance of canola varieties depends largely on the individual response each variety has to environmental influences. Despite this, the performance of the early maturing varieties (such as Rivette and Ag-Outback) was better than the mid-maturing varieties (such as Rainbow and Oscar) in the very dry 2002 season. Conversely, in 2003, with increased soil moisture, the mid-season varieties demonstrated increased plant growth and subsequent grain yield. However, the early maturing varieties recorded higher water use efficiencies than the later maturing varieties and this is an important consideration for canola production in a low rainfall environment. In particular, it may suggest that specific varieties suited to central western NSW need to be bred, or that other oilseed species such as Indian Mustard may provide a more viable option and that current varietal choice depends on the seasonal conditions and outlook at the time of sowing. From the experiments a variety is needed which has high dry matter production under early sowing, a high harvest index, and a high water use efficiency and this may be easier to find in an Indian Mustard breeding population than a canola population however, there are other production factors which are not as favourable in Indian Mustard than canola such as low oil concentration.

7.3 Conclusions and Recommendations

7.3.1 Conclusions

The work presented in this thesis provides clear evidence that sowing canola earlier than currently recommended, has the potential to increase grain yield and oil concentration by increasing plant growth and water use efficiency. It also demonstrates that it is possible to grow canola in low rainfall environments of Australia, such as that at Condobolin. The differences in grain yield and oil concentration are related to increased plant growth through larger leaf area and dry matter production due to increased water use and water use efficiency. The choice of variety depends largely on the time of sowing and the quality characteristics of the available varieties. Early maturing varieties do have higher water use efficiencies, which is important in low rainfall environments particularly when sowing time is delayed due to seasonal conditions.

7.3.2 Recommendations

It is recommended that research into the production of canola in low rainfall environments be continued, with particular emphasis on issues such as row spacing and sowing rate now that the optimum sowing time has been identified. This would lead to further research on plant architecture and water use efficiency, briefly touched on in this thesis. Of particular interest would be the identification of the optimum plant architecture to achieve maximum efficiency and hence maximum grain yield and oil concentration. This may include the investigation of new canola varieties or alternative oilseed species (such as Indian Mustard) suited to low rainfall environments. There are many factors that may influence these issues and these could be the focus of future research.

The use of plant growth regulators may improve the efficiency of canola production through increasing plant growth to achieve maximum water use efficiency, grain yield and oil concentration and may also assist in combating the effects of frost. The screening of canola varieties to identify efficient osmotic regulators in an effort to increase the harvest index of plants may also lead to more efficient canola production. If these other issues could be addressed, the production of canola in low rainfall environments could be expanded. However, the effects of frost associated with the early April sowing times should not be discounted and research into the effects of frost on canola production in low rainfall environments, particularly on plant efficiency, is also required. Other more general agronomic factors, such as weed and insect control, treatment of seed against disease, and improved crop nutrition, in association with the effects of frost, need to be considered to improve the efficiency of canola production.

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APPENDICES

Appendix 2.1

THIRTEENTH BIENNIAL

AUSTRALIAN RESEARCH ASSEMBLY ON BRASSICAS

CONFERENCE PROCEEDINGS

8th – 12th September 2003

Tamworth Regional Entertainment Centre
Tamworth, New South Wales

The Effect of Sowing Time, Supplementary Water and Variety on Yield and Oil Concentration of Canola (*Brassica napus*)

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Keywords *Brassica napus*, canola, sowing time, yield, oil, Condobolin

Abstract

The effects of sowing time, water treatment and variety on yield and oil concentration of canola (*Brassica napus*) were investigated at Condobolin in the central west of New South Wales in 2002. Eight canola varieties differing in maturity were established at three sowing times from mid April to mid June. There were two water treatments namely rainfed and supplementary irrigation of 22 mm in mid August. Both variety and sowing time had significant effects on yield and oil. Yield declined with each delay in sowing time, while oil concentration declined only at the last sowing date. Supplementary water increased yield at all sowing dates but did not significantly affect oil concentration. There was a significant interaction between sowing time and variety on yield. A similar trial is being conducted in 2003, including mustard and an earlier sowing date.

INTRODUCTION

The central west of New South Wales is a major producer of cereal grains but the area of alternative crops (pulse/oilseed) is low. Many producers would like to grow canola because of the likely benefit to their cereal crops but are concerned that the crop is not reliable, particularly in the lower rainfall areas. Condobolin is typical of the region, having an average annual rainfall of 400 – 450 mm of which approximately 200 mm falls between April and October. Fallow moisture is likely to be one of the keys to a successful crop. Early sowing may also be important to allow seed filling before the high temperatures and evaporation rates of late spring, but this may vary with cultivars of different maturity class. The correct combination of sowing time, variety and moisture (stored or in-crop rainfall) are vital to increasing canola production in the central west of New South Wales. These factors were studied in a field trial conducted at Condobolin in 2002.

MATERIALS AND METHODS

Eight canola varieties differing in maturity (Ag-Outback, Rivette, Emblem, Rainbow, Ripper, Oscar, Hyola 60 and Dunkeld) were sown on three dates (April 22, May 17 and June 14) at the Condobolin Agricultural Research & Advisory Station in 2002. Two water treatments were planned, rainfed and supplementary irrigation in spring. However, because of the severe drought in 2002, three irrigations totalling 52 mm of water were applied to the whole trial to supplement the 86.2 mm of in-crop rainfall. The irrigated treatment was given an additional 22 mm of water on August 15. All water was applied with a linear move irrigator. There were three replicates, with water and sowing times as main plots and varieties as sub plots. The sub plot size was 20m by 2.1 m.

Seed yield was measured on October 30 using a plot harvester. A subsample was used to determine seed moisture, oil concentration, protein concentration and seed weight. Data was analysed by analysis of variance using ASREML (Gilmour *et al.*, 2002), and predicted values were determined.

