Muresk Institute of Agriculture

Adaptation of Indian Mustard (*Brassica juncea* L.) to Short Season Dryland Mediterranean-type Environments

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

Signature: _____

Date: 01-05-2003

DEDICATION

Without his love, care and encouragement I could not have completed my PhD. I dedicate this thesis to my loving husband, Ruwan, in appreciation of his invaluable commitment, support and all the sacrifices made for me.

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ABSTRACT

Indian mustard (*Brassica juncea* L.) has recently been identified as a potential and profitable alternative oilseed crop in the grain growing regions of Australia. To date, no research has been reported on adaptation of mustard in water limited Mediterranean-type environments in south Western Australia. Experiments presented in this thesis were undertaken to study adaptation of mustard in the Mediterranean-type environments in south Western Australia, with the hypothesis that mustard would be better adapted to these environments due to its reputation for drought tolerance. Experiments were conducted with three main aims. Firstly, to identify the effects of genotype, environment (times of sowing/seasons/sites) and genotype x environment interaction on the phenology, growth, dry matter production, seed yield, oil and protein contents of mustard and canola. Secondly, to identify phenological, morphological and physiological characters responsible for adaptation and yield improvement of mustard in these environments. Thirdly, to study the response of mustard to soil moisture deficits, especially in the post-flowering period, in comparison to canola.

Adaptation of six mustard breeding lines/cultivars varying in maturity, height and oil quality and three canola cultivars varying in maturity were tested at a medium rainfall site (Northam) in the 1999 growing season. These genotypes were sown at four times after the break of the season and their phenology, growth, morphology, dry matter production and partitioning, radiation absorption, seed yield and its components, and seed oil and protein concentrations were measured. Adaptation of mustard to short season, low rainfall areas was tested, in the 2000 and 2001 growing seasons, at three sites (Merredin, Mullewa and Newdegate), by sowing seven genotypes of mustard and canola at three times after the break of the season. Seed yield, oil and protein concentrations were measured at all three sites and detailed measurements of phenology, morphology, dry matter production and partitioning, radiation absorption, seed yield and its components, and seed oil and protein concentrations were taken only at Merredin. The effects of post-flowering soil moisture stress on mustard and canola was studied in detail using rainout shelters at Merredin in the 2001 growing season. Measurements of water use, leaf water potential, osmotic potential, osmotic adjustment, relative water content, and leaf diffusive conductance were taken together with morphology, dry matter production

and partitioning, radiation absorption, seed yield and its components, and seed oil and protein concentration.

Mustard produced seed yields similar to canola at a medium rainfall site at Northam in south Western Australia. Early sowing (May) was more suitable for mid and late maturing genotypes and mid sowing (early June) was optimum for early maturing genotypes at this site. Dry matter production and seed yield was highest in early sowing due to balanced pre-anthesis and post-anthesis development of the crop and its ability to avoid terminal drought. Very late sowing (after July) significantly reduced the dry matter production, seed yield and oil concentration of mustard and canola due to poor establishment, reduced post-anthesis duration, soil moisture and high temperature stresses which occurred at the end of the season. Mustard did not produce significantly higher dry matter and seed yield compared to canola at the medium rainfall site, Northam.

Seed yield and oil concentration of mustard and canola in low rainfall environments (Merredin, Mullewa and Newdegate) were higher when sown early in the season (May). Longer growing duration and post-anthesis duration were favourable for higher yields. Higher rainfall during the post-anthesis phase, warmer pre-anthesis phase and cooler post-anthesis phase were associated with higher seed yield in these environments. As shown by the Principal Component Analysis and the Finlay Wilkinson Analysis, adaptation of mustard genotypes to low rainfall environments was better compared to canola genotypes. Mustard genotypes, 887.1.6.1, 82 No 22-98 demonstrated their general adaptability by producing the highest mean seed yield across all environments and showing average phenotypic stability across all environments. The low yielding canola genotype, Oscar was best adapted to high yielding environments and showed below average phenotypic stability. Low yielding mustard genotypes, JM 25 and JM 33 were best adapted to low yielding environments and showed above average phenotypic stability.

Early flowering and developmental plasticity had a significant contribution to yield potential and its stability. All mustard genotypes were more tolerant to soil moisture and high temperature stresses and exhibited early vigour compared to canola varieties. Mustards produced significantly higher dry matter compared to canola under soil moisture and high temperature stresses. Yield reduction due to late sowing

was greater in canola compared to mustards. Greater dry matter production of mustards under severe soil moisture stress was related to their higher water use and radiation use, which in turn was related to their superior osmotic adjustment. Osmotic adjustment improved dry matter production in mustards as it allowed stomata to remain partially open at progressively lower leaf water potentials and maintained higher stomatal conductance, maintained leaf area and reduced the rate of leaf senescence by increasing both avoidance and tolerance of dehydration and thereby increased radiation use, increased water use by stomatal adjustment, and increased soil moisture uptake by producing deeper roots.

Mustard exhibited many agronomic advantages over canola, such as vigorous seedling growth, quick ground covering ability, early vigour, and the feasibility of direct harvesting due to non-shattering pods. Despite all these advantages currently available mustard genotypes do not have the ability to out yield canola due to their lower efficiency of conversion of dry matter to seeds, as indicated by lower harvest indices, and inferior yield component structure. Further breeding in mustard is required to modify its morphology and yield component structure. Mustard plants with more pods and pods with more seeds would produce higher yields. Shorter, compact plant stature and reduced branching would improve harvest index in mustard. Furthermore, development of mustard genotypes with high oil quality and concentration similar to canola would improve its market value as an oil seed crop.

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CHAPTER 1

GENERAL INTRODUCTION

Four major *Brassica* oilseed species that are widely cultivated throughout the world are, *Brassica napus* L., *B. rapa* L., *B. juncea* L. Czern. and Coss., and *B. carinata* Braun (Downey and Rimmer, 1993). *Brassica napus* L. (canola) is one of the five major oilseed crops grown profitably in Australia. *Brassica juncea* L. Czern. and Coss. (Indian mustard) has recently been identified as a potential and profitable alternative oilseed crop in Australia particularly for short season, low rainfall cropping regions (Kirk and Oram, 1978; Marcroft, 1997; Potter *et al.*, 1997; Parker, 1999). Indian mustard is a valuable oilseed crop in India, USSR, Canada and Sweden (Downey and Rimmer, 1993). In Australia, however, current commercial production of mustard is mainly on the southwest slopes of New South Wales, where around 300 t of grain per annum is produced. Considerable breeding and agronomic research is required in order to further develop mustard commercially as an oilseed crop in Australia (Parker, 1999).

Indian mustard with high oil content and quality similar to canola can be used for oil production. It is also used as a condiment for the production of table mustard products and as a green manure specifically for biofumigation (Parker, 1999). Mustard has several agronomic advantages to make it an attractive alternative to canola. Mustard exhibits vigorous seedling growth, quick ground covering ability, greater tolerance to certain diseases, notably black leg, and to some insect pests. Its resistance to shattering makes mustard suitable for direct harvest and this lowers cost of production (Kirk and Oram, 1978; Parker, 1999). Furthermore, mustard has a reputation for greater tolerance to soil moisture and high temperature stresses than canola, especially during the grain filling period (Wright *et al.*, 1992; 1996; Niknam and Turner, 1999). Mustard is considered more suitable for low rainfall cropping regions and it has a potential to reduce the risk of crop failure due to drought and blackleg fungal disease.

Canola grown in Australia currently has an oil profile of around 61 % oleic acid, 21 % linoleic acid, 11 % linolenic acid, 7 % saturated fats, and less than 1 % erucic acid (English and Jausler, 2001). In the 1970's, the potential of mustard oil to be

interchangeable with canola oil was limited by high glucosinolate level in seed meal, and high erucic acid and low oleic acid content in oil (Kirk and Oram, 1978). Recently, mustard has been developed into an edible oil crop with a fatty acid profile that is very similar to canola, through extensive breeding undertaken over the last few decades, especially in Canada. Recently, mustard lines have been developed in Australia containing zero erucic acid (Kirk and Oram, 1981), 55 to 60 % oleic acid (Burton *et al.*, 2001), 6.5 % linolenic acid, 31 to 33 % linoleic acid (Burton *et al.*, 1999), and glucosinolate concentration 0 to 20 μ mol/g of seed (Burton *et al.*, 1999).

Recently developed early maturing mustard of quality similar to canola has shown significant yield advantages over early maturing canola varieties (Burton et al., 1999). Yield increases to the present level of 1.0 to 1.5 t/ha in low rainfall environments have been achieved by shortening the time to flowering and by increasing pod length (Burton *et al.*, 1999). However, more recently developed high quality mustard lines are yet to be tested in multi-location replicated trials across Australia to assess their adaptability to Australian environments (Burton *et al.*, 1999). Limited yield trials carried out in the northern and central cropping regions of Western Australia suggest that mustard has a higher yield potential in the medium and low rainfall regions of south Western Australia (Oram *et al.*, 1997).

The Mediterranean-type climate of south Western Australia, is characterised by long, hot and dry summers and short, mild and wet winters. In these areas, crops are mainly planted under dry land conditions soon after the first autumn rains and undergo vegetative growth in winter. They switch to reproductive growth in spring when temperature and photoperiod increases, and mature in early summer. The constraints to crop growth in Mediterranean-type environments vary but rainfall is usually the most limiting factor when crop management is adequate (Loss and Siddique, 1994). Soil moisture is usually exhausted by the time the crop reaches maturity, often referred to as terminal drought. Both low and high temperatures limit crop growth in Mediterranean-type environments. Vegetative growth rate is restricted by low temperatures (0 to 7^0C) in mid winter and seed yield is adversely affected by high temperatures (25 to 40^0C) at the end of the season in spring and early summer.

Many strategies have been proposed for improving adaptation and yield in water limited Mediterranean-type environments (Thurling, 1991; Loss and Siddique, 1994; Turner, 1997; Siddique *et al.*, 1999; Turner *et al.*, 2001). Strategies that improve adaptation and yield of cereals (Loss and Siddique, 1994; Turner, 1997), pulses (Thomson and Siddique, 1997; Siddique *et al.*, 1999; Turner *et al.*, 2001), and rapeseed/canola (Thurling, 1974 a; Richards, 1978 a & b; Thurling, 1991) in water limited Mediterranean-type environments in Australia have been studied extensively. However, to date no such study has been reported on mustard.

Studies undertaken to gather information that are necessary to develop mustard as an oilseed crop in Australian farming systems are presented in this thesis. It was hypothesized that mustard would be well adapted to these environments compared to canola due to its greater ability to tolerate soil moisture stress, which has been proven in many previous studies. Experiments presented in this thesis were undertaken with three main aims.

1. To identify the effects of genotype, environment (e.g. times of sowing, seasons, sites) and genotype x environment interaction on phenology, growth, yield, oil and protein contents of mustard
2. To study phenological, morphological and physiological basis of adaptation and yield of mustard in the Mediterranean-type environments
3. To investigate the response of mustard to soil moisture deficits, especially in the post-flowering period

Adaptation of mustard was studied initially in a medium rainfall site at Northam and in subsequent years in the low rainfall cropping regions at three sites (Merredin, Mullewa, Newdegate) in south Western Australia.

CHAPTER 2

REVIEW OF LITERATURE

2.1. *Brassica juncea* as an oilseed crop

Brassica crops are widely cultivated throughout the world as vegetable crops for human consumption, as condiments and spices for improved flavor of human diets, and as fodder crops for livestock feeding and for biofumigation in crop rotation programs. However, the largest cultivation of these crops is for edible vegetable oil production (Downey and Rimmer, 1993). The ability of *Brassica* seeds to germinate and the plants to thrive at low temperatures have made *Brassica* one of the few edible oilseed crops that can be cultivated as winter crops in the temperate agricultural zones of the world (Kimber and McGregor, 1995). The small spherical seed normally contains over 40 % oil, while the meal residue after oil extraction contains 36 to 44 % protein (Kimber and McGregor, 1995).

2.1.1. Origin, Taxonomy and Morphology of *Brassica* oilseed species

Brassica oilseed species are herbaceous annuals belonging to the family Cruciferae. Four related species are cultivated worldwide as a source of vegetable oil, namely *Brassica napus* L., *Brassica rapa* L., *Brassica juncea* L., and *Brassica carinata* Braun (Downey and Rimmer, 1993). The botanical relationships between the *Brassica* species were established by means of taxonomic studies carried out in the 1930s (Kimber and McGregor, 1995). The three species with higher chromosome numbers, *Brassica napus* L. (n=19, AACC), *Brassica juncea* L. (n=18, AABB) and *Brassica carinata* L. (n=17, BBCC) are amphidiploids derived from the diploid species *Brassica nigra* (L.) Koch (n= 8, BB), *Brassica rapa* L. (n=10, AA) and *Brassica oleracea* L. (n=9, CC).

Brassica napus L. (n=19, AC genomes) is the rape or rapeseed, more recently called canola, which is commonly grown in Europe, Canada and Australia. It is believed to be derived from a cross between *B. rapa* L. and *B. oleracea* L.. Since the latter was originally confined to the European-Mediterranean region, it is believed that *B. napus* L. originated in Southern Europe from where it was introduced into Asia (Downey and Robbelen, 1989). Leaves of this species lack a true petiole, but partial clasping of the stem occurs. *B. napus* L. differs from *B. juncea* L. by having thick,

glabrous leaves and relatively larger (1.2 to 1.5 cm long) dark yellow flowers. The seed is dark in colour and no natural yellow seeded forms are known (Downey and Rimmer, 1993). Unless otherwise mentioned, the term 'canola' refers to *B. napus* L. in this thesis.

Brassica rapa L. (n=10, A genome), formerly *Brassica campestris* L. is known as turnip rape and in Canada as Polish rape after its country of origin. It is believed to be the oldest *Brassica* species and to have had the widest distribution from the west of Europe to the east of China and Korea, and from Norway to the north of Sahara and India. Europe, Central Asia, Afghanistan or India are thought to be centres of origin of *B. rapa* L. (Kimber and McGregor, 1995). The most cold hardy cultivars of the *Brassica* oilseeds belong to this species. It has a relatively high growth rate under low temperatures, matures early and produces abundant seed (Downey and Rimmer, 1993).

Brassica carinata Braun, (n=17, BC genome) is relatively slow growing and believed to have arisen in north eastern Africa where the parent species *B. nigra* L. and *B. olerecea* L. overlap in the wild (Downey and Robbelen, 1989). Cultivation is limited to the Ethiopian plateau and adjacent areas in East Africa (Downey and Rimmer, 1993). The seed is large and predominantly dark, though there are yellow seeded forms available. *B. carinata* is being investigated as a source of large yellow seeds. Leaves are generally waxy and light green in colour and are attached to the stem with a true petiole (Downey and Rimmer, 1993).

2.1.2. Origin, Taxonomy and Morphology of *Brassica juncea*

Brassica juncea L. Czern. and Coss., (n=18, AB genomes) is generally thought to have originated in the Middle East where *B. rapa* and *B. nigra* overlap in the wild (Kimber and McGregor, 1995). Central Asia and China have also been suggested as sites of primary origin (Downey and Rimmer, 1993). *B. juncea* is also considered to have arisen by independent hybridization at secondary centres in India, China and the Caucasus where *B. nigra* was widely used as a commercial species from early times (Hemingway, 1976). It has been mainly grown for condiment purposes and as an oilseed crop in Western Canada (Woods *et al.*, 1991) and is considered suitable as an oilseed crop in Australia (Kirk and Oram, 1978).

Brassica juncea cultivars are distinguished by the colour of the seed. The brown seeded cultivars are known as brown mustard while the yellow seeded cultivars are referred to as yellow or Oriental mustard. *B. juncea* is well adapted to drier conditions and matures relatively quickly (Kimber and McGregor, 1995). It is an erect, highly branched annual with a tap root. This species is characterized by a high leaf area ratio, leaves with true petioles and pale yellow flowers. Thin leaves vary considerably in shape but are generally dark green (Downey and Rimmer, 1993). Inflorescence is an ebracteate raceme. The seeds are spherical, about 3 to 5 cm long and are positioned in a single row in each loculus (Purseglove, 1968). Unless otherwise mentioned, the term 'mustard' refers to *Brassica juncea* L. Czern. and Coss. in this thesis.

2.1.3. Economic value of mustard and canola

Oilseed *Brassicas* account for approximately 10 % of the total world oilseed production and 14 to 15 % of the total edible vegetable oil production (Downey and Rimmer, 1993). Mustard has been cultivated in 53 countries spreading over the six continents across the globe covering an area of 622,843 hectares with a total production of 354,353 metric tons (MT) in the year 2001 (Table 2.1). The major mustard growing countries are Canada, Russian Federation, India, Europe, United States of America and China (Table 2.1). In Australia, mustard is commercially produced on the South West slopes of NSW where around 300 tons of grain is produced. There is a potential for increasing the production for both the domestic and export markets, but this market will not become a reality until the supply of large volumes of oil can be guaranteed (Parker, 1999).

Oil contents within and among *Brassica* oilseed species range from 35 to 44 % of the air-dried seed (Downey and Rimmer, 1993). *Brassica* oil is composed predominantly of fatty acid containing triacylglycerols (90 %). Polar lipids like phospholipid, glycolipid and galactolipid acids constitute about 4 to 5 % and trace amounts of monoacylglycerols, diacylglycerols and free fatty acids (0.5 %) are also present. Fatty acid composition is an important quality parameter dictating the nutritional and industrial value of *Brassica* oil. The fatty acid profile of *Brassica* seed oils consists of palmitic, palmitoleic, stearic, oleic, linoleic, linolenic, archidic, behenic, eicosenoic, erucic, and lignoceric acid (Uppstrom, 1995). Canola grown in Australia

Table 2.1. Production of mustard and canola/rapeseed by main producing countries/regions in 2001.

Source: FAOSTATS, 2001 (www. fao.org.)

Country	Mustard		Canola/rapeseed	
	Area harvested (ha)	Production (Mt)	Area harvested (ha)	Production (Mt)
Canada	218, 000	88, 900	3, 828, 900	5, 062, 000
India	188, 455	132, 331	4, 626, 000	4, 088, 000
China	20, 000	13, 000	8, 000, 000	11, 320, 000
Europe	115, 531	67, 665	4, 667, 913	12, 151, 931
Russian Federation	78, 000	30, 000	165, 000	112, 000
USA	17, 840	18, 650	590, 000	908, 350
Australia	310	200	1, 500, 000	1, 900, 000
World	622, 843	354, 353	23, 961, 310	36, 216, 536

currently has an oil profile of around 7 % saturated fats, 61 % oleic acid (mono unsaturated), 21 % linoleic acid (poly unsaturated), 11 % linolenic acid (poly unsaturated) and less than 1 % erucic acid (toxic) (English and Jausler, 2001).

Brassica oilseeds are produced not only for their oil, but also for their meal, which is a good source of protein for both animal and human consumption. The meal of *Brassica* species remaining after oil extraction containing about 36 to 44 % protein in contrast with 20 to 30 % on a whole seed basis. Seed meal is generally used as an animal feed and has a great potential for producing protein concentrates and isolates for human consumption. The three major classes of proteins that have been identified in *Brassica* oilseeds are albumins, globulins and oleosins. The quality of *Brassica* oilseed proteins is determined to a large degree by the amino acid composition. The protein is rich in lysine and has substantial amounts of the sulphur amino acids, methionine and cystine, which are limited in most cereal and other oilseed proteins. It also contains a substantial amount of threonine. Next to proteins, carbohydrates are the largest component of the meal. Also present are phytates, phenolic compounds and glucosinolates (Uppstrom, 1995).

2.1.4. Oil content, composition and quality of *Brassica juncea*

A zero erucic acid *B. juncea* line was isolated in 1981 by Kirk and Oram in Australia, containing 44 to 46 % of oil. Double low (low erucic, low glucosinolate) *B. juncea* lines containing 48 % (Burton et al., 1997) and 38 to 40 % oil (Burton *et al.*, 1999) have recently been developed in Australia. In Canada, the oil content of recently developed high quality *B. juncea* lines varies from 43 to 45 % (Potts *et al.*, 1999). In India, the oil content of *B. juncea* seed varies from 30 to 42 %. In the U.S.S.R., varieties with particularly high oil content (48.8 %) have been developed. The yellow seeded *B. juncea* lines have a thinner seed coat than the brown seeded lines and consequently have an oil content that is 4 to 7 % (of seeds weight) higher (Kirk and Oram, 1978).

In the 1970s, the main disadvantage of *B. juncea* was that its oil contained about 18 to 55 % erucic acid. As the erucic acid present in *Brassica* oilseeds is harmful to health, some countries have placed upper limits (in Canada and Australia for instance the limit is 5 %) on the amount of erucic acid which may be present in margarine or cooking oil. The identification of plants with essentially no erucic acid in their seed oil in *Brassica napus* (Stefansson *et al.*, 1961) and *Brassica rapa* (Dorrell and Downey, 1964) resulted in the development of nutritionally superior canola cultivars. In 1981, Kirk and Oram isolated two zero erucic acid lines of *Brassica juncea,* called Zem 1 and Zem 2, and this work initiated the development of this species as an edible oil crop. TERI(OO)R985 and TERI(OO)R986 are zero erucic acid *B. juncea* lines developed in India (Agnihotri and Kaushik, 1999). Oil from high erucic acid (> 50%) cultivars is also useful as it can enter the industrial oil market where there are many applications.

Higher percentages of oleic acid are desirable, as monounsaturated fats improve the stability of oil and they also have health benefits (English and Jausler, 2001). In order to meet canola standards, *Brassica juncea* breeders aimed at raising oleic acid levels to around 60 to 70 %. The zero erucic acid lines of *B. juncea* isolated by Kirk and Oram (1981) containing 50 % oleic acid. *B. juncea* lines containing 45 to 55 % (Burton *et al.*, 1999) and 55 to 60 % oleic acid (Burton *et al.*, 2001) were reported recently and these studies have shown there is a possibility to raise oleic acid levels by further crosses and selection and by anti – sense technology. In Canada, a high oleic variant of *B. juncea* (63 %) was discovered (Potts *et al.*, 1999) and *B. juncea* lines with oleic acid levels as high as 73 % have been developed (Stoutjesdijk *et al.*, 1999).

Lower linolenic acid (3 %) and higher linoleic acid (20 %) improves the quality of the oil. Lower levels of linolenic acid are desirable to improve the storage characteristics of the oil while a higher linoleic acid (vitamin F) content may be nutritionally desirable (Uppstrom, 1995). Highly unsaturated linolenic acid is readily oxidized, causing a distasteful flavor and reducing frying life of the oil (English and Jausler, 2001; Gurung *et al.*, 2001). Extensive *B. juncea* breeding programs undertaken during the last few decades, resulted in cultivars containing higher linoleic and lower linolenic acids. Putative mutants with lower linolenic acid

contents in the seed oil ranging from 9.5 % to 12.4 % have been isolated from the low or zero erucic acid lines containing 13 to 15 % of linolenic acid (Oram and Kirk, 1991). The linolenic acid content of *B. juncea* was reduced from 16 % to 6.5 % by mutagenesis and recombination. These lines contain 31 to 33 % linoleic acid (Oram *et al.*, 1999).

2.1.5. Composition and quality of *Brassica juncea* seed meal

In Australia, *B. juncea* cv. Stroke containing 42.3 % protein in its oil free meal and 25.3 % in the seed has been reported, compared to 37.2 % in the meal and 21.2 % in the seed of *B. campestris* L. cv. Span. (Kirk and Oram, 1978). *B. juncea* lines containing 23 to 30 % (Burton *et al.*, 1999) protein in the seed have also been reported in Australia. *B. juncea* meal proteins had a FAO protein score of 82. Soybean (*Glycine max*) meal has a score of 73, a score of 70 or more being regarded as satisfactory for growth and maintenance (Kirk and Oram, 1978). *B. juncea* not only has high protein contents but also an excellent amino acid composition. Lysine and methionine contents of 5.4 % and 1.7 % for *B. juncea* may be compared with 6 % and 1.6 % in soybean meal (Kirk and Oram, 1978).

Glucosinolates present in *Brassica* seed meal have long been known to reduce mineral availability, to bind to protein, reducing digestibility and amino acid availability and to reduce the activity of amylase, thus reducing starch hydrolysis. Intact glucosinolates have generally been considered to be innocuous. But hydrolysis products produce several physiological effects when they are present in large quantities in animal feeds (Uppstrom, 1995). Glucosinolates present in *B. juncea* seeds are either important anti-nutritional factors or valuable flavour compounds. *B. juncea* predominately contains allyl glucosinolate (trival name sinigrin) and gives rise to allyl isothiocyanate, which is more volatile and responsible for the pungent character of the mustard paste made from seeds of these species. However, low glucosinolate contents of less than 20 μmol/g of seed (the canola standard) is desirable for using *B. juncea* meal in animal feed. The low glucosinolate trait has been developed only recently in *B. juncea* by interspecific hybridization in Canada (Love *et al.*, 1990) and by mutagenesis in Australia (Palmer *et al.*, 1988; Oram and Kirk, 1992). In 1995, total concentration of glucosinolates was reduced below 15 μ mol/g of seed in Australia (Oram and Kirk, 1995). The best canola quality *B. juncea*

lines containing glucosinolate concentrations of 2 to 20 μ mol/g of seed (Burton *et al.*, 1997; 2001; Oram *et al.*, 1999) and 0 to 20 μ mol/g of seed (Burton *et al.*, 1999) have recently been developed in Australia.

2.2. Growth, development, phenology, and yield of mustard and canola, and crop response to environment

2.2.1. Overview of development and growth

By definition, 'development' is the progress of a plant through the stages of its life cycle and 'growth' is the increase in size of organs, and the accumulation of dry matter, firstly as sugars and then as structural and storage materials in leaves, stems, roots and grains/pods/fruits (Mendham and Salisbury, 1995). The interaction between development and growth at each stage builds up the potential, and the realisation of the potential yield. Each stage and process is under genetic control, and is affected in varying ways by environmental factors such as temperature, photoperiod, nutrient supply and moisture stress (Mendham and Salisbury, 1995).

Numerical keys are used in research in order to define and quantify the stages of development precisely. Much of the published work on crop physiology of *Brassicas* has been carried out on *B. napus.* The first key that was widely used to define and quantify the stages of development of *B. napus* was developed in Canada (Harper and Berkenkamp, 1975). In 1984, a more elaborate key (Table 2.2) was developed in the United Kingdom (Sylvester-Bradley and Makepeace, 1984). However, no such key has been developed specifically for *B. juncea.* Since, both species progress through similar developmental stages, the same keys could be used to define and quantify the stages of development of *B. juncea.* However, there is a variation in the time taken to complete different developmental stages by these two species.

Development and growth of roots, leaves, branches, pods and seeds of mustard and canola and the effect of environment on their growth and development are discussed in detail in this section.

Table 2.2. Definitions and codes for stages of development in oilseed rape (*B. napus*). Source: Sylvester-Bradley and Makepeace (1984).

Definition	Code
Germination and emergence	
Dry seed	0.0
Imbibed seed	0.2
Radicle emerged	0.4
Hypocotyl extending	0.6
Cotyledons emerged	0.8
Leaf production	
Both cotyledons unfolded and green	1.00
First true leaf exposed	1.01
Second true leaf exposed	1.02
.	.
.	.
.	.
Tenth true leaf exposed	1.10
.	.
.	.
.	.
Twentieth true leaf exposed	1.20
Stem extension	
No internodes detectable ('rosette')	2.00
One internode detectable	2.01
Two internodes detectable	2.02
.	.
.	.
.	.
Ten internodes detectable	2.10
.	.
.	.
.	.
Twenty internodes detectable	2.20

Note: The following descriptions should normally be applied to the raceme on the main stem. Otherwise the raceme position should be stated.

Table 2.2 continued

Definition	Code
Flower bud development	
Only leaf buds present	3.0
Flower buds present but enclosed by leaves	3.1
Flower buds visible from above ('green bud')	3.3
Flower buds raised above leaves	3.5
First flower stalks extending	3.6
First flower buds yellow ('yellow bud')	3.7
More than half flower buds on raceme yellow	3.9
Flowering	
First flowers opened	4.1
20% of all buds on raceme flowering or flowered	4.2
30% of all buds on raceme flowering or flowered	4.3
40% of all buds on raceme flowering or flowered	4.4
50% of all buds on raceme flowering or flowered	4.5
60% of all buds on raceme flowering or flowered	4.6
70% of all buds on raceme flowering or flowered	4.7
80% of all buds on raceme flowering or flowered	4.8
All visible buds on raceme finished flowering	4.9
Pod development	
Lowest pods more than 2 cm long	5.1
20% potential pods on raceme more than 2 cm long	5.2
30% potential pods on raceme more than 2 cm long	5.3
40% potential pods on raceme more than 2 cm long	5.4
50% potential pods on raceme more than 2 cm long	5.5
60% potential pods on raceme more than 2 cm long	5.6
70% potential pods on raceme more than 2 cm long	5.7
80% potential pods on raceme more than 2 cm long	5.8
All potential pods on raceme more than 2 cm long	5.9

Note: The following descriptions should normally be applied to the lowest third of the raceme on the main stem. Otherwise, position on the raceme should be stated.

Seed development	
Seeds present	6.1
Most seeds translucent but full size	6.2
Most seeds green	6.3
Most seeds green brown mottled	6.4
Most seeds brown	6.5
Most seeds dark brown	6.6
Most seeds black but soft	6.7
Most seeds black and hard	6.8
All seeds black and hard	6.9

2.2.2. Germination and Emergence

During germination of mustard and canola, a radical emerges first and then the hypocotyl extends and cotyledons emerge. Soil temperature is the main factor affecting germination once seeds have imbibed water. A laboratory study (Kondara *et al.*, 1983) showed that *B. rapa* L. had a significantly lower germination percentage (34 %) than *B. napus* L. (90 %) at 7 ^{0}C or below and at 25 ^{0}C and presumably above. Germination time varied with temperature, from 11 to 14 days at 2 ^{0}C to 1 day at 21 to 25 ^{0}C. In areas where autumn sowing is normal, as in Australia, soil moisture is as important as temperature for germination (Mendham and Salisbury, 1995).

Mustard germinates better than canola in dry soils in Pakistan and this is the reason for success of the crop in these areas (Oram and Kirk, 1992). The presence of higher concentrations of mucilage in the testa of mustard seeds is suggested to contribute to its greater ability to germinate in soils with sub-optimal moisture content (Oram and Kirk, 1992). Mustard has also shown tolerance to waterlogging and it makes aerial sowing of mustard more reliable on soils that are too soft for ground sowing. Aerial sowing has been attempted with canola with minimal success in the Riverina region of New South Wales after a late break of season and heavy winter rainfall (Oram and Kirk, 1992). A range of other factors also affects the rate and final percentage of emergence of *B. napus*. Seed that was fully mature on the mother plant was observed to have faster radical emergence than immature seed. Larger seeds, for example from main stem or upper branches produced larger cotyledons and hence more vigorous seedlings. However, plant population or final yield was not affected by seed size (Major, 1977; Mendham *et al.*, 1981b).

2.2.3. Root growth

Rapid root growth after establishment consists of the vertical extension of a taproot, lateral growth of secondary roots and then deposition of reserves principally in the taproot. Most studies of roots include only those accessible to digging, i.e. to about 30 cm. About 27 to 52 % of roots are distributed in the top 20 cm of soil, and 1 % or less below 1 m (Almond *et al.*, 1984). Root distribution is close to the maximum at the end of flowering, so earlier flowering *B. rapa* L. lacks an extensive root system (Richards and Thurling, 1978b). Almond *et al.* (1984) showed that rooting is limited to the surface when direct drilling was practiced on a compacted soil. On less

compacted soils however, direct drilling gave a well-developed and well-distributed root system with depth. Crops extracted water up to 40 cm deep early in the season and to 110 cm by maturity, as measured by neutron probe readings and the differences were related to root distribution and soil compaction (Almond *et al.*, 1984).

2.2.4. Canopy development

2.2.4.1. Leaf initiation and appearance

The growing point of the plant produces leaf initials in a helical arrangement with a phyllotaxy of about 130^0 between leaves. As the early growth of the *Brassica* plant is very much dependent on temperature and photoperiod, these factors have a large effect on leaf initiation, appearance and expansion (Mendham and Salisbury, 1995). The environmental parameters that determine final leaf number are most likely to be those triggering the plant from vegetative to floral development. Nanda *et al.* (1995) observed a reduction in final leaf number under lengthening photoperiods and lower temperatures. Leaf appearance of *B. napus* was more sensitive to weather parameters than *B. juncea.* Nanda *et al.* (1995) studied the effects of temperature and photoperiod on the rate of leaf appearance in *Brassica* species in India and observed rapid development of leaves with the lengthening of photoperiod. Appearance of the first leaf was delayed by 1.35 days for each 1^0C reduction in mean temperature. The leaf number at any time after the appearance of leaf one, would be equally well predicted by using a relationship based on leaves per day as well as on leaves per degree day.

2.2.4.2. Leaf area development

Controlled environmental studies on leaf expansion and duration (Morrison *et al.*, 1992) showed that leaf area development of *B. napus* cultivar Westar followed logistic shape growth functions. There is evidence for an effect of temperature and photoperiod on leaf area development. Morrision *et al.* (1992) found that the optimum temperature range for leaf development in *B. napus* cultivar Westar is 13 to 22 ^{0}C (17 ^{0}C mean temperature). Leaf expansion rates of individual leaves increased linearly as temperature increased from 10 to 25 ^{0}C. Photoperiod influences the reproductive development of crops and rapid development of the reproductive phases will limit the leaf initiation in crops with a terminal raceme such as canola and

mustard. Depending on the photoperiodic response crops will develop lesser number of leaves.

Higher leaf area indices (LAI) can be achieved by either faster leaf expansion rates or longer periods between sowing and flowering. However, the advantage of using later flowering cultivars, could only be achieved in a long growing season (Mendham and Scott, 1975). A LAI of 3 to 4 is sufficient to intercept about 90 % of solar radiation. The characteristics of the leaf canopy change with time. In the rosette stage, the large leaves have an intermediate angle with the stem, and bend to horizontal orientation, giving an extinction coefficient of 0.6 or greater. During stem elongation the smaller leaves or bracts subtending branches on the main stem are more upright with an extinction coefficient of 0.4 to 0.6. A value of 0.6 is satisfactory to the transmission or interception of about 45, 70 and 84 % of solar radiation at a LAI of 1, 2 and 3 respectively (Mendham and Salisbury, 1995). *B. napus* produced much larger leaves than *B. juncea* (Nanda *et al.*, 1995).

2.2.5. Flowering

The first sign of flowering commences on the main stem, which becomes the terminal inflorescence or raceme. Once the main stem flower buds are formed, axillary buds lower down will then begin to develop sequentially into the primary branches in a basipetal direction (Mendham and Scott, 1975). In general, first flowering occurs in the first primary branch and sequence downwards. (Tayo and Morgan, 1975). There are four main controls over inflorescence initiation and flowering; a minimum number of leaf initials before initiation takes place, the basic temperature response or plastochron in ^{0}Cd per leaf, vernalization responses mainly operating before initiation and day length responses operating before both initiation and flowering. Flowering is a result of more than one factor and/or their interactions, hence the effect of a single factor on flowering is very difficult to identify (Mendham and Salisbury, 1995).

Several of the *Brassica* species have been shown to flower earlier after exposure to lower temperatures. European winter cultivars required vernalisation before flowering. In most other cultivars, either vernalisation or long days were necessary for prompt flowering, with only a few lines such as very early Indian *B. rapa*

showing little response to either (Myers *et al.*, 1982). Australian cultivars were intermediate and Canadian cultivars were least responsive (Thurling, 1974 a; Salisbury and Green, 1991). Temperatures of around 3 to 7 ^{0}C appear to be most effective for vernalisation (Mendham and Salisbury, 1995). Robertson *et al.* (2002) found that the vernalisation response of *B. napus* and *B. juncea* saturates with 25 days at 3 ^{0}C and the base and optimum temperatures for development were confirmed at 0 and 20 ^{0}C respectively.