RESULTS

Yield

Sowing time, water treatment and variety had significant effects on yield. The interaction between sowing time and variety was significant, but all other two-way and three-way interactions were not significant.

The main effects of sowing time and water treatment are shown in Table 1. Yields were highest for the April sowing (average 0.99 t/ha), declining with delay in sowing to an average of 0.72 t/ha for mid May and 0.20 t/ha for the mid June sowing. The August irrigation increased yields for all sowing times and although the increase was greatest for the mid May sowing, the interaction of irrigation and sowing time was not significant.

Table 1. Main effect of sowing time and water treatment on seed yield at Condobolin in 2002

Sowing date	Water treatment	Yield (t/ha)
April 22	Rainfed	0.951
May 17	Rainfed	0.598
June 14	Rainfed	0.137
April 22	Irrigated	1.023
May 17	Irrigated	0.847
June 14	Irrigated	0.267

The yield for each variety and sowing time, averaged across the water treatments, is presented in Table 2. Hyola 60 gave the highest average yield across all sowing times followed by Rivette and Outback while Ripper was consistently poor. However, there were significant interactions. Hyola 60 and Outback performed well at all sowing dates whereas Rivette was high yielding only in the April sowing.

Table 2. Seed yield (t/ha) for eight canola varieties sown at three dates at Condobolin in 2002, averaged across water treatments.

	April 22	May 17	June 14
Outback	0.977	0.724	0.382
Rivette	1.141	0.795	0.162
Emblem	0.958	0.651	0.181
Rainbow	0.945	0.744	0.191
Ripper	0.881	0.697	0.093
Oscar	0.942	0.694	0.120
Hyola 60	1.076	0.840	0.391
Dunkeld	0.979	0.641	0.104

l.s.d (P=0.05): 0.141

Oil Concentration

Variety and sowing time, but not water treatment had significant effects on oil concentration. All other interactions were not significant. Ripper (42.3%), Hyola 60 (41.8%), and Rivette (41.7%) had the highest oil concentrations whereas Rainbow (39.1%) and Oscar (38.0%) had low oil concentrations (Table 3).

Table 3. Oil concentration for eight canola varieties, averaged over sowing times and water treatments at Condobolin in 2002

Variety	Oil concentration (%)
Ripper	42.3
Hyola60	41.8
Rivette	41.7
Dunkeld	41.0
Emblem	40.0
Outback	39.8
Rainbow	39.1
Oscar	38.0

l.s.d (P=0.05): 0.90

The April and May sowing times had similar average oil concentrations (41%) but the June sowing had significantly lower (39.3%) oil concentration (Table 4).

Table 4. Oil concentration for three sowing times, averaged over varieties and water treatments at Condobolin in 2002

Sowing date	Oil concentration (%)
April 22	41.0
May 17	41.0
June 14	39.3

l.s.d (P=0.05): 0.63

DISCUSSION

Yield

Delaying sowing past April 22 caused a major yield reduction in all varieties to levels which would be unacceptable to farmers. Current recommendations for central NSW are for sowing from late April onward, except for the drier western areas where sowing from early to late April is suggested (McRae *et al.,* 2003). Our results support these recommendations. Interestingly, early maturing varieties such as Outback and Rivette performed well from April sowing, even though they reached 50% flowering in early August, a time when frosts are common. The mid-late variety Dunkeld was almost 3 weeks later to this stage while, Hyola 60 considered a mid-maturity variety, was only days behind Rivette and Outback. These three varieties had started siliqua filling by mid August and continued filling for about six weeks.

By comparison, early maturing varieties sown in mid May reached 50% flowering about three weeks later than those of April sowing, but reached physiological maturity only a week later than the April sowing, giving a two week shorter siliqua filling period. Again, Hyola 60 performed more like an early-mid variety, flowering only a week later than Rivette although it was a little later to mature. For this sowing time, there was a tendency for the later flowering varieties to be lower yielding.

Yields for the June sowing were very low for all varieties and based on this one year's result it suggests canola should not be sown this late. Even the quickest variety, Outback, did not reach 50% flowering until almost mid September and most seed growth occurred in early October, a time of rising temperatures and high evaporative demand. With this late sowing, Outback and Hyola 60 were the highest yielding varieties, while the longer season varieties were very poor.

Although the interactions of sowing time and variety with water treatment were not statistically significant, there were some interesting trends that may warrant further investigation. Yield responses to the extra water for the April sowing were generally small, the exceptions being Outback and Hyola 60. The water was applied in mid August when the early maturing varieties were at about 100% flowering and the later varieties at early to mid flowering. It is likely that any increases in siliqua or seed set at this stage did not generally lead to higher seed yields. By comparison, yield responses to additional water tended to be greater for the May sowing and tended to be greater for the later maturing varieties. The May sown plots were at early to mid flowering when the water was applied and it is likely that the additional water increased seed set. Detailed yield component and soil moisture measurements taken on the trial should provide information on the mechanisms of the yield responses to sowing date and water.

Oil

The oil concentration of seed produced from varieties sown on June 14 was significantly less than for the earlier sowings, probably because of the higher temperatures during seed filling which may also have contributed to the smaller seed size observed for this sowing date.

There were significant differences between varieties for oil percentage but the lack of interactions with sowing time and water confirms the strong genetic control for this character. The oil concentrations and variety rankings are in close agreement with those from NSW Agriculture variety trials (McRae *et al.,* 2003). The results show that high yield and high oil are not mutually exclusive characters, as both Rivette and Hyola 60 had both high yields and high oil percentages. They also highlight the problems that are likely to arise if a low oil variety is sown late.

CONCLUSION

The results from the 2002 trial confirm the need for April sowing for high yield and oil content in this environment and suggest that the maturity grouping of the variety is less important. An important question that remains is how much earlier could canola be sown without yield penalty from frost and what maturity type might perform best from very early sowing. This is being investigated in a trial at Condobolin in 2003.

REFERENCES

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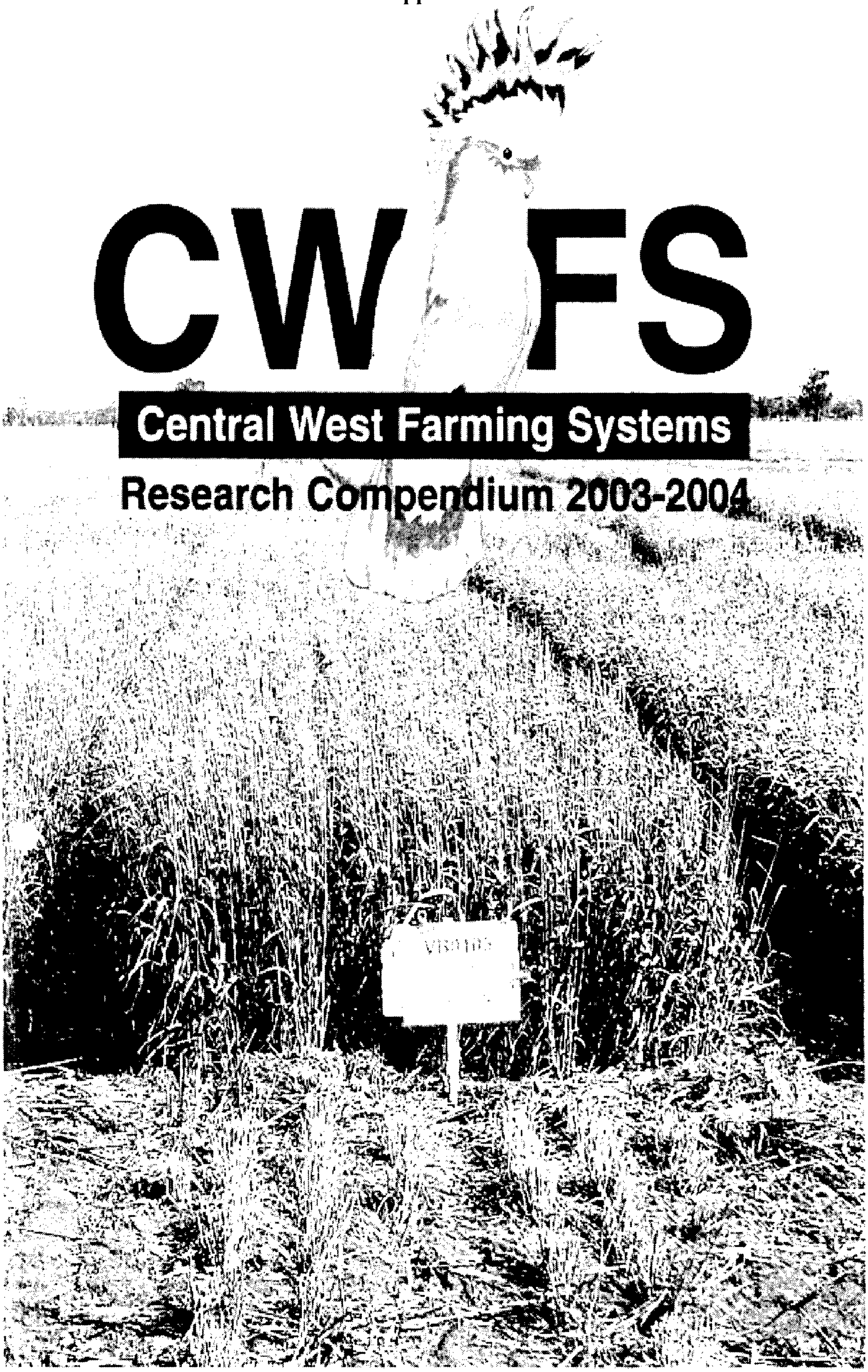
McRae, F.J., McCaffery, D.W. and Carpenter, D.J. (2003) *Winter Crop Variety Sowing Guide 2003.* NSW Agriculture, N.S.W.

ACKNOWLEDGEMENTS

Grain Research and Development Corporation
NSW Agriculture
Sharon Nielsen (Biometrician), NSW Agriculture, Forest Road, Orange, NSW

Appendix 2.2


CWFS
Central West Farming Systems
Research Compendium 2003-2004

The Effect of Sowing Time and Variety on Yield and Oil Concentration of Canola (*Brassica napus*)

Georgina MacKinnon, Neil Fettell and Jack Freeman
New South Wales Agriculture, PO Box 300 Condobolin, New South Wales, 2877, Australia

Summary

- The effects of sowing time and variety on yield and oil concentration of canola (*Brassica napus*) were investigated at Condobolin in 2002 and 2003.
- Eight canola varieties and two Indian mustard varieties differing in maturity were established at four sowing times from early April to mid June
- Yield and oil concentration declined with each delay in sowing time in both years
- Early sowing increased yield and oil concentration
- Variety maturity type is not as important as early sowing

Introduction

The central west of New South Wales is a major producer of cereal grains but the area of alternative crops (pulse/oilseed) is low. Many producers would like to grow canola due to the likely benefit to their cereal crops but are concerned that the crop is not reliable, particularly in lower rainfall areas. Two Indian mustard varieties were included in the 2003 trials as an alternative oilseed crop to canola. Condobolin is typical of the region, having an average annual rainfall of 400 – 450 mm of which approximately 200 mm falls between April and October. Early sowing and fallow moisture are the keys to a successful crop. Early sowing is important to allow grain fill before the high temperatures and evaporation rates of late spring, and fallow moisture is important to minimise water stress during crop growth. The correct combination of sowing time, variety and moisture (stored or in-crop rainfall) are vital to increasing canola production in this area.