Photoperiod response of *B. napus* and *B. juncea* occurs between 10.8 and 16.3 hours (Robertson *et al.*, 2002). Nanda *et al.* (1996) found that the greatest response occurred between 12 and 14 hours. On average a change in photoperiod from 12 to 14 hours reduced the time to flowering by 40 %. Temperature and photoperiod can interact very strongly to change phenological development in many crops. High temperatures delay development at short photoperiods, but accelerate it at long photoperiods (Mendham *et al.*, 1990; Salisbury and Green, 1991; Nanda *et al.*, 1996). Hence, the duration taken to complete a phenological phase is better expressed by thermal time above a base, as it masks any differential effect of temperature and exposes and highlights the effects of photoperiod (Nanda *et al.*, 1996). Later flowering genotypes respond more to vernalisation and photoperiod than early flowering genotypes (Robertson *et al.*, 2002).

There is evidence of interaction effects of light intensity and temperature on development. Salisbury and Green (1991) showed that the phase of emergence to flowering responds to light intensity and a low light regime delayed flowering. Nanda *et al.* (1996) found that low night temperatures also had an effect on the phenological development between plant emergence and bud development. The development is accelerated in relation to the reciprocal of the minimum night temperature above 2 ^{0}C.

2.2.6. Pod and seed production

Pods commence rapid growth in length within a few days of anthesis, whereas rapid seed growth occurs after about 20 days. Pods reach full length before rapid seed growth start, and seeds attain 35 % of their final dry weight when the pod wall reaches full size and weight. The pod wall gains no more dry weight after dehydration commences, at 50 days from anthesis, whereas seeds increase dry matter

by 42 % during their period of dehydration, from 50 to 75 days after anthesis. When rapid pod growth commences, stem and branch dry weight accumulation and extension are close to their maximum, and leaf area is already declining rapidly (Hocking and Mason, 1993).

2.2.6.1. Determination of the number of pods

Position on the plant is a major determinant of the likely success of a flower in forming a pod. The terminal raceme carries 25 % of the total flowers on the plant and 38 % of the final number of pods. The success rate with which flowers that formed pods, decreased from 68 % on the terminal raceme to 22 % on the fifth branch (Tayo and Morgan, 1975). Very few of the many flowers that opened after the 18^{th} day on any branch, carried pods to harvest (Tayo and Morgan, 1975). Although enormous amount of flowers (25,000 per m^2) are produced, half or more of the potential pod site may be lost (Mendham *et al.*, 1981a). Some are lost just after flowering due to poor pollination and the majority is lost as either abscised flowers or young pods, or all seeds are aborted and pods remain small. Most of the losses occur in a 3 to 4 week period after full flower. This period is the time of maximum growth rate of pod walls and of maximum demand for assimilates and nutrients.

Water and nutrient stress either curtails flowering or limits success rate. A direct relationship was shown between the date of last nitrogen application and success rate of flowers (Mendham and Salisbury, 1995). In 1994, Kumar *et al.* found that water stress has a significant adverse effect on the number of pods produced and subsequent yield reduction. A relationship between the amount of solar radiation intercepted per flower and its likelihood of success was also found. With less than 20 KJ per flower during its flowering period, the success rate was roughly proportionate to radiation, but with more than 20 KJ per flower about 70 to 80 % success was recorded regardless of the radiation level (Mendham and Salisbury, 1995).

2.2.6.2. Determination of the number of seeds per pod

Seed survival until final harvest depends on factors such as supply of assimilates and water (Mendham and Salisbury, 1995). Mendham *et al.* (1981a) observed the changes in number of seeds per pod with pod growth. From a consistent number of around 30 seeds per pod at flowering, the numbers of surviving seeds declined over a 3 week period, being stable in the last 3 to 4 weeks before maturity. Pods produced

on average 13, 11 and 8 seeds in upper, middle and lower sections of the canopy when sown early in the season. In the denser pod canopy of the early sowing, seed losses were greater and mainly in the lower levels of the canopy, whereas in the late sowing with less competition between pods, there was little difference in seed abortion between levels of the canopy.

The period over which seeds were lost coincided with the main growth of the pod walls and before the seeds themselves commenced rapid increase in dry weight. A study conducted under glass house conditions also revealed that the critical period for seed abortion is 2 to 3 weeks after flowering (Tayo and Morgan, 1979). Similar results were found in *in vivo* observations of developing pods using X radiation and photography of developing pods (Pechan and Morgan, 1985). Duration for seed growth was determined by Mendham *et al.* (1981a) as ranging from 35 to 55 days starting from 23 days after flowering. The rate of growth per seed, ranged from 0.08 to 0.12 mg/day and was a function of internal (crop size, leaf and other photosynthetic area, carbohydrate reserves) and external factors (radiation, water supply, temperature).

2.2.7. Quality changes during seed development

During seed development a number of quality changes occur before the final chemical composition of the mature seed is realised. During seed development the rate of oil deposition follows a sigmoid curve. Oil concentration increased in a similar way to seed dry weight, reaching a maximum percentage after about 60 days, but the total oil concentration increased further with dry matter accumulation. Droplets of storage oil are first evident about 18 days after pollination. They increase in size and number between approximately 20 and 30 days after anthesis. Oil concentration reaches a plateau at physiological maturity with little further change occurring until seed maturity (Fowler and Downey, 1970; Rakow and McGregor, 1975). At seed maturity, about 80 % of the oil is concentrated in droplets in the cotyledonary cells. Oil concentration in the hypocotyl and radicle of mature seed is low while the seed coat contains only 7 to 12 % (Fowler and Downey, 1970). Rapid nitrogen accumulation occurs in the early stages of seed development. Storage protein begins to accumulate when the embryo commences to grow rapidly to replace the endosperm and fill the fully expanded seed coat. The onset of seed

protein accumulation coincides with rapid cell expansion and rapid increase in embryo weight. Most of the proteins in mature seed are found in the cotyledons.

Among the environmental factors that regulate oil concentration, temperature has been found to be one of the most important, with high temperature reducing oil concentration (Hocking and Mason, 1993). Irrigation can increase oil concentration (Krogman and Hobbs, 1975) while waterlogging and water stress can reduce it (Mendham and Salisbury, 1995). In 1999, Walton found that oil concentration of canola increased by 0.06 % for each 1 mm increase in rainfall and by 0.86 % for 1 ^{0}C fall in average daily temperature. He also found a strong correlation (r^2 = 0.65) between post-anthesis duration and oil concentration. Heenan and Armstrong. (1993), Jensen *et al.* (1996), and Hocking *et al.* (1997) also reported the negative effects of drought and high temperatures, that usually occurs during the later part of crop growth in Mediterranean-type environments, on oil concentration of canola. High nitrogen fertility tends to reduce oil concentration (Krogman and Hobbs, 1975). Oil concentration can also be reduced when frost prematurely arrests seed development (Mendham and Salisbury, 1995). Blondel *et al.* (1999) found a negative relationship between oil and protein concentrations and reported that high temperatures increased protein content at both high and low water deficits.

2.3. Adaptation of mustard and canola to short season, Mediterranean-type environments

2.3.1. The Mediterranean-type environment and its limitations to crop growth

Mediterranean-type climates are characterised by long, hot, dry summers and short, mild, wet winters (Aschmann, 1973). Parts of South Australia, south Western Australia, California, West Asia, North Africa, parts of South Africa and South America, Southern Europe (Spain, Italy, Greece) experience Mediterranean-type climates. Crops are mainly grown under dry land conditions in these areas. Crops are planted soon after the first autumn rains and undergo vegetative growth in winter. They switch to reproductive growth as temperature and photoperiod increases in spring, and mature in early summer. The constraints to crop growth vary in Mediterranean-type environments (Loss and Siddique, 1994).

2.3.1.1. Rainfall

Adequate rainfall is usually the most limiting environmental factor in Mediterranean-type environments in Australia. Mediterranean-type environments receive between 275 and 900 mm of annual rainfall with the majority (>65%) in winter (Aschmann, 1973). In general, winter rainfall exceeds crop demands because of mild temperatures, low evaporation, slow growth rates and the high reliability of these rains. Intermittent drought during winter is rare, but waterlogging can be a problem on some soil types in wet years. During spring, rainfall becomes less frequent, and temperatures and vapour pressure deficit increase. Soil moisture is usually exhausted by the time the crop reaches maturity, often referred to as terminal drought. Timing of terminal drought varies according to the last spring rains, temperatures, soil types and crop growth.

2.3.1.2. Solar radiation

Solar radiation has a large influence on temperatures and evaporation regimes, and hence on crop growth. In Mediterranean-type environments, mid day solar radiation is about 6 to 10 MJ per m^2 per day in mid winter, and it is unlikely that radiation limits crop growth as the temperature and crop leaf area are low at this time. In spring, when the leaf area index is about 3, the upper leaves and flowers shade the lower canopy of the crop. In this situation solar radiation may limit photosynthesis of the lower leaves. In mid summer, the sun elevation is high, there is low incidence of cloud cover, and mean mid day solar radiation is about 25 to 30 MJ per m^2 per day (Loss and Siddique, 1994).

2.3.1.3. Temperature

Both low and high temperatures limit crop growth in Mediterranean-type environments. Temperatures follow trends in solar radiation. Maximum summer temperatures range between 25 and 40 ^{0}C along western coasts of south Western Australia and between 30 and 45 ^{0}C inland and in the more easterly regions. At least one month of the year has an average temperature below 15 ^{0}C and less than 3 % of the year experiences minimum temperatures below 0 ^{0}C (Aschmann, 1973). Average minimum monthly temperatures in mid winter range from about 0 to 7 ^{0}C and in some regions, especially inland areas, temperatures fall below 0 ^{0}C during some nights. Vegetative growth rate is restricted by low temperatures in mid winter, but

minimum temperatures are generally not low enough to cause long term frost damage. However, most economic losses occur due to spring frosts when the crops are flowering, growing rapidly and are more susceptible.

2.3.1.4. Growing season and planting date

In Mediterranean-type environments, the period of crop growth is usually restricted by lack of rainfall and high temperatures at the start and end of the season. Potential evaporation exceeds rainfall for a large proportion of the year. The timing of the first autumn rains can vary considerably, and sowing times vary from year to year over a period of 8 to 10 weeks. Due to the limitations of rainfall and evaporation, there is limited scope for improving yield by extending the period for crop growth. With the adoption of early sowing, there is also a risk of an extended period of dry weather after the initial autumn rain, and under such conditions early sown crops can be subjected to water stress soon after emergence. Winter can change abruptly into spring and the termination of the growing season varies depending on rainfall, temperatures and soil type. Most crops in south Western Australia depend on current rainfall because of the poor water holding capacity of soils, particularly in the low rainfall areas. Rainfall largely determines the length of the growing season in Mediterranean-type environments and the pattern and efficiency of water use has a large effect on crop yields.

Seed yields declined with later sowings in temperate to sub-tropical environments (Hocking *et al.*, 1991; Heenan and Armstrong, 1993; Hocking and Stapper, 1993; Semmel *et al.*, 1995; Robertson *et al.*, 1999). However, the magnitude of the decline in yield with delayed sowing was highly variable from study to study and poorly defined for different environments (Robertson *et al.*, 1999). Robertson *et al.* (1999) collated published sowing date studies conducted on *B. napus* and *B. juncea* in Australia and found that yield declined with delayed sowing by on average 5 % per week delay in sowing. Further to yield reduction, late sowings results in lower oil concentration (Mendham *et al.*, 1981a; Hocking *et al.*, 1991). Delayed sowing reduces seed oil concentration of *B. napus* and *B. juncea* at the rate of 1.5 % for each 1 ^{0}C rise in average temperature (Hocking and Stapper, 1993).

Late sown crops suffer from increasing temperatures, water stress and pest damage during reproductive development (Mendham *et al.*, 1990). Delays in sowing *B. napus*

were associated with reductions in the duration of vegetative development (Thurling and Vijendra Das, 1979). Mendham *et al.* (1990) found that hastened development combined with reduced post-anthesis growth reduced yields from late sowings. Delayed sowing can reduce the pre-anthesis period, duration to anthesis and pod filling period (Hocking *et al.*, 1991). All yield components are reduced by late sowings of *B. napus* and *B. campestris*, the most sensitive being pod number per plant (Richards and Thurling, 1978b) and seed number per unit area (Thurling and Vijendra Das, 1979). Efficiency of post-anthesis growth declined from about 1 g/MJ intercepted radiation on early sown crops to about 0.2 g/MJ on late sown crops. Yield of *B. juncea* was higher than *B. napus* in late sowings (Hocking *et al.*, 1991; Hocking and Stapper, 1993).

2.3.2. Morphological and physiological basis of adaptation and yield in Mediterranean-type environments

Two key aspects of crop adaptation and yield in Mediterranean-type environments are presented in this section. Useful conceptual growth models for analysing yield variation are discussed under 'Components of Yield'. Specific physiological traits of improving yields in water limited environments are discussed under 'Determinants of Survival'.

2.3.2.1. Components of Yield

A number of crop analytical models have been proposed to describe yield in terms of a number of independent physiological components which effectively integrate numerous complex processes into fewer biologically meaningful parameters. A useful conceptual framework for analysing yield (Y) is provided by the relationship;

$$Y = TDM \times HI$$

Where TDM is the total above ground dry matter and HI is the harvest index. The components of this model can be further partitioned into functional components that describe more detailed physiological processes responsible for variation in TDM and HI (Turner *et al.*, 2001). In 1977, Passioura proposed that in water limited environments, dry matter production is a function of the water used by the crop (WU), and the efficiency (WUE) with which it is converted into TDM.

$$TDM = WU \times WUE$$

$$Y = WU \times WUE \times HI$$

Subsequent analysis by Fischer (1981) has suggested that the yield is related to the water passing through the crop by transpiration (T) rather than that lost by soil evaporation. Hence dry matter production is also related to the transpiration (T) and the efficiency with which transpiration water is utilized to produce dry matter (Transpiration Efficiency; TE). Hence:

$$Y = T \times TE \times HI$$

Monteith (1977) considered that Y is a function of the amount of radiation intercepted by the crop (RI), the efficiency of conversion of radiation into dry matter (RUE), and the partitioning of dry matter into the reproductive component (HI), hence:

$$Y = RI \times RUE \times HI$$

Each sub component of these relationships represents an integrated function of a number of developmental, morphological, physiological and biochemical attributes. These models have become a framework for examining ways to improve crop yields and their adaptation to water limited environments (Ludlow and Muchow, 1990; Loss and Siddique, 1994; Turner, 1997; Siddique *et al.*, 2001; 2003; Turner *et al.*, 2001).

2.3.2.1.1. Water Use and Water Use Efficiency

Water use is usually considered as soil evaporation (E) plus transpiration (T), while water runoff and drainage are often negligible in dryland areas and are ignored. In Mediterranean-type environments, E usually accounts for about 40 to 60 % of the WU and most of soil moisture is lost early in the season when the crop biomass and ground cover are small (French and Schultz, 1984; Siddique *et al.*, 1990). Water use can be increased by (i) increasing T relative to E and (ii) increasing soil water uptake (Turner *et al.*, 2001).

Any strategy that increases the rate of canopy closure should increase the proportion of T relative to E and thereby increase dry matter production and yield (Turner *et al.*, 2001). Some genotypes, which have genetic potential for rapid early growth or early vigour, have a higher rate of canopy closure. Increased canopy cover can also be achieved by management strategies such as mulching, planting arrangements and

increased fertilizer use. In Mediterranean-type environments, plants use water more efficiently during winter, when the vapor pressure deficit between the leaf and the air is low, the humidity is high and temperatures are low. Therefore, yields can be increased by increasing the proportion of water transpired during winter, but this is possible with genotypes having early vigour (Ludlow and Muchow, 1990; Loss and Siddique, 1994; Turner, 1997; Siddique *et al.*, 2001; Turner *et al.*, 2001).

Early vigour also has a positive influence on yield potential due to increased radiation interception and eventually to accumulate sufficient pre-anthesis biomass to support seed development under sub optimal temperatures and radiation levels (Ludlow and Muchow, 1990). Vigorous early growth also enables greater root development, so that yield is not restricted by terminal drought stress (Ludlow and Muchow, 1990). In 1996, Wright *et al.* observed that early vigour is more pronounced in *B. juncea* than *B. napus,* which in turn is associated with its greater dry matter production at maturity.

The ability of roots to exploit water reserves in the subsoil strongly influences seed yield by the direct effect on T (Passioura, 1977). A more extensive and deeper root system could increase the amount of water transpired (Ludlow and Muchow, 1990; Turner et al., 2001). A more uniform root distribution in the profile, through a decrease in surface roots and an increase in root depth could increase soil water extraction without the cost of additional transpiration (Ludlow and Muchow, 1990). Inherently late flowering cultivars use more water because more time is available during vegetative development for root extension into deeper soil horizons.

Water Use Efficiency (WUE) is the ratio of grain or biomass yield produced per unit evapotranspiration or water use (Turner, 1997). WUE is inversely related to the saturation deficits of the air. Differences in WUE among crop species are related to the carboxylation pathway and energy required to produce dry matter whereas apparent differences between cultivars of the same species can be related to differences in soil evaporation and chemical composition of dry matter (Ludlow and Muchow, 1990). In contrast, Transpiration Efficiency (TE) is the crop assimilation or dry matter production per unit of water lost by transpiration. The key plant factor influencing TE is the ratio of the partial pressure of CO_2 in the leaf and that outside of the leaf. Decreasing the internal partial pressure of CO_2 causes an increase in TE.

Increasing the photosynthetic efficiency of the plant or closing the stomata will decrease partial pressure of CO_2, hence increase TE. Therefore, the variation in TE arises from either differences in photosynthetic efficiency or stomatal conductance, or both (Turner, 1997). Earlier planting, use of increased levels of fertilizer (especially nitrogen and phosphorus), stubble retention, minimum tillage, use of rotation to improve the nutrition and root penetration of crops are the practices that have been adopted by farmers to improve WUE in the Mediterranean-type environments of south Western Australia (Turner, 1997).

Considerable variation in water use has been observed among *Brassica* species grown on stored water in northern India (Kumar *et al.*, 1987) with average water use during the growing season of 205, 180 and 229 mm for *B. juncea*, *B. napus* and *B. carinata* respectively. The greater water use efficiency of *B. juncea* has attracted attention in Canada and Australia (Kirk and Oram, 1978; Woods *et al.*, 1991). Under drought stress conditions *B. juncea* showed up to 50 % more water use efficiency (Kumar *et al.*, 1987).

2.3.2.1.2. Radiation Use and Radiation Use Efficiency

The use of radiation and water is linked together in photosynthesis. Radiation is much less limiting than water in Mediterranean-type environments. In fact, excessive radiation can have detrimental effects during the post-anthesis period. Radiation use is therefore less likely to be manipulated to improve biomass production compared to water use. The amount of radiation intercepted is related to leaf appearance, size, orientation, branching habit and leaf senescence. During the seedling stages of development, photosynthesis is limited by the ability of the plant to intercept radiation.

Before flowering, leaves are almost the only green photosynthetic organs. During and after flowering, most of the leaf area is rapidly lost on most crops, and then green areas on stems and pods have been shown to take over photosynthesis. The duration of the leaf area has been found to be highly correlated with the grain yield (Wright *et al.*, 1995; 1996). The stage at which the mass of yellow flowers is produced at the top of the canopy is considered a critical time because it reflects around 50 % of total radiation and 20 % of photosynthetically active radiation. An experimental apetalous line allowed 70 to 75 % of radiation through to the canopy,

resulting in greater leaf persistence, better seed survival and growth, and 8 to 48 % higher seed yields (Rao *et al.*, 1991).

Improvement of the environment within the canopy to absorb more photosynthetically active radiation for a relatively longer duration of crop growth would have a potential to improve CO_2 fixation of a crop. Removal of branches, flowers and pods has improved light relations within canopy (Mendham and Salisbury, 1995). Development of cultivars with restricted branches either by breeding or manipulation of management factors like plant growth regulators would therefore be beneficial. Attempts have been made to develop *B. juncea* varieties with less secondary and tertiary branches in India as it has been identified as strategy to improve yield potential of *B. juncea* (Yadava and Singh, 1999). The characteristics of the pods themselves could also be improved. Some *B. rapa* lines have characteristically vertical pods, set at an acute angle to the stem. This should allow better distribution of radiation over the pod surfaces (Rao and Mandham, 1991). Preventing lodging is also an aspect that could be followed. Lodging could be controlled by growth regulators or plant density or by using robust cultivars with minimum lodging. Indian varieties, particularly taller varieties of *B. juncea,* tend to lodge under good management conditions of irrigation and high fertilizer applications. In India, attempts have been made to develop *B. juncea* varieties, which are less prone to lodging and most of these varieties have short plant stature (Yadava and Singh, 1999).

2.3.2.1.3. Harvest Index

Harvest index (HI) is the ratio of seed yield (Y) to the biological yield (TDM) at the physiological maturity of a crop (Donald and Hamblin, 1976). This simple ratio varies depending on the ability of a genotype to partition current assimilates to the seed and the re-allocation of stored or structural assimilates to the seed (Turner *et al.*, 2001). Proportional increase in the allocation of dry matter to reproductive organs are a familiar aspect of adaptation of higher plants to dry and cold environments. HI is a useful indicator of the efficiency of converting assimilates into economically important parts of the plant, but is not a fundamental physiological parameter. Strong correlation between HI and yield is expected since yield is the numerator of the HI ratio. However, HI does not have an effect on reduced or increased grain yield.

Therefore, the positive correlation of HI and grain yield within existing cultivars does not provide evidence of the value of HI as a selection criterion in breeding (Donald and Hamblin, 1976). However, increase in the fraction of above ground dry matter partitioned to useful parts has been a feature of selection and breeding of higher yielding crops (Hay, 1995). Progress in breeding higher yielding cultivars has been associated with rising values of harvest index. However this increase was unplanned secondary effort of breeding for higher grain yield, short stature and earliness (Donald and Hamblin, 1976). The reduction in plant height, so evident in more recent cultivars, increased grain yield which in turn lead to an increased HI, not only through a reduction in the weight of vegetative parts but also through direct contribution to grain production (Hay, 1995).

As a ratio of grain to dry matter yield, the HI can be affected by any factor that influences the two components of yield. Population density, water availability, and nitrogen supply and their interactions are the three major components of the environment which influence HI (Donald and Hamblin, 1976). Crops suffering from water stress have lower HI and the application of nitrogen reduces HI (Donald and Hamblin, 1976; Hay, 1995). HI increases up to a density giving the highest grain yield, and it progressively declines at densities above the maximum grain yield (Donald and Hamblin, 1976; Hay, 1995). HI depends on the relative proportion of pre-anthesis and post-anthesis dry matter production and the mobilisation of pre-anthesis assimilates to the grain (Ludlow and Muchow, 1990). HI of crops that rely predominately on stored water is related to the amount of water available after anthesis (Passioura, 1977). Correlation between HI and post-anthesis water use (Passioura, 1977; Siddique *et al.*, 2001) suggests that yield is strongly dependent on biomass accumulation after anthesis in water limited environments. However, a significant contribution to yield of pre-anthesis assimilates under drought has been shown (Passioura, 1977). The pattern of water supply also has a large effect on HI. Adequate water supply until flowering, followed by drought resulted in a large biomass and small HI and the reverse sequence of water supply resulted in more grain from much less biomass (Ludlow and Muchow, 1990).

2.3.2.2. Drought tolerance

Plants must survive intermittent short-term water deficits if they are to contribute to economic yield. Moreover, in a terminal drought stress, the longer the leaves and other plant parts can survive during grain filling, the more likely they are to contribute to yield by supplying carbon to developing seeds (Ludlow and Muchow, 1990). Drought escape, dehydration postponement, and dehydration tolerance have been proposed as the three categories of drought resistance in water limited environments (Turner *et al.*, 2001).

2.3.2.2.1. Drought escape

Plants are said to escape drought, if they could germinate after rain, grow rapidly, flower and set seeds before the soil water is exhausted. Matching the phenology to the water supply is the primary way in which yields have been improved in water limited environments. As genetic variation in growth duration is large in crop plants they can readily be selected by observing days to flowering, podding, seed filling and maturity (Turner et al., 2001). In environments where terminal drought is likely, selection for shorter time to flowering has been highly successful (Lewis and Thurling, 1994; Loss and Siddique, 1994; Siddique *et al.*, 1999; 2001; 2003). Genotypes with an ability to fill their seed quickly also have an advantage in water limited environments with short, hot and dry grain filling periods (Turner, 1997).

Rapeseed/canola yield can be severely depressed by water deficits during reproductive development and yields are sensitive to drought stress after commencement of stem elongation. Water deficits during flowering and early pod development reduces yield of *B. napus* and *B. campestris* by reducing both pod number per plant and seed number per pod. Irrigation during this period substantially increases yield by increasing seed number per pod (Richards and Thurling, 1978a). Early flowering of rapeseed/canola ensures terminal drought escape as it allows the completion of seed development before the onset of terminal drought (Thurling, 1991). Early flowering however, may not always increase yield in environments with unpredictable and intermittent drought or in climates with a high risk of frost damage at flowering (Siddique and Sedgley, 1986).

Selection for earlier flowering and more determinate types also results in the lack of capacity to respond to the additional rainfall in more favourable seasons.

Consequently, developmental plasticity is considered an important characteristic in drought prone environments (Turner *et al.*, 2001). Developmental plasticity is the mechanism whereby the duration of the growth period varies depending on the extent of water deficits. Drought induced early maturity may be advantageous in dry years. However, as it is a facultative response the plant is still able to respond to longer seasons and produce a higher yield during wetter years. Developmental plasticity ensures that all the available water is transpired (Ludlow and Muchow, 1990). Indeterminate flowering could also be worthwhile where water supply during flowering is uncertain or total seasonal supply is highly variable, as this permits fruiting to occur in flushes during favourable parts of the season. However, both mechanisms have the disadvantage of uneven maturation, hence HI tends to be low with mechanised harvesting (Ludlow and Muchow, 1990).

2.3.2.2.2. Dehydration postponement

Some plants avoid dehydration of their tissues, despite adverse environmental conditions such as high vapour pressure deficits and soil water deficits, by maintaining cell turgor and cell volume. Turgor can be maintained by maintaining water uptake, reducing water loss or by osmotic adjustment (Turner *et al.*, 2001).

Located at the boundary between the moist interior and the exterior of the leaf, the stomata play the major role in regulating water loss. Leaf hydration and the humidity of the air are considered to have a major influence on the conductance of stomata in the field (Turner *et al.*, 2001). Various characteristics such as low conductance, high sensitivity to leaf water status and saturation deficit, and abscisic acid (ABA) accumulation have been suggested as desirable traits to improve yield in water limited environments. All these characteristics reduce water loss and lower the probability of desiccation (Ludlow and Muchow, 1990). However, as stomata influence the influx of CO_2 into leaves, low stomatal conductance inevitably lowers photosynthetic rate, hence the usefulness of reduced stomatal conductance depends on a trade off between loss of production and the need to prevent dehydration. Lowered conductance should improve yield stability, however it could be achieved at the cost of reduced yield potential (Ludlow and Muchow, 1990).

Osmotic adjustment is the active accumulation of solutes by the plant in response to increasing water deficits in the soil and/or plant, thereby maintaining turgor or

reducing the rate of turgor loss as the water potential decreases. Osmoregulation or osmotic adjustment has emerged as a more dynamic measure of response to water stress, capable of better discrimination between genotypes than measuring leaf conductance, osmotic potential etc. (Kumar *et al.*, 1984). Osmotic adjustment is not an inherited trait, but an inducible or facultative trait. However, the capacity to adjust when the plant experiences water stress is inherited (Ludlow and Muchow, 1990). In leaves with high osmotic adjustment, stomata remain partially open to progressively lower water potential. This stomatal adjustment has positive effects on photosynthetic activity as it promotes continued water loss (Ludlow, 1987). Osmotic adjustment delays leaf senescence and death as it increases both avoidance and tolerance of dehydration (Turner, 1997). Genotypes with high osmotic adjustment produce more root biomass and greater root length density and extract more soil water (Turner, 1986). They have reduced flower abortions (Turner, 1997; Turner *et al.*, 2001).

Osmotic adjustment has no effect on WUE (Ludlow *et al.*, 1990), but it contributes to yield in water limited conditions by (i) increasing the amount of water transpired and (ii) minimizing the reduction in HI (Ludlow and Muchow, 1990). Increases in the amount of water transpired result from stomatal adjustment, maintenance of leaf area, and increased soil water uptake. Osmotic adjustment maintains a higher HI by increasing assimilate supply during seed filling, reducing leaf senescence, maintaining photosynthetic activity of remaining leaves and increasing the use of pre-anthesis assimilates in seed filling (Ludlow and Muchow, 1990).

The capacity for osmotic adjustment was found to vary among *Brassica* species. Kumar *et al.* (1984) found that one *B. carinata* line was able to adjust more effectively than *B. napus* and hence the growth and yield were almost double that of *B. napus*. In 1987, Kumar *et al.* extended the study to a wider range of genotypes. They found that general cultivars of *B. juncea* and *B. carinata* maintained high leaf water potentials and consequently, maintained relatively normal rates of transpiration as evidenced by high stomatal conductance. This study confirmed that the high conductance was due to osmoregulation. Indian *B. juncea* and *B. carinata* lines showed the greatest osmoregulation and the highest yield. Canadian *B. juncea* and a range of *B. napus* lines showed the least osmoregulation and low yields with *B. rapa*

lines intermediate for both. Nicknam and Turner (1999) found a significant negative correlation between percentage yield depression and osmotic adjustment of *B. napus* and *B. juncea* under soil moisture stress. Osmotic adjustment of *B. juncea* appeared in earlier stages of development, at the elongation, anthesis as well as the post-anthesis stage, but that of *B. napus* was evident only at the post-anthesis stage.

2.3.2.2.3 Dehydration tolerance

The ability of cells to continue metabolism at low water status is termed dehydration tolerance. Proline accumulation and membrane stability are mechanisms associated with dehydration tolerance (Turner *et al.*, 2001). Dehydration tolerance was also related to the degree of osmotic adjustment (Fowler and Ludlow, 1987). The lethal water/osmotic potential, i.e., the lowest water/osmotic potential experienced by the last viable leaf is a key measure of dehydration tolerance (Sinclair and Ludlow, 1986). The degree to which plant parts withstand desiccation is expressed as the relative water content (RWC) or water potential at which leaves die, hence called lethal values. Low lethal water status refers to more negative water potentials than low RWC (Ludlow and Muchow, 1990). Some work has shown that leaves die when they reach critical RWC rather than when they reach a critical leaf water potential (Flower and Ludlow, 1986). As low water status influences survival it contributes to yield stability but has no direct effect on yield components. High dehydration tolerance assists survival of leaves and plants until the next rain in intermittent stress environments. In terminal stress environments, it lengthens the time between when growth and photosynthesis cease and when leaves die. It also allows time for pre-anthesis dry matter to be translocated and hence contribute to HI and finally to yield.

In 1996, Wright *et al.* found that the ability of *B. juncea* leaves to maintain their turgor under high water deficits was greater than that of *B. napus* leaves. Total leaf area duration of *B. juncea* was 1.5 times longer than that of *B. napus* and the crop growth rate was two times higher than that of *B. napus* and these differences in growth were positively correlated with leaf turgor. Tolerance characteristics such as proline accumulation and chlorophyll stability were found between and within species of *B. napus* (Richards, 1978).

2.3.3. Genotype x Environment interactions

Yield variations between genotypes are a function of genetic effects (G) and environmental effects (E). Variation observed due to G is relatively small in comparison to E, so that inheritance or repeatability of seed yield is very low (Siddique *et al.*, 1999; Turner *et al.*, 2001). Furthermore, different genotypes respond differently to different environments. The differential response of genotypes to environmental changes is a genotype x environment interaction (G x E) (Vargas *et al.*, 2001). The G x E term of the phenotypic model for yield combines all the unknown specific genotypic responses to varying environmental conditions into one parameter. Understanding the biological significance and reasons for G x E interactions could potentially increase yields in specific environments by better exploitation of appropriately adapted genotypes (Turner *et al.*, 2001).

The ability of some crop varieties to perform well over a wide range of environmental conditions has long been appreciated by the agronomists and plant breeders. Adaptability of genotypes to a range of environments can be best explained by their phenotypic stability (developmental homeostasis). Research into phenotypic stability, heterosis and response to environmental changes has provided considerable, detailed and fundamental knowledge, about the nature and significance of adaptation in both plants and animals (Finlay and Wilkinson, 1963). In trying to meet the demands for varieties that are better adapted to changing conditions, the plant breeder is faced with the choices of breeding either for closely defined ecological conditions or for more extensive conditions which includes a considerable range of environments. The latter approach requires the development of varieties possessing general adaptability (Finlay and Wilkinson, 1963). Finlay and Wilkinson (1963) have described the '*ideal*' genotype having general adaptability as one with maximum yield potential in the most favourable environments and maximum phenotypic stability.

2.3.3.1. Measuring G x E interactions

Defining and measuring the performance of genotypes over a range of environments or seasons is important in breeding programs and multi-locational variety testing trials to explain their adaptability. The classical method of summarizing the variation in responses of a number of genotypes grown in different environments is by

partitioning the sums of squares into components due to genotypes, environment and their interactions (Kempton, 1984; Kempton and Fox, 1997). However, this method conveys limited information on the individual patterns of response. Further partitioning of interaction sum of squares by grouping genotypes or environments may help to identify major sources of interactions (Kempton, 1984; Kempton and Fox, 1997). Genotype x location or genotype x season interactions are used widely as basic measures of adaptability (Yates and Cochran, 1938; Finlay and Wilkinson, 1963). However, such groupings are often difficult to interpret biologically and not repeated in subsequent years. Another method, used extensively for describing patterns in G x E interactions, is regression of individual yield of genotype onto an independent environmental variable, or into the mean yield of all genotypes for each environment. This method was first proposed by Yates and Cochran (1938) and further developed by Finlay and Wilkinson (1963).

2.3.3.1.1. Finlay and Wilkinson method

The statistical technique developed by Finlay and Wilkinson (1963) provides a numerical grading for environments. For each genotype, a linear regression of individual yield on the mean yield of all genotypes for each environment is computed. The mean yield of all genotypes at each environment is referred as the 'site mean' and is a useful evaluation of the environment. At low yielding environments, mean yield of all genotypes is low or vice versa. In this way the mean yield of a large group of genotypes is used to describe a complex natural environment without complexities of defining or analysing the interacting edaphic and seasonal factors. When the individual genotype yield is plotted against the mean of all genotypes, the population mean has a regression coefficient (b) of 1.0. The regression coefficient illustrates different types of genotypic response to the range of environments, i.e. phenotypic stability.

Genotypes characterized by b = 1.0 have average phenotypic stability over all environments. If any genotype shows average stability and also produces above average yields in all environments, it is said to have general adaptability. On the other hand, if any genotype shows average stability but produces below average yields in all environments, it is poorly adapted to all environments. Some genotypes are specifically adapted to high yielding environments, and are characterised by a

regression coefficient significantly greater than 1.0 and said to have below average phenotypic stability. They are very sensitive to changes in the environment, small change in the environments produce large changes in the yield. They produced very little yield in poor environments, but as the environment improves yield increases at the rate well above the average. In contrast, some genotypes are specifically adapted to poor yielding environments, and are characterised by a regression coefficient significantly less than 1.0 and said to have above average phenotypic stability. They produced above average yields in poor environments but small yield in high yielding environments. They are less sensitive to environmental changes and despite large changes in the environment, the change in yield is very little. Finlay and Wilkinson (1963) suggested that no common morphological and physiological factors could be found within a generally adapted group, but consists of different growth forms and physiology, whereas genotypes adapted to any specific environment share many morphological and physiological factors common to all genotypes.

2.3.3.1.2. Principal component analysis and biplots

Principal component (PC) analysis is one of the most frequently used multivariate methods. It aims to transform the data from one set of coordinate axes to another, which concentrates most of the data structure in the first principal component axis. This analysis can effectively reduce the structure of a two-way genotype (G) x environment (E) data matrix of G points in E dimensions into a subspace of fewer dimensions. However, in this process of data reduction, some original information is inevitably lost. The principal component analysis with the first three principal axes accounting for 76 % variation is found to be statistically effective (Crossa, 1990). The first PC is the axis that maximizes the variation among genotypes. The second PC is perpendicular to the first and maximizes the remaining variation. The display of the genotypes and environments along the first two PC axes for the interaction table of residuals is called principal component biplot (Kempton, 1984). The biplot visualises the overall pattern of response as well as specific interactions between genotypes and environment (Crossa, 1990).