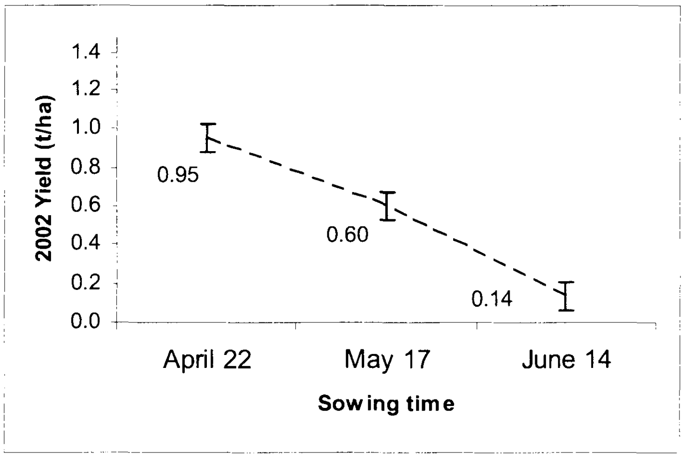
Material and Methods

Eight canola varieties differing in maturity (Ag-Outback, Rivette, Ag-Emblem, Rainbow, Ripper, Oscar, Hyola 60 and Dunkeld) were sown on three dates (April 22, May 17 and June 14) at Condobolin in 2002. In 2003 six canola varieties (Ag-Outback, Rainbow, Ripper, Oscar, Hyola 60 and Dunkeld) and two Indian mustard varieties (M887 and JN28) were sown on four dates (April 2, April 22, May 13 and June 6).
Due to the drought, three irrigations totalling 52 mm of water were applied to the whole trial to supplement the 86.2 mm of in-crop rainfall in 2002 and this still did not represent average rainfall (200mm) in the growing season. In 2003 three irrigations totalling 70mm were applied to the whole trial prior to sowing the April 2, April 22 and May 13 plots, to allow sowing to commence due to the lack of rainfall pre-season (132 mm between November 2002 and April 2003), however due to increased in crop rainfall the trial received 270mm during the growing season which would be considered above average. Seed was harvested and seed moisture, oil concentration, protein concentration and seed weight were analysed.

Results

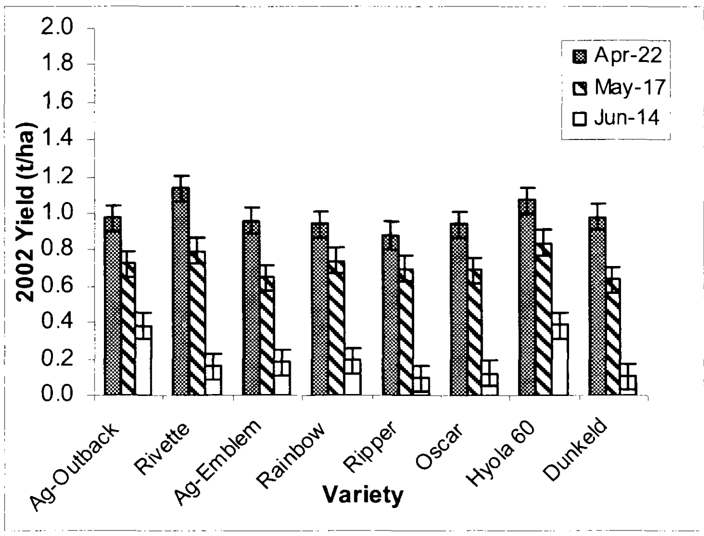
Yield 2002
Sowing time and variety had significant effects on yield. The effects of sowing time are presented in Figure 1. The highest yield was recorded for April 22 sowing time (average 0.95 t/ha) after which yield declined with each delay in sowing time. The lowest yield was recorded for the June 14 (0.14 t/ha) sowing time.

Figure 1. Yield (t/ha), averaged across eight canola varieties, of three sowing times at Condobolin in 2002.



Yield for each variety over the three sowing times is presented in Figure 2. Hyola 60 yielded well across all three sowing times recording the highest yield for the May 17 and June 14 sowing times. Rivette yielded highly for April 22 (1.14 t/ha) and May 17 (0.80 t/ha) sowing times, out-yielding Hyola 60 in the April 22 sowing time. Ag-Outback yielded highly only in the June 14 (0.38 t/ha) sowing time. The lowest yield was recorded for Ripper sown on June 14 (0.09 t/ha).

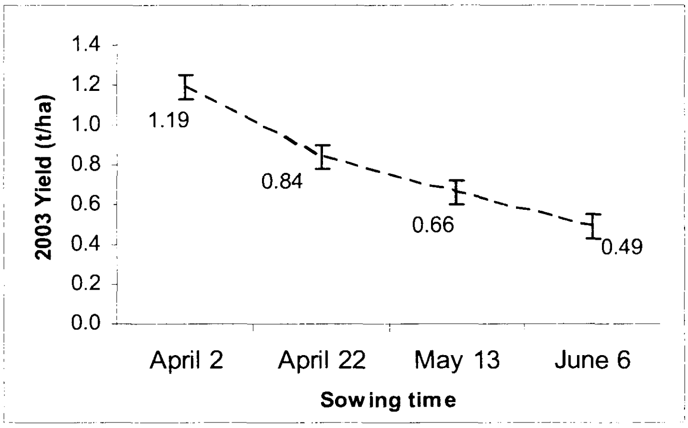
Figure 2. Yield (t/ha) for eight canola varieties sown at three different times, at Condobolin in 2002.



Yield 2003

Sowing time and variety had significant effects on yield. The effects of sowing time are presented in Figure 3. The highest yield was recorded for the April 2 sowing time with an average of 1.19 t/ha. All yields declined with delay in sowing time beyond April 2.

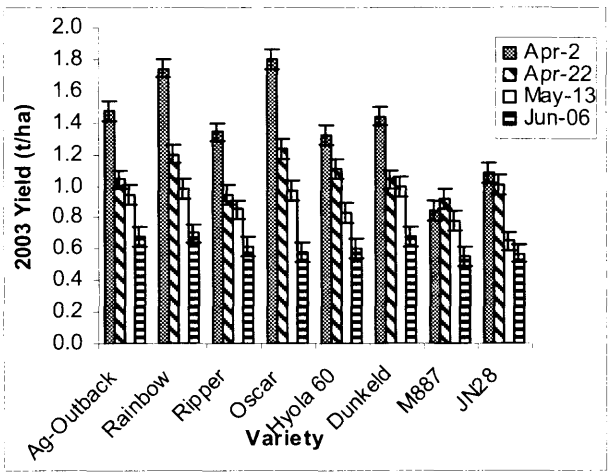
Figure 3. Yield (t/ha), averaged across six canola varieties and two Indian mustard varieties, of four sowing times at Condobolin in 2003.



The yield for each variety across the four different sowing times is presented in Figure 4. For the canola varieties, Oscar yielded the highest for the April 2 (1.80t/ha) and April 22 (1.23t/ha) sowing times but lowest for the June 6 sowing time (0.58t/ha). Hyola 60 yielded well for the April 22 sowing time but was the lowest yielder for the April 2 (1.32t/ha) and May 13 (0.83t/ha) sowing times, while Ripper was the lowest yielder for the April 22 (0.95t/ha) sowing time. The April 2 sowing time yielded the highest across all varieties (except for M887) and this declined with a delay in sowing time.

Both Indian mustard varieties performed poorly across all sowing times yielding less than all the canola varieties.

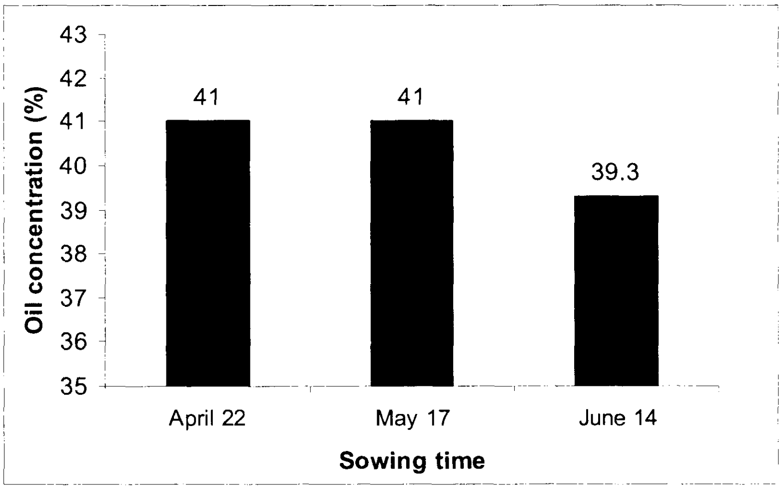
Figure 4. Yield (t/ha) for six canola varieties sown at four different times, at Condobolin in 2003.



Oil concentration 2002

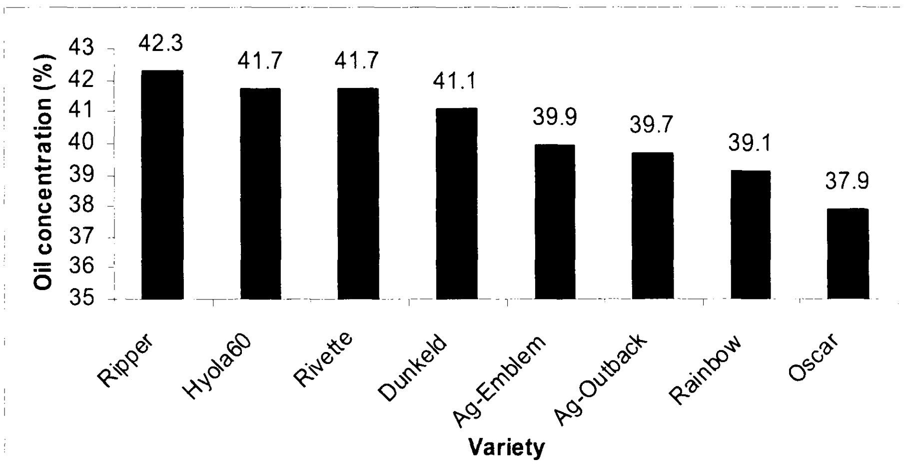
Oil concentration for the three sowing times averaged across variety are presented in Figure 5. The April 22 (41.0%) and May 13 (41.0%) sowing times had similar oil concentrations, however the June 14 (39.3%) sowing time had a significantly lower oil concentration.

Figure 5. Oil concentration (%) for three sowing times, averaged across eight canola varieties, at Condobolin in 2002.



Variety and sowing time had significant effects on oil concentration. The effect of variety on oil concentration is presented in Figure 6. Ripper (42.3%), Hyola 60 (41.7%) and Rivette (41.7%) had significantly higher oil concentrations than the mean (40.5%) for all canola varieties. Rainbow (39.1%) and Oscar (37.9%) had significantly lower oil concentrations than the mean.

Figure 6. Oil concentration (%) for eight canola varieties, averaged across three sowing times, at Condobolin in 2002.



Oil concentration 2003

Sowing time and variety had significant effects on oil concentration. Figure 7 presents the oil concentration for four different sowing times. Oil concentration declined with each delay in sowing time. The April 2 (40.33%) sowing time had a significantly higher oil concentration than the other three sowing times. The June 6 (36.1%) sowing time had the lowest oil concentration.

Figure 7. Oil concentration (%) for four sowing times, averaged across six canola varieties and two Indian mustard varieties, at Condobolin in 2003.