2.4. Conclusions

Breeding programs during the last few decades have altered mustard into an edible oil crop with a fatty acid profile very similar to that of canola. The best *B. juncea* lines of quality similar to canola developed in Australia are not only double low quality (zero erucic and low glucosinolate) but also appear to have greater adaptation to low rainfall environments compared to *B. napus*. Now, since high yielding new mustard lines of quality similar to canola are available, research on their adaptation in different environments has become a necessity, if this crop is to be widely adopted in Australian farming systems.

In Mediterranean-type environments, experienced in south Western Australia, the period of crop growth is usually restricted by lack of rainfall, water deficits and high temperatures at the start and end of the season and early terminal drought restricts yield. Strategies of improving adaptation and yield of cereals, pulses and rapeseed/canola in the Mediterranean-type environments in south Western Australia have been studied extensively. However, to date no such study has been reported on mustard. As proven for other crop species in many previous studies, those with enhanced drought tolerance characteristics (drought escape, dehydration postponement and dehydration tolerance characteristics) are more adapted to these environments. Rapid phenological development associated with early vigour is an important aspect of crop adaptation in these environments. Early flowering genotypes are expected to have a long grain filling period and complete their life cycle before terminal drought sets in. Furthermore, greater dry matter combined with high efficiencies of converting assimilates into grain increases seed yield in these environments. Strategies that improve water use, water use efficiency, radiation use, and radiation use efficiency will increase dry matter production.

If mustard to be adapted into these environments therefore, must posses all above characteristics, and its any added agronomical, morphological or physiological advantages over canola would ensure production of seed yields greater than canola. As discussed in this chapter, mustard posses many of such advantages over canola. Mustard seeds can germinate well even under low soil moisture conditions, so that very early or late sowing is possible. Mustard's well known early vigor would ensure establishment of seedlings, rapid seedling development and canopy development

under sub optimal temperatures experienced in early winter in Mediterranean-type environments. This would improve radiation use and water use and eventually to produce greater pre-anthesis and post-anthesis dry matter. Mustard is well known for its ability to produce higher dry matter compared to canola, particularly under low rainfall conditions, which would be translated to higher seed yield, provided with the efficient conversion of assimilates into seed yield. However, previously reported efficiencies of dry matter conversion into seeds in mustard were lower compared to canola and this would be a major disadvantage for producing greater seed yields. Reputation of mustard's drought tolerance characteristics is reviewed in greater extent in this chapter. With these attributes mustard have considerable potential as an oilseed crop in Australia. Therefore, it can be hypothesized that that mustard would be well adapted to these environments compared to canola.

Genotypic differences play a major role in adaptability of crop plants to specific environments. Furthermore, the differential responses of genotypes to environmental changes (genotype x environment interaction) exist. The ability of some crop species/varieties to perform well over a wide range of environmental conditions or their general adaptability is important in the crop growing regions of south Western Australia, due to the large edaphic variation between localities and large seasonal variation within one locality. Therefore, understanding the biological significance and reasons for G x E interactions could potentially lead to increased yields in specific environments by better exploitation of appropriately adapted genotypes of mustard.

Taking all these into consideration, experiments presented in this thesis were designed to investigate the effects of genotype, environment (e.g. times of sowing, seasons, sites) and genotype x environment interaction on phenology, growth, yield, oil and protein contents of mustard, to study phenological, morphological and physiological basis of adaptation and yield of mustard in the Mediterranean-type environments, and to study physiological aspects of drought tolerance in mustards.

CHAPTER 3

Response of mustard and canola genotypes to time of sowing at a medium rainfall site

3.1. INTRODUCTION

Seed yields of oilseed *Brassica* species decline with delayed sowings in temperate and sub-tropical environments (Hocking *et al.*, 1991; Heenan and Armstrong, 1993; Hocking and Stapper, 1993; Semmel *et al.*, 1995; Robertson *et al.*, 1999). Reduced yields from late sown crops is related to reduced pre-anthesis duration (Thurling and Vijendra Das, 1979), reduced post-anthesis duration (Hocking et al., 1991), increasing soil moisture and high temperature stresses and pest damage during reproductive development (Mendham *et al.*, 1990), and reduced yield components (Richards and Thurling, 1978b). In addition, late sowings result in lower oil concentration in *Brassica* oilseed species (Mendham *et al.*, 1981a; Hocking *et al.*, 1991).

Genotypes that can escape terminal drought have a better chance of producing higher yields in Mediterranean-type environments (Turner *et al.*, 2001). Matching the phenology to the water supply is the primary way in which higher yields have been achieved in Mediterranean-type environments. Genotypes which flower early are better adapted to these environments (Lewis and Thurling, 1994; Loss and Siddique, 1994; Siddique *et al.*, 1999; 2001; 2003). Genotypes with an ability to fill their seed quickly also have an advantage in water limited environments with a short, hot and dry grain filling period (Turner, 1997). Furthermore, early sowing gives crops a better chance of escaping terminal drought. Identification of the optimum planting date and an optimum flowering time, which recognizes a balanced pre-anthesis and post-anthesis development, are therefore important aspects of yield improvement and adaptation in Mediterranean-type environments.

Although adaptation of cereals, grain legumes, rapeseed or canola have been studied extensively in south Western Australia, to date no such study has been reported on mustard. The aim of this study was to examine the adaptation of mustard compared to canola at a medium rainfall site in south Western Australia by evaluating the

effects of genotype, times of sowing, and their interaction on the phenology, dry matter production, seed yield, oil and protein concentrations.

Northam, a medium rainfall site in south Western Australia was selected for this initial study, as it was a closer location so that detailed measurements could be taken. Detailed measurements were necessary to study morphological and agronomic characteristics of the genotypes and to evaluate their performances, so that better genotypes could be selected to be used in future experiments. Nine genotypes of mustard and canola were sown in four different times to create a range of environmental conditions and where early sowing will generally have better rainfall and delayed sowing will predispose the crops to high temperature and soil moisture stress.

3.2. MATERIALS AND METHODS

3.2.1. Experimental design and trial management

A field experiment was conducted on the Research Farm, Muresk Institute of Agriculture, Northam, Western Australia (31^0 43'S, 116^0 38'E, altitude 150m, mean annual rainfall of 456mm) in 1999 (Figure 4.1). Treatment combinations were arranged in a split plot design with three replicates. The effect of times of sowing was studied in the main plots and included four levels; early sowing (12 May), mid sowing (2 June), late sowing (23 June) and very late sowing (14 July). The effects of genotypes were studied in subplots and consisted of six mustard genotypes varying in height, maturity and oil quality and three canola varieties varying in maturity (Table 3.1).

The field site was of medium loam to sandy loam soil with a pH of 4.8 (in 1:5 $CaCl_2$) that contained 17 mg/Kg of total Nitrogen, 20 mg/Kg of Phosphorus, 118 mg/Kg of Potassium, 1.11% of Organic Carbon, 505 mg/Kg of Reactive Iron. The site was cropped with lupins (*Lupinus angustifolius* L.) in 1995, wheat (*Tritium aestivum* L.) in 1996, pasture (*Trifolium subterraneum* L.) in 1997 and wheat in 1998. Excess cereal stubble was burnt before sowing and the plots were limed at the rate of 1 t/ha. Plots were sown at the seed rate of 6 kg/ha with a cone seeder and were 1.44 m wide (8 rows, 18 cm apart) and 20 m long. Double Superphosphate (17.5 % P, 3.5 % S) was applied at the rate of 114.2 kg /ha at sowing. Urea (46 % N) was applied at the rate of 65 kg/ha very close to rows at sowing and top dressed at 87 kg/ha four to five weeks after sowing.

Weeds were controlled a week before sowing with Roundup at 1 l/ha (glyphosate 450 g ai/L). Grass weeds and broad leaf weeds that emerged after sowing were controlled with Fusilade at 250 ml/ha and Lontrel at 500ml/ha respectively and by hand weeding where required. Redlegged earth mite (*Halotydeus destructor*) and Cutworm (*Agrostis* spp.) were controlled at the vegetative phase using Endosulfan (350 g/l) at 2.1 l/ha. Aphids (*Aphis craccivora*) and Cabbage moth (*Plutella xylostella*) were controlled by spraying Endosulfan (350 g/l) at 2.1 l/ha during flowering and pod development.

Table 3.1. Description of mustard and canola genotypes used in the study

Genotype	Description
887.1.6.1	Early maturing, near canola quality* mustard, shorter and compacted stature, shorter than JM 25, JM 33 and JM 29, taller than Muscon M-973, 82 No 22-98 and canola genotypes, indeterminate, produce higher number of secondary and tertiary pods, shorter pods with small yellow seeds
JM 25	Mid maturing, near canola quality mustard, taller but compacted stature, shorter than JM 33 and JM 29, taller than 887.1.6.1, Muscon M-973, 82 No 22-98 and canola genotypes, indeterminate, produce about eight primary branches, very less number of secondary and tertiary pods, lower number of longer pods with heavy yellow seeds
JM 33	Mid maturing, near canola quality mustard, taller and larger stature, shorter than JM 29 and taller than all other genotypes, indeterminate, produce about eight primary and higher number of secondary and tertiary branches, produce higher number of secondary and tertiary pods, higher number of shorter pods with very small yellow seeds
JM 29	Late, near canola quality mustard, tall but compact stature, taller than all other genotypes, indeterminate, produce lower number of shorter pods with very small seeds, rarely produce secondary or tertiary pods
Muscon M-973	Very early maturing, condiment quality mustard, shorter compact stature, shorter than Charlton and Oscar and all other mustard genotypes and same height as 82 No 22-98 and Monty, determinate, produce higher number of longer pods with heavier brown or yellow seeds, produce higher number of secondary and tertiary pods
82 No 22-98	Very early, condiment quality mustard, shorter compact stature, shorter than Charlton and Oscar and all other mustard genotypes and same height as Muscon M-973 and Monty, determinate, produce higher number of longer pods with heavier brown seeds, produce higher number of secondary and tertiary pods
Monty	Early maturing canola, shorter compact stature, determinate, produce longer pods with many larger black seeds
Oscar	Mid maturing canola, shorter compact stature, determinate, produce longer pods with many larger black seeds
Charlton	Mid to late maturing canola, Taller and larger stature, determinate, produce longer pods with many larger black seeds

* - Zero erucic, low glucosinolate mustard

3.2.2. Measurements

3.2.2.1. Weather

Daily maximum and minimum temperatures and daily rainfall were recorded at a nearby weather station. The mean thermal time in growing degree days (GDD) was calculated above a base temperature of 0 ^{0}C as;

$$GDD = {}_{S1}\Sigma^{S2} \ (T_m - b_0)$$

Where T_m is the mean daily temperature, b_0 is the base temperature and S_1 and S_2 are two developmental stages.

3.2.2.2. Phenology

The following phenological stages were estimated in each plot according to the development key of Sylvester-Bradley and Makepeace (1984) (Table 2.2).

1. Date of emergence when 90 % of the plants are visible at the soil surface
2. Date on which 50 % of plants commenced stem elongation when apical meristem is 5 cm higher than cotyledons
3. Date on which 50 % of plants produced their first open flower
4. Date on which 50 % of plants ceased flowering on the terminal raceme
5. Date on which 50 % of plants reached a stage of physiological maturity when seeds in two lowest pods were dark brown color

3.2.2.3. Leaf Area Index and radiation absorption

For leaf area measurements, two representative mustard genotypes (82 No 22-98 and JM 33) and one representative canola genotype (Oscar) were sampled every four weeks commencing from six weeks after emergence. Twelve adjacent plants on a row were cut at ground level from each selected plot. Two smallest and largest plants were discarded. On the remaining eight median plants; fully expanded leaves were separated. Area of leaves was measured using a Leaf area meter (Model LI 3050 A/4). Leaf Area Index (LAI) was calculated from the leaf area/plant multiplied by the plant density of each selected plot.

Photosynthetically Active Radiation (PAR) absorbed by the crop canopy of above genotypes was measured every four weeks commencing from six weeks after emergence using a Sunflek Ceptometer model SF-80 (CEP-UM-8, Decagon;

Pullman, Washington, USA) in the absence of cloud cover near mid-day. Percentage of absorbed PAR (R) was calculated using the following formula.

$$R = ((R_1 - R_2 - R_3 + R_4) / R_1) \text{ X } 100$$

Where; R_1 is the incident radiation approximately 1 m above the canopy, R_2 is the upward reflected radiation above the canopy (obtained by inverting the ceptometer above the canopy), R_3 is the transmitted radiation at the base of the canopy, and R_4 is the reflected radiation from the soil below the canopy (obtained by inverting the ceptometer below the canopy).

3.2.2.4. Seed yield and Harvest Index

Seed yield, above ground biomass at harvest and harvest index were determined from two quadrats, 1 m^2 each, taken from two random positions from each plot. The number of plants in each quadrat was counted to determine the plant density at harvest. Samples were dried at 75 ^{0}C to a constant weight. After drying, seeds of each sample were separated and weighed. Harvest Index was calculated as the ratio of seed weight to the total above ground biomass at harvest (Donald and Hamblin, 1976; Hay, 1995).

3.2.2.5. Yield components

Yield components were estimated from ten plants randomly selected from each plot. Height of each plant was measured separately to determine plant height at final harvest. Number of primary branches (branches on main stem including terminal raceme), number of secondary branches (branches on primary branches), number of tertiary branches (branches on secondary branches), and number of other branches (branches on tertiary branches) in each plant were separated. Number of pods on primary, secondary, tertiary, and other branches were counted separately and summed to calculate total number of pods/plant.

To calculate number of seeds per pod, 50 pods were selected randomly (not within branch levels) and seeds were separated and counted using a seed counter (Count A – pak, model 77, Seedburo equipment company, Chicago). About 3000-5000 seeds were counted and weighed to determine 1000 seed weight.

3.2.2.6. Seed quality

Oil content and protein content of the seed was determined using Infratec 1241 grain analyzer (FOSS TECATOR).

3.2.3. Statistical analyses

All data collected and derived were statistically analysed using GENSTAT for Windows Release 5.0. Effects of treatments were estimated using Analysis of Variance (ANOVA) and means were compared using Least Significant Difference (LSD) at $P = 0.05$. The relationship between various measurements and seed yield were investigated using the correlation coefficient.

As a significant variation in plant density at final harvest was observed (Table 3.2), plant density was used as a covariate in the statistical analysis and means were adjusted for the covariate in measurements where the effect of the covariate was significant. The covariate effect of plant density at final harvest was significant for seed yield, total dry matter at harvest and total pods/plant, hence their means were adjusted accordingly.

3.3. RESULTS

3.3.1. Weather

1999 was a relatively wet year and rainfall was largely confined to May to November growing season (Figure 3.1). Some moisture was stored in the soil from rainfall prior to planting due to relatively higher summer rainfall (January to April). May to November rainfall was 415.4 mm and was much higher than the long-term average of 360 mm (Figure 3.1). Rainfall was well distributed from June to October. Air temperatures were similar to the long-term average. No frost damage was observed either in mustard or canola in 1999.

3.3.2. Plant density

Plant density at harvest was significantly lower from very late sowing compared to early, mid and late sowings due to lower soil and air temperatures experienced during germination (Table 3.2). Mean plant density was highest in 82 No 22-98, Monty, and Oscar.

3.3.3. Phenology

The duration from sowing to emergence was 21 days in early, mid and late sowings (Figure 3.2). Emergence was delayed by 7 to 14 days in the very late sowing due to relatively lower air and soil temperature during germination. Duration to first flower from sowing (DOF) did not differ between times of sowing in all genotypes except in JM 29 (Table 3.2). DOF in JM 29 was significantly longer in early sowing compared to very late sowing.

All early and early to mid maturing mustard genotypes produced their first flower before the early canola variety Monty in all times of sowing. Mustard line, 82 No 22-98 was the first line to flower in all times of sowing and the mustard line, JM 29 flowered late in all times of sowing. The mean thermal time (above a base temperature of 0 ^{0}C) from sowing to first flower varied from 996 growing degree days (GDD) for the earliest mustard line to 1692 GDD for the late mustard line in the early sowing. In the very late sowing it varied from 960 GDD to 1446 GDD respectively (Figure 3.2). In canola it varied from 1145 GDD to 1391 GDD in early sowing and 1071 GDD to 1446 GDD in very late sowing respectively.

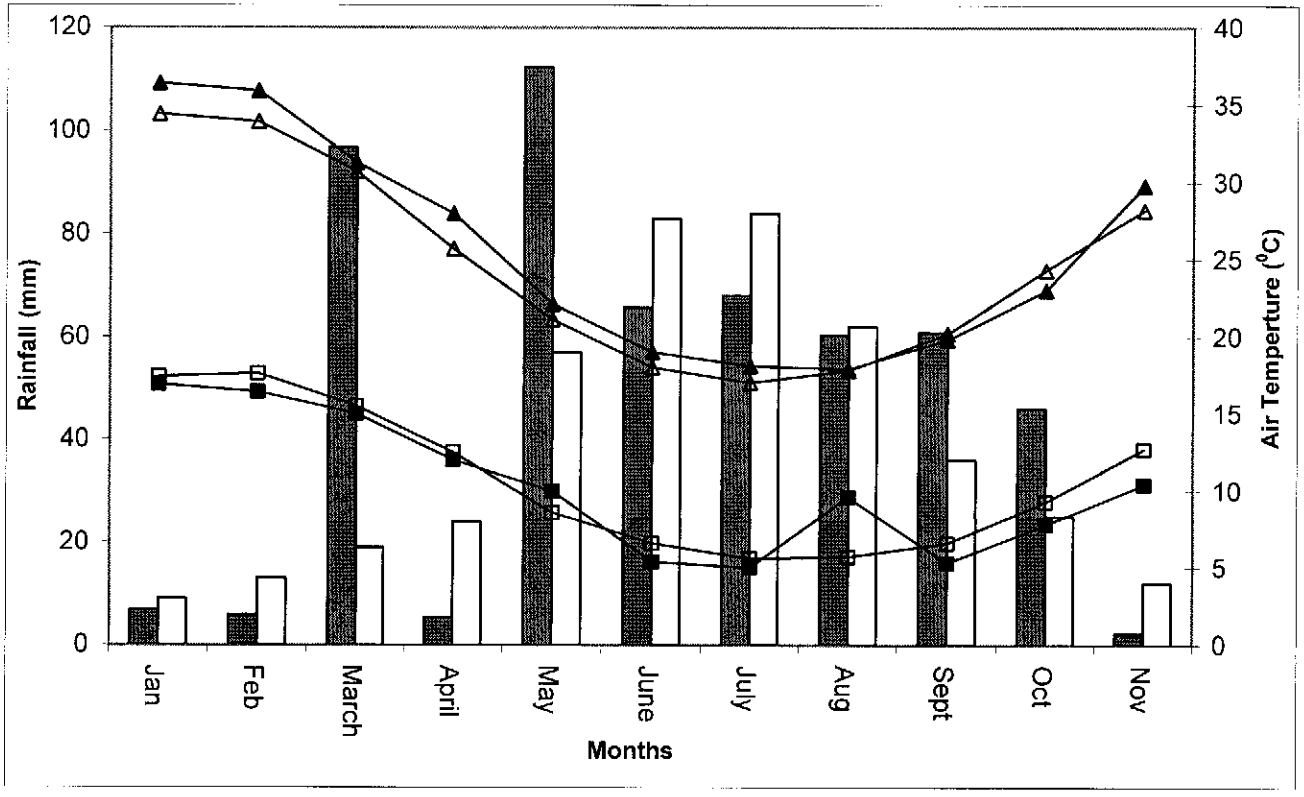

Figure 3.1. Total monthly rainfall (solid histogram), long term average monthly rainfall (open histogram), mean daily maximum temperature (▲), long term mean daily maximum temperature (Δ), mean daily minimum temperature (■), and long term mean daily minimum temperature (□) at Northam, WA in 1999.

Table 3.2. Plant density at final harvest and duration to flowering in nine genotypes of mustard and canola sown at four times at Northam in 1999.

Genotype	Plant density at final harvest (plants/m^2)					Duration to flowering (DAS)				
	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean
887.1.6.1	65	85	95	37	66	82	84	78	78	81
JM 25	43	72	56	30	50	93	89	85	78	86
JM 33	57	70	58	13	50	90	89	82	82	86
JM 29	57	84	64	18	56	130	115	100	104	112
Muscon	54	90	97	26	67	78	77	78	74	77
82 No 22- 98	65	85	95	37	71	76	74	74	74	75
Monty	58	109	84	46	74	90	86	85	82	86
Oscar	76	105	102	52	84	107	102	94	95	100
Charlton	55	78	58	47	60	104	94	94	95	97
Mean	59	88	77	32	64	94	90	86	85	89
LSD (P = 0.05)	TOS = 12 VAR = 15 TOS X VAR = 29 VAR / Same levels of TOS = 29					TOS = 9 VAR = 4 TOS X VAR = 11 VAR / Same levels of TOS = 7				

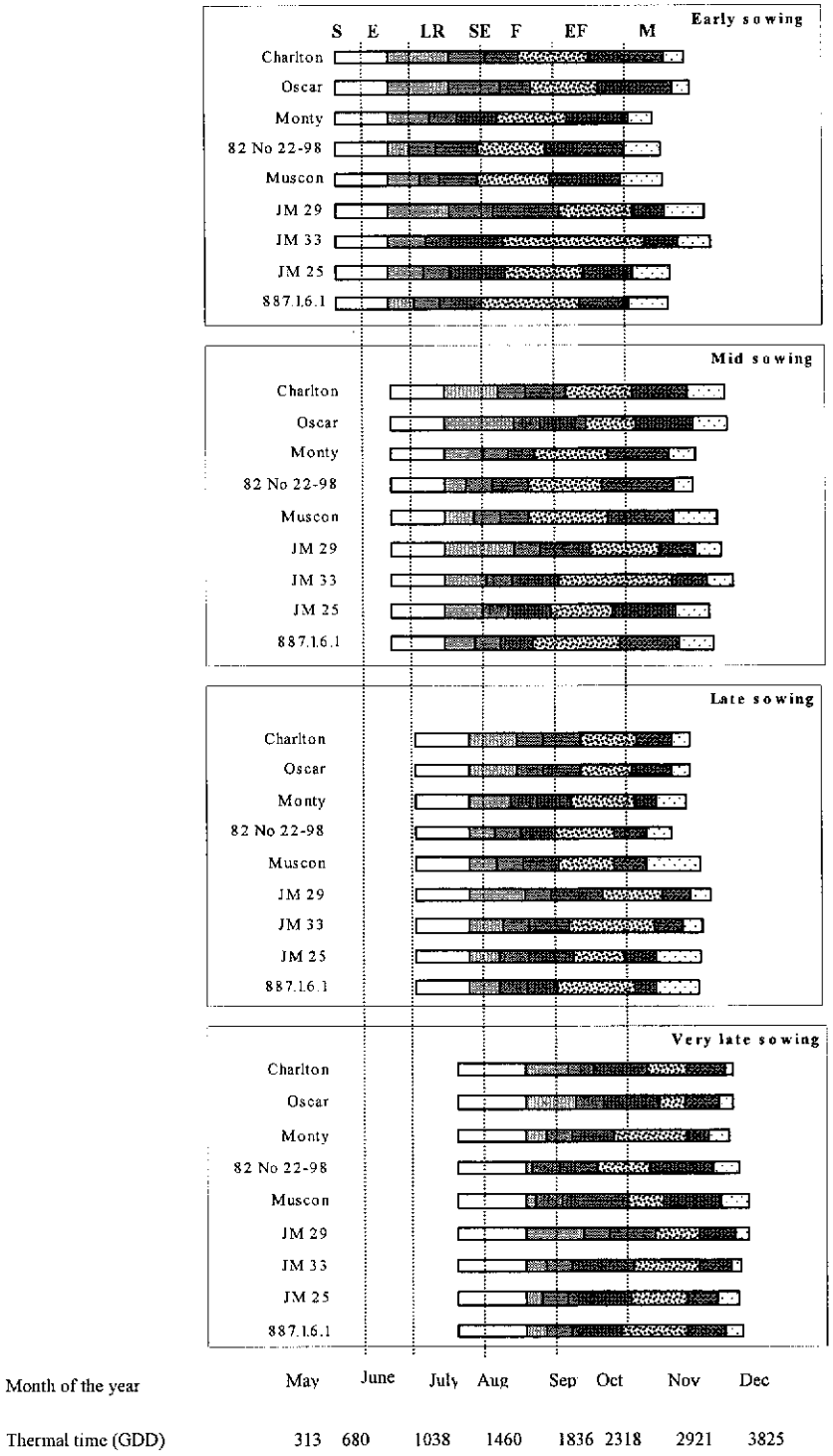

Figure 3.2. Phenological development in nine genotypes of mustard and canola sown at four times at Northam, WA in 1999.

Sowing (S) to emergence (E) - Leaf rosette (LR) stage - Stem elongation (SE) - SE to flowering (F) - F to end of flowering (EF) - EF to maturity (M) - M to harvest -

Considering the large difference in sowing times, difference in date of the last flower and date of maturity were small. Duration to maturity decreased significantly with delayed sowing. Genotypes which were late to commence flowering had short reproductive phases and the duration was progressively shortened with the delayed sowing. All mustard genotypes had relatively longer reproductive period compared to canola.

3.3.4. Canopy development and radiation absorption

82 No 22-98, JM 33 and Oscar produced maximum LAI of 5, 4 and 6 when sown early in the season at 105, 133 and 133 DAS respectively (data not presented). Maximum LAI declined progressively and significantly with delayed sowing regardless of the genotype. 82 No 22-98, JM 33 and Oscar achieved maximum LAI of 4, 2, and 1; 4, 2 and 1; 4, 4, and 2 in mid, late and very late sowings respectively. All genotypes achieved their maximum LAI within a relatively shorter duration with delayed sowing.

The pattern of the absorption of photosynthetically active radiation followed the pattern of LAI in the three genotypes. Maximum PAR absorption in 82 No 22-98, JM 33 and Oscar varied from 76 to 92 % and was consistent across early, mid and late sowings but significantly declined to 57 to 67 % in the very late sowing (data not presented).

Plant height of all genotypes was highest from early sowing and reduced with delayed sowing (Table 3.3). Plants were significantly shorter in very late sowing compared to early, mid or late sowing in all genotypes. Average plant height in mustards is significantly higher compared to canola. JM 33 and JM 29 were tallest and Muscon and 82 No 22-98 were shortest in all times of sowing.

Number of primary branches was not significantly affected by times of sowing in 887.1.6.1 and 82 No 22-98 (Table 3.3). The number of primary branches in very late sowing was significantly lower compared to early, mid and late sowing in Muscon, and canola genotypes. Number of primary branches were significantly lower in very late sowing compared to early sowing in JM 25 and JM 29 and that in JM 33 was significantly higher in mid sowing compared to late sowing. Taller genotypes, JM 25 and JM 29 had the highest number of primary branches.

Table 3.3. Primary and secondary branches/plant and plant height at maturity in nine genotypes of mustard and canola sown at four times (early, mid, late and very late) at Northam, WA in 1999.

Genotype	Primary branches / plant					Secondary branches / plant					Plant height at maturity (cm)				
	Early	Mid	Late	V late	Mean	Early	Mid	Late	V late	Mean	Early	Mid	Late	V late	Mean
887.1.6.1	6	6	7	6	6	12	7	11	4	9	137	125	117	84	116
JM 25	9	8	8	7	8	11	10	9	5	9	149	140	128	74	123
JM 33	7	8	6	7	7	14	16	12	6	12	155	149	126	99	132
JM 29	10	8	8	8	8	13	10	8	7	9	179	157	137	137	153
Muscon	7	6	6	4	6	16	10	10	3	10	137	117	116	81	113
82 No 22- 98	7	7	7	6	7	13	13	13	6	11	129	123	120	86	115
Monty	6	7	6	4	6	5	8	8	5	6	103	107	100	79	97
Oscar	7	6	6	2	5	6	8	4	4	6	118	108	98	64	97
Charlton	6	6	6	4	6	6	5	5	2	5	132	106	109	70	104
Mean	7	7	7	6	7	11	10	9	3	8	138	126	117	86	117
LSD (P = 0.05)	TOS = 1 VAR = 0.5 TOS X VAR = 1 VAR / Same levels of TOS = 1					TOS = 6 VAR = 2 TOS X VAR = 5 VAR / Same levels of TOS = 5					TOS =1.4 VAR = 6 TOS X VAR = 17 VAR / Same levels of TOS = 13				

Number of secondary branches did not differ significantly between times of sowing in canola genotypes (Table 3.3). Number of secondary branches in JM 33, Muscon and 82 No 22-98 was significantly lower in very late sowing compared to early, mid and late sowing. Number of secondary branches in 887.1.6.1 and JM 29 was significantly lower in very late sowing compared to early sowing. Mustard genotypes produced significantly more (8 to 11) secondary branches than canola (4 to 6).

3.3.5. Seed yield

Seed yield was significantly affected by the variation in plant density. Therefore, means were adjusted accordingly by using the plant density at harvest as a co-variate (Table 3.4). The effect of time of sowing on seed yield was significant ($P< 0.05$) and the effect of genotype and genotype x time of sowing interaction were highly significant ($P< 0.01$). Seed yield was significantly lower in very late sowing.

Seed yield in JM 33, 82 No 22-98 and all canola varieties was significantly lower in very late sowing compared to early, mid and late sowings. Seed yield in 887.1.6.1, JM 25, JM 29, and Muscon was significantly lower in very late sowing compared to mid sowing (Table 3.4). Seed yield differed significantly between genotypes in early and mid sowings but did not differ significantly between genotypes in late and very late sowing. Mean seed yield was highest in 82 No 22-98, Monty, Oscar, and Charlton and JM33.

3.3.6. Final above ground dry matter production

Total above ground dry matter at final harvest (FAGDM) was significantly affected by the variation in plant density. Therefore, means were adjusted accordingly by using the plant density at harvest as a co-variate (Table 3.4). The effect of times of sowing on FAGDM as significant ($P< 0.05$) and the effect of genotype and genotype x times of sowing interaction was highly significant ($P< 0.01$).

Table 3.4. Seed yield (t/ha), final above ground dry matter production (t/ha) and harvest index (%) in nine genotypes of mustard and canola sown at four times (early, mid, late and very late) at Northam, WA in 1999.

Genotype	Seed yield (t/ha)					Final above ground dry matter (t/ha)					Harvest Index (%)				
	Early	Mid	Late	V late	Mean	Early	Mid	Late	V late	Mean	Early	Mid	Late	V late	Mean
887.1.6.1	1.7	2.8	2.1	0.7	1.8	7.4	10.9	7.5	2.8	7.2	23	26	28	25	26
JM 25	1.9	3.1	1.8	0.6	1.9	4.2	11.8	7.4	3.1	6.6	21	26	24	19	23
JM 33	3.1	3.0	2.5	0.3	2.2	15.0	13.1	10.4	1.8	10.1	21	24	24	17	21
JM 29	1.6	2.2	1.6	0.3	1.4	9.8	8.1	7.5	1.9	6.8	16	27	21	16	20
Muscon	1.6	2.6	1.8	0.4	1.6	8.7	10.9	7.4	2.0	7.3	18	24	24	20	22
82 No 22- 98	2.3	3.1	2.5	0.5	2.1	7.8	11.1	8.7	3.0	7.7	29	28	29	17	26
Monty	2.3	3.2	2.7	0.6	2.2	8.3	11.1	9.1	4.2	8.2	28	29	30	14	25
Oscar	3.4	3.0	2.5	0.1	2.3	10.8	11.0	9.0	2.3	8.3	31	27	28	4	22
Charlton	3.0	3.0	2.3	0.3	2.2	11.2	11.5	10.0	2.9	8.9	27	26	23	10	22
Mean	2.3	2.9	2.2	0.4	2.0	9.2	11.0	8.6	2.7	7.9	24	26	26	16	23
LSD (P = 0.05)	TOS = 1.7 VAR = 0.4 TOS X VAR = 1.4 VAR / Same levels of TOS = 1.1					TOS = 5.1 VAR = 1.7 TOS X VAR = 4.8 VAR / Same levels of TOS = 4.3					TOS = 6 VAR = 3 TOS X VAR = 7 VAR / Same levels of TOS = 5				

FAGDM was significantly lower in very late sowing compared to early, mid and late sowings in all genotypes except 887.1.6.1, JM 25 and Monty (Table 3.4). FAGDM of 887.1.6.1 and JM 25 was significantly lower in very late sowing compared to mid sowing and that of Monty was significantly lower in very late sowing compared to mid and late sowings. FAGDM differed significantly between genotypes in early and mid sowings but not in late and very late sowing. Mean FAGDM was highest in Charlton and JM 33.

3.3.7. Harvest Index

Harvest Index (HI) did not differ between times of sowing in 887.1.6.1, JM 25, JM 33, and Muscon (Table 3.4). HI in 82 No 22-98 and in all canola genotypes was significantly lower in very late sowing compared to early, mid and late sowings. HI was significantly higher in mid sowing compared to early and very late sowings in JM 29. HI differed significantly between genotypes in early, late and very late sowings, but not in mid sowing (Table 3.4). HI was highest in 82 No 22-98 and all canola genotypes in early sowing. HI was highest in 887.1.6.1 and Muscon in very late sowing.

3.3.8. Yield components

Total number of pods per plant of all genotypes was highest from the early sowing and decreased with delayed sowing (Table 3.5). Total number of pods/plant in Monty was not significantly affected by times of sowing. Total number of pods/plant in 887.1.6.1, JM 29, 82 No 22-98, Oscar and Charlton was significantly lower in very late sowing compared to early sowing. Total number of pods/plant in JM 25, JM 33, and Muscon was significantly lower in very late sowing compared to early, mid and late sowings. Total number of pods/plant differed significantly between genotypes in all times of sowing. All canola genotypes had significantly less number of pods/plant compared to all mustard genotypes in early sowing.

Number of primary pods/plant was significantly lower in very late sowing compared to early and mid sowing in all canola genotypes and in JM 29 (Table 3.6). All other mustard genotypes had significantly less number of primary pods in very late sowing compared to early, mid and late sowings. Number of secondary and tertiary pods/plant did not differ between times of sowing in JM 25 and all canola genotypes. All other mustards had significantly more secondary and tertiary pods/plant in early

Table 3.5. Yield components (total number of pods/plant, number of seeds /pod and 1000 seed weight (g)) in nine genotypes of mustard and canola sown at four times (early, mid, late and very late) at Northam, WA in 1999.

Genotype	Total number of pods/ plant					Number of seeds / pod					1000 seed weight (g)				
	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean
887.1.6.1	390	181	181	89	210	15	14	14	11	14	3.2	3.2	3.1	3.4	3.2
JM 25	312	247	222	95	219	13	13	13	14	13	3.5	3.2	3.2	3.4	3.3
JM 33	450	407	321	144	331	10	10	10	12	11	3.2	3.2	3.0	3.4	3.2
JM 29	386	322	171	139	255	10	11	11	12	11	2.9	3.1	2.9	3.5	3.1
Muscon	364	189	189	53	199	13	12	13	12	13	3.6	3.8	3.8	3.6	3.7
82 No 22- 98	298	209	194	86	197	11	12	12	10	11	3.8	4.1	3.9	3.8	3.9
Monty	147	154	114	70	121	24	25	19	20	22	4.1	4.1	3.8	3.9	4.0
Oscar	178	137	45	11	93	25	23	19	15	21	3.6	3.7	3.6	3.7	3.6
Charlton	167	132	95	33	107	25	23	19	17	21	3.9	4.0	3.8	3.8	3.9
Mean	299	220	170	69	192	16	16	15	14	15	3.5	3.6	3.4	3.6	3.5
LSD (P = 0.05)	TOS = 181 VAR = 48 TOS X VAR = 135 VAR / Same levels of TOS = 99					TOS = 1 VAR = 1 TOS X VAR = 2 VAR / Same levels of TOS = 2					TOS = 0.4 VAR = 0.2 TOS X VAR = 0.3 VAR / Same levels of TOS = 0.3				

Table 3.6. Number of pods on primary, secondary and tertiary branches/plant in nine genotypes of mustard and canola sown at four times (early, mid, late and very late) at Northam, WA in 1999.