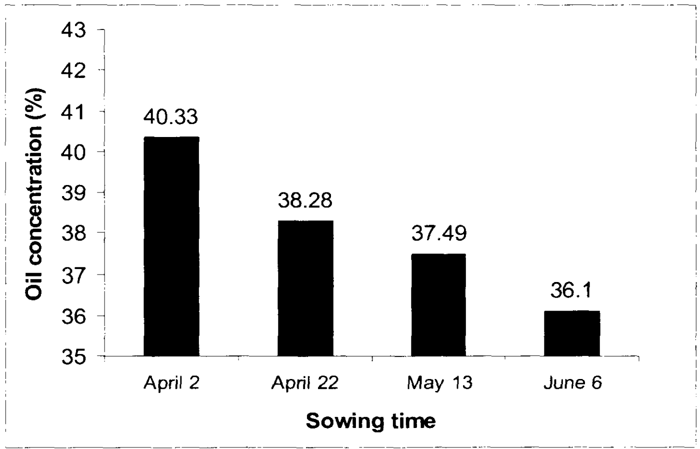
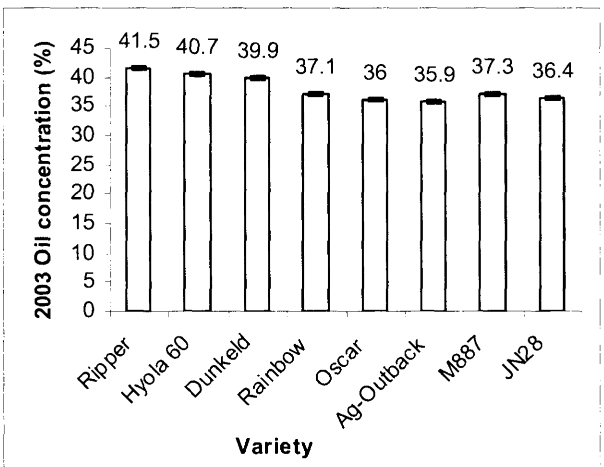


Figure 8 presents the effects of variety on oil concentrations. Ripper (41.5%) and Hyola 60 (average 40.7%) achieved the highest oil concentrations. The lowest oil concentrations in canola varieties were from Oscar (average 36%) and Ag-Outback (averaged 35.9%).
The Indian mustard varieties did not achieve outstanding oil concentrations and were below the values for each sowing time (Figure 8).

Figure 8. Oil concentration (%) for six canola varieties and two Indian mustard varieties, averaged across four sowing times, at Condobolin in 2003.



Discussion

Yield

Delaying sowing past April 22 in 2002 and April 2 in 2003 caused a major yield reduction in all varieties. With a loss of 0.35 t/ha when sowing was delayed until April 22, 0.0.53 t/ha if sowing is delayed until May 13 and 0.7 t/ha when sowing was delayed until June 6. Current recommendations for central NSW are for sowing from late April onward, except for the drier western areas where sowing from early to late April is suggested in the NSW Agriculture Variety Guides produced every year. Our results support these recommendations.

Interestingly, early maturing varieties such as Ag-Outback and Rivette performed well from April sowings, even though they reached 50% flowering in early August, a time when frosts are common. The mid-late variety Dunkeld was almost 3 weeks later to this stage while, Hyola 60 considered a mid-maturity variety, was only days behind Rivette and Ag-Outback. These three varieties had started siliqua filling by mid August and continued filling for about six weeks.

By comparison, early maturing varieties sown in mid May reached 50% flowering about three weeks later than those of April sowing, but reached physiological maturity only a week later than the April sowing, giving a two week shorter siliqua filling period. Again, Hyola 60 performed more like an early-mid variety, flowering only a week later than Rivette although it was a little later to mature. There was a tendency for the later flowering varieties to be lower yielding for this May sowing time.

Yields for the June sowing in both 2002 and 2003 were very low for all varieties and based on these results it suggests canola should not be sown this late. Even the earliest maturing variety, Ag-Outback, did not reach 50% flowering until almost mid September and most seed growth occurred in early October, a time of rising temperatures and high evaporative demand. With this late sowing, Ag-Outback and Hyola 60 were the highest yielding varieties, while the longer season varieties were generally poor performers.

Oil

The oil concentration of seed produced from varieties sown on June 14 in 2002 was significantly less than for the earlier sowings, and this may be due to higher temperatures during seed filling which may also have contributed to the smaller seed size observed for this sowing date. In 2003 these reduced oil concentrations were also recorded suggesting that late sowing can lead to severe reduction in oil concentration in the seed. Each weeks delay in sowing time incurred an 0.5% loss in oil concentration.

There were significant differences between varieties for oil percentage but the lack of interactions with sowing time and water confirms the strong genetic control for this character. The oil concentrations and variety rankings are in close agreement with those from NSW Agriculture variety trials. The results show that high yield and high oil are not mutually exclusive characters, as both Rivette and Hyola 60 had both high yields and high oil percentages in both years. They also highlight the problems that are likely to arise if a low oil variety is sown late.

Conclusion

The results from these trials confirm the need for early sowing and in particular April sowing in order to achieve high yield and oil content in this environment and suggest that the maturity grouping of the variety is less important. The trial also suggests that sowing beyond mid-May will cause unacceptable losses in yield and oil concentration. An important question that remains is the extent of yield penalty which may occur with these early sowing times from frost.

The 2003 trial demonstrated with the Indian mustard varieties used, had lower yield and oil concentrations than the canola varieties, despite the water stress canola was under, and it is not recommended that Indian mustard be chosen as an alternative to canola at this stage.

Appendix 3.1

Incitec FERTILIZERS **NUTRIENT ADVANTAGE**

Standard Interpretation Status Report

Trading Name	[illegible]	Field Name	EXP 1 2002		
Location		Section of Field	REP OF A[illegible]		
Contact Name		GPS Latitude		Longitude	
Work Phone		Sample Type	Soil	Depth	[illegible]
Advisor	[illegible]	Lab Report No	[illegible]	Sample	[illegible]
Phone	[illegible]	Crop			
		Growth Stage			
Interpretation	12 Aug 2002	Planting		Target Yield (t/ha)	[illegible]
Chart	WINTER CEREALS (Grain) Western Plains NSW				

The following information and recommendations are suggested for your consideration and are the opinion of the interpreter

Analyte	Value	Def	Low	< Opt/Norm or Mod	Generally Satisfactory	> Opt Norm	High	Excess
pH (1:5 Water)	6.30				■			
pH (1:5 CaCl2)	5.60				■			
Organic Carbon (%C)	1.40			■				
Nitrate Nitrogen mg/kg	21.40				■			
Sulfate Sulfur (MCP) mg/kg	12.00							
Phosphorus (Colwell) mg/kg	[illegible]	■						
Potassium (Amm acet) meq/100g	[illegible]				■			
Calcium (Amm acet) meq/100g	[illegible]				■			
Magnesium (Amm acet) meq/100g	[illegible]				■			
Sodium (Amm acet) meq/100g	[illegible]							
Chloride mg/kg	10.00				■			
Elect. Conductivity dS/m	[illegible]							
Molybdenum								
Amm. Nitrogen (KCl) mg/kg	[illegible]							
Cation Exch. Cap. meq/100g	[illegible]							
Calcium/Magnesium ratio	[illegible]				■			
Sodium % of cations (ESP)	[illegible]				■			
Elec. Cond. (Sat. Ext.) dS/m	[illegible]				■			

Texture: Clay Loam

Note: Interpretations and recommendations given here are a guide only and depend on representative samples being analysed. Additionally environmental and managerial factors influence production. Therefore Incitec Limited and Dealers do not accept any liability whatsoever arising out of these interpretations and recommendations for any damage, loss or injury of any nature and the user takes these interpretations and recommendations on these terms. This recommendation is made in good faith, based on the best technical information available.

Chart Use: [illegible]

Appendix 3.2

[redacted]

SOIL ANALYSIS REPORT

[redacted] Incitec Fertilizers Ltd.
A B N [illegible]

Pannga Road Gibson Island Murarrie
P.O. Box 140, Morningside, Qld 4170
Tel (07) 3867 9300
Website www.incitecfertilizers.com.au

NUTRIENT
ADVANTAGE

[illegible]
[illegible] AG N VET SERVICES
CONDOBOLIN
NSW 2877

Phone		Fax	
Nearest Town		Postcode	
Distance to Town		Direction to Town	
Australian Map Grid Ref		Average Annual Rainfall	mm

SOIL SAMPLE AND SITE INFORMATION:

Sampling depth(cm)	0 10 Surface	Months of fallow	
Sampling depth(cm)	Deep	Age of cultivation	yrs
		Drainage	
Paddock area	ha	Stubble/Trash	
Soil type		Tillage	
Slope		Irrigation	
Soil profile depth	m		
Reason for sampling	1		
	2		

PRODUCTION INFORMATION: yrs mths

Main species to be fertilised		Age established	
Variety		Root stock(Hort)	
Previous best yield		Plant population	ha
Yield last year		Canopy radius(Hort)	m
Vigour of growth		Grain protein	
Row/tree spacing(Hort)	m x m	Legume content	
Row spacing(Grain/Cotton)		Stock type	
Interrow treatment		Stock number	
Stage in Crop Cycle(Sugar Cane)			
Method of fertiliser placement:			
1	2	3	

The data, calibrations or measurements covered by this document have been performed in accordance with NATA requirements which include the requirements of ISO/IEC 17025 and are traceable to national standards of measurement. This document shall not be reproduced except in full.

NATA

NATA Accredited Laboratory
Number 1292

Registered Signatory

Patricia Ferguson
Laboratory Analyst

The Laboratory is not associated with the sampling process.
Samples are analysed as received after drying at 40°C.

Results of Analysis

PADDOCK NAME	TIME TRIAL
ORDER NUMBER	000177
PRODUCT	SO 2002/124 SOIL
SAMPLE BAG NUMBER SURFACE	47495
CORRESPONDING DEEP SOIL BAG No	
DATE OF SAMPLING	30/04/03
DATE RECEIVED	08/05/03
DATE OF REPORT	15/05/03

Soil Texture	Clay Loam
pH(1:5 Water)	5.9
pH(1:5 CaCl2)	[illegible]
Organic Carbon OC	[illegible]
Nitrate Nitrogen mg/kg	36.2
Sulfur (MCP) mg/kg	[illegible]
Phosphorus(Colwell) mg/kg	31
Potassium(Amm.Ac.)meq/100g	2.0[illegible]
Calcium (Amm.Ac.) meq/100g	5.15
Magnesium(Amm.Ac.)meq/100g	2.2[illegible]
Aluminium (KCl) meq/100g	0.06
Sodium (Amm.Ac.) meq/100g	0.22
Chloride mg/kg	2[illegible]
Electrical Conduct. dS/m	0.1[illegible]
Amm. Nitrogen(KCl) mg/kg	5

Calculations

Cation Exch. Cap. meq/100g	9.[illegible]
Calcium/Magnesium Ratio	2.29
Aluminium Saturation %	0.7
Sodium% of cations(ESP)	2.22
Elec.Conductivity(Se) dS/m	[illegible]

Methods, Calculations outlined overpage.

FOR INTERPRETATION OF THESE RESULTS,
PLEASE CONTACT YOUR DEALER: 02 6895 2527
AG N VET CONDOBOLIN
PO BOX 90
CONDOBOLIN 2877

OR YOUR INCITEC AREA MANAGER
NICK FELL 0417 657466

Appendix 3.3

y ~ water + variety + water.variety + sow_time + water.sow_time + variety.sow_time + water.variety.sow_time + block + block.column + replicate + replicate.sow_time_row + replicate.sow_time_row.row.block + block.column.replicate.sow_time_row

Notation: Terms fitted in the model as random are underlined, all other terms are fitted as fixed terms.