Genotype	Primary pods/plant					Secondary pods/plant					Tertiary pods/ plant				
	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean
887.1.6.1	153	112	127	41	108	171	57	48	34	78	56	10	3	8	19
JM 25	220	204	170	64	165	97	56	55	22	58	1	0	0	0	0
JM 33	162	228	172	67	157	199	178	137	57	143	27	9	11	7	14
JM 29	176	217	103	76	143	143	105	57	54	90	64	15	15	16	28
Muscon	166	132	118	26	111	167	54	65	18	76	33	7	7	4	13
82 NO 22- 98	124	133	112	45	103	130	70	73	28	75	41	10	7	5	16
Monty	113	118	66	18	79	35	41	40	26	35	1	0	6	4	3
Oscar	117	104	24	11	52	51	40	13	0	21	6	0	2	0	2
Charlton	130	112	70	31	86	40	23	22	3	22	0	3	3	0	1
Mean	151	151	107	33	112	115	69	57	24	66	26	6	6	5	11
LSD (P = 0.05)	TOS = 96 VAR = 25 TOS X VAR = 71 VAR / Same levels of TOS =51					TOS = 78 VAR = 25 TOS X VAR = 63 VAR / Same levels of TOS = 51					TOS = 10 VAR = 7 TOS X VAR = 15 VAR / Same levels of TOS = 13				

sowing compared to very late sowing. Mustard lines produced more secondary and tertiary pods than canola.

Number of seeds per pod did not differ between times of sowing in all mustard genotypes except in 887.1.6.1 (Table 3.5). Number of seeds per pod in 887.1.6.1 was significantly lower in very late sowing compared to early, mid and late sowings. All canola varieties produced significantly more number of seeds/pod in early and mid sowings compared to late and very late sowings. Number of seeds per pod differed significantly between genotypes in all times of sowing. Canola genotypes produced significantly more number of seeds/pod than mustard genotypes regardless of the times of sowing.

1000 seed weight did not differ between times of sowing in all genotypes except in JM 33 and JM 29 (Table 3.5). 1000 seed weight was significantly higher in very late sowing compared to late sowing in JM 29 and JM 33. 1000 seed weight differed significantly between genotypes in all times of sowing. Monty, Charlton, Oscar, 82 No 22-98, and Muscon produced the heaviest seeds.

3.3.9. Seed quality

Oil concentration was significantly lower in very late sowing (Table 3.7). Oil concentration of all canola varieties was significantly higher in early sowing compared to very late sowing. Oil concentration differed significantly between genotypes in all times of sowing (Table 3.7). All canola varieties and mustard genotype 887.1.6.1 produced significantly higher oil concentrations than other mustard genotypes regardless of the times of sowing.

Protein concentration was inversely proportionate to oil concentration (Figure 3.3. & Table 3.7). Protein concentration of all genotypes was significantly higher from very late sowing. Protein concentration differed significantly between genotypes in all times of sowing (Table 3.7). JM 29 produced significantly higher protein concentration than other genotypes in early, mid and late sowings and JM 33 produced same level of protein concentration as JM 29 in very late sowing (Table 3.7).

Table 3.7. Oil and protein concentrations (%) at 13.5 % moisture in nine genotypes of mustard and canola sown at four times (early, mid, late and very late) at Northam, WA in 1999.

Genotype	Oil concentration (%)					Protein concentration (%)				
	Early	Mid	Late	V. Late	Mean	Early	Mid	Late	V. Late	Mean
887.1.6.1	43.4	43.7	42.8	39.9	42.5	19.8	20.4	20.7	23.7	21.1
JM 25	40.9	40.4	39.8	38.9	40.0	20.0	20.3	21.3	23.3	21.2
JM 33	38.6	38.4	38.1	36.5	37.9	22.3	22.6	21.9	25.4	23.1
JM 29	38.5	38.2	38.6	36.9	38.1	23.1	23.3	23.3	25.7	23.9
Muscon	38.5	38.7	38.5	37.6	38.3	21.8	22.1	21.9	25.3	22.8
82 No 22- 98	38.7	39.1	38.5	37.0	38.3	22.6	22.6	21.7	24.9	23.0
Monty	45.4	42.6	42.2	38.9	42.3	17.6	19.3	19.7	23.3	20.0
Oscar	43.1	41.3	40.9	39.3	41.2	19.5	21.1	21.5	23.9	21.5
Charlton	46.8	44.2	44.2	41.0	42.5	19.4	21.1	20.5	24.2	21.3
Mean	41.5	40.7	40.4	38.5	40.3	20.7	21.4	21.4	24.4	22.0
LSD (P = 0.05)	TOS = 1.1 VAR = 0.6 TOS X VAR =1.5 VAR / Same levels of TOS = 1.2					TOS = 0.1 VAR = 0.2 TOS X VAR = 0.4 VAR / Same levels of TOS = 0.4				

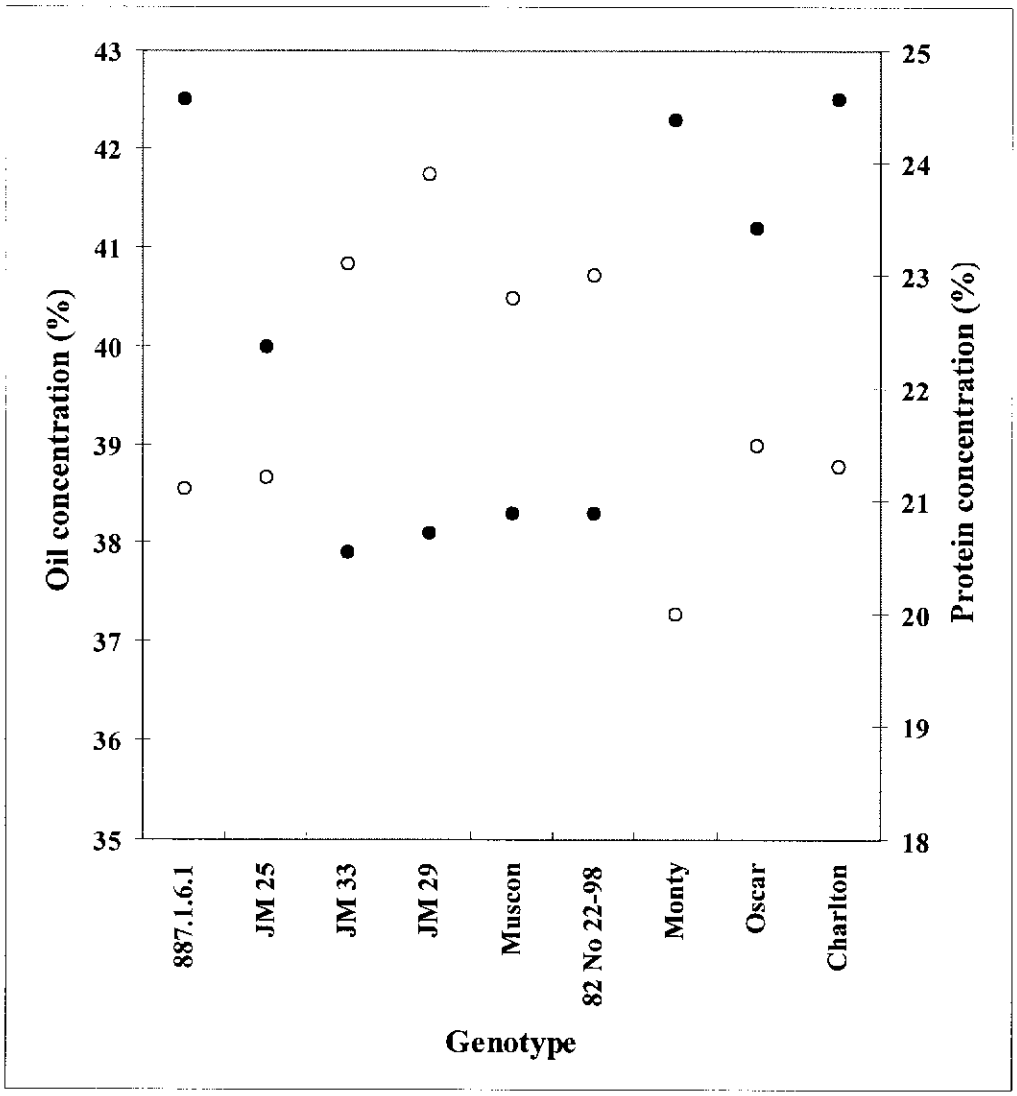

Figure 3.3. Inverse relationship between average oil concentration (●) and average protein concentration (○) in nine genotypes of mustard and canola sown at four times at Northam, WA in 1999.

3.4. DISCUSSION

The results of this one year study at a single site demonstrate the potential adaptation of mustard in medium rainfall environments in south Western Australia. Seed yield of mustard and canola was strongly correlated with final above ground dry matter production (r^2 = 0.93) and harvest index (r^2 = 0.75). Yield components such as total number of pods/plant (r^2 = 0.46), number of secondary pods/plant (r^2 = 0.40), and number of seeds/pod (r^2 = 0.36) were significantly correlated with seed yield. Plant height at maturity (r^2 = 0.46) was also well correlated with seed yield. Of the phenological stages, the duration from first flower to maturity (r^2 = 0.40) was significantly correlated with seed yield. However, seed yield was not correlated with the duration from sowing to first flower (DOF).

Seed yield, dry matter production and harvest index were significantly lower in very late sowing compared to early, mid and late sowings (Table 3.4). Lower dry matter is related to reduced post-anthesis duration, leaf area development and radiation absorption, soil moisture and high temperature stresses, which occurred at the end of the season. Very late sown crops flowered late when temperature and day length increased in October. Post-anthesis duration was therefore significantly shortened in very late sowing. Very low rainfall (2 mm) was received during post-anthesis period for the last sown crop. Yield of *Brassica* oilseed species can be severely reduced by water deficits during flowering and early pod development (Wright *et al.*, 1992). Reduced yield components (number of pods/plant and seeds/pod) also contributed to lower seed yield (Table 3.5). Poor establishment of the crop is also a reason for lower seed yield and dry matter in very late sowing. Low temperatures reduced germination percentage and delayed emergence by 7 to 14 days in very late sowing.

In contrast, crops sown early (12 May), mid (2 June) and late (23 June) in the season were able to germinate after rain, flower early and set seeds before the terminal drought. Dry matter production in early, mid and late sown crops was associated with longer post-anthesis duration, higher leaf area development and radiation absorption. Crops did not achieve any advantage from early sowing, as flowering and maturity of early, mid and late sown crops occurred in the same times of the year (Figure 3.2). However, due to genotype x times of sowing interaction some exceptions were observed. Dry matter production and seed yield differed significantly between

genotypes in early sowing and were highest in JM 33, Oscar and Charlton (Table 3.4). Mid maturing genotypes took advantage of a longer growing duration, which resulted from early sowing. Greater dry matter is associated with a longer reproductive phase (Duncan *et al.*, 1978). Significantly higher seed yields in mid maturing JM 33, Oscar and Charlton are therefore related to their greater dry matter production resulting from a longer post-anthesis period.

Lower seed yields in early maturing mustards with early sowing is related to lower dry matter. High dry matter does not always translate into high seed yields. Partitioning of dry matter into seeds and the ability of the plants to redistribute reserves are also necessary for high seed yield (Leport *et al.*, 1999). It is reasonable to expect higher yields from late maturing genotypes than mid maturing genotypes from early sowing, as they can take advantage of the longer growing periods. However, seed yield of the late maturing JM 29 was significantly lower compared to that of JM 33, Oscar and Charlton in early sowing (Table 3.4). This may be related to the inherited low efficiencies of dry matter conversion into seeds in JM 29, as it is a plant with tall and large vegetative structure. Plant height of early and mid maturing mustard was reduced with delaying sowing (Table 3.3). Therefore, HI in mustards was similar to canola and hence seed yield did not differ between species (mustard vs canola) in mid, late and very late sowings. Development of shorter mustard cultivars with restricted branches, particularly less secondary and tertiary branches, either by breeding or manipulation of agronomic management practices was considered to be beneficial as these attributes improve HI in mustards (Yadava and Singh, 1999).

Seed yield and dry matter did not differ between genotypes in late and very late sowings (Table 3.4). Phenology in mid and late maturing genotypes was highly responsive to environmental changes. These genotypes grew faster and flowered earlier in late and very late sowings due to increasing temperature and day length in October. As an example, LAI in early maturing 82 No 22-98 and mid maturing JM 33 were equal in very late sowing, although LAI in JM 33 was lower in early sowings compared to 82 No 22-98. Therefore, they were able to produce similar levels of dry matter and seed yield to early maturing genotypes. Mustard was expected to produce more dry matter and seed yield than canola in very late sowing as mustards are reputed to tolerate soil moisture and high temperature stress better

than canola (Kirk and Oram, 1978; Kumar *et al.*, 1987; Wright *et al.*, 1996; 1997; Wright and Morgan, 1998). However, seed yield and dry matter did not differ between species in late and very late sowings in this study. These results agreed with those of Wright *et al.* (1995), who found that mustard and canola produced similar yields under low water deficits but under high soil water deficits seed yields in mustard was more than double that of canola. The soil moisture and high temperature stresses experienced in this medium rainfall site may not have been sufficient to express a yield advantage of mustard over canola. 1999 was a relatively wet year and even the very late sown crop received 260 mm of rainfall during its growing period (Figure 3.1). This adequate rainfall may not have brought any water stress conditions in canola, resulting in yields similar to mustard. Results would have been different if the crop had been sown at a low rainfall site such as Merredin, where July to November rainfall was just 102 mm (Source: www.agric.wa.gov.au/weather) in the same year, which may cause water stress conditions in canola. HI of early maturing mustard genotypes from very late sowing was however significantly higher compared to canola varieties (Table 3.4). This may be related to reduced plant height in mustard with delayed sowing.

Drought and high temperature stresses have a negative effect on oil concentration (Heenan and Armstrong, 1993; Jensen *et al.*, 1996; Hocking *et al.*, 1997; Blondel and Renard, 1999; Walton, 1999). Oil concentration was significantly lower in very late sowing (Table 3.7) and associated with soil moisture and high temperature stresses at the end of the season. The yellow seeded *B. juncea* have a thinner seed coat than the brown seeds and as a consequence have oil concentrations 4 to 7 % higher (Kirk and Oram, 1978). As expected, some yellow seeded mustard genotypes (887.1.6.1 and JM 25) produced higher oil concentrations compared to brown seeded genotypes (82 No 22-98). Protein concentration has generally shown an inverse relationship to oil concentration and was less under warm, dry conditions (Uppstrom, 1995; Blondel and Renard, 1999). Similarly, protein concentration of the seed was higher in very late sowing in this study and genotypes that produced lower oil concentration produced higher protein concentration (Figure 3.3 and Table 3.7).

3.5. CONCLUSIONS

Mustard genotypes used in this study produced seed yields similar to canola at Northam showing their potential adaptation as an oilseed crop in medium rainfall areas of south Western Australia. However, despite its reputation for greater tolerance to heat and drought stress, mustard did not produce significantly higher dry matter and seed yield than canola in very late sowing. However, harvest index of mustard was higher than canola in very late sowing due to reduced plant height.

Dry matter production and seed yield was highest in early sowing due to a balanced pre-anthesis and post-anthesis development of the crop and the ability to avoid terminal drought. Very late sowing (after July) significantly reduced the dry matter production and seed yield of mustard and canola. Very late sowing also reduced oil concentration presumably due to low rainfall received during this period.

Mustard may produce more dry matter and seed yield than canola under greater soil moisture and high temperature stress conditions frequently experienced in the low rainfall cropping regions of south Western Australia. Further detailed studies are therefore necessary to investigate the adaptation of mustard to low rainfall areas. Studies undertaken to find this information are presented in subsequent chapters.

CHAPTER 4

Genotype x environment interactions and yield determinants of mustard and canola

4. 1. INTRODUCTION

Genotypic differences play a major role in adaptability of crop plants to specific environments. However, plant breeders have been unable to exploit them fully in breeding programs and crop variety testing trials due to complexities of natural environments (Finlay and Wilkinson, 1963). The differential response of genotypes to environmental changes is a genotype x environment interaction (G x E) (Vargas *et al.*, 2001). The G x E term of the phenotypic model for yield combines all the unknown specific genotypic responses to varying environmental conditions into one parameter. Understanding the biological significance and reasons for G x E interactions could potentially lead to increased yields in specific environments by better exploitation of appropriately adapted genotypes (Turner *et al.*, 2001).

Adaptability of genotypes to a range of environments can be best explained by their phenotypic stability (developmental homeostasis). Research into phenotypic stability, heterosis and response to environmental changes has provided considerable detailed and fundamental knowledge about the nature and significance of adaptation in both plants and animals (Finlay and Wilkinson, 1963). The ability of some crop species/varieties to perform well over a wide range of environmental conditions has long been appreciated by the agronomists and plant breeders. General adaptability has proved to be of particular importance in environments where edaphic variation between localities is large (Finlay and Wilkinson, 1963). Even in a uniform edaphic environment, a considerable degree of general adaptability will be important, because of the marked fluctuation of climatic conditions from season to season. Over the last few decades, plant breeders have met the demand for varieties which are better adapted to changing conditions by breeding either for closely defined ecological conditions or for more extensive conditions which includes a considerable range of environments.

In the crop growing regions of south Western Australia, general adaptability is important due to the large edaphic variation between localities and large seasonal

variation within one locality. Due to the Mediterranean-type climate experienced in these areas, temperature, rainfall and soil moisture are the most important climatic factors varying from season to season (Loss and Siddique, 1994). Crops with more drought resistance characteristics are therefore better adapted to these environments (Turner et al., 2001). Mustard was considered as a potential new crop and a better alternative to canola particularly for the low rainfall growing regions of south Western Australia due to its reputed tolerance to soil moisture and high temperature stress (Kumar *et al.*, 1984; 1987; 1994; Wright *et al.*, 1992; Wright *et al.*, 1995; 1996; Niknam and Turner, 1999). As shown in the previous study (Chapter 3), mustard had a yield potential similar to canola in the medium rainfall areas of south Western Australia. Aim of this study was to investigate adaptation of mustard and canola in low rainfall areas in south Western Australia.

Experiments presented in this chapter were designed to investigate, the effects of genotypes, environment and their interactions. Responsiveness and stability of different mustard and canola genotypes to varying environmental conditions in south Western Australia were studied to investigate their adaptation. Investigations of genotype x environment interactions are of less value unless they can be explained in terms of yield determinants. Therefore, the roles of some morphological attributes, dry matter production and partitioning and yield components on seed yield in mustard and canola in the low rainfall environments were also studied.

4.2. MATERIALS AND METHODS

4.2.1. Experimental design and trial management

Identical field experiments were conducted at three sites in the low rainfall cropping regions of south Western Australia (Figure 4.1) at Merredin (31°29'S, 118°18' E, average annual rainfall 315 mm), Mullewa (28° 33'S, 115° 25'E, average annual rainfall 337 mm) and Newdegate (36° 51'S, 119° 1'E, average annual rainfall 363 mm) in 2000 and 2001 growing seasons. Five improved mustard breeding lines/varieties (887.1.6.1, JM25, JM33, Muscon, 82 No 22-98) varying in height, maturity and oil quality (Table 3.1) and two commercial canola varieties (Monty and Oscar) varying in height and maturity (Table 3.1) were sown at three times in both years.

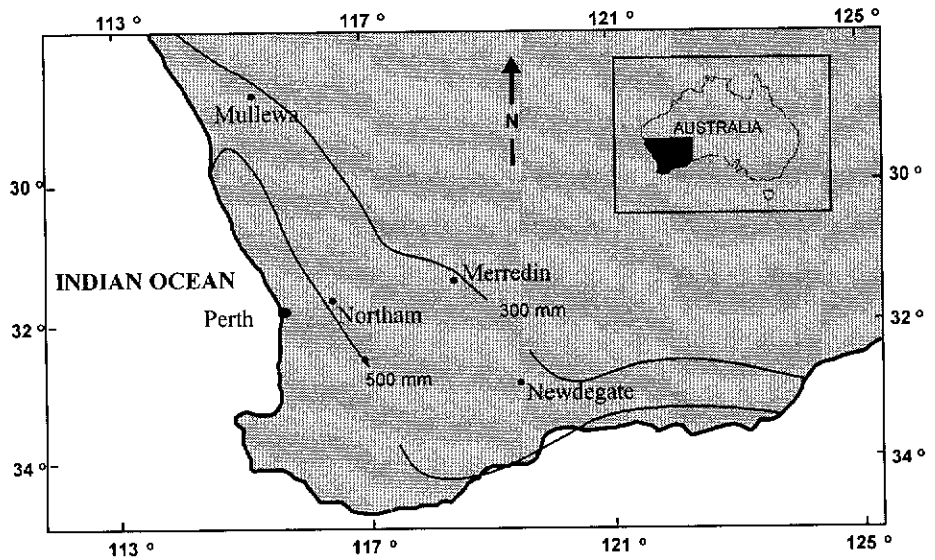

Fig. 4.1. The location of the experimental sites in south Western Australia in 1999, 2000 and 2001.

Treatment combinations were arranged in a split-plot design with three replicates at all sites in both years. The effect of times of sowing was studied in the main plots and seven genotypes in the sub plots. Sowing dates, soil type, soil pH and crop rotations of the experimental sites in 2000 and 2001 growing seasons are presented in the Table 4.1.

Plots were sown with a cone seeder at the seed rate of 6 kg/ha at all sites in both years. All plots were 1.44 m wide (8 rows, 18 cm apart), length varied between sites. At Merredin, plots were 30 m long in both years and at Newdegate and Mullewa, they were 20 m long in both years. Double Superphosphate was applied at the rate of 114.2 kg /ha at sowing. Urea was top-dressed at the rate of 130 kg/ha four weeks after sowing. Weeds were controlled a week before sowing with Roundup® at 1L/ha. Grass and broad leaf weeds that emerged after sowing were controlled with Fusilade® at 250 ml/ha and Lontrel® at 500 ml/ha respectively. Redlegged earth mite (*Halotydeus destructor*) and Cutworm (*Agrostis* spp.) were controlled at the vegetative phase using Endosulfan® (350 g/L) at 2 L/ha. Aphids (*Aphis craccivora*) and Cabbage moth (*Plutella xylostella*) were controlled by spraying Endosulfan® (350 g/L) at 2.0 L/ha during flowering and pod development.

4.2.2. Measurements

4.2.2.1. Genotype x environment interactions

Unless otherwise mentioned, the following is a common description of the measurements taken from three sites in both years.

4.2.2.1.1. Weather

Daily maximum and minimum temperatures and daily rainfall were recorded at nearby weather stations. Growing degree-days (GDD) were calculated as described in the section 3.2.2.1.

4.2.2.1.2. Plant density

Plant density was measured at 28 days after sowing (DAS) using three, 1 m^2 quadrats at three positions along the length of each plot, chosen within the border rows.

Table 4.1. Sowing dates, soil type, soil pH and cropping history of the experimental sites in 2000 and 2001.

Site	Sowing date	Soil type	Soil pH (0-10 cm) ($CaCl_2$)	Cropping history
		2000		
Merredin	16 May (early) 9 June (mid) 30 June (late)	loamy sand soil down to sandy clay at depth	4.9	wheat (1999) chickpea (1998) wheat (1997)
Mullewa	1 May (early) 13 June (mid) 5 July (late)	loamy earth	6.0	wheat (1999) wheat (1998) lupin (1997)
Newdegate	16 June (early) 30 June (mid) 14 July (late)	greyish brown sand over yellowish red medium clay soil	4.9	lupin (1999) wheat (1998) lupin (1997)
		2001		
Merredin	24 May (early) 15 June (mid) 13 July (late)	loamy sand soil	5.6	wheat (2000) lupin (1999) wheat (1998)
Mullewa	7 June (early) 21 June (mid) 4 July (late)	loamy earth	5.9	wheat (2000) medic pasture (1999) lupin (1998)
Newdegate	1 June (early) 10 July (mid) 24 July (late)	sandy loam over reddish yellow gravelly sandy clay loam soil	5.1	lupin (2000) wheat (1999) lupin (1998)

4.2.2.1.3. Phenology

Number of days from sowing to the date when 50 % of plants produce their first open flower (DOF) of all genotypes from all times of sowing was recorded. DOF was not recorded at Newdegate. Crop duration was calculated from the date of sowing to final harvest.

4.2.2.1.4. Seed yield and quality

Plots were machine harvested at maturity. Oil and protein content of the seed was determined using Infratec 1241 grain analyzer (FOSS TECATOR V1.52). In 2001, the experiment at Mullewa was abandoned before harvest due to drought and insect pest damage. Yield, oil, and protein data for Mullewa 2001 are therefore not available.

4.2.2.2. Yield determinants

Yield determinants of mustard and canola were studied only at Merredin in 2000 and 2001 growing seasons. Following measurements were taken.

4.2.2.2.1. Dry matter production and harvest index

To determine dry matter production at flowering, plants of two 1 m^2 quadrats were cut at ground level when 50 % of plants had produced their first open flower (DOF). Samples were dried separately in a ventilated oven maintained at 75 ^{0}C to a constant weight. Above ground biomass at final harvest and HI was determined as described in the section 3.2.2.4.

4.2.2.2.2. Yield components, branch counts and plant height

Yield components, number of branches and plant height at final harvest were determined as described in the section 3.2.2.5.

4.2.3. Statistical analyses

All data for six experiments (three sites in two years) were analysed separately using GENSTAT for Windows Release 5.0. Effects of genotype, times of sowing (TOS), and their interaction were estimated using Analysis of Variance (ANOVA) and means within experiments were compared using Least Significant Difference (LSD) at P = 0.5. Combined analysis across sites and years was done using Restricted Maximum Likelihood (REML) procedure and fixed terms were added sequentially to

fit a variance component model which allows different variances between main plots and sub plots at each site and year. Variations between experiments (site/year), TOS, crop (mustard vs canola) and genotype and their two way, three way and four way interactions were tested using the Wald tests for fixed effects.

After removing the main effects of environments (each TOS/year/site), the genotype x environment interaction on seed yield, seed oil and protein content was examined by producing biplots based on the first two principal components (Kempton and Fox, 1997). The genotype x environment interaction was examined further by conducting a Finlay Wilkinson analysis (Finlay and Wilkinson, 1963). For each genotype, a linear regression of individual yield on the mean yield of all genotypes for each environment was computed. The mean yield of all genotypes at each environment is referred to as 'environment mean /site index' and is a useful evaluation of the environment. When the individual genotype yield is plotted against the mean of all genotypes at each environment, the regression coefficient illustrates phenotypic stability or responsiveness of genotypes to a range of environments. Genotypes characterized by b = 1.0 have average phenotypic stability, b significantly greater than 1.0 have below average phenotypic stability and b significantly less than 1.0 have above average phenotypic stability.

Principal component analysis on environmental parameters was conducted to identify variations and similarities between environments. The correlation of effect of various environmental parameters on seed yield, oil and protein contents was also determined. Parameters were used as fixed terms and were sequentially added to fit a variance component model and Wald statistics were produced. Significance of these parameters on seed yield, oil and protein contents was tested by the Wald test.

The relationships between seed yield and its determinants were investigated using correlation coefficients and principal component analysis. Principal component biplots for yield determinants were produced based on the first two principal components (Kempton and Fox, 1997).

4.3. RESULTS

4.3.1. Weather

Year 2000 was a relatively dry year and annual rainfall and the total rainfall during the growing season (May to November) were lower than the long-term average at all three sites (Figure 4.2). Total rainfall of 131, 95 and 144 mm were recorded during the growing season at Merredin, Mullewa and Newdegate compared to long term averages of 228, 261 and 266 mm respectively. Lowest rainfall was recorded at Mullewa where very low rainfall occurred in August compared to the other two sites. In the year 2000, all three sites received significantly more summer (January to March) rainfall than the long-term average (Figure 4.2).

Year 2001 also was a relatively dry year, but annual rainfall was comparatively higher than 2000. Annual rainfall and the growing season rainfall at Merredin and Mullewa were lower than the long-term averages in 2001 (Figure 4.2). Total rainfall of 207 and 212 mm was recorded during the growing season at Merredin and Mullewa respectively. Though the total rainfall recorded at Newdegate during the growing season (272 mm) was slightly higher than the long-term average, about 87 mm was recorded in November and December outside the crop growth period. Since this rainfall was considered not useful to the crop, it was excluded from the analyses. June 2001 was unusually dry at all three sites, which delayed mid and late sowings and emergence of early sown crops. Vegetative growth stages of early sown crops were visibly water stressed during this period. In 2001, a significant amount of summer rainfall was recorded only at Merredin.

There were no major differences between mean daily maximum and minimum air temperatures and their long-term averages during 2000 and 2001 growing seasons (Figure 4.2). In both years temperatures were relatively higher at Mullewa compared to Merredin and Newdegate. No frost damage was observed in either mustard or canola at any site. The early sown crop at Newdegate was subjected to post-emergence sand blasting in 2000.

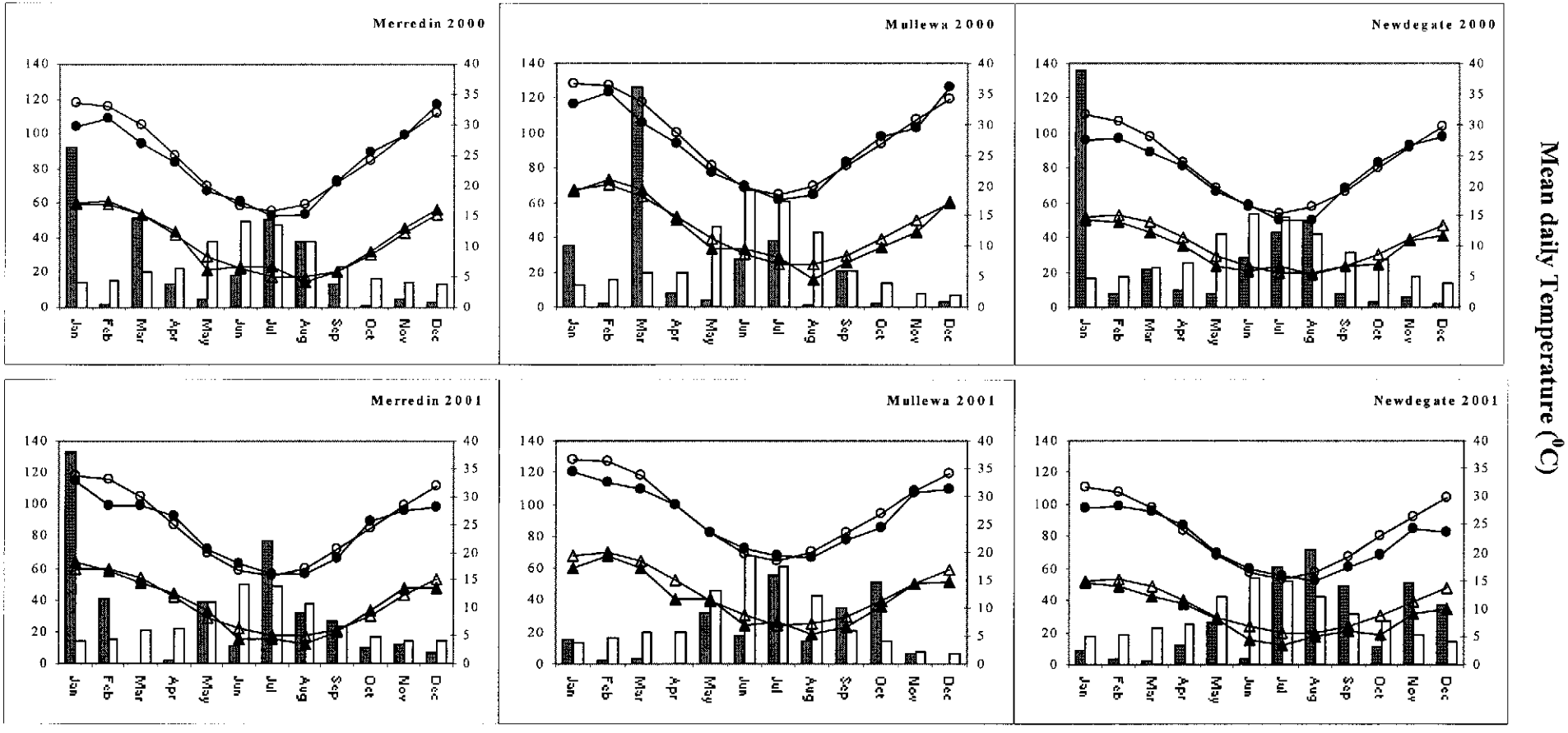

Figure 4.2. Total monthly rainfall (solid histogram), long term average total monthly rainfall (open histogram), mean daily maximum temperature (●), long term average mean daily maximum temperature (○), mean daily minimum temperature (▲), and long term average mean daily minimum temperature (Δ) at Merredin, Mullewa and Newdegate, WA in 2000 and 2001.

Hereafter, the 15 environments studied are denoted as follows; M - (Merredin), MU - (Mullewa), N - (Newdegate), 00 - (2000 growing season), 01- (2001 growing season), S1 - (early sowing), S2 - (mid sowing), S3 - (late sowing). For example, early sowing at Merredin in 2000 is denoted as M00S1 and late sowing at Newdegate in 2001 as N01S3. Details of key crop growth durations, rainfall and temperature received during growing period, pre-anthesis and post-anthesis periods and correlation of each parameter to seed yield, oil and protein concentrations are given in Table 4.2.

4.3.2. Principal component analysis of environments

Principal component analysis of trial site environments also showed that there were considerable differences between the 15 environments studied (Figure 4.3). The first two principal components have accounted for 88 % of the variation. Each environment parameter was plotted using values for principal component 1 (PC1) and principal component 2 (PC2). The environments were plotted on the same graph so that similar environments could be identified. Almost all of the variation in total rainfall was explained by the positive axis of PC1. Post-anthesis and pre-anthesis rainfalls were separated along the positive direction of the PC1, but in opposite directions on PC2. Average maximum temperature during pre-anthesis and post-anthesis periods were separated along the negative direction of the PC1, but in opposite directions on PC2.

The main results exhibited by the biplot (Figure 4.3) were; (i) Environments receiving higher rainfall and lower temperature (M00S1, M00S2, N00S1, N00S2, M01S1, M01S2, N01S1, N01S2, and N01S3 were well separated from those receiving lower rainfall and higher temperature (MU00S1, MU00S2, MU0S3, M00S3, N00S3, and M01S3), (ii) Environments receiving higher rainfall during post-anthesis period (M01S1, N01S1, and MU00S1) were grouped. (iii) Environments receiving higher rainfall during pre-anthesis period (M00S1, M00S2, N00S1, N00S2, M01S2, and N01S2) were grouped. (iv) Warmer environments during pre-anthesis period (MU00S1, MU00S2, MU00S3, and M01S1) were separated. (v) Warmer environments during post-anthesis period (M00S3, N00S3, M01S3, MU00S2, and MU00S3) were separated. Environments were however not grouped in the biplot according to total GDD and soil surface pH.

Table 4.2. Key crop growth durations, rainfall and temperature received during pre-anthesis and post-anthesis durations at 15 environments and correlation of each parameter to seed yield, seed oil and protein concentrations (* - significant at P<0.05, ** - significant at P < 0.01).

Environment	Growing period (days)	Total rainfall (mm)	Total GDD	Pre-anthesis period					Post-anthesis period				
				Period (days)	Rainfall (mm)	GDD	Ave max t^0C	Ave daily t^0C	Period (days)	Rainfall (mm)	GDD	Ave max t^0C	Ave daily t^0C
M00S1	163	122	1861	88	81	1010	17	11	75	41	851	23	15
M00S2	162	125	2195	85	109	927	17	12	77	16	1268	25	19
M00S3	141	107	1940	78	102	846	17	11	63	5	1094	27	19
MU00S1	154	95	2629	73	47	1088	20	14	81	48	1541	24	15
MU00S2	140	86	2041	70	63	902	19	13	70	23	1139	29	17
MU00S3	153	43	1912	67	36	862	20	13	86	7	1050	26	20
N00S1	187	119	1981	98	113	787	15	11	89	16	1194	23	16
N00S2	165	102	1822	88	86	826	16	11	77	16	996	25	17
N00S3	133	82	1999	80	66	878	16	11	53	16	1121	26	18
M01S1	178	175	2553	88	119	952	18	12	90	55	1601	24	17
M01S2	139	158	2245	104	133	1118	17	11	35	24	1127	26	19
M01S3	126	136	1945	82	114	906	17	12	44	21	1039	26	19
N01S1	194	195	2332	98	139	1002	16	10	96	56	1330	23	15
N01S2	154	180	1915	88	170	939	16	10	66	10	975	24	15
N01S3	163	187	2180	80	166	1112	17	11	83	21	1068	24	17
corr vs yield	0. 51*	0. 24	0. 69 **	0. 10	-0. 08	0. 32	0. 29	0. 19	0. 51 *	0. 82 **	0. 68 **	-0. 51 *	-0. 49 *
corr vs oil	0. 29	0. 19	0. 46	0. 32	-0. 04	0. 25	-0. 09	-0. 04	0. 13	0. 61 *	0. 44	-0. 49 *	-0. 37
corr vs protein	-0. 24	-0. 62 **	-0. 67 **	-0. 35	-0. 37	-0. 74 **	-0. 01	0. 11	-0. 06	-0. 69 **	-0. 44	0. 42	0. 49 *

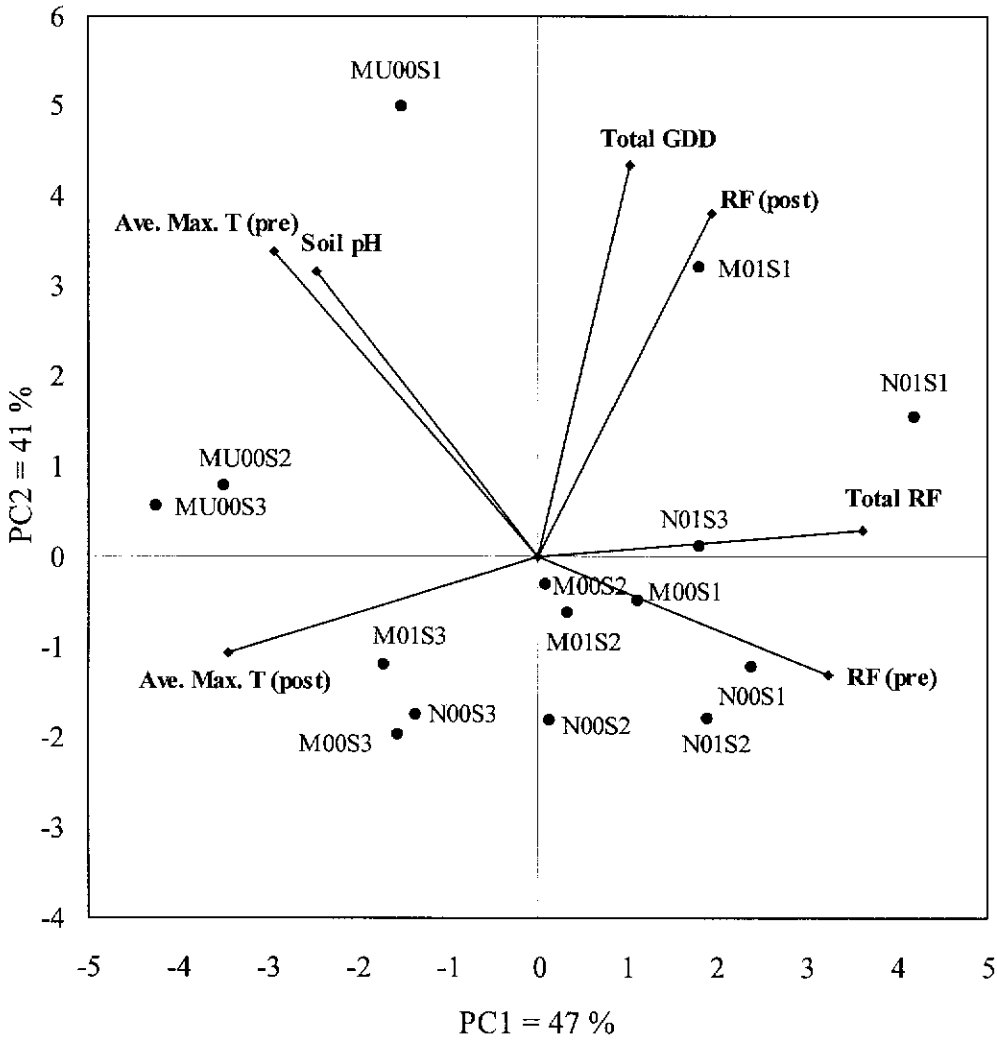

Figure 4.3. Principal component analysis of trial site environments. Loading of environment variables in components 1 and 2 are shown by the direction and strength of the biplot lines. Percentage variation explained by each component is given next to the axis.

(M–Merredin, **MU**–Mullewa, **N**–Newdegate, **00**–2000 growing season, **01**-2001 growing season, **S1**-early sowing, **S2**- mid sowing, **S3**- late sowing. As an example first sowing at Merredin in 2000 - **M00S1)**

4.3.3. Plant density

Plant density was significantly different between experiments (site/year) and genotypes. Plant density at Merredin was higher than Mullewa and Newdegate in both years from all times of sowing (Table 4.3). Establishment of the early sown crop at Merredin was significantly poor compared to mid and late sowings in 2000. Establishment of mid sown crops at Mullewa and Newdegate was significantly higher than early and late sown crops in 2000. Plant density in the early sown crop was significantly higher than that of mid and late sown crops at Merredin in 2001 (Table 4.3). Plant density did not differ significantly between times of sowing at Mullewa and Newdegate in 2001. Establishment of Muscon, 82 No 22-98, and Monty was poor at Merredin in both years (Table 4.3). Establishment of Monty was poor at Mullewa in 2000 and that of 82 No 22-98 and Monty were poor in 2001. Plant density of Muscon and Monty was lower at Newdegate in 2000 and that of 82 No 22-98 and Monty were lower in 2001.

The effect of plant density on yield was not significant within an experiment, hence means were not adjusted for the variation in plant density. Since plant density was significantly different between experiments, for combined analyses of seed yield across experiments, fixed terms of variance component model were fitted sequentially to remove the effect of plant density (Table 4.4).

4.3.4. Days to flowering

Number of days from sowing to the date when 50 % of plants produce their first open flower (DOF) in all genotypes in all times of sowing was earlier at Mullewa than that at Merredin in both years (Table 4.5). DOF in late sowing was significantly less compared to early and mid sowings at Merredin and Mullewa in both years. DOF of all genotypes from mid sown crop at Merredin in 2001 was significantly longer compared to early and late sown crops. Muscon and 82 No 22-98 produced flowers earlier than other genotypes regardless of the times of sowing, sites, and years (Table 4.5). The DOF of Muscon and 82 No 22-98 was not significantly affected by times of sowing and that of other genotypes was significantly earlier in late sowing compared to early and mid sowings at Merredin in 2000.

Table 4.3. Plant density at 28 DAS in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, Mullewa and Newdegate, WA in 2000 and 2001.

Genotype	Merredin 2000				Merredin 2001			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (24 May)	Mid (15 June)	Late (13 July)	Mean
887.1.6.1	96	154	151	134	207	70	110	129
JM 25	100	150	153	134	175	91	114	127
JM 33	105	148	167	140	182	86	133	133
Muscon	97	126	157	127	157	66	96	107
82 No 22-98	97	134	123	118	138	77	62	92
Monty	94	119	124	113	116	80	97	98
Oscar	97	128	135	120	175	91	111	126
Mean	98	137	144	126	164	80	104	116
LSD (P = 0.05)	TOS = 30 VAR = 11 TOS X VAR = 30 VAR / Same levels of TOS = 18				TOS = 29 VAR = 21 TOS X VAR = 41 VAR / Same levels of TOS = 37			

Genotype	Mullewa 2000				Mullewa 2001			
	Early (1 May)	Mid (13 June)	Late (5 July)	Mean	Early (7 June)	Mid (21 June)	Late (4 July)	Mean
887.1.6.1	47	78	51	59	45	29	25	33
JM 25	41	72	58	57	37	27	23	29
JM 33	48	77	61	62	40	33	29	34
Muscon	45	81	58	61	32	29	25	29
82 No 22-98	43	77	58	59	25	28	13	22
Monty	47	65	38	47	33	26	11	23
Oscar	53	74	51	53	45	28	15	29
Mean	42	75	54	57	37	29	20	28
LSD (P = 0.05)	TOS = 12 VAR = 10 TOS X VAR = 18 VAR / Same levels of TOS = 11				TOS = 30 VAR = 9 TOS X VAR =30 VAR / Same levels of TOS = 16			

Genotype	Newdegate 2000				Newdegate 2001			
	Early (16 June)	Mid (30 June)	Late (14 July)	Mean	Early (1 June)	Mid (10 July)	Late (24 July)	Mean
887.1.6.1	33	49	25	35	14	17	23	18
JM 25	39	46	35	40	12	18	23	18
JM 33	36	48	29	38	13	19	19	17
Muscon	29	44	29	34	13	20	24	19
82 No 22-98	32	46	31	36	13	11	16	13
Monty	21	44	25	30	11	16	17	14
Oscar	31	43	31	35	16	18	13	16
Mean	32	46	29	36	13	17	19	16
LSD (P = 0.05)	TOS = 10 VAR = 5 TOS X VAR = 11 VAR / Same levels of TOS = 9				TOS = 6 VAR = 3 TOS X VAR = 7 VAR / Same levels of TOS = 5			

Table 4.4. Wald statistics and significance of selected fixed terms that were sequentially added to fit variance component models for combined analyses of plant density, seed yield, oil and protein concentrations across experiments.

Descriptor	Fixed term	Wald statistics	d.f	Chi – sq prob
Plant density (plant/ m^2)	Experiment (site/year)	1571.9	5	<0.001
	TOS	22.24	2	<0.001
	Crop	27.46	1	<0.001
	Crop. Genotype	37.48	5	<0.001
	Experiment. TOS	181.44	10	<0.001
	Experiment. Crop	21.49	5	<0.001
	Experiment. TOS. Crop	21.71	10	0.017
	Experiment. Crop. Genotype	60.47	25	<0.001
	TOS. Crop. Genotype	15.76	10	0.107
Seed Yield (t/ha)	Experiment (site/year)	129.58	4	<0.001
	TOS	354.51	2	<0.001
	Experiment. TOS	140.62	8	<0.001
	Plant density	29.64	1	<0.001
	Crop	21.05	1	<0.001
	Crop. Genotype	272.88	5	<0.001
	Experiment. Crop. Genotype	239.11	24	<0.001
	TOS. Crop. Genotype	102.27	12	<0.001
	Experiment. TOS. Crop. Genotype	218.76	48	<0.001
Oil concentration (%)	Experiment (site/year)	46.24	4	<0.001
	TOS	917.16	2	<0.001
	Crop	6772.42	1	<0.001
	Crop. Genotype	2305.14	5	<0.001
	Experiment. TOS	281.21	8	<0.001
	Experiment. Crop	664.41	4	<0.001
	Experiment. TOS. Crop	370.14	8	<0.001
	Experiment. Crop. Genotype	207.08	20	<0.001
	TOS. Crop. Genotype	172.02	10	<0.001
Protein concentration (%)	Experiment (site/year)	4727.79	4	<0.001
	TOS	13681.69	2	<0.001
	Crop	1718.13	1	<0.001
	Crop. Genotype	16944.50	5	<0.001
	Experiment. TOS	9472.99	8	<0.001
	Experiment. Crop	1648.82	4	<0.001
	Experiment. TOS. Crop	322.70	8	<0.001
	Experiment. Crop. Genotype	960.93	20	<0.001
	TOS. Crop. Genotype	243.35	10	<0.001

Table 4.5. Number of days from sowing to the date when 50 % of plants produce their first open flower (DOF) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin and Mullewa, WA in 2000 and 2001.

Genotype	Merredin 2000				Merredin 2001			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (24 May)	Mid (15 June)	Late (13 July)	Mean
887.1.6.1	84	83	77	81	88	103	81	91
JM 25	93	90	77	87	88	103	81	91
JM 33	100	100	84	95	95	106	91	97
Muscon	66	69	70	68	81	101	76	86
82 No 22-98	66	69	70	68	81	103	76	87
Monty	93	90	77	87	88	101	76	88
Oscar	114	93	91	99	95	108	91	98
Mean	88	85	78	84	88	104	82	91
LSD (P = 0.05)	TOS = 4 VAR = 3 TOS X VAR = 5 VAR / Same levels of TOS = 5				TOS = 5 VAR = 3 TOS X VAR = 6 VAR / Same levels of TOS = 5			

Genotype	Mullewa 2000				Mullewa 2001			
	Early (1 May)	Mid (13 June)	Late (5 July)	Mean	Early (7 June)	Mid (21 June)	Late (4 July)	Mean
887.1.6.1	63	65	62	63	77	84	51	71
JM 25	73	72	70	72	89	81	55	75
JM 33	71	73	70	71	87	89	58	78
Muscon	60	62	58	60	74	75	50	66
82 No 22-98	62	63	62	62	84	80	53	72
Monty	75	69	67	70	91	85	59	79
Oscar	106	87	79	91	*	*	*	*
Mean	73	70	67	70	84	82	54	73
LSD (P = 0.05)	TOS = 3 VAR = 2 TOS X VAR = 4 VAR / Same levels of TOS = 4				TOS = 3 VAR = 2 TOS X VAR = 4 VAR / Same levels of TOS = 4			

* = plants have died before flowering

DOF did not differ significantly between genotypes except Monty and Oscar at Mullewa in 2000 (Table 4.5). Monty and Oscar produced flowers earlier in late sowings. All genotypes produced flowers significantly earlier in late sowing at Mullewa in 2001.

4.3.5. Seed yield

Seed yield was significantly different between experiments, TOS, species and genotypes (Table 4.4). Average seed yield was highest at Merredin in both years. In general seed yield was higher from the early sown crops of all experiments and progressively decreased with delayed sowing (Tables 4.6 and 4.7). Seed yields from early sown crops at Mullewa in 2000 and at Merredin in both years were significantly higher compared to mid and late sown crops. However, seed yield was not significantly affected by times of sowing at Newdegate in both years. There was a greater variation in seed yields (1.81 to 0.03 t/ha) of seven genotypes from different experiments (Table 4.6 and 4.7). Mustard genotypes 887.1.6.1, Muscon, 82 No 22-98 and Monty were higher yielding and JM 25, JM 33 and Oscar were lower yielding genotypes.

4.3.6. Genotypes x environment interaction on seed yield

The differential response of genotypes to different environments (i.e. genotype x environment interaction) on seed yield is presented in the principal component biplot (Figure 4.4). In the principal component analysis, the first two principal components have accounted for 77 % of the variation in seed yield. Each genotype was plotted using values for genotype component 1 and 2. The environments were plotted on the same graph so that genotypes that performed relatively well at particular environments could be identified by projecting each genotype onto each environment line.

The main results shown by the biplot (Figure 4.4) were; (i) four higher yielding genotypes (887.1.6.1, Muscon, 82 No 22-98, and Monty) were well separated from the lower yielding genotypes (JM 33, JM25, and Oscar), (ii) ten better yielding environments (M00S1, MU00S1, N00S1, M01S1, N01S1, M00S2, N00S2, N00S3, M01S2, and M01S3) were well separated from the five poor yielding environments, i.e. later sowings (M00S3, MU00S2, MU00S3, N01S2, and N01S3), (iii) genotypes performed relatively well at particular environments were well exhibited (For an example, Monty produced highest yields at M01S1, N00S1, M00S2, i.e. earlier sowings).

Table 4.6. Machine harvested seed yield (t/ha) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, Mullewa and Newdegate, WA, in 2000.

Genotype	Merredin 2000				Mullewa 2000				Newdegate 2000			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (1 May)	Mid (13 June)	Late (5 July)	Mean	Early (16 June)	Mid (30 June)	Late (14 July)	Mean
887.1.6.1	1.04	0.73	0.51	0.76	1.39	0.21	0.17	0.59	0.46	0.27	0.14	0.29
JM 25	0.84	0.49	0.34	0.56	0.99	0.11	0.29	0.47	0.27	0.13	0.05	0.15
JM 33	0.68	0.41	0.29	0.46	0.93	0.36	0.33	0.54	0.24	0.13	0.04	0.14
Muscon	1.01	0.79	0.61	0.80	1.18	0.20	0.15	0.51	0.30	0.22	0.12	0.21
82 No 22-98	0.99	0.75	0.51	0.75	1.34	0.25	0.20	0.60	0.36	0.20	0.14	0.23
Monty	0.99	0.62	0.22	0.61	1.29	0.23	0.31	0.61	0.53	0.21	0.09	0.28
Oscar	0.68	0.35	0.11	0.38	0.98	0.21	0.16	0.45	0.20	0.09	0.03	0.11
Mean	0.89	0.59	0.37	0.62	1.16	0.23	0.23	0.54	0.34	0.18	0.09	0.20
LSD (P = 0.05)	TOS =0.24 VAR = 0.07 TOS X VAR = 0.24 VAR / Same levels of TOS = 0.12				TOS = 0.28 VAR = 0.09 TOS X VAR = 0.28 VAR / Same levels of TOS = 0.17				TOS = 0.22 VAR = 0.05 TOS X VAR = 0.22 VAR / Same levels of TOS = 0.08			

Table 4.7. Machine harvested seed yield (t/ha) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin and Newdegate, WA, in 2001.

Genotype	Merredin 2001				Newdegate 2001			
	Early (24 May)	Mid (15 June)	Late (13 July)	Mean	Early (1 June)	Mid (10 July)	Late (24 July)	Mean
887.1.6.1	1.35	0.22	0.14	0.57	0.85	0.31	0.22	0.46
JM 25	0.97	0.18	0.14	0.43	0.56	0.31	0.11	0.34
JM 33	0.91	0.18	0.11	0.40	0.78	0.33	0.31	0.47
Muscon	1.09	0.21	0.14	0.48	0.70	0.49	0.00	0.40
82 No 22-98	1.11	0.32	0.13	0.52	0.91	0.42	0.22	0.52
Monty	1.81	0.29	0.19	0.76	0.74	0.32	0.12	0.39
Oscar	1.70	0.13	0.06	0.63	0.72	0.27	0.07	0.35
Mean	1.28	0.22	0.13	0.54	0.76	0.35	0.15	0.42
LSD (P = 0.05)	TOS = 0.64 VAR = 0.08 TOS X VAR = 0.28 VAR / Same levels of TOS =0.20				TOS = 0.57 VAR = 0.16 TOS X VAR = 0.56 VAR / Same levels of TOS= 0.23			

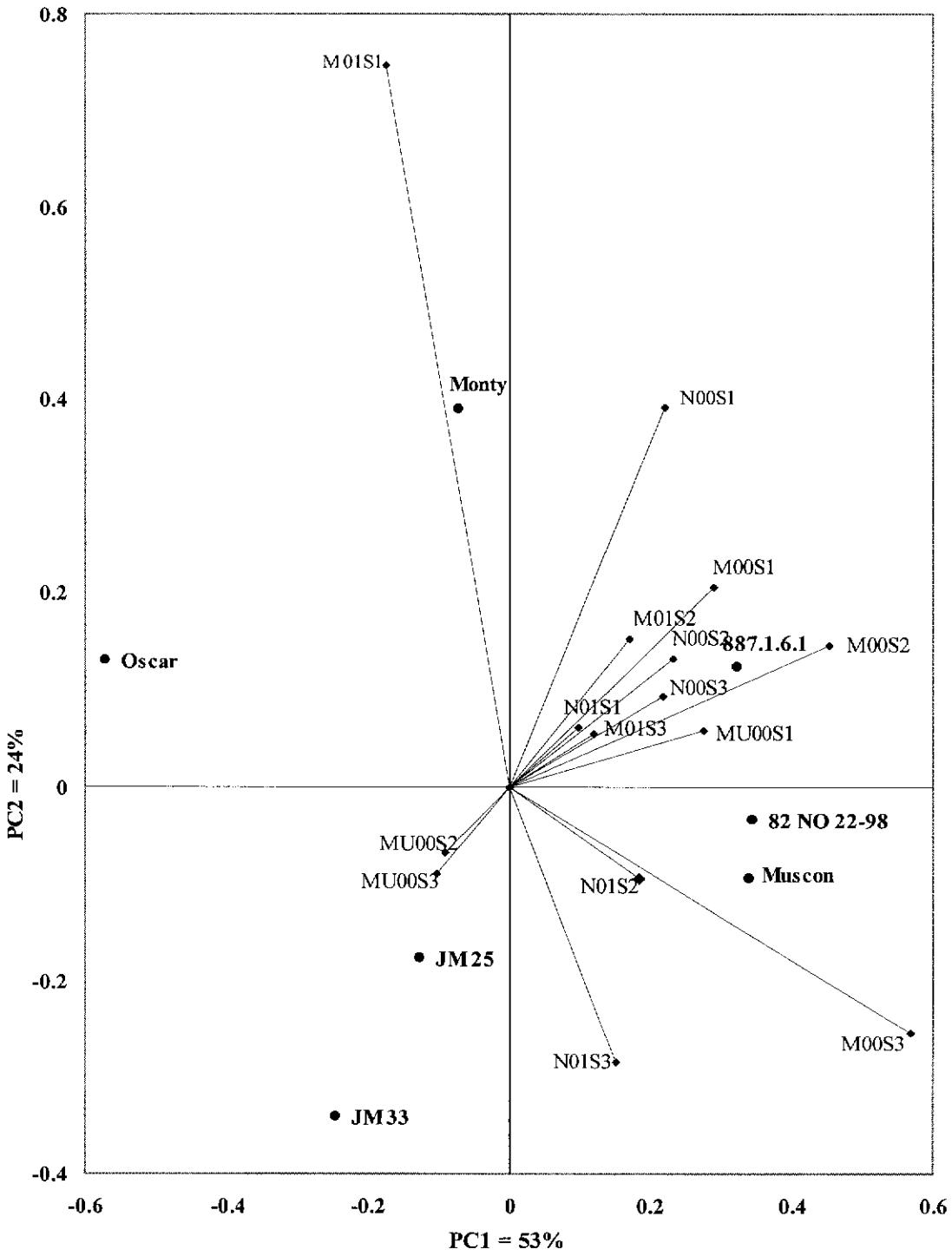

Figure 4.4. Principal component (1 and 2) biplot showing genotype x environment interaction in seed yield for seven genotypes of mustard and canola (bold) grown in 15 environments in WA. Loading of environments in components 1 and 2 are shown by the direction and strength of the biplot lines. Percentage variation explained by each component is given next to the axis.
(**M**–Merredin, **MU**–Mullewa, **N**–Newdegate, **00**–2000 growing season, **01**-2001 growing season, **S1**- early sowing, **S2**- mid sowing, **S3**- late sowing. As an example first sowing at Merredin in 2000 - **M00S1**)

Mustard genotype 887.1.6.1 produced above average seed yield in all environments except at MU00S2 and MU00S3 (Tables 4.6 and 4.7, Figure 4.4). 887.1.6.1 has separated with 82 No 22-98 and Muscon on the PC1 but in opposite directions on PC2. 82 No 22-98 produced below average yield only at M01S1 and Muscon produced below average yield at M01S1, N00S1, MU00S2 and MU00S3 (Figure 4.4). Low yielding mustard genotypes JM 25 and JM 33 performed well at the environments where 887.1.6.1 performed poorly (MU00S2, MU00S3 and N01S3). It appears that canola genotypes Monty and Oscar behaved similarly and performed better in similar environments, but opposite to 82 No 22-98 and Muscon. Monty behaved quite similarly to 887.1.6.1 in early sowings but performed poorly in late sowings. Oscar was the poorest yielding genotype in all environments and produced above average yield only at M01S1.

The Finlay-Wilkinson analysis (Finlay and Wilkinson, 1963) demonstrated that the regression of individual seed yield of genotype on the mean seed yield for each environment was significant and accounted for 92 % variation in the data (Figure 4.5a). Mean seed yield of genotypes across environments was in the following decreasing order: 887.1.6.1, 82 No 22-98, Monty, Muscon, JM 33, JM 25, and Oscar. The responsiveness of genotypes to the environment in respect to seed yield potential ranged from 0.82 to 1.14 and was in the following increasing order: JM 33, JM 25, 82 No 22-98, Muscon, Monty, 887.1.6.1, and Oscar (Figure 4.5b).

82 No 22-98, Muscon, Monty, and 887.1.6.1 showed average phenotypic stability and there was no significant difference between their responsiveness. Oscar was specifically adapted to high yielding environments and showed below average phenotypic stability (Figure 4.5b). Oscar produced very little yield in marginal environments, particularly in mid and late sowings, but as the environment improved (M01SI) yield increased at the rate well above the average for the group.

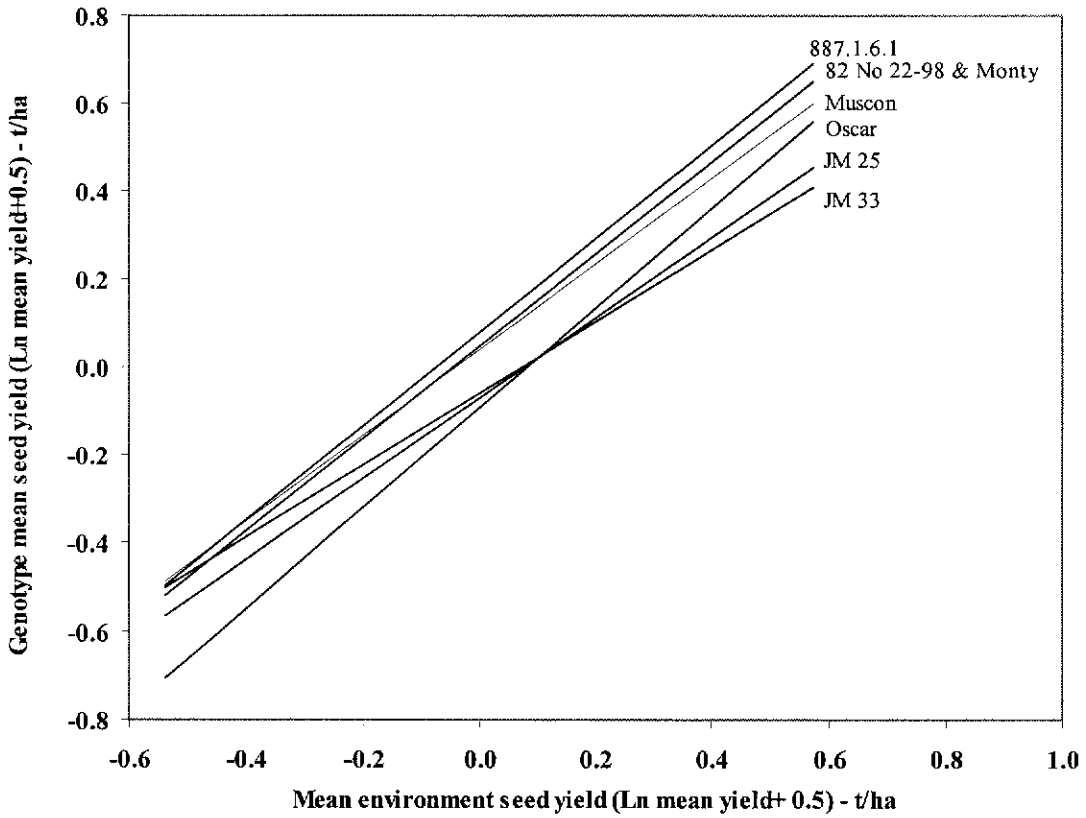

Figure 4.5. (a). Plot of linear regressions between individual seed yields in seven genotypes of mustard and canola and mean environment seed yield calculated from 15 environments.

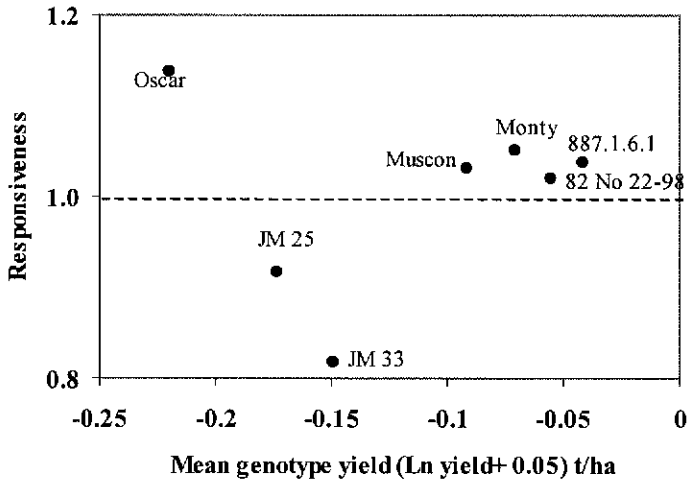

Figure 4.5 (b). Plot of responsiveness in seed yield to environments for seven genotypes of mustard and canola grown in 15 environments.

The mustard lines JM 25 and JM 33 exhibited the opposite type of adaptation to Oscar and showed above average phenotypic stability (Figure 4.5b). They produced above average yields in marginal environments, but below average yield in high yielding environments and therefore were specifically adapted for low yielding environments.

4.3.7. Seed oil concentration

Seed oil concentration was significantly different between experiments, TOS, species and genotypes (Table 4.4). Oil concentration was higher at Merredin than at Mullewa and Newdegate from all three times of sowing in both years (Tables 4.8 and 4.9). Oil concentration was significantly lower in late sowings at Merredin in both years and at Mullewa in 2000. Oil concentration was not significantly affected by times of sowing at Newdegate in both years. There was a greater variation in seed oil concentration of genotypes from three times of sowing at three sites in two years (45.8 to 32.3 %). Monty produced the highest oil concentration except from late sowing at Mullewa in 2000 (Table 4.8) and mid and late sowing at Newdegate in 2001 (Table 4.9). 887.1.6.1 had the highest oil concentration of all mustard genotypes in all environments except from the late sowing at Mullewa in 2000. This genotype produced similar or higher oil concentration than Oscar in most of the environments except from early and mid sowings at Merredin in both years.

4.3.8. Genotype x environment interaction on oil concentration

The biplot presented in the Figure 4.6 is an indication of the genotype x environment interaction in oil concentration after the main effect of site has been removed. In the principal component analysis, the first two principal components have accounted for 93 % of the variation in seed oil content. The main results from the biplot (Figure 4.6) are; (i) three genotypes producing higher oil concentration (Monty, Oscar and 887.1.6.1) were well separated from the genotypes producing lower oil concentration (82 No 22-98, Muscon, JM 33, and JM25), (ii) twelve environments producing higher oil concentration (M00S1, MU00S1, N00S1, M01S1, N01S1, M00S2, MU00S2, N00S2, M01S2, N00S3, M00S3and M01S3) were well separated from the three environments producing lower oil concentration (MU00S3, N01S2, and N01S3), (iii). Environments where specific genotypes produced higher oil concentration were clearly shown.

Table 4.8. Seed oil concentration (%) at 6.5 % moisture in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, Mullewa and Newdegate, WA in 2000.

Genotype	Merredin 2000				Mullewa 2000				Newdegate 2000			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (1 May)	Mid (13 June)	Late (5 July)	Mean	Early (16 June)	Mid (30 June)	Late (14 July)	Mean
887.1.6.1	39.8	39.0	37.9	38.9	39.7	37.5	33.4	36.8	37.9	37.4	37.8	37.7
JM 25	37.7	37.3	36.9	37.3	37.5	36.8	35.8	36.7	37.0	37.0	37.5	37.2
JM 33	36.8	36.6	36.5	36.6	36.9	36.4	35.6	36.3	36.1	35.8	35.9	35.9
Muscon	36.7	36.7	36.5	36.6	36.8	35.9	35.3	36.0	36.4	36.2	36.3	36.3
82 No 22-98	37.1	36.7	36.2	36.7	38.4	34.8	32.3	35.2	36.0	34.8	35.5	35.4
Monty	45.8	42.9	40.7	43.1	43.7	38.4	33.8	38.6	40.0	41.0	41.1	40.7
Oscar	41.7	40.6	38.5	40.3	38.7	34.8	33.4	35.6	38.1	38.8	37.1	38.0
Mean	39.4	38.6	37.6	38.5	38.8	36.4	34.2	36.5	37.4	37.3	37.3	37.3
LSD (P = 0.05)	TOS = 0.3 VAR = 0.3 TOS X VAR =0.6 VAR / Same levels of TOS =0.6				TOS = 0.6 VAR = 0.8 TOS X VAR = 1.38 VAR / Same levels of TOS = 1.43				TOS = 0.4 VAR = 0.3 TOS X VAR = 0.58 VAR / Same levels of TOS = 0.56			

Table 4.9. Seed oil concentration (%) at 6.5 % moisture in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin and Newdegate, WA in 2001.

Genotype	Merredin 2001				Newdegate 2001			
	Early (24 May)	Mid (15 June)	Late (13 July)	Mean	Early (1 June)	Mid (10 July)	Late (24 July)	Mean
887.1.6.1	38.7	37.3	37.5	37.8	38.3	38.0	38.0	38.1
JM 25	37.4	36.9	37.0	37.1	37.3	37.2	37.3	37.3
JM 33	37.0	36.8	36.5	36.8	38.3	36.8	36.7	37.2
Muscon	36.3	36.1	35.9	36.1	36.5	36.4	36.4	36.4
82 No 22-98	36.7	35.9	35.3	36.0	36.8	36.2	36.5	36.5
Monty	45.2	38.1	38.6	40.6	39.3	34.9	34.6	36.3
Oscar	41.9	40.7	35.5	39.4	35.8	34.8	34.5	35.0
Mean	39.0	37.4	36.6	37.7	37.5	36.3	36.3	36.7
LSD (P = 0.05)	TOS = 0.5 VAR = 0.3 TOS X VAR = 0.7 VAR / Same levels of TOS = 0.6				TOS = 2.7 VAR = 0.8 TOS X VAR = 2.8 VAR / Same levels of TOS = 1.7			

Monty, Oscar and 887.1.6.1 have produced higher oil concentrations in most of the environments. Monty has produced above average oil concentration (Tables 4.8 & 4.9) at all environments except in MU00S3, N01S2 and N01S3 (Figure 4.6). Oscar produced above average oil concentration at most of the environments except at MU00S2, MU00S3, N01S1, N01S2, and N01S3. Mustard genotype 887.1.6.1 produced below average oil concentration only at MU00S3, M01S1, and M01S2. Oscar and 887.1.6.1 produced same levels of mean genotype oil concentrations (Figure 4.7b), but they performed better in different environments. Mustard genotypes 82 No 22-98, Muscon, JM 33, and JM25 on the other hand produced above average oil concentrations only at MU00S3, N01S1, N01S2 and N01S3.

The Finlay Wilkinson analysis (Finlay and Wilkinson, 1963) demonstrated that the regression of individual oil concentration on the mean oil concentration for each environment was significant and accounted for 80 % variation in the data (Figure 4.7a). Mean oil concentrations was in the following decreasing order: Monty, Oscar, 887.1.6.1, JM 25, JM 33, Muscon and 82 No 22-98. The responsiveness of genotypes to the environment in respect to oil concentration ranged from 0.21 to 2.80 and was in the following increasing order: Monty, Oscar, 887.1.6.1, 82 No 22-98, JM 25, Muscon, and JM 33. (Figure 4.7b). Canola genotypes were more responsive to environmental changes compared to mustards.

Though Monty produced highest mean oil concentration it has shown a below average stability across environments. Oil concentration of Monty was below average in poor environments, particularly from late sowings at Newdegate and Mullewa, though it performed very well in better environments (Table 4.8 and 4.9). Oscar was in the medium oil producing group but has shown below average stability similar to Monty. The highest oil producing mustard genotype, 887.1.6.1 had similar levels of mean oil concentration to Oscar and more importantly has shown general stability across all environments (Figure 4.7b). Mustard genotypes JM 25, Muscon, and JM 33 produced low oil concentrations and have shown above average stability. Although 82 No 22-98 produced lowest oil concentration it has shown general stability across all environments (Figure 4.7b).

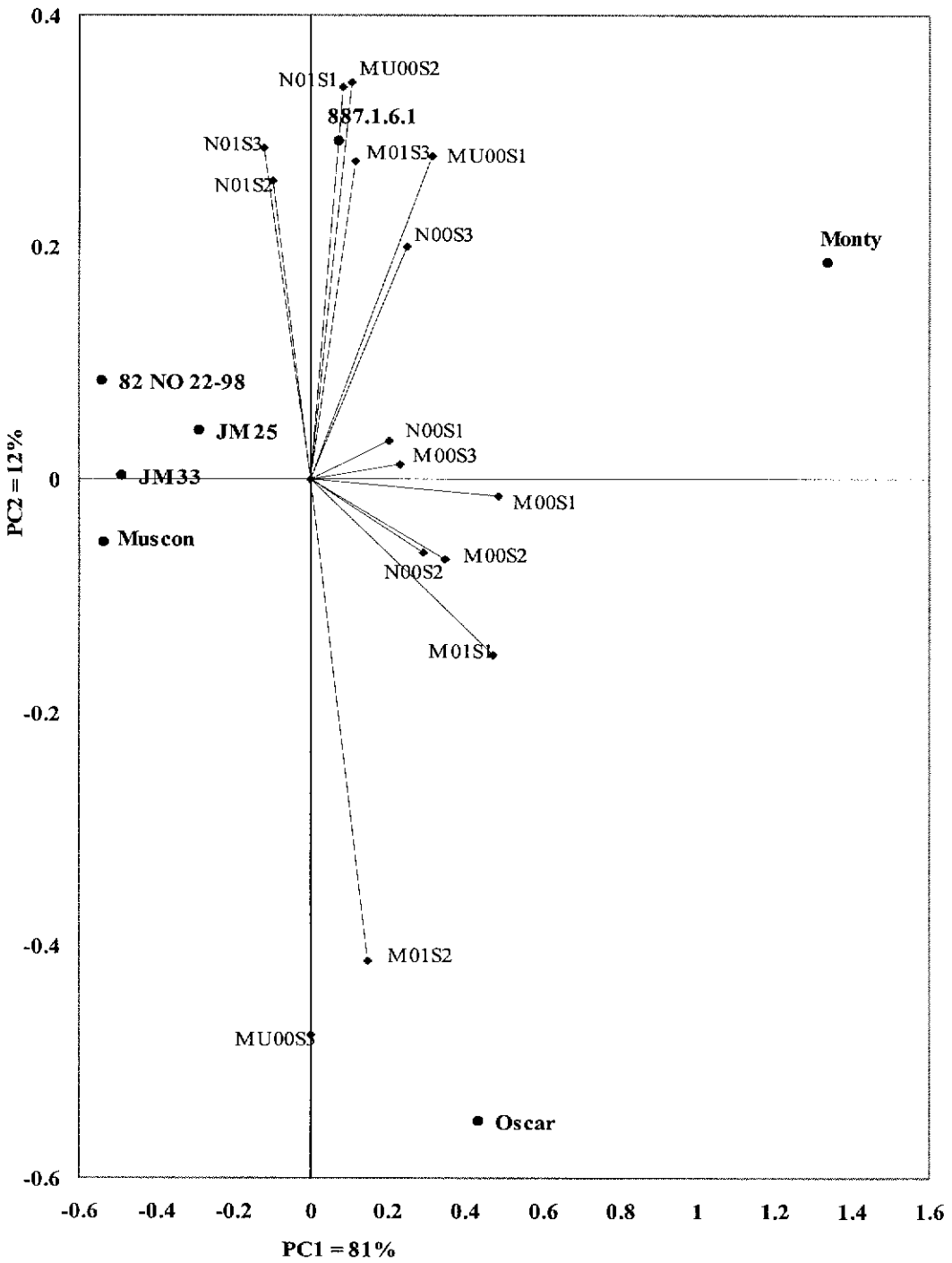

Figure 4.6. Principal components (1 and 2) biplot showing genotype x environment interaction in oil concentration for seven genotypes of mustard and canola (bold) grown in 15 environments in WA. Loading of variables in components 1 and 2 are shown by the direction and strength of the biplot lines. Percentage variation explained by each component is given next to the axis.
(M–Merredin, MU–Mullewa, N–Newdegate, 00–2000 growing season, 01-2001 growing season, S1- early sowing, S2- mid sowing, S3- late sowing. As an example first sowing at Merredin in 2000 - M00S1)

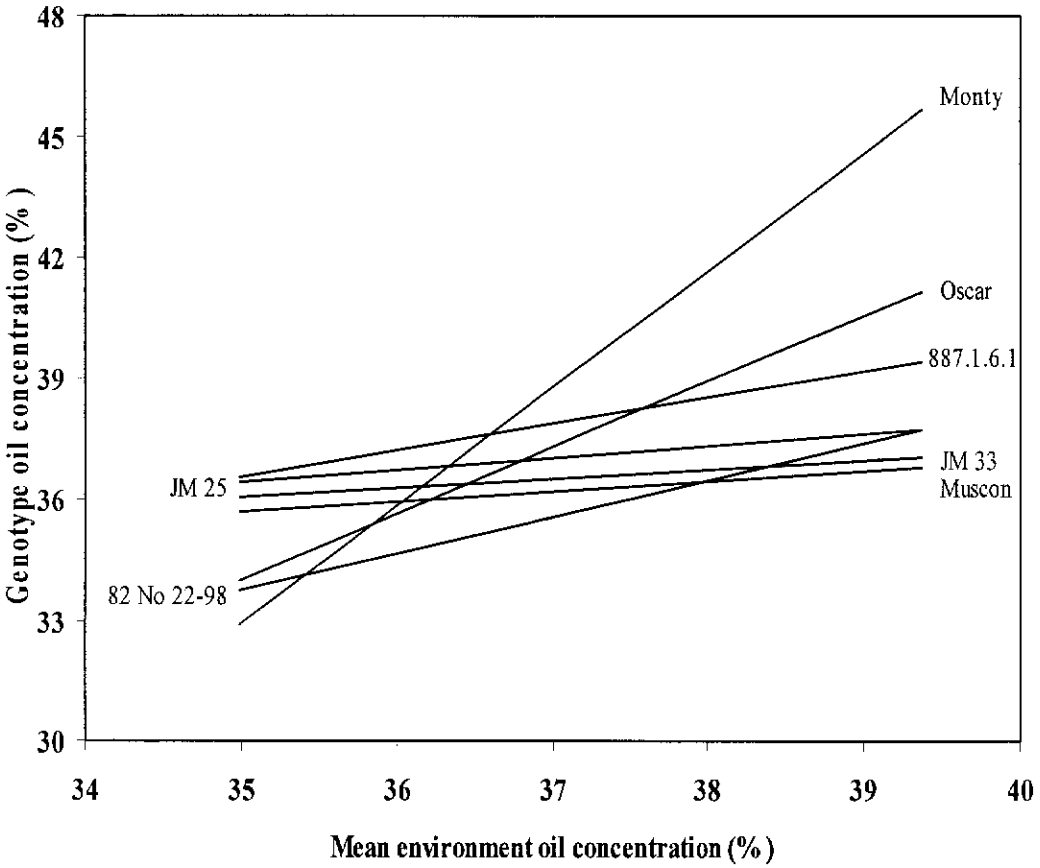

Figure 4.7. (a). Plot of linear regressions between individual oil concentration in seven genotypes of mustard and canola and mean environment oil concentration calculated from 15 environments.

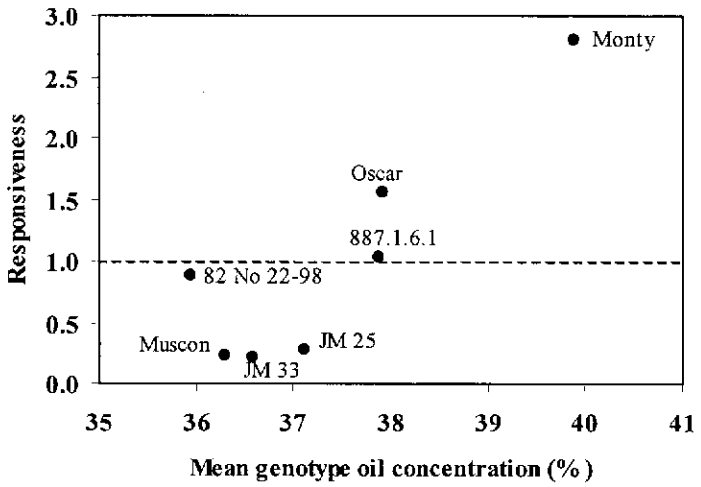

Figure 4.7 (b). Plot of responsiveness in oil concentration to environments for seven genotypes of mustard and canola grown in 15 environments.

4.3.9. Seed protein concentration

Seed protein concentration was inversely proportional to seed oil concentration. Genotypes that produced less oil have produced more protein and the environments, which unfavorably contributed to oil production, have favorably contributed to protein production. Seed protein concentrations were significantly higher from late sown crops at Merredin in both years (Tables 4.10 & 4.11) and at Mullewa in 2000 (Table 4.10). Seed protein concentrations were unusually low in the late sowing at Newdegate in 2000 and did not differ significantly between times of sowing at Newdegate in 2001 (Table 4.11).

There was a greater variation in seed protein concentration (19.9 to 31.8 %) depending on genotypes, times of sowing, sites, and years. 82 No 22-98, Muscon and JM 33 produced higher protein concentrations in all environments (Tables 4.10 & 4.11). Oscar behaved quite similarly to the above mustard group and produced similar levels of protein particularly in late sowings. Monty, JM 25 and 887.1.6.1 produced the least concentration of protein in all environments.

4.3.10. Genotype x environment interaction in protein concentration

The biplot presented in the Figure 4.8 exhibited the genotype x environment interaction in protein concentration after the main effect of sites has been removed. In the principal component analysis, the first two principal components have accounted for 91 % of the variation in protein concentrations. The main results from the biplot (Figure 4.8) are; (i) three genotypes (82 No 22-98, Muscon, and JM 33) producing higher protein concentrations were separated from genotypes producing lower protein concentrations (Oscar, JM25, Monty, and 887.1.6.1), (ii) Biplot vectors based on component loadings show that environments were not separated on negative zone of principal component 1 unlike in the biplots for seed yield and oil concentrations. (iii) genotypes that performed relatively well at particular environments were clearly shown.

Mustard genotypes 82 No 22-98 and Muscon produced above average protein concentrations in all environments. JM 33 produced below average protein concentrations only at M01S1 and N01S2.

Table 4.10. Seed protein concentrations (%) at 6.5 % moisture in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, Mullewa and Newdegate, WA in 2000.

Genotype	Merredin 2000				Mullewa 2000				Newdegate 2000			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (1 May)	Mid (13 June)	Late (5 July)	Mean	Early (16 June)	Mid (30 June)	Late (14 July)	Mean
887.1.6.1	20.4	20.8	22.9	21.3	19.9	23.8	27.1	23.6	25.1	26.6	24.8	25.5
JM 25	21.6	22.6	26.0	23.4	22.3	27.7	30.6	26.9	28.0	28.8	25.8	30.9
JM 33	24.6	26.0	29.1	26.6	23.0	29.5	31.6	28.0	31.4	31.5	29.9	25.3
Muscon	25.7	24.7	28.2	26.2	25.3	30.1	31.1	28.8	30.1	31.8	30.3	30.7
82 No 22-98	26.2	26.0	28.5	26.9	24.7	30.5	31.5	28.9	30.9	31.7	30.3	31.0
Monty	20.0	21.9	24.8	22.2	20.9	26.7	30.5	28.8	26.0	25.9	24.1	25.3
Oscar	23.1	24.5	26.9	24.8	24.3	29.8	31.1	28.4	27.9	26.9	26.1	27.0
Mean	23.1	23.8	26.6	24.5	22.9	28.3	30.5	27.2	28.5	29.0	27.3	28.3
LSD (P = 0.05)	TOS =0.05 VAR = 0.2 TOS X VAR = 0.4 VAR / Same levels of TOS = 0.4				TOS = 0.12 VAR = 0.17 TOS X VAR = 0.29 VAR / Same levels of TOS = 0.3				TOS = 0.21 VAR = 0.20 TOS X VAR = 0.36 VAR / Same levels of TOS = 0.35			

Table 4.11. Seed protein concentrations (%) at 6.5 % moisture in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin and Newdegate, WA in 2001.

Genotype	Merredin 2001				Newdegate 2001			
	Early (24 May)	Mid (15 June)	Late (13 July)	Mean	Early (1 June)	Mid (10 July)	Late (24 July)	Mean
887.1.6.1	21.0	22.1	23.2	22.1	21.9	22.3	22.4	22.2
JM 25	22.6	23.2	24.5	23.4	23.7	24.6	23.7	24.0
JM 33	22.7	24.8	27.6	25.0	24.5	25.1	24.9	24.9
Muscon	28.4	29.7	31.1	29.7	25.9	28.0	26.7	26.9
82 No 22-98	25.7	27.7	29.7	27.7	24.6	26.8	26.4	25.9
Monty	19.7	21.8	25.4	22.3	22.2	25.9	24.0	24.1
Oscar	22.7	21.0	27.6	23.8	24.7	26.9	26.0	25.9
Mean	23.2	24.3	27.0	24.6	24.0	25.7	24.9	24.8
LSD (P = 0.05)	TOS = 0.8 VAR = 0.5 TOS X VAR =1.0 VAR / Same levels of TOS = 0.8				TOS = 2.6 VAR = 0.5 TOS X VAR = 2.5 VAR / Same levels of TOS = 0.9			

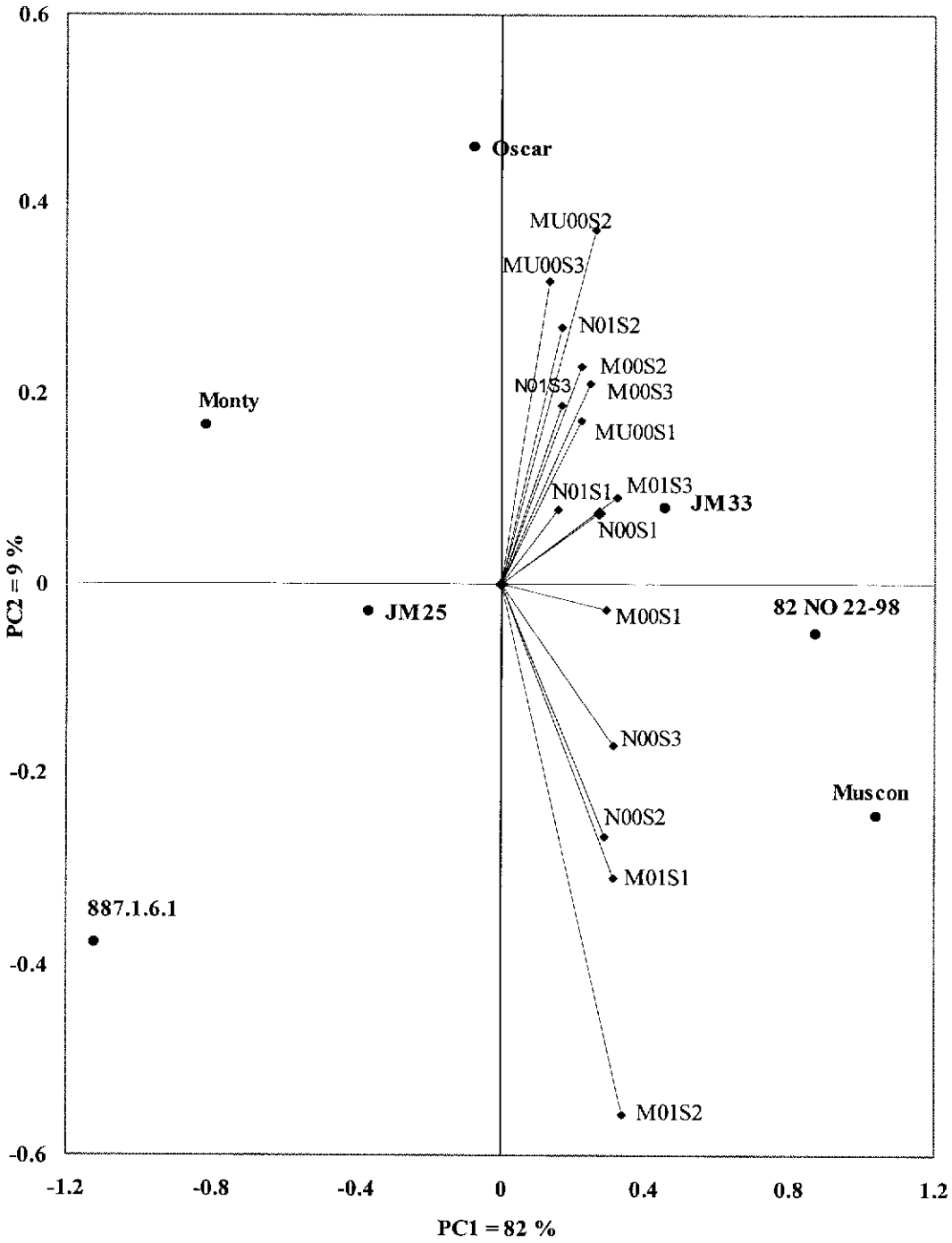

Figure 4.8. Principal components (1 and 2) biplot showing genotype x environment interaction in protein yield for seven genotypes of mustard and canola (bold) grown in 15 environments in WA. Loading of variables in components 1 and 2 are shown by the direction and strength of the biplot lines. Percentage variation explained by each component is given next to the axis.
(**M**–Merredin, **MU**–Mullewa, **N**–Newdegate, **00**–2000 growing season, **01**-2001 growing season, **S1**- early sowing, **S2**- mid sowing, **S3**- late sowing. As an example first sowing at Merredin in 2000 - **M00S1)**

Oscar produced lower protein concentrations in most of the environment and it produced above average protein concentrations at few environments (MU00S1, MU00S2, MU00S3, M00S2, M00S3, N01S2, and N01S3). Monty produced above average protein concentrations only at MU00S3 and N01S2 and JM 25 only at MU00S3. 887.1.6.1 produced below average protein concentrations in all environments. The Finlay-Wilkinson analysis (Finlay and Wilkinson, 1963) demonstrated that the regression of individual protein concentrations of genotypes on the mean protein concentrations for each environment was significant and accounted for 89 % variation in the data (Figure 4.9a).

The responsiveness of genotypes to the environment in respect to protein concentration ranged from 0.80 to 1.2 and was in the following increasing order: Muscon, 887.1.6.1, Oscar, 82 No 22-98, JM 25, Monty, and JM 33 (Figure 4.9b). Unlike the responsiveness of genotypes to increasing seed yield potential and oil concentrations at these environments, genotypes responded quite similarly to environments in producing protein.

Muscon showed general adaptability to all environments while producing higher protein concentrations. JM 33 and 82 No 22-98 also produced higher protein concentrations, but were slightly sensitive to environmental changes. JM 33 showed slightly below average stability and tended to perform better in favourable environments particularly in late sowings. 82 No 22-98 showed slightly above average stability and tended to perform better in poor environments particularly in early sowings. Oscar produced medium levels of protein concentrations and showed general stability. JM 25 also showed general adaptability but produced low protein concentrations. Monty and 887.1.6.1 produced the least concentrations of protein and showed slight below and above average stability respectively.

4.3.11. Significance of environmental parameters on seed yield, oil and protein concentrations

Selected environment parameters were used as fixed terms and were sequentially added to fit a variance component model to test significance of parameters on seed yield, oil and protein concentrations (Table 4.12). The model shows that variations in seed yield between experiments were explained entirely by the environmental parameters, such as total rainfall, post-anthesis rainfall, total GDD, growing period,

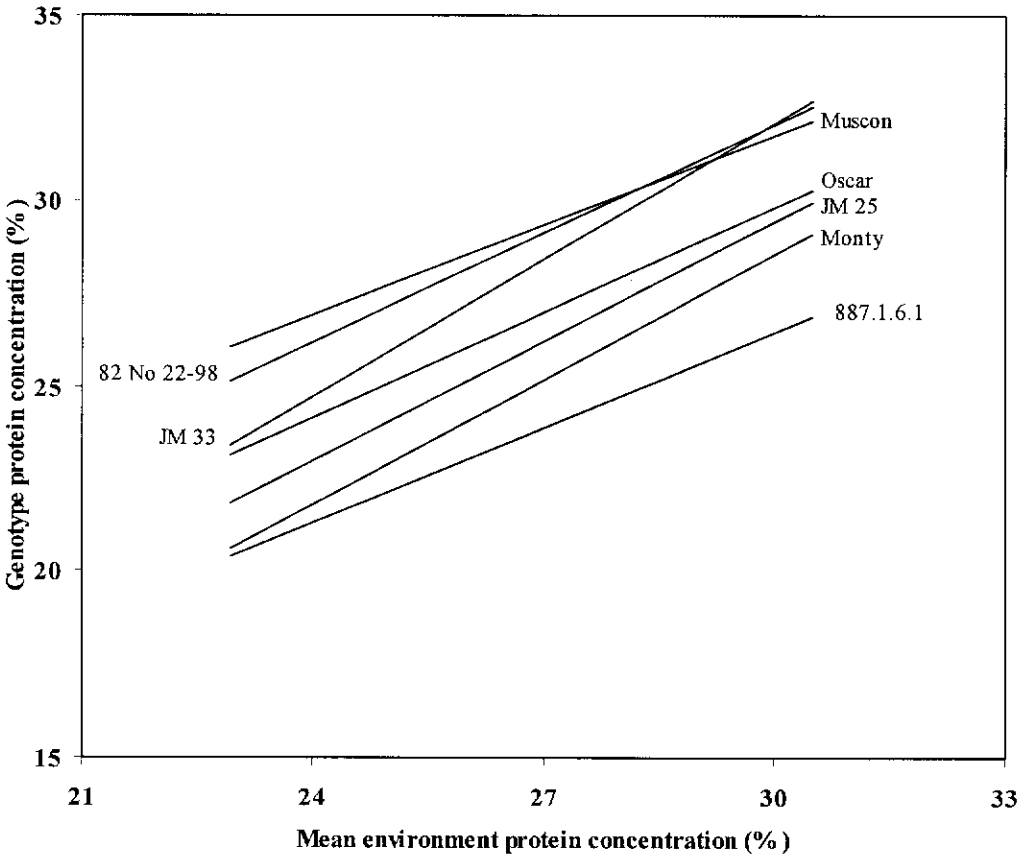

Figure 4.9. (a). Plot of linear regressions between individual protein concentration in seven genotypes of mustard and canola and mean environment protein concentration calculated from 15 environments.

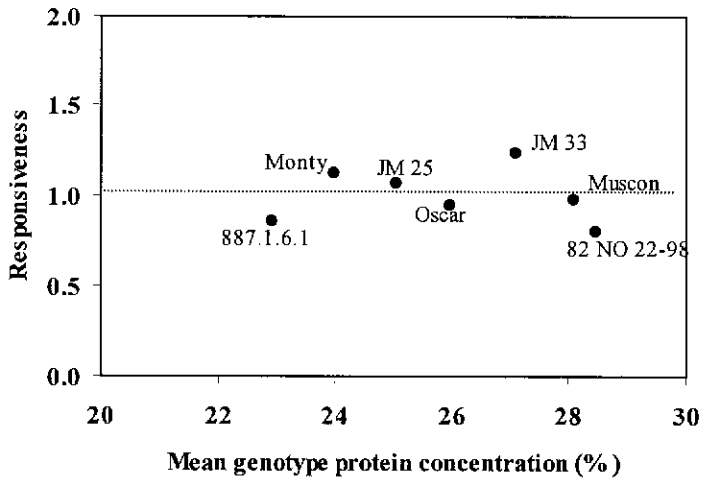

Figure 4.9 (b). Plot of responsiveness in protein concentration to environments for seven genotypes of mustard and canola grown in 15 environments.

Table 4.12. Wald statistics and significance of selected environment parameters on seed yield, oil and protein concentrations. Fixed terms were sequentially added to fit variance component model.

Descriptor	Fixed term	Wald statistics	d.f	Chi – sq prob
Seed Yield (t/ha)	Total rainfall	71.85	1	<0.001
	Post anthesis rainfall	395.08	1	<0.001
	Total GDD	50.70	1	<0.001
	Growing period	45.68	1	<0.001
	Post anthesis period	12.29	1	<0.001
	Ave. Max. temperature (post anthesis)	27.97	1	<0.001
	Ave. Max. temperature (pre anthesis)	109.72	1	<0.001
	Soil surface pH	34.98	1	<0.001
	Experiment (site/year)	5.58	2	0.061
	TOS	1.13	1	0.287
	Species	0.59	1	0.443
	Species. Genotype	36.38	5	<0.001
	Experiment. Species. Genotype	13.90	12	0.307
	TOS. Species. Genotype	27.23	12	0.007
	Experiment. TOS. Species. Genotype	41.82	24	0.014
Oil concentration (%)	Total rainfall	22.97	1	<0.001
	Post anthesis rainfall	91.24	1	<0.001
	Total GDD	0.033	1	0.871
	Growing period	0.88	1	0.349
	Post anthesis period	42.00	1	<0.001
	Ave. Max. temperature (post-anthesis)	0.78	1	0.006
	Ave. Max. temperature (pre-anthesis)	7.65	1	0.377
	Soil surface pH	106.72	1	<0.001
	Experiment (site/year)	9.41	2	0.009
	TOS	2.40	1	0.121
	Species	225.87	1	<0.001
	Species. Genotype	147.53	5	<0.001
	Experiment. Species. Genotype	108.09	12	<0.001
	TOS. Species. Genotype	99.42	12	<0.001
	Experiment. TOS. Species. Genotype	94.16	24	<0.001
Protein concentration (%)	Total rainfall	760.97	1	<0.001
	Post-anthesis rainfall	281.14	1	<0.001
	Total GDD	31.73	1	<0.001
	Growing period	1.12	1	0.289
	Post-anthesis period	13.89	1	<0.001
	Ave. Max. temperature (post-anthesis)	11.53	1	<0.001
	Ave. Max. temperature (pre-anthesis)	30.17	1	<0.001
	Soil surface pH	247.02	1	<0.001
	Experiment (site/year)	34.17	2	<0.001
	TOS	10.00	1	0.002
	Species	107.56	1	<0.001
	Species. Genotype	957.58	5	<0.001
	Experiment. Species. Genotype	57.49	12	<0.001
	TOS. Species. Genotype	19.75	12	<0.001
	Experiment. TOS. Species. Genotype	40.30	24	0.072

average maximum post-anthesis and pre-anthesis temperatures and soil surface pH. However, the model showed that some variations between experiments for oil and protein concentrations are not explained entirely by the above parameters. For seed yield, the effect of species and genotype x environment interaction can be explained entirely by these parameters, but not for oil and protein concentrations.

4.3.12. Determinants of seed yield

Seed yield was strongly correlated to final above ground dry matter, post-anthesis dry matter, harvest index (HI), total number of pods/plant, primary pods/plant, secondary pods/plant, final plant height and number of primary branches in both years at Merredin (Table 4.13). Number of secondary branches and 1000 seed weight were significantly correlated with average seed yield in 2000 but not in 2001 at Merredin. Duration to flowering and number of seeds/pod were not significantly correlated with seed yield in either year at Merredin (Table 4.13). Seed yield, final above ground dry matter, harvest indices and yield component data are presented in the appendices 1, 2, 3 and 4.

Principal component biplots for 2000 and 2001 (Figure 4.10) demonstrate the relationship between average seed yield and some phenological (flowering date), morphological (plant height, number of branches), physiological (dry matter production and partitioning) traits and yield components (number of pods/plant, number of seeds/pod and 1000 seed weight) at Merredin. All the above parameters were plotted on the same graph to identify their contribution to seed yield in each genotype. In the principal component analysis, the first two PCs accounted for 81 % of the variation in data in 2000 but accounted for only 69 % of the variation in data in 2001. Therefore, results of the principal component biplot for 2000 are in more agreement with the correlations presented in Table 4.13 compared to that of 2001.

Variation in seed yield in 2000 was more explained by the PC2 and the strong correlation of final above ground dry matter and harvest index (HI) is shown in the biplot. Average seed yield in 2000 was higher from 82 No 22-98, 887.1.6.1, Muscon and Monty and was lower from JM 25, JM 33 and Oscar. All mustard genotypes were separated in the right side quadrants of the biplot as they produced more final above ground dry matter, primary and secondary branches, pods/plant, primary and

Table 4.13. Correlation between seed yield and some phenological, morphological attributes and yield components in mustard and canola sown at three times (early, mid, late) at Merredin, WA in 2000 and 2001.

Measurement	Correlation co-efficient	
	2000	2001
Final above ground DM	0.90 **	0.88 **
Pre-anthesis DM	0.51 **	0.20 *
Post-anthesis DM	0.77 **	0.88 **
Total pods/plant	0.60 **	0.42 **
Primary pods/plant	0.65 **	0.41 **
Secondary pods/plant	0.32 **	0.32 **
Final plant height	0.48 **	0.32 **
Primary branches	0.46 **	0.26 *
Post-anthesis duration	0.54 **	0.72 **
Secondary branches	0.34 **	0.24 ns
1000 seed weight	0.41 **	0.00 ns

secondary pods/plant, dry matter at flowering and were taller than canola genotypes Monty and Oscar. On the other hand, Monty and Oscar were separated in left side quadrants of the biplot as they produced heavier seeds, more seeds/pod, and longer pods and had higher HI than mustards. Oscar and JM 33 were the late flowering genotypes.

Variation in seed yield in 2001 was more explained by the PC1. As Oscar and Monty have produced higher yields in 2001 compared to 2000, they were separated in right side quadrants of the biplot for 2001 and mustards in left side. In 2001, also canola and mustard genotypes have been differentiated by the same morphological and physiological traits. However, seed weight was not different between two species in 2001. Unlike in 2000, the strong correlation of HI with seed yield was only well explained in the biplot. Since canola produced lower final above ground dry matter but higher seed yields, two measurements were separated in opposite directions in the biplot for 2001 unlike in 2000. Late flowering Oscar and JM 33 flowered earlier in 2001 than in 2000, hence these genotypes were not separated based on the flowering date.

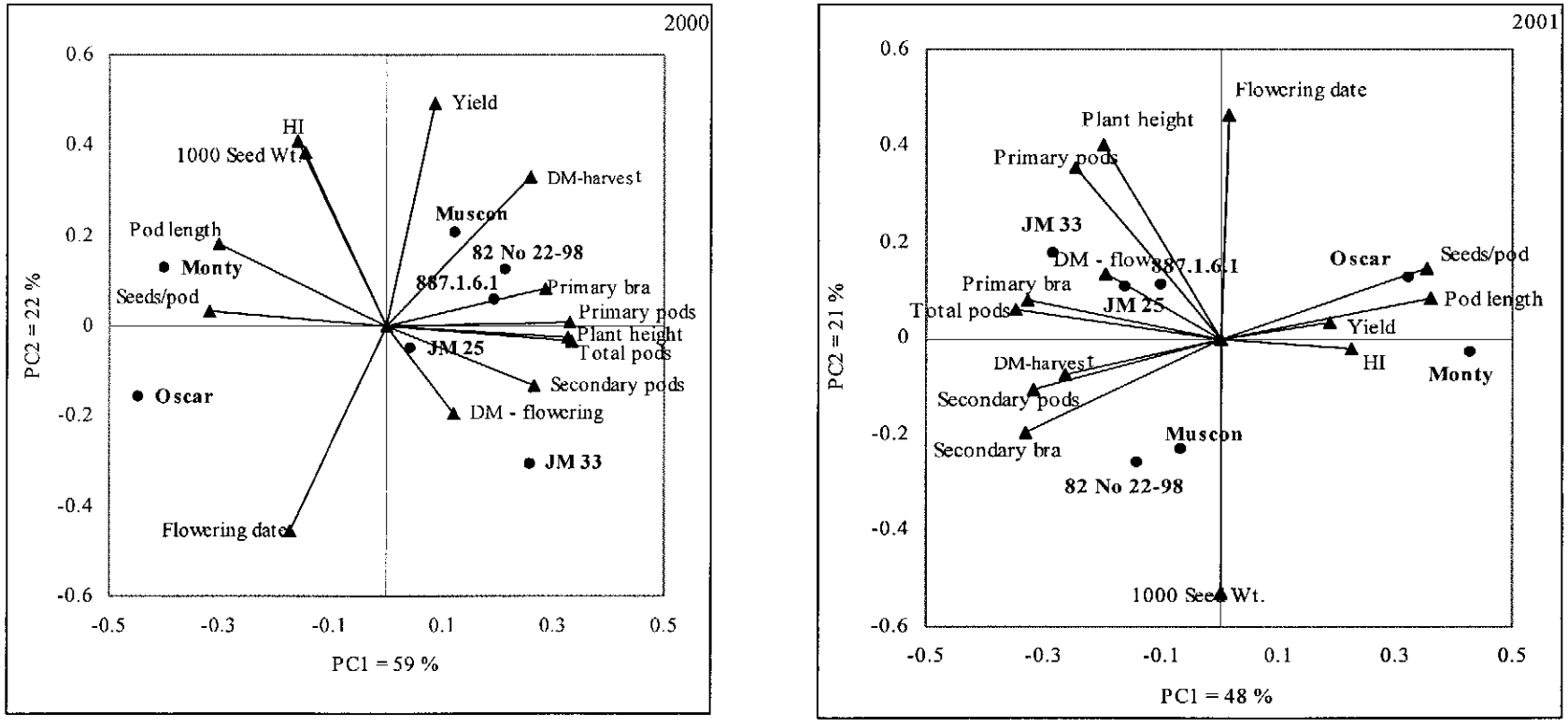

Figure 4.10. Principal component analysis of some phenological and morphological traits, and yield components in seven genotypes of mustard and canola sown at Merredin, WA in 2000 and 2001.

4.4. DISCUSSION

Discussion in this chapter is divided into two parts; the first addresses the significance of environmental parameters in determining seed yield, oil and protein concentrations of mustard and canola. The second focuses on the genotype x environment interaction on responsiveness and adaptation of mustard and canola genotypes to a range of environments.

4.4.1. The effect of environmental parameters on seed yield, oil and protein concentrations

Based on the environment mean for seed yield obtained from Finlay Wilkinson analysis (Figure 4.5.a), environments examined in this study appeared to fall into three categories. M01S1, MU00S1, M00S1, and N01S1 were higher yielding environments. M00S2, M00S3, N01S2 and N00S1 were medium yielding and MU00S3, M01S2, MU00S2, N00S2, N01S3, M01S3 and N00S3 were lower yielding environments. By analysing the characteristics of these environments (Table 4.2) factors contributing to a range of seed yields could be identified.

In the higher yielding environments, crops were sown early in the season mostly in May, except at N01S1. Crop growing and post-anthesis durations were longer in these environments. Despite later sowing (mid June) compared to the other three higher yielding environments, growing duration at N01S1 was longer due to unusual rainfall, which occurred at the end of the season (Figure 4.2). Growing season rainfall was higher in these environments (100 to 200 mm) and more importantly during the post-anthesis phase, it was more than 75 mm. Temperature was relatively higher (18 to 20 ^{0}C) during the pre-anthesis phase of the crop (except at Newdegate) and was relatively lower (less than 24 ^{0}C) during the post-anthesis phase in these environments.

In medium yielding environments crops were sown in early June to early July. During the pre-anthesis phase, relatively higher rainfall was received but temperature was relatively low (15 to 17 ^{0}C). Rainfall during the post-anthesis phase was low (5 to 16 mm) and temperatures were relatively higher (24 to 27 ^{0}C). During reproductive development crops suffered from soil moisture due to low rainfall and high temperature stresses. Temperatures at Merredin were relatively warmer (17 ^{0}C) during the pre-anthesis phase of the crop compared to Newdegate (15 to 16 ^{0}C), but

temperature during the post-anthesis phase was higher at Merredin (25 to 27 ^{0}C) than at Newdegate (24 ^{0}C).

Crops in the lower yielding environments were sown very late in the season from mid June to late July. The lowest amount of rainfall was recorded at MU00S2, MU00S3, and N00S3 and the rainfall recorded during post-anthesis phase in all of these environments was lower (7 to 24 mm). Temperature during pre-anthesis phase was higher (17 to 20 ^{0}C) except at N00S2 and N00S3 (16 ^{0}C). Temperature during post-anthesis phase was also higher (25 to 29 ^{0}C) compared to high and medium yielding environments. Although lower yielding environments (except MU00S3) received similar post-anthesis rainfall as medium yielding environments, seed yields were lower as a result of insect pest attack and relatively higher temperatures during reproductive development.

Seed yields of canola declined with later sowings in temperate to sub-tropical environments (Hocking *et al.*, 1991; Heenan and Armstrong, 1993; Hocking and Stapper, 1993; Semmel *et al.*, 1995; Robertson *et al.*, 1999). In the present study, seed yield of mustard and canola declined by 0.09 and 0.16 kg per week delay in sowing at Merredin in 2000 and 2001 respectively. At Mullewa seed yield of mustard and canola declined by 0.10 kg per week delay in sowing in 2000, and at Newdegate the corresponding figures were 0.06 and 0.09 in 2000 and 2001 respectively. Seed yields from late sown *Brassica* oilseed crops are lower due to reductions in the duration of pre-anthesis development due to hastened phenological development (Thurling and Vijendra Das, 1979; Mendham *et al.*, 1990; Hocking *et al.*, 1991) combined with reduced post-anthesis growth (Mendham *et al.*, 1990; Hocking *et al.*, 1991). Walton (1999) found that seed yield of canola was correlated with post-anthesis duration (r^2 = 0.53) in similar environments. Similarly, Seed yield was correlated to growing duration (r^2 = 0.51) and post-anthesis duration (r^2 = 0.51) in this study (Table 4.2). Post-anthesis duration of higher yielding environments was longer than medium and low yielding environments. Longer reproductive growth led to higher dry matter (Duncan *et al.*, 1978). As a result, crops in higher yielding environments accumulated more pre-anthesis and post-anthesis dry matter and produce higher seed yields. As found at Merredin, seed yield was strongly correlated

to final above ground dry matter and post-anthesis dry matter in both years (Table 4.13).

In Mediterranean-type environments, where terminal drought is likely, seed yields from late sowings are reduced by low rainfall and high temperature stress usually occurring at the end of the growing season (Turner, 1986; Loss and Siddique, 1994; Turner, 1997; Turner *et al.*, 2001). Water deficits during flowering and early pod development of *B. napus* and *B. campestris*, have a great impact on seed yield (Richards and Thurling, 1978a; Tayo and Morgan, 1979; Mendham *et al.*, 1981a). Higher rainfall and cooler temperatures during seed development produce higher seed yields in canola (Walton, 1999). Similar effects of post-anthesis rainfall and temperature on seed yield were found in this study. Seed yield was positively correlated (Table 4.2) with post-anthesis rainfall (r^2 = 0.82) and was negatively correlated with average daily temperature (r^2 = -0.49) and average maximum daily temperature (r^2 = -0.51) during post-anthesis phase. Seed yield increased by 0.02 kg for each 1 mm rise in rainfall and by 0.12 kg for each 1 ^{0}C fall in average daily or average maximum temperature during post-anthesis period in this study. Relatively higher rainfall and lower temperatures received during pod development and seed filling periods in higher yielding environments are associated with reduced stresses due to low soil moisture and high temperature. These conditions are favourable for greater post-anthesis biomass production. Late sown crops were not able to escape the increasing temperatures and soil moisture stress resulted from the low rainfall that occurred at the end of the growing season, leading to lower seed yield.

Seed yield was not strongly correlated with any of the environmental parameters during the pre-anthesis phase (Table 4.2) in this study. However, the establishment and the vegetative development of the crop were favoured by the warmer conditions during the pre-anthesis phase. Low air and soil temperatures normally experienced in early winter after sowing in Mediterranean-type environments, can reduce germination, delay seedling emergence, limit seedling growth rate and rate of leaf appearance of *Brassica* oilseed species (Thurling, 1974 a). Reduction in leaf numbers and leaf area renders an inability to attain full ground cover resulting in lower photosynthesis and dry matter production (Mendham *et al.*, 1981a; Hocking *et al.*, 1991). Pre-anthesis phases were relatively warmer in higher yielding environments, compared to medium yielding environments and some of the low yielding

environments in this study. Higher rate of leaf and branch appearance favoured by warmer conditions in higher yielding environments have resulted in a good canopy that absorbed more radiation and produced higher amounts of biomass before flowering. Under these conditions the crop uses water more efficiently by increasing the proportion of water transpired relative to evaporation losses.

Of the higher yielding environments, the pre-anthesis phase was relatively cooler at N01S1 (Table 4.2) and this could be a reason for the relatively lower seed yields compared to the other three, despite the very high rainfall recorded at this environment. Lower plant densities that resulted from poor germination due to lower temperatures and wind blast at N01S1 was a factor for lower seed yields. Of the medium yielding environments, crops at Merredin may have been favoured by the relatively warmer pre-anthesis phase compared to those at Newdegate. Of the lower yielding environments, crops at Mullewa performed better despite the very low rainfall recorded and this also may be related to warmer conditions during the pre-anthesis period.

Based on the site index for oil concentration in the Finlay-Wilkinson analysis (Figure 4.7a), M00S1, M01S1, MU00S1, and M00S2 were higher oil producing environments. M00S3, N01S1, M01S2, N00S1, N00S3, and N00S2 were medium oil producing environments and lowest oil concentrations were from M01S3, MU00S2, N01S2, N01S3 and MU00S3. Drought and high temperatures have a negative effect on oil concentration (Heenan and Armstrong, 1993; Jensen *et al.*, 1996; Hocking *et al.*, 1997; Blondel and Renard, 1999; Walton, 1999). Similarly, oil concentrations were higher from the environments that received higher rainfall and cooler temperatures during post-anthesis period (Table 4.2) in this study. As found previously (Blondel and Renard, 1999), oil and protein concentrations were negatively correlated and protein concentration increased with low soil moisture and high temperature in this study.

Oil concentration was correlated positively to rainfall (r^2 = 0.61) and negatively to average daily temperature (r^2 = -0.37) and average maximum temperatures (r^2 = -0.49) during post-anthesis period in this study (Table 4.2). Oil concentration increased by an average of 0.04 % over all genotypes and environments, for each 1 mm rise in rainfall and by 0.27 % for each 1^0C fall in average daily temperature.

Results agreed with those of Walton (1999), who found that the oil concentration of canola increased by 0.06 % for each 1 mm rise in rainfall and by 0.86 % for each 1 ^{0}C fall in average daily temperature. Protein concentration was correlated negatively to rainfall (r^2 = -0.69) and positively to average daily temperature (r^2 = 0.42) and average daily maximum temperature (r^2 = 0.49) during the post-anthesis period (Table 4.2). Protein concentration increased by an average of 0.11 % over all genotypes and environments, for each 1 mm fall in rainfall and by 0.63 % for each 1 ^{0}C rise in average daily temperature.

4.4.2. Genotype x environment interaction on seed yield, oil and protein concentrations

Genotype x environment interaction on seed yield was presented in the principal component biplot (Figure 4.4). Principal component 1 (PC1) scores were significantly and negatively correlated to soil surface pH (r^2 = -0.64) and average maximum temperature during the pre-anthesis period (r^2 = -0.49). Principal component 2 (PC2) scores were significantly correlated to post-anthesis rainfall (r^2 = 0.57), growing period (r^2 = 0.50), pre-anthesis period (r^2 = 0.46) and negatively to average maximum temperature during post-anthesis period (r^2 = -0.49). Plot of responsiveness (Figure 4.5b) explains the phenotypic stability and adaptability of genotypes over the environments studied. Mustard genotypes 887.1.6.1 and 82 No 22-98 have the highest environment mean index for seed yield and have shown average phenotypic stability. Finlay and Wilkinson (1963) have described the 'ideal' genotype having general adaptability as the one with maximum yield potential in the most favorable environments and average phenotypic stability. Based on this definition, 887.1.6.1 and 82 No 22-98 can be described as genotypes having general adaptability. Muscon and Monty also showed average phenotypic stability but their environment mean index for seed yield was lower compared to 887.1.6.1 and 82 No 22-98. JM 33 and JM 25 showed above average phenotypic stability and Oscar showed below average stability. The principal component biplot for seed yield (Figure 4.4) explains the factors contributing to the phenotypic stability of the genotypes.

Mustard genotypes 887.1.6.1, 82 No 22-98 and Muscon separated in opposite directions on the PC1 axis to Oscar, Monty, JM 25 and JM 33 showing that

887.1.6.1, 82 No 22-98 and Muscon performed better on lower pH soils while the others performed better on soils with higher pH (Table 4.1). Although an apparent genotype sensitivity to pH was observed in this study, it is hard to draw conclusions about the genotype sensitivity to pH without further research as the range of pH measured in the experiments are quite small, and lower pH ones were in one site. Monty, Oscar and 887.1.6.1 have separated in top quadrants and 82 No 22-98, Muscon, JM 25 and JM33 in bottom quadrants of the biplot (Figure 4.4). It explains that Monty, Oscar and 887.1.6.1 produce higher seed yields in the environments where, post-anthesis rainfall is higher, and post-anthesis temperature is lower. Higher PC2 scores of Monty and Oscar explains that they are more sensitive to low rainfall and high temperature stresses during the post-anthesis development compared to 887.1.6.1. This could be a reason for below average stability and lower mean seed yield of Monty and Oscar compared to 887.1.6.1. Mustard genotypes 82 No 22-98, Muscon, JM 25 and JM 33 were more tolerant to low rainfall and high temperature stress during post-anthesis period compared to Monty, Oscar and 887.1.6.1. This may be related to higher stability of Muscon and 82 No 22-98 compared to 887.1.6.1. Tolerance to low rainfall and high temperature stress was in the following decreasing order; JM 33, JM 25, Muscon, 82 No 22-98, 887.1.6.1, Oscar and Monty. This result agrees with many other studies that showed a greater tolerance of mustard to low rainfall and high temperature stress compared to canola (Kumar *et al.*, 1984; 1987; 1994; Wright *et al.*, 1992; 1995; 1996; Niknam and Turner, 1999).

Separation in opposite directions on PC1 also shows that seed yields in Oscar, Monty, JM 25 and JM 33 was higher at the environments where temperatures during the pre-anthesis period was higher. Rapid early growth under lower temperatures or early vigour is more pronounced in 887.1.6.1, 82 No 22-98 and Muscon compared to Monty, Oscar, JM 25 and JM 33. The higher rate of leaf production under low temperatures is considered as a selection criterion for an ideotype in Mediterranean-type environments (Lewis and Thurling, 1994). Rapid early growth under lower temperatures or early vigour accelerates the rate of canopy closure and eventually increases the amount of water transpired compared to soil evaporation. Early vigour therefore, increases water use, dry matter production and seed yield (Turner *et al.*, 2001). Early vigour also has a positive influence on yield potential due to increased radiation interception and dry matter production (Ludlow and Muchow, 1990).

Vigorous early growth also enables greater root development, so that yield is less restricted by terminal drought stress (Ludlow and Muchow, 1990).

Early growth in Monty and Oscar was slower unless relatively warmer conditions are met during vegetative development. This was observed at Merredin where detailed measurements of dry matter were taken in two different growing seasons in 2000 and 2001 (data not presented). Early crop growth rate (28 DAS to 88 DAS), based on dry matter accumulation, in 82 No 22-98, JM 33 (8.3 and 7.8 g/m^2/day respectively) was higher compared to Oscar (4.5 g/m^2/day) at Merredin in 2000. However, the pattern of dry matter accumulation changed in 2001. Early crop growth rate (28 DAS to 88 DAS), based on dry matter accumulation, in Oscar (5.5 g/m^2/day) was similar to 82 No 22-98 and JM 33 (5.6 and 5.0 g/m^2/day respectively). Temperature sensitive early growth in Oscar was accelerated by relatively higher temperatures during pre-anthesis phase at M01S1. Detailed studies of leaf area development and radiation absorption have shown that leaf area index and total intercepted radiation in 82 No 22-98 and JM 33 was higher compared to those in Oscar (data not presented). Wright *et al.* (1999) also found that early vigour is more pronounced in *B. juncea* than *B. napus*, which in turn is associated with greater dry matter production of *B. juncea* at maturity. Vigorous seedling growth, quick ground covering ability and early vigour of mustard have been identified as agronomic advantages over canola (Kirk and Oram, 1978; Parker, 1999).

Separation in top quadrants in the biplot (Figure 4.4) shows that seed yields in Monty, Oscar and 887.1.6.1 was higher in environments where growing period was longer, whereas seed yields in Muscon, 82 No 22-98, JM 33 and JM 25 was higher in environments where growing period was shorter. This shows that 887.1.6.1, Oscar and Monty have greater capacity to respond to longer seasons compared to Muscon, 82 No 22-98, JM 33 and JM 25. The ability to adjust the growth period depending on the extent of water deficits, i.e. developmental plasticity, is considered an important characteristic in drought prone environments (Turner *et al.*, 2001). Being more stable Muscon and 82 No 22-98 lacked in capacity to respond to longer and favourable seasons and this may be related to their lower mean seed yields compared to that of 887.1.6.1. JM 25 and JM 33 were also not able to explore longer growing seasons hence showed above average phenotypic stability and produced lower seed yields.

Although 82 No 22-98 and Muscon had similar characteristics and similar phenotypic stability, mean seed yield in Muscon was lower compared to that of 82 No 22-98, which is difficult to explain using environmental parameters that correlated with principal component scores. Detailed measurements of harvest index (HI) and yield components taken at Merredin in 2000 and 2001 shows that, lower seed yield of Muscon was associated with its inferior yield components and lower efficiency with which dry matter is converted to seed yield (Appendices 1 & 2). Yield components such as pods/plant and seeds/pod in Muscon were more sensitive to environmental changes compared to those of 82 No 22-98. Seed weight between Muscon and 82 No 22-98 was not different, however, due to reduced pod number/plant in Muscon, its seed yield was lower compared to that in 82 No 22-98 (Appendices 3 & 4).

The effect of genotype x environment interaction on oil concentration is shown in the principal component biplot for oil concentration (Figure 4.6). The PC1 scores for oil were significantly correlated to post-anthesis rainfall ($r^2 = 0.49$) and PC2 scores were significantly and negatively correlated to average maximum temperature during the post-anthesis period ($r^2 = -0.51$). Monty, Oscar and 887.1.6.1 were the higher oil producing genotypes. Stability of Monty and Oscar across environments was below average while 887.1.6.1 showed general stability. According to the biplot, these three genotypes produced highest oil concentrations in the environments that received higher rainfall during the post-anthesis period. Monty and 887.1.6.1 produced highest oil concentration when post-anthesis temperature was lower but Oscar was able to tolerate higher temperatures than all other genotypes. Monty was more susceptible to low rainfall than the other two and this may be the reason for it's below average stability (Figure 4.7b). Mustard genotypes 82 No 22-98, Muscon, JM 25 and JM 33 were the lowest oil producing group. They were able to produce higher oil concentrations under low rainfall and high temperature stress conditions during the post-anthesis phase. They performed better in low oil producing environments and showed above average stability. Muscon and 82 No 22-98 were more tolerant to low rainfall than JM 25 and JM 33, while Muscon was more tolerant to high temperature stress than the other three.

The effect of genotype x environment interaction on protein concentrations is illustrated in the principal component biplot (Figure 4.8). PC1 scores for protein were significantly and negatively correlated to duration of post-anthesis phase (r^2 = -0.58) and PC2 scores were significantly and negatively correlated to duration of pre-anthesis phase (r^2 = -0.63). Unlike seed yield and oil concentration, environmental variation of rainfall and temperature were not correlated with either of the principal component scores. This may be related to the general stability showed by all genotypes in producing protein (Figure 4.9b). Mustard genotypes Muscon, 82 No 22-98 and JM 33 produced higher protein concentration when the post-anthesis phase was shorter while the two canola genotypes and 887.1.6.1 and JM 25 showed opposite responses.

4.5. CONCLUSIONS

Seed yield of mustard and canola in low rainfall Mediterranean-type environments was higher when;

1. Sown early in the season (May) with growing duration of 155 to 195 days and post-anthesis duration of 75 to 90 days
2. Rainfall during the post-anthesis phase was >75 mm
3. Average daily temperature/average maximum daily temperature during the pre-anthesis phase was 18 ^{0}C to 20 ^{0}C, and
4. Above temperatures during the post-anthesis phase was < 24 ^{0}C.

Oil concentration of mustard and canola in Mediterranean-type environments was higher, but protein concentration was lower when;

1. Rainfall during the post-anthesis phase was <75 mm, and
2. Average daily temperature/average maximum daily temperature during the post-anthesis phase was < 24 ^{0}C.

Average phenotypic stability of mustard genotypes, 887.1.6.1, Muscon and 82 No 22-98 was mainly associated with their;

1. Grater tolerance to stressful conditions associated with low rainfall, high temperature and late sowing
2. Early Vigour
3. Shorter pre-anthesis phases, and
4. Greater dry matter production even under stressful environments.

Above average phenotypic stability of mustard genotypes, JM 25 and JM 33 were associated with their greater tolerance to stressful conditions associated with low rainfall, high temperature and late sowing.

Although the canola genotype, Monty showed average phenotypic stability, the mean seed yield in Monty was lower compared to higher yielding mustard genotypes, 887.1.6.1, and 82 No 22-98. This was related to its susceptibility to stressful conditions associated with low rainfall, high temperature and late sowing. Canola genotype Oscar was even more sensitive to stressful environments than Monty, hence was best adapted to high yielding environments and showed below average phenotypic stability.

Monty, Oscar and 887.1.6.1 were the higher oil producing genotypes. Monty and Oscar produced high oil concentrations from higher yielding environments. 887.1.6.1 showed average stability across all environments for oil concentration. All genotypes showed average stability across the environments for protein yield. 82 No 22-98 had the highest protein concentration and 887.1.6.1 the least.

This study showed that both canola and mustard were adapted to the environment tested and capable of producing better seed yields, oil concentrations and protein concentrations. Mustards were generally more adapted to more stressful conditions associated with low rainfall, high temperature and late sowing as inferred from the Principal Component and Finlay-Wilkinson analyses. Detailed studies on dry matter production at Merredin (Appendices 1 & 2) showed that mustard can produce significantly higher dry matter compared to canola particularly in later sowings. Yield reduction due to late sowing at Merredin was higher in canola (75 % and 88 % in 2000 and 2001 respectively) compared to that of mustards (58 % and 77 % in 2000 and 2001 respectively). Physiological aspects of adaptation of mustard and canola to low rainfall environments need further investigation. Studies undertaken to investigate the effect of water stress after flowering in mustard and canola are presented in the next chapter.

CHAPTER 5

Response of mustard and canola genotypes to soil moisture stress during the post-flowering period

5.1. INTRODUCTION

In the Mediterranean-type environments of south Western Australia rainfall, and thus soil moisture is the most important environmental factor affecting crop production. Seed yields are primarily limited by the short duration of the growing season and the severity of soil moisture deficits experienced during the latter phase of reproductive development (Loss and Siddique, 1994). Genotypes with drought resistant characteristics have improved adaptation and seed yields in these environments. Drought escape, dehydration postponement, and dehydration tolerance have been proposed as the three categories of drought resistance in water limited environments (Turner *et al.*, 2001).

Plants are said to escape drought, if they could germinate after rain, grow rapidly, flower and set seeds before the soil moisture is exhausted (Turner *et al.*, 2001). Selection for shorter time to flowering has been highly successful in Mediterranean-type environments (Lewis and Thurling, 1994; Loss and Siddique, 1994; Siddique *et al.*, 1999; 2001; 2003). In addition to earliness, the longer the leaves and other plant parts can survive during grain filling, the more likely they are to contribute to yield by supplying carbon to developing seeds (Ludlow and Muchow, 1990). Some plants avoid dehydration of their tissues, despite soil water deficits, by maintaining cell turgor and cell volume. Turgor can be maintained by maintaining water uptake, reducing water loss or by osmotic adjustment (Turner *et al.*, 2001). Low stomatal conductance reduces water loss; however, its usefulness depends on the trade-off between loss of production and the need to prevent dehydration (Ludlow and Muchow, 1990). In leaves with osmotic adjustment, stomata remain partially open to progressively lower water potential. This strategy allows photosynthetic activity to continue during soil water deficits (Ludlow, 1987).

Osmotic adjustment is the active accumulation of solutes by the plant in response to increasing water deficits in the soil and/or plant, thereby maintaining turgor or reducing the rate of turgor loss as water potential decreases (Turner *et al.*, 2001). It maintains stomatal conductance and photosynthesis at low water potential, delays leaf senescence and death, reduces flower abortion and improves root growth and water extraction from the soil as water deficits develop (Turner, 1997; Turner *et al.*, 2001). Osmotic adjustment maintains higher harvest index by increasing assimilate supply during seed filling, by delaying leaf senescence, by maintaining photosynthetic activity of remaining leaves, and by increase use of pre-anthesis assimilates in seed filling (Ludlow and Muchow, 1990). Osmotic adjustment also has been related to dehydration tolerance as it reduces the rate of leaf senescence (Fowler and Ludlow, 1987). The lethal water/osmotic potential, i.e., the lowest water/osmotic potential experienced by the last viable leaf, is a key measure of dehydration tolerance (Sinclair and Ludlow, 1986). Low lethal water status refers to more negative water potentials and low RWC (Ludlow and Muchow, 1990).

Indian mustard is reputed to be more drought tolerant than canola. Mustard produces higher above ground dry matter and seed yields compared to canola under severe soil moisture deficits (Wright *et al.*, 1995; 1996; 1997). Mustard leaves have higher turgor pressure than those of canola under severe soil moisture deficit, which helps to maintain longer leaf area duration (Wright *et al.*, 1996; 1997; Wright and Morgan, 1998). Osmotic adjustment in mustard is greater compared to canola (Kumar *et al.*, 1984; 1987; Wright *et al.*, 1996; 1997; Kumar and Singh, 1998; Wright and Morgan, 1998). Due to osmotic adjustment, mustard can maintain high leaf water potential and consequently, maintain relatively normal rates of transpiration as evidenced by high stomatal conductance (Kumar *et al.*, 1987). A negative correlation between osmotic adjustment and percentage yield reduction under soil moisture stress in *B. juncea* and *B. napus* was found by Niknam and Turner (2000).

Mustard genotypes had better performance and greater adaptation to low rainfall and high temperature stresses than canola in the genotype x environment interaction study (Chapter 4). In order to understand the superior performance of mustard in these environments, its water use and the morphological and physiological basis of adaptation to soil moisture stress were investigated in this study.

5.2. MATERIALS AND METHODS

5.2.1. Experimental design and trial management

A field experiment was conducted in the low rainfall cropping region of Western Australia at Merredin (31°29'S, 118°18' E) in the 2001 growing season. Two mustard breeding lines; Muscon (Early maturing, short, condiment line) and 887.1.6.1 (Early maturing, short, near canola quality line) and an early maturing commercial canola variety Monty, were tested for their response to water stress after flowering. Three stress treatments were imposed; all rain excluded (severe water stress), rainfed (medium water stress) and irrigated (control). The crop was sown in three adjacent blocks. The first block was positioned so that it could be covered by a rainout shelter during rainfall events, the second block was rainfed and the third block was trickle irrigated. Each block was a randomized complete block design with four replicates.

Plots were hand seeded on 6 June 2001 at the rate of 6 kg/ha. Plots were 1.8 m wide (10 rows, 18 cm apart) and 4 m long. The trial site was of sandy loam soil with a pH of 4.7 at 10 cm and 5.2 at 30 cm (in $CaCl_2$). The paddock was cropped with wheat in 2000, pasture in 1999 and canola in 1998. Weeds were controlled a week before sowing with Roundup at 1 L/ha (glyphosate 450 g ai/L). Double Superphosphate was direct drilled at the rate of 114.2 kg/ha before sowing. Urea was applied at the rate of 130 kg/ha at sowing. Redlegged earth mite (*Halotydeus destructor*) and Cutworm (*Agrostis* spp.) were controlled at the vegetative phase using Endosulfan (350 g/L) at 2.0 L/ha. Aphids (*Aphis craccivora*) and Cabbage moth (*Plutella xylostella*) were controlled by spraying Endosulfan (350 g/L) at 2.0 L/ha during flowering and pod development.

To impose severe water stress a rainout shelter was erected 80 DAS when 50 % of plants produced their first open flower in all plots in the first block. Thereafter, the plots in this block were covered by the rain out shelter before each rainfall event until physiological maturity. The third block was trickle irrigated commencing at flowering (80 DAS) until physiological maturity. Plots were irrigated twice a week, equivalent to the pan evaporation occurring during that period, corresponding to 228 mm of water, measured by a water measurement gauge, applied over a 53 day period. Daily rainfall, maximum and minimum temperatures were recorded using an

automatic weather station at the site. Web published data (www.agric.wa.gov.au), recorded at Merredin Research Station of daily evaporation were used to calculate the amount of irrigation to apply and daily total incident radiation (S) were used to calculate the radiation use efficiency.

5.2.2. Measurements

5.2.2.1. Days to flowering

The date on which 50 % of plants produced their first open flower (DOF) was recorded in each plot.

5.2.2.2. Plant water relations

The leaf water potential (Ψ), relative water content (RWC) and osmotic potential (π) of leaves were measured in all plots of rainout shelter and irrigated blocks commencing at DOF until leaf senescence.

The leaf water potential (Ψ_l) of uppermost fully expanded, unshaded leaves was measured at weekly intervals between 78 to 142 DAS around midday (10.00 to 14.00 h) on a clear sunny day using the pressure chamber technique (Scholander et al., 1964) and following the recommended precautions (Turner, 1988). The selected leaf was inserted into a polythene bag to minimize evaporation with the petiole exposed and the leaf was cut at the stem end. Then the leaf enclosed in the polythene bag was quickly transferred to the pressure chamber and sealed properly with the cut end exposed. The chamber was pressurized until the first appearance of xylem sap at the cut end of the petiole was observed through a microscope and the pressure was recorded. Three measurements were made on separate plants selected at random in each plot.

The same leaves used to measure Ψ_l were used for relative water content (RWC) and osmotic potential (π) measurements when plants were younger and leaves bigger. Other leaves in addition to the three leaves used to measure Ψ_l were used for relative water content (RWC) and osmotic potential (π) measurements, closer to maturity, when plants had much smaller leaves. A single measurement of π and RWC was made per plot and per date of measurement. When plants were younger and leaves bigger, discs of 1 cm in diameter were taken and combined. Closer to maturity, when plants had much smaller leaves, discs of 0.5 cm diameter were taken and combined.

RWC was measured as described previously (Barrs and Weatherley, 1962). Five to six (1 cm in diameter) or ten to twelve (0.5 cm in diameter) leaf discs were taken from the combined sample and transferred immediately into a pre-weighed McCartney bottle. The bottles were sealed to avoid desiccation and stored in a cooled container until taken to the laboratory. Bottles with leaf discs were weighed to get fresh weight (W_f). Leaf discs were then floated in deionised water for 4 hours in petri dishes. After rehydration the turgid weight of discs was taken (W_t). Then the leaf discs were oven dried at 70 ^{0}C to a constant weight and dry weight of leaf discs was taken (W_d). Relative Water Content (RWC) was calculated as;

$$RWC = (W_f - W_d) / (W_t - W_d) * 100$$

At the same time, five to six (1 cm diameter) or ten to twelve (0.5 cm diameter) leaf discs taken from the equivalent leaves were immediately wrapped in aluminum foil and frozen in liquid nitrogen for osmotic potential measurements. Frozen samples were thawed and the sap was expressed by squeezing the sample in a 5 ml syringe. Osmotic potential was measured by vapour pressure osmometry using Wescor (Wescor Inc., Logan, UT, USA) C-52 sample chambers and a Wescor HR-33T dew point microvoltometer. The measurement was replicated four times per sample. The π at full turgor (π_{100}) was calculated as;

$$\pi_{100} = \pi * RWC$$

5.2.2.3. Stomatal conductance

Stomatal conductance of uppermost fully expanded and unshaded leaves was measured in all plots of rainout shelter and irrigated blocks commencing at DOF until leaf senescence. Measurements were taken around mid day (10.00 to 14.00 h) on clear sunny days at weekly intervals between 78 to 142 DAS using a Delta- T Automatic Porometer Mk3 (Delta-T Devices Ltd, Burwell, Cambridge, UK). The adaxial and abaxial stomatal conductances were measured separately on the same leaf and added to give Leaf Diffusive Conductance (LDC). The measurement was replicated three times per plot per date of measurement using three different plants selected randomly.

5.2.2.4. Leaf Area Index

Leaf Area Index (LAI) of all the plots were measured at four weekly intervals commencing from six weeks after emergence. Leaf Area Index (LAI) was measured using an AccuPAR (Linear PAR/LAI Ceptometer, model PAR – 80 Decagon; Pullman, Washington, USA) near mid-day in the absence of cloud cover. AccuPAR calculates LAI based on the average intercepted ratio of above to below canopy intercepted PAR, zenith angle calculated from altitudes and latitudes of the experimental site and leaf distribution parameter of the crop. Altitude and the latitude of the experimental site and leaf distribution parameter (0.6 for rapeseed) were input to the AccuPAR before measurements. Above canopy and below canopy PAR was measured. Calculated LAI was recorded.

5.2.2.5. Radiation absorption and Radiation Use Efficiency

Percentage absorption of Photosynthetically Active Radiation (PAR) of all the plots was measured at four weekly intervals commencing from six weeks after emergence as described in the section 3.2.2.3.

Total incident radiation (S) recorded with a LiCo solar pyranometer at a nearby weather station was used for radiation use efficiency (RUE) calculations. Percentage PAR absorption was used as the fraction of incident radiation intercepted (f_i). As point measurements of PAR absorption were made, average percentage PAR absorption between two measurement dates was considered as the approximate value of f_i on days within the particular period. The total amount of radiation intercepted (S_i) was calculated as the cumulative product of the daily f_i and S (Sinclair and Muchow, 1999), for the period of 43 DAS to 127 DAS (at peak dry matter). RUE at peak dry matter was calculated as the ratio of total amount of dry matter accumulated from 43 DAS to 127 DAS to the total amount of radiation intercepted from 43 DAS to 127 DAS.

5.2.2.6. Flower and pod set

Four plants were selected randomly from each plot and tagged to study flower and pod production. Newly formed flowers on the main stem (terminal raceme); first, second, third, fourth, fifth and sixth primary branches and on secondary branches; were counted separately at weekly intervals commencing from flowering (DOF) to end of flowering (EOF). These counts were accumulated to calculate total number of

flowers produced over the flowering period. Total number of pods on the main stem (terminal raceme); first, second, third, fourth, fifth and sixth primary branches and on secondary branches; were counted separately at EOF and at final harvest.

Percentage floral abortion at EOF and at harvest was calculated as;

$$\% \text{ floral abortion} = \frac{\text{(Total number of flowers- Total number of pods at EOF/harvest)}}{\text{(Total number of flowers)}} \text{ x100}$$

5.2.2.7. Dry matter production and partitioning

To determine dry matter partitioning, twelve adjacent plants on a row were cut at ground level from each plot. The two smallest and largest plants were discarded. Each plant was then separated into stems, leaves, flowers, pods, pod wall and seeds. After flowering, when plants were larger, only seven plants were cut at ground level and five median plants were used for measurements. All plant components were dried separately in a ventilated oven maintained at 75 ^{0}C to a constant weight. The partitioning of biomass was calculated on an area basis (m^2) using the plant density measured at each date of sampling. Dry weight of stems, leaves, flowers and pods were accumulated to calculate total dry matter.

5.2.2.8. Final above ground dry matter, seed yield and harvest index

Four quadrats, 1 m^2 each, were harvested randomly from each plot at maturity. Samples were threshed and the separated seeds were weighed to determine seed yield. Final above ground dry matter, and HI were determined from two 1 m^2 quadrats as described in the section 3.2.2.4.

5.2.2.9. Yield components

Seed yield components were estimated by taking ten adjacent plants from each plot at maturity as described in the section 3.2.2.5.

5.2.2.10. Soil moisture extraction and total water use

Soil moisture was measured in all plots of the rainout shelter and rainfed blocks using a neutron moisture meter (Campbell Pacific Nuclear model 503). A polyvinylchloride access tube in each plot was installed as described previously (Greacen, 1981). Neutron moisture meter readings were taken at 10 cm from the soil surface and at 20 cm intervals down the soil profile to 170 cm. All tubes were read at

planting and then at four weekly intervals until harvesting of the crop. The neutron moisture meter was calibrated at the site as described by Greacen (1981). Total water use (WU) was determined according to the equation;

$$WU = \Delta\theta + P$$

Where $\Delta\theta$ is change in soil moisture stored in the profile over the period considered and P is recorded rainfall. Observations made on the surface conditions after rain indicated that no run-off occurred at this site. From the inspection of the sequential soil water profile data, it was assumed that drainage was negligible. Approximate WU of the three genotypes in the irrigated block was determined by adding the amount of water applied by trickle irrigation, measured by a water measuring gauge, to the WU of the corresponding genotype from the corresponding replicate in rainfed block assuming that there was no difference in soil moisture status between two adjacent blocks.

5.2.2.11. Water Use Efficiency

Water Use Efficiency based on dry matter (WUE_{dm}) was estimated as the ratio of above ground dry matter at maturity to total WU. Water Use Efficiency based on seed yield (WUE_{gr}) was estimated as the ratio of seed yield (oven dried) to WU.

5.2.2.12. Seed quality

Oil and protein concentration of the seed was determined using Infratec 1241 grain analyzer (FOSS TECATOR V1.52).

5.2.3. Statistical analyses

All data collected and derived were statistically analysed as described in the section 3.2.3.

5.3. RESULTS

5.3.1. Weather

Total annual rainfall in 2001 (364.5 mm) was higher than the long-term average (315.8 mm). Rainfall during the growing period (May to November) was 200 mm, lower than the long-term average of 224 mm during this period. June was exceptionally dry, but the July rainfall was 40 % higher than the long-term average (Figure 5.1). All plots received 111.7 mm rainfall from sowing until flowering.

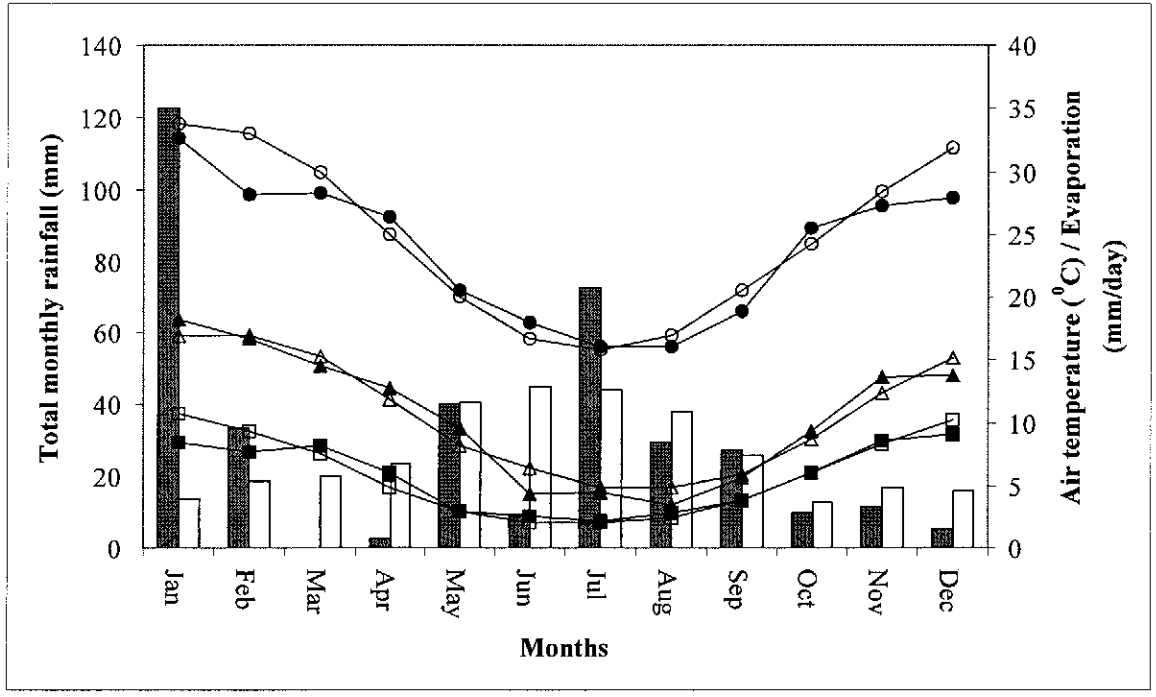

Figure 5.1. Total monthly rainfall (solid histogram), long term average of total monthly rainfall (open histogram), mean daily maximum temperature (●), long term average of mean daily maximum temperature (○), mean daily minimum temperature (▲), long term average of mean daily minimum temperature (Δ), average daily evaporation (■), and long term average daily evaporation (□) at Merredin, WA in 2001.

Plots in the rainfed and irrigated blocks received 48.4 mm rainfall after flowering, but this rainfall was excluded from the rainout shelter block. Plots in the irrigated block received 228 mm of water from 24 August to 16 October. Mean daily evaporation during the growing period was similar to the long-term average daily evaporation (Figure 5.1). The mean daily evaporation during August, September and October was 2.8, 3.8, 6 mm/day respectively. There was no deviation of the mean daily maximum and minimum air temperatures from their long-term averages during winter (Figure 5.1). However, the spring and the summer were relatively cool and mild. Therefore, the expected level of water stress in the severe water stress treatment did not develop.

5.3.2. Days to flowering

The duration from sowing to the date at which 50 % of plants produced their first open flower (DOF) of Muscon was 80 days and that of 887.1.6.1 and Monty was 84 days. DOF did not differ between blocks.

5.3.3. Plant water relations

5.3.3.1. Leaf Water Potential

Leaf water potential (Ψ_l) of all genotypes did not differ significantly between blocks until after water stress treatments were imposed. Ψ_l of all genotypes from severe stress treatment decreased compared to that of irrigated treatment two weeks after treatments were imposed (Figure 5.2). Ψ_l of Muscon in severe stress treatment was significantly lower compared to that of irrigated treatment from 98 DAS until leaf senescence. Ψ_l of 887.1.6.1 and Monty in severe stress treatment was significantly lower compared to that of irrigated treatment from 105 DAS until leaf senescence. There was no difference in Ψ_l between genotypes in irrigated treatment at all the dates of measurement. However, Ψ_l of Monty was significantly higher than that of Muscon and 887.1.6.1 from 112 DAS until leaf senescence (Figure 5.2) in severe stress treatment. Leaf water potential of Monty at leaf senescence was 30 % and 25 % higher than that of 887.1.6.1 and Muscon respectively. Although Ψ_l of Muscon and 887.1.6.1 were not significantly different until 126 DAS, Ψ_l of 887.1.6.1 decreased significantly faster compared to that of Muscon after 126 DAS until the leaf senescence. Therefore, at the leaf senescence, Ψ_l of 887.1.6.1 was significantly higher than that of Muscon.

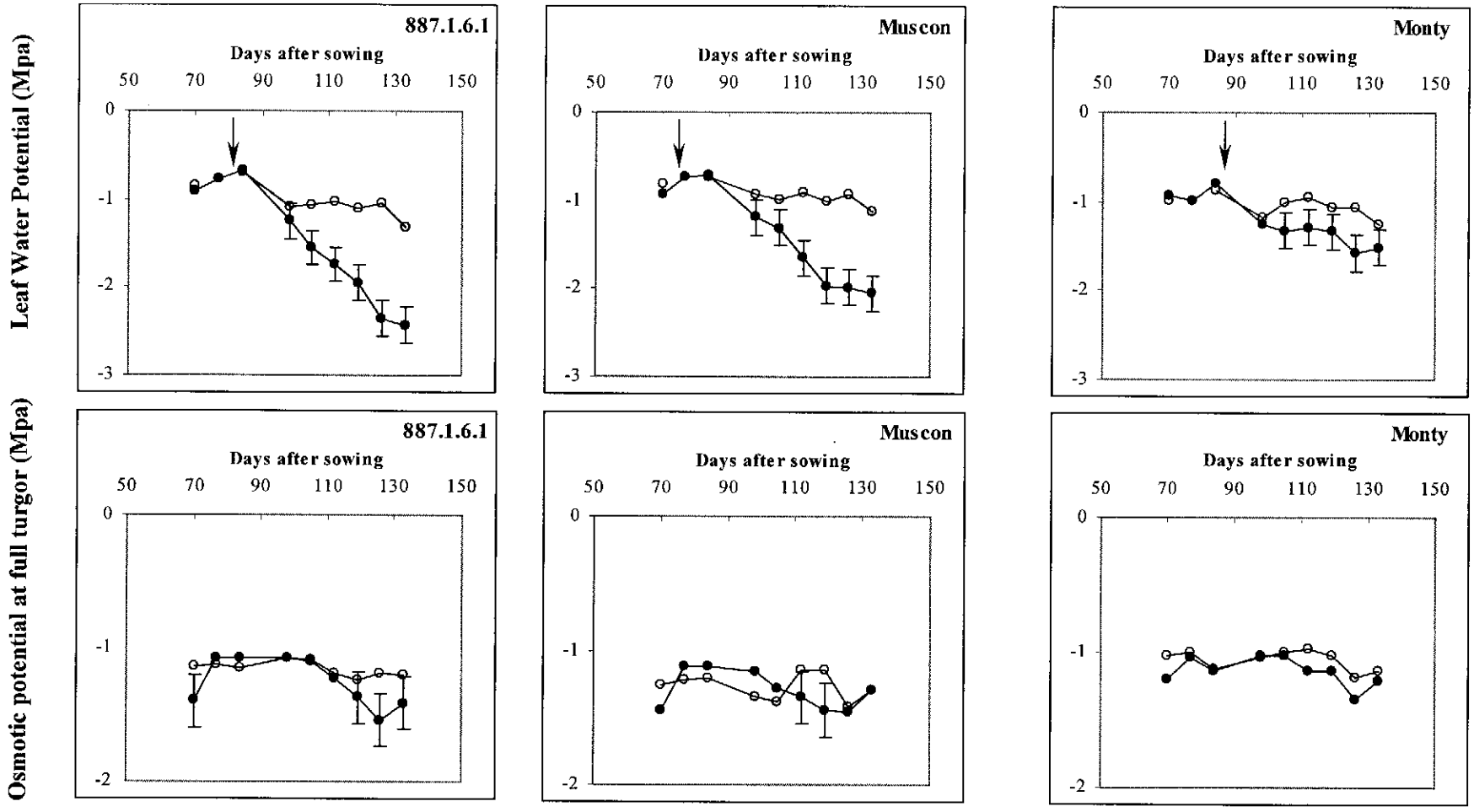

Figure 5.2. Leaf Water Potential (Ψ) and Osmotic Potential at full turgor (π_{sat}) in two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) from severe water stress (solid symbols) and irrigated (open symbols) treatments at Merredin, WA in 2001. Bars indicate +/- LSD (P = 0.05) for selected dates and stress treatments when means are significantly different. Arrows indicate the date on which treatments were first imposed/ flowering.

5.3.3.2. Osmotic potential at full turgor

There was no significant difference in osmotic potential at full turgor (π_{sat}) between treatment blocks until after water stress treatments were imposed. A significant difference in π_{sat} between severe stress and irrigated treatments was not observed in any genotype until 28 days after flowering (Figure 5.2). π_{sat} of Muscon was significantly different between severe stress and irrigated treatments from 112 to 119 DAS. π_{sat} of 8871.6.1 was significantly different between severe stress and irrigated treatments from 126 DAS until leaf senescence. However, π_{sat} of Monty did not differ significantly between stress treatments at any time. Under severe stress treatment π_{sat} of Muscon was significantly lower than 887.1.6.1 and Monty from 105 to 112 DAS (Figure 5.2). After 112 DAS, π_{sat} of 887.1.6.1 fell to the level of Muscon so that π_{sat} of both Muscon and 887.1.6.1 was significantly lower than Monty from 119 DAS until leaf senescence. π_{sat} of Muscon from irrigated treatment was significantly lower than that of the other two genotypes at 98 to 105 DAS and at 126 DAS.

5.3.3.3. Osmotic adjustment

Osmotic adjustment, judged by differences in π_{sat} between severe stress and irrigated treatments, was observed in all genotypes (Table 5.1 & Figure 5.2).

Table 5.1. Osmotic adjustment of two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) under severe water stress at Merredin, WA in 2001.

Genotype	Osmotic adjustment (MPa)				
	105 DAS	112 DAS	119 DAS	126 DAS	133 DAS
887.1.6.1	0.01	0.04	0.14	0.35	0.19
Muscon	0.0	0.16	0.30	0.04	0.0
Monty	0.02	0.06	0.12	0.17	0.08

LSD (P = 0.05) genotypes /measurement date = 0.19

A clear osmotic adjustment in Muscon was observed earlier in the season (from 112 DAS) than in 887.1.6.1, however it was not evident after 119 DAS. Therefore, at the end of the season π_{sat} of Muscon between severe stress and irrigated treatments was not significantly different. Osmotic adjustment of 887.1.6.1 was observed after 119 DAS (Table 5.1 & Figure 5.2). Since π_{sat} of 887.1.6.1 in the irrigated treatment did not change much even at the end of the season, osmotic adjustment of 887.1.6.1 was continuously observed until leaf senescence at 133 DAS. Although a difference in π_{sat} between severe stress and irrigated treatments in Monty was observed in the period from 112 to 126 DAS (Table 5.1 & Figure 5.2), the difference was not significant, hence osmotic adjustment of Monty was less than in the mustards.

5.3.3.4. Relative Water Content

Relative Water Content (RWC) of 887.1.6.1 in the severe stress treatment was significantly lower than that in the irrigated treatment after 105 DAS until leaf senescence (Figure 5.3). The RWC of Muscon and Monty in the severe stress treatment was significantly lower than the irrigated treatment from 98 DAS until leaf senescence. Muscon was able to maintain higher water contents under the severe stress treatment than 887.1.6.1 and Monty throughout the growing period. The RWC of Muscon and 887.1.6.1 in the severe stress treatment was significantly higher than that of Monty until 112 DAS (Figure 5.3). However, as the stress developed rapidly, the RWC of 887.1.6.1 fell down to the level of Monty. Therefore, RWC of Muscon was significantly higher than 887.1.6.1 and Monty from 119 DAS until leaf senescence. RWC did not differ significantly between genotypes in the irrigated treatment.

5.3.4. Leaf Diffusive Conductance

Leaf Diffusive Conductance (LDC) of 887.1.6.1 under severe stress was significantly lower than that of the irrigated treatment only at 105 DAS (Figure 5.3). However, LDC of Muscon and Monty under severe stress was significantly lower than that of irrigated treatment at 105 to 112 DAS. LDC did not differ significantly between genotypes at any measurement date.

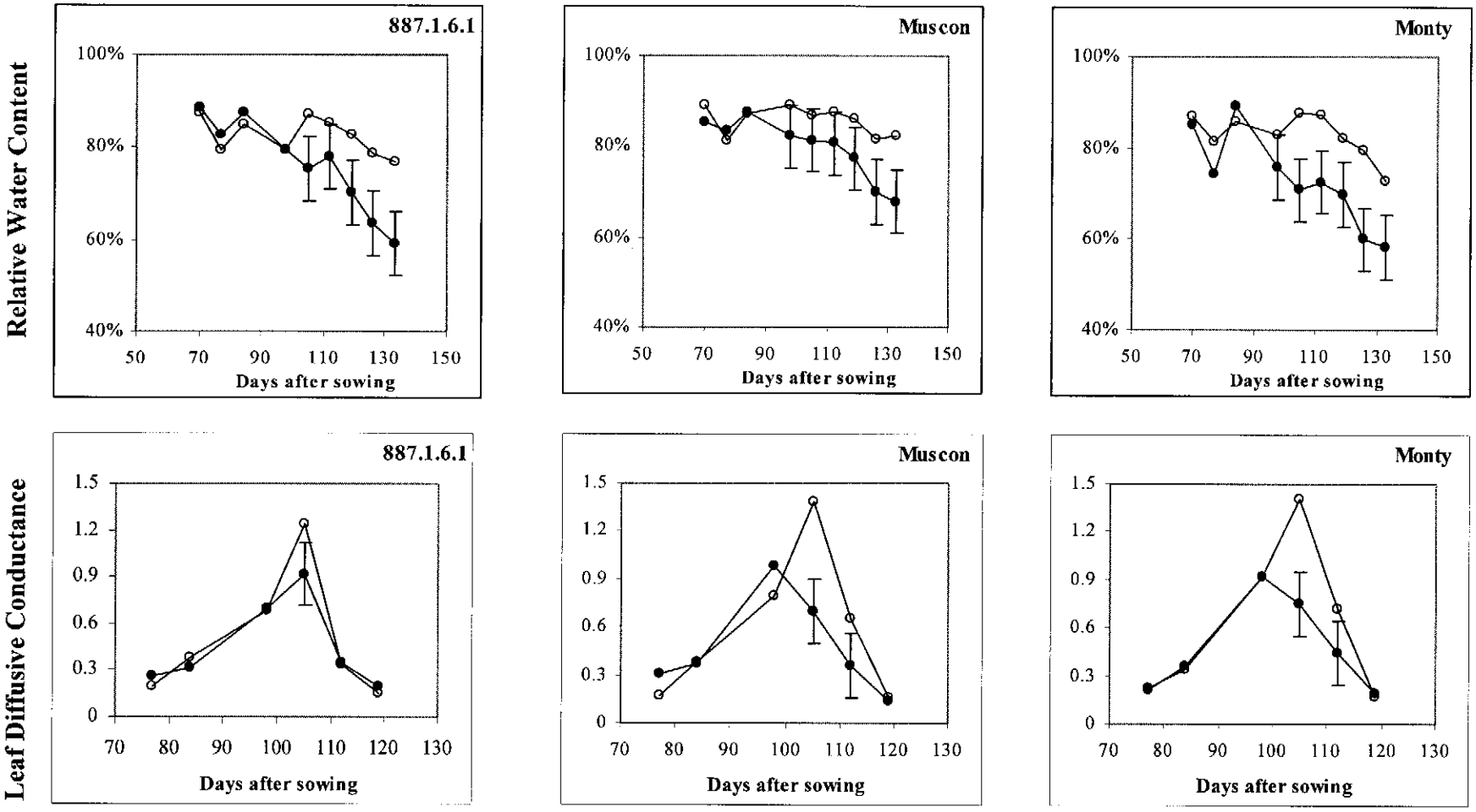

Figure 5.3. Relative Water Content (%) and Leaf Diffusive Conductance (cm/s) in two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) under severe water stress (solid symbols) and irrigated (open symbols) treatments at Merredin, WA in 2001. Bars indicate +/- LSD (P = 0.05) for selected dates and stress treatments when means are significantly different.

5.3.5. Canopy development

Maximum Leaf Area Index (LAI) was lowest in severe stress treatment and highest in irrigated treatment in all genotypes (Table 5.2). Maximum LAI did not differ significantly between genotypes in severe stress treatment. However, maximum LAI of Monty was significantly lower than that of Muscon in mild stress treatment. Maximum LAI of Monty was significantly lower than that of Muscon and 887.1.6.1 in irrigated treatment.

The number of primary branches at final harvest was not affected significantly by water stress treatments in any genotype (Table 5.3). Primary branch numbers did not differ significantly between genotypes regardless of the stress treatments. Secondary branches at final harvest were not affected significantly by water stress treatments in Muscon and Monty. However, 887.1.6.1 produced significantly more secondary branches in mild stress treatment than in severe stress and irrigated treatments. Muscon and 887.1.6.1 produced significantly more secondary branches than Monty in all water stress treatments (Table 5.3).

Plants were significantly taller in irrigated treatment compared to severe and mild stress treatments (Table 5.3). Mustard plants were significantly taller than Monty in all water stress treatments. Monty and 887.1.6.1 plants were significantly taller in the irrigated treatment compared to mild and severe stress treatments and Muscon plants were tallest in mild stress treatment.

5.3.6. Radiation absorption

Maximum percentage absorption of Photosynthetically Active Radiation (PAR) was significantly higher in mild stress and irrigated treatments compared to severe stress treatment (Table 5.2). Maximum PAR did not differ significantly between stress treatments in 887.1.6.1 and Muscon, but that of Monty was significantly lower in severe stress treatment compared to mild stress and irrigated treatments. Maximum PAR absorption did not differ significantly between genotypes in mild stress and irrigated treatment. However maximum PAR absorption of Monty was significantly lower than 887.1.6.1 and Muscon in severe stress treatment.

Table 5.2. The effect of genotype, water stress and their interaction on maximum LAI and PAR absorption (%) in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Maximum LAI				Maximum PAR absorption (%)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	2.4	3.1	4.2	3.2	85	89	89	88
Muscon	2.6	3.5	4.1	3.4	87	85	89	87
Monty	2.2	2.9	2.9	2.7	71	85	84	80
Mean	2.4	3.2	3.7	3.1	81	86	87	85
LSD (P = 0.05)	stress = 0.3 genotype = 0.3 stress x genotype = 0.5				stress = 3 genotype = 3 stress x genotype = 7			

Table 5.3. Primary and secondary branches/plant and plant height (cm) at final harvest in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Primary branches/plant				Secondary branches/plant				Plant height (cm)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	6	5	5	5	2	4	2	3	138	141	155	144
Muscon	5	5	4	5	2	2	3	2	143	139	149	144
Monty	5	5	4	5	0	0	0	0	88	88	102	93
Mean	5	5	5	5	1	2	2	2	123	123	135	127
LSD (P=0.05)	stress = 1 genotype = 1 stress x genotype = 1				stress = 1 genotype = 1 stress x genotype = 1				stress = 5 genotype = 5 stress x genotype = 9			

Total intercepted radiation for the period of 43 DAS to 127 DAS (at peak dry matter) was significantly higher in irrigated treatment than that of mild and severe stress treatments (Table 5.4). Muscon and 887.16.1 intercepted significantly higher radiation compared to Monty during this period. Total intercepted radiation did not differ between stress treatments in Monty and Muscon but 887.16.1 intercepted significantly more radiation in irrigated treatment compared to severe stress treatment. Total intercepted radiation did not differ between genotypes in severe and mild stress treatments but 887.1.6.1 and Muscon intercepted significantly more radiation in irrigated treatment compared to Monty.

5.3.7. Soil moisture extraction, total water use and rooting depth

Maximum extractable water (MEW), defined as the difference between maximum water content in each layer and the minimum at maturity in the 0 to 170 cm layer in severe water stress treatment was higher compared to that in mild stress treatment in all genotypes (Figure 5.4). MEW in 887.1.6.1, Muscon and Monty in severe stress treatment was 145, 148 and 136 mm and in mild stress treatment was 119, 115 and 83 mm respectively.

Mustards extracted more soil moisture compared to Monty from sowing to final harvest. Mustards extracted more soil moisture in the severe stress treatment compared to the mild stress treatment. However, Monty extracted similar levels of soil moisture regardless of the stress treatments. Total amount of soil moisture extracted from sowing to final harvest in Muscon, 887.1.6.1 and Monty under severe stress treatment was 104, 111 and 66 mm respectively and that under mild stress treatment was 87, 81 and 64 mm respectively.

Total water use (WU) was significantly higher in the irrigated treatment than in the severe or mild stress treatments in all genotypes (Table 5.4). WU did not differ significantly between genotypes in the severe stress or irrigated treatments, but WU of 887.1.6.1 and Muscon was significantly higher than that of Monty in the mild stress treatment.

Maximum rooting depth, judged by soil moisture extraction pattern (Figure 5.4), is 150, 130 and 110 cm for Muscon, 887.1.6.1 and Monty under the severe stress treatment. Maximum rooting depth for Muscon, 887.1.6.1, and Monty under the mild stress treatment was 150, 110 and 90 cm respectively.

5.3.8. Flower and Pod set

Total number of flowers produced over the flowering period did not differ significantly between stress treatments in Muscon and Monty (Table 5.5). Total number of flowers of 887.1.6.1 in irrigated treatment was significantly higher than in mild and severe stress treatments. Total number of flowers did not differ significantly between genotypes in severe and mild stress treatments. However, total number of flowers of 887.1.6.1 was significantly higher than that of Monty and Muscon in the irrigated treatment (Table 5.5).

Percentage floral abortion at end of flowering did not differ significantly between stress treatments in any genotype (Table 5.5). Percentage floral abortion of 887.1.6.1 at final harvest was not affected significantly by stress treatments. However, percentage floral abortion of Muscon and Monty in severe stress treatment was significantly higher than in mild stress and irrigated treatments. Percentage floral abortion of Monty was significantly higher than that of 887.1.6.1 and Muscon at the end of flowering and at the final harvest regardless of the stress treatments (Table 5.5).

All genotypes produced more flowers and pods on the main stem (terminal raceme) followed by first primary, second primary, third primary, fourth primary, and fifth primary branches sequentially downwards regardless of the stress treatments (Figure 5.5). Higher percentage of pods were borne on main stem, first, second and third primary branches compared to those on fourth and fifth primary branches in severe stress treatment regardless of the genotype. This was more obvious in Monty (Figure 5.5). In the mild stress and irrigated treatments, all genotypes produced more pods on fourth and fifth primary branches compared to severe stress treatment. 887.1.6.1 and Muscon produced more secondary pods than Monty regardless of the stress treatments. However, the percentage of secondary pods produced by mustards in severe stress treatment was lower than in mild stress and irrigated treatments (Figure 5.5).

Table 5.4. The effect of genotype, water stress and their interaction on total intercepted radiation and total water use in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Total intercepted radiation (MJ/m^2)				Total water use (mm)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	834	915	1004	918	216	247	459	307
Muscon	879	905	967	917	223	241	436	300
Monty	812	837	854	834	203	197	443	281
Mean	842	886	942	890	214	228	446	296
LSD (P=0.05)	stress = 55 genotype = 55 stress x genotype = 95				stress = 16 genotype = 24 stress x genotype = 34			

Table 5.5. Total number of flowers/plant and percentage abortion at end of flowering and at final harvest in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Total number of flowers/plant				% abortions at end of flowering				% abortions at final harvest			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	169	224	263	219	22	21	17	20	48	39	37	41
Muscon	186	174	154	171	17	13	15	15	42	26	26	31
Monty	178	208	178	188	57	60	47	55	66	61	50	59
Mean	178	202	199	193	32	31	26	30	51	42	38	44
LSD (P=0.05)	stress = 47 genotype = 47 stress x genotype = 81				stress = 8 genotype = 8 stress x genotype = 13				stress = 9 genotype = 9 stress x genotype = 15			

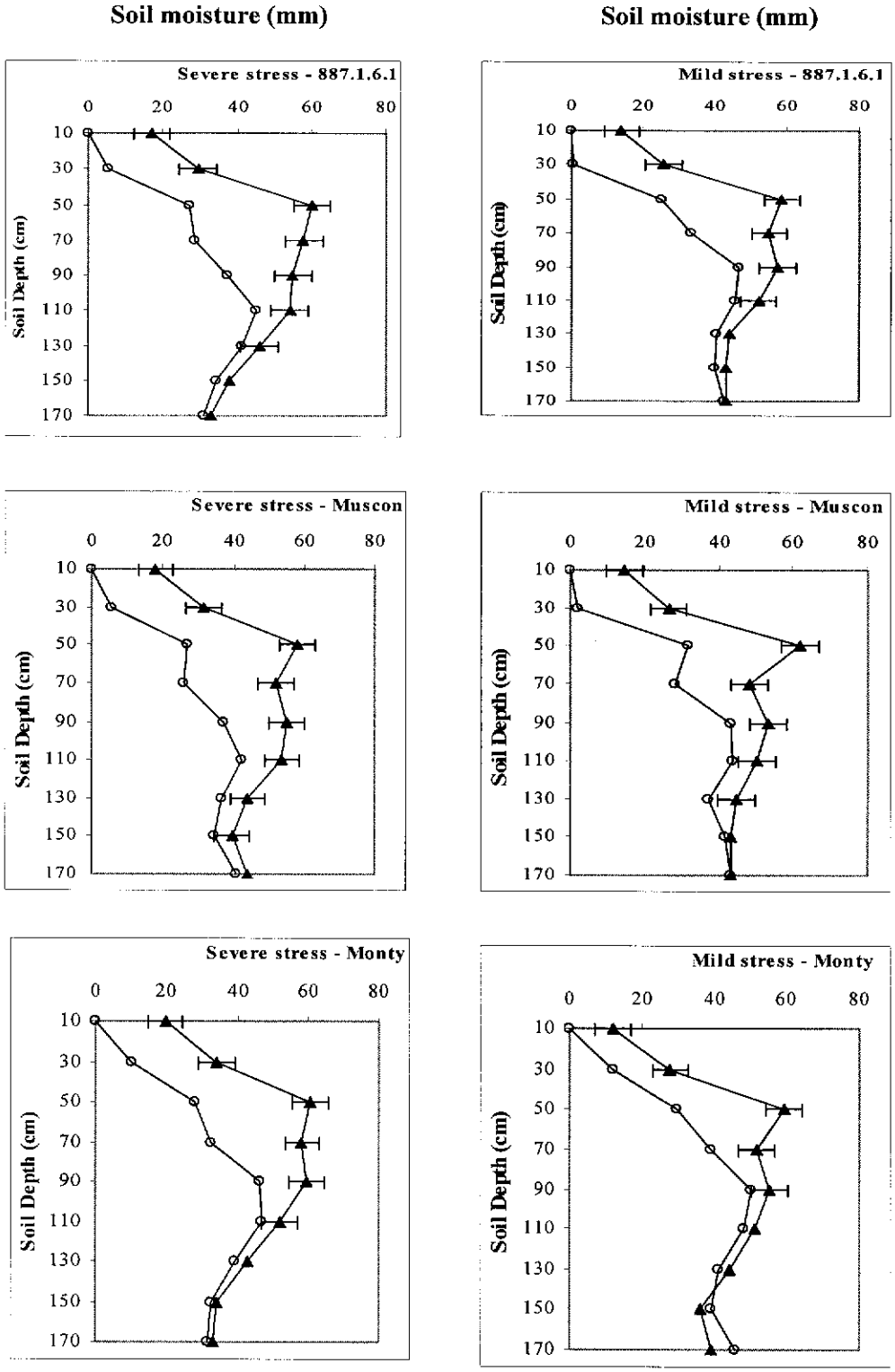

Figure 5.4. Soil moisture extraction pattern in various depth of soil with time (▲- at maximum re-charge (71 DAS) and ○ - at final harvest (171 DAS) in two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) under severe and mild water stress treatments at Merredin, WA in 2001. Bars indicate +/- LSD (P = 0.05) at selected depths when means are significantly different.

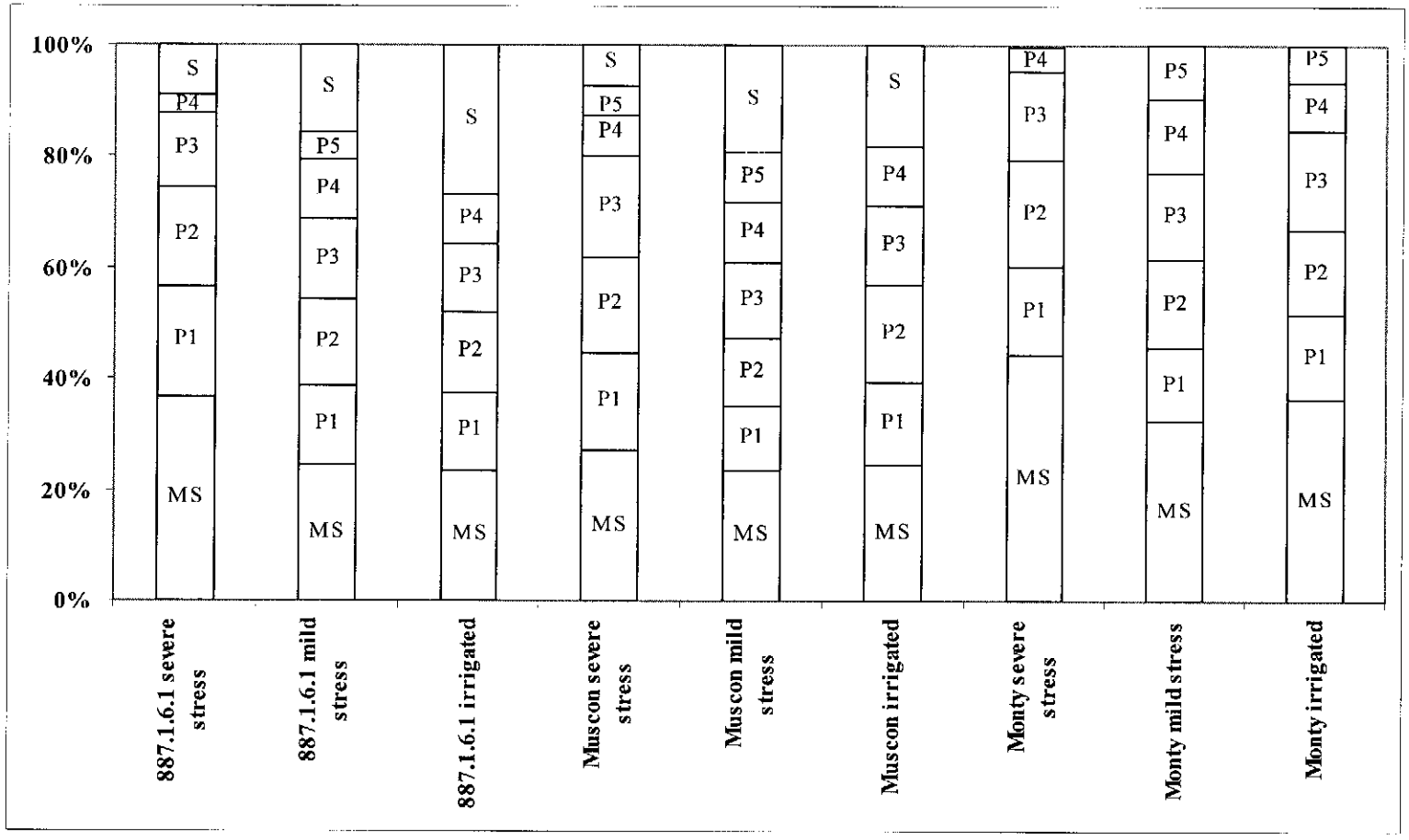

Figure 5.5. Percentage distribution of pods/plant on main stem – (MS), and First primary – (P1), Second primary – (P2), Third primary – (P3), Fourth primary – (P4), Fifth primary – (P5), all secondary – (S) branches at final harvest in two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) under three water stress treatments (severe stress, mild stress and irrigated) at Merredin WA in 2001.

5.3.9. Dry matter production and partitioning

Early dry matter production in the vegetative phase of all genotypes was partitioned almost equally between leaves and stems regardless of the stress treatments (Figure 5.6). When internode length increased, stems elongated, and more branches appeared, more dry matter was partitioned into stems than leaves regardless of the genotype and stress treatments. Dry matter production of all genotypes at flowering did not differ significantly between stress treatments. Before maximum dry matter was achieved some pod wall and seed growth was observed in each genotype and stress treatments (Figure 5.6). Seed development of Muscon and Monty was observed at the same time in all stress treatments. Although seed development of 887.1.6.1 was observed at the same time as Muscon and Monty in the severe and mild stress treatments, seed development of 887.1.6.1 in the irrigated treatment was later than in Muscon or Monty.

Final above ground dry matter (FAGDM) significantly decreased with increasing water stress (Table 5.6). FAGDM was significantly higher in the irrigated treatment than in the severe stress or mild stress treatments in Muscon and 887.1.6.1 and that of Monty was significantly higher in the irrigated treatment than in the severe stress treatment. FAGDM did not differ significantly between severe and mild stress treatments in any genotype (Table 5.6). 887.1.6.1 produced significantly more FAGDM than Monty in all stress treatments. Mean FAGDM in Muscon was significantly lower compared to that of 887.1.6.1, but significantly higher compared to that of Monty.

5.3.10. Seed Yield

Mean seed yield decreased significantly with increasing water stress (Table 5.6). Seed yield was significantly higher in irrigated treatment than in the severe stress treatment in all genotypes (Table 5.6). Seed yield between severe stress and mild stress treatment was not significantly different in 887.1.6.1 and Muscon. However, seed yield of Monty in mild stress treatment was significantly higher than in severe stress treatment. Seed yield between mild stress treatment and irrigated treatment was not significantly different in any genotype. Seed yield between genotypes was not significantly different regardless of the stress treatment (Table 5.6).

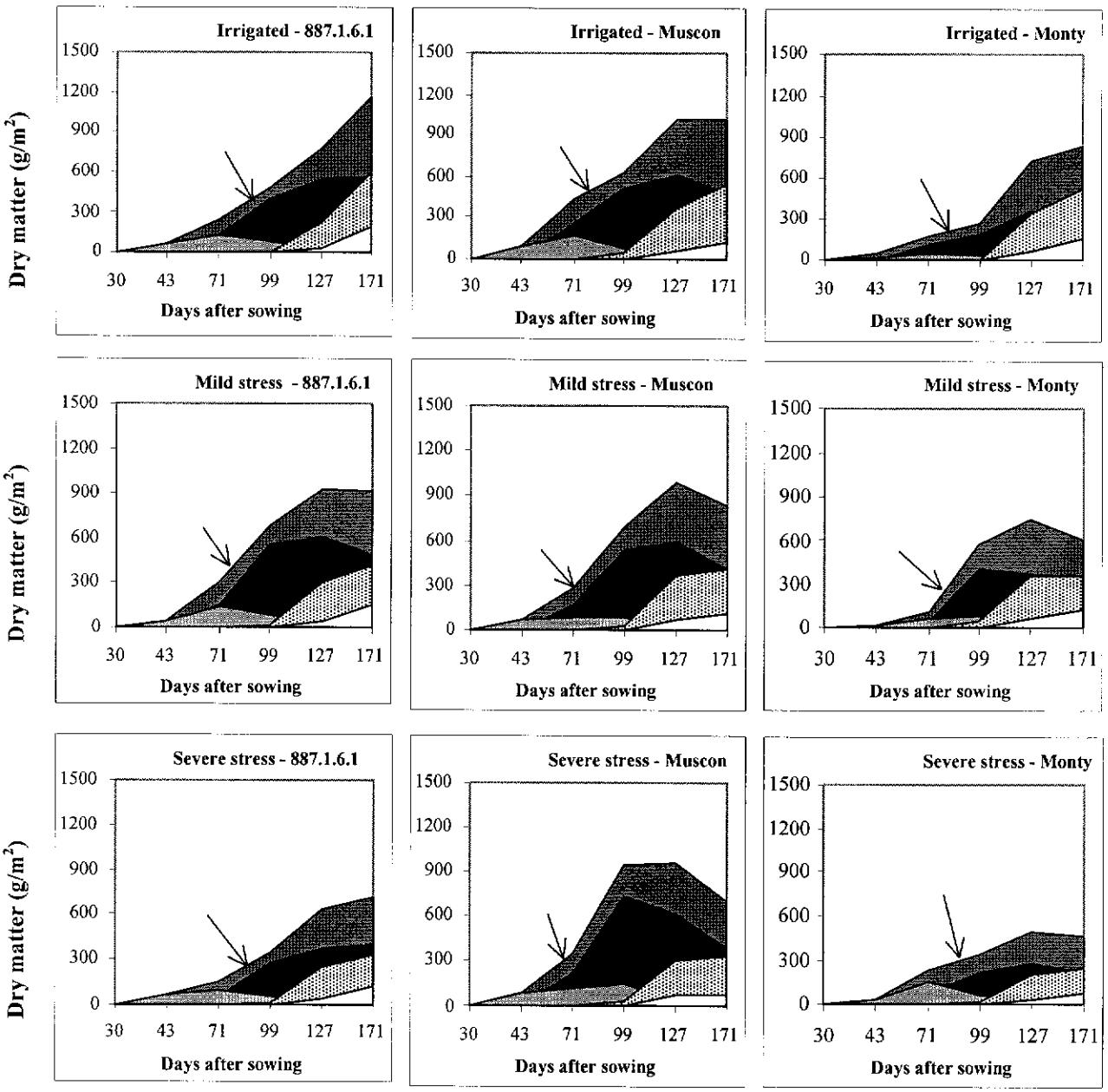

Figure 5.6. The effect of genotype and water stress on dry matter production and partitioning in two mustard genotypes (887.1.6.1 and Muscon) and one canola variety (Monty) under three water stress treatments (irrigated, mild and severe stress) at Merredin in 2001. Arrows indicate flowering.

Total DM ■ Stem DM ■ Leaf DM ■ Pod DM ■ Seed DM □

Table 5.6. The effect of genotype, water stress and their interaction on seed yield (t/ha), final above ground dry matter (t/ha) and harvest index (%) in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Seed yield (t/ha)				Final above ground dry matter (t/ha)				Harvest Index (%)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	1.2	1.6	1.9	1.6	7.6	9.1	10.9	9.2	15.6	17.6	17.4	16.9
Muscon	1.0	1.2	1.5	1.2	6.8	7.9	9.9	8.2	14.7	15.2	15.2	15.0
Monty	1.1	1.6	1.9	1.5	5.6	7.0	8.4	7.0	19.6	22.9	22.6	21.7
Mean	1.1	1.4	1.8	1.4	6.6	8.0	9.7	8.1	16.6	18.6	18.4	17.9
LSD (P=0.05)	stress = 0.2 genotype = 0.2 stress x genotype = 0.4				stress = 1.1 genotype = 1.0 stress x genotype