Appendix 3.4

y ~ mean + linear(harvest_number) + contrast(sample_time_1) + variety + sow_time + water + sow_time.linear(harvest_number) + variety.linear(harvest_number) + water.linear(harvest_number) + sow_time.contrast(sample_time_1) + variety.sow_time + water.sow_time + variety.contrast(sample_time_1) + variety.water + water.contrast(sample_time_1) + water.variety.linear(harvest_number) + water.variety.sow_time + variety.sow_time.linear(harvest_number) + variety.sow_time.contrast(sample_time_1) + water.sow_time.linear(harvest_number) + water.variety.contrast(sample_time_1) + water.variety.sow_time.linear(harvest_number) + curvature(harvest_number) + sow_time.curvature(harvest_number) + variety.curvature(harvest_number) + water.curvature(harvest_number) + water.sow_time.curvature(harvest_number) + water.variety.curvature(harvest_number) + variety.sow_time.curvature(harvest_number) + water.variety.sow_time.curvature(harvest_number) + lack_of_fit(harvest_number) + sow_time.lack_of_fit(harvest_number) + variety.lack_of_fit(harvest_number) + water.lack_of_fit(harvest_number) + water.sow_time.lack_of_fit(harvest_number) + water.variety.lack_of_fit(harvest_number) + variety.sow_time.lack_of_fit(harvest_number) + water.variety.sow_time.lack_of_fit(harvest_number) + block + block.column + replicate replicate.sow_time_row + replicate.sow_time_row.row.block + block.column.replicate.sow_time_row + block.column.replicate.sow_time_row.factor(harvest_number) + block.column.replicate.sow_time_row.row

Notation: Terms fitted in the model as random are underlined; all other terms are fitted as fixed terms.

Appendix 3.5

y ~ water + variety + water.variety + sow_time + water.sow_time + variety.sow_time + water.variety.sow_time + probe_time + water.probe_time + variety.probe_time + water.variety.probe_time + sow_time.probe_time + water.sow_time.probe_time + variety.sow_time.probe_time + water.variety.sow_time.probe_time + depth + water.depth + variety.depth + water.variety.depth + sow_time.depth + water.sow_time.depth + variety.sow_time.depth + water.variety.sow_time.depth + probe_time.depth + water.probe_time.depth + variety.probe_time.depth + water.variety.probe_time.depth + sow_time.probe_time.depth + water.sow_time.probe_time.depth + variety.sow_time.probe_time.depth + water.variety.sow_time.probe_time.depth + block + block.column + replicate + replicate.sow_time_row + block.replicate.sow_time_row.row + block.column.replicate.sow_time_row + block.column.replicate.sow_time_row.row + [block.column.replicate.sow_time_row.row.probe_time.probe_depth]

Notation: Terms fitted in the model as random are underlined, all other terms are fitted as fixed terms.

Appendix 3.6

y ~ water + variety + sow_time + plant_density + water.variety + water.sow_time + variety.sow_time + plant_density.sow_time + plant_density.variety + plant_density.water + water.variety.sow_time + block + block.column + replicate + replicate.sow_time_row + replicate.sow_time_row.row.block + block.column.replicate.sow_time_row

Notation: Terms fitted in the model as random are underlined, all other terms are fitted as fixed terms.

Appendix 3.7

y ~ mean + water + variety + sow_time + linear(probe_number) + linear(depth) + water.variety + water.sow_time + variety.sow_time + water.linear(probe_number) + variety.linear(probe_number) + sow_time.linear(probe_number) + water.linear(depth) + variety.linear(depth) + sow_time.linear(depth) + variety.sow_time.linear(depth) + linear(probe_number).linear(depth) + water.variety.sow_time + water.variety.linear(probe_number) + water.sow_time.linear(probe_number) +

variety.sow_time.linear(probe_number) + water.variety.linear(depth) + water.sow_time.linear(depth) + water.linear(probe_number).linear(depth) + variety.linear(probe_number).linear(depth) + sow_time.linear(probe_number).linear(depth) + water.variety.sow_time.linear(probe_number) + water.variety.sow_time.linear(depth) + water.variety.linear(probe_number).linear(depth) + water.sow_time.linear(probe_number).linear(depth) + variety.sow_time.linear(probe_number).linear(depth) + water.variety.sow_time.linear(probe_number).linear(depth) + curvature(probe_number) + lack_of_fit(probe_number) + curvature(depth) + lack_of_fit(depth) + water. curvature(probe_number) + variety. curvature(probe_number) + sow_time.curvature(probe_number) + water.curvature(depth) + sow_time.curvature(depth) + variety.curvature(depth) + water.lack_of_fit(probe_number) + variety.lack_of_fit(probe_number) + sow_time.lack_of_fit(probe_number) + water.lack_of_fit(depth) + variety.lack_of_fit(depth) + sow_time.lack_of_fit(depth) + water.variety.curvature(probe_number) + water.variety.lack_of_fit(probe_number) + water.variety.curvature(depth) + water.variety.lack_of_fit(depth) + variety.sow_time.curvature(probe_number) + variety.sow_time.lack_of_fit(probe_number) + variety.sow_time.curvature(depth) + variety.sow_time.lack_of_fit(depth) + water.sow_time.curvature(probe_number) + water.sow_time.lack_of_fit(probe_number) + water.sow_time.curvature(depth) + water.sow_time.lack_of_fit(depth) + block + block.column + replicate + replicate.sow_time_row + block.replicate.sow_time_row.row + block.column.replicate.sow_time_row.row

Notation: Terms fitted in the model as random are underlined, all other terms are fitted as fixed terms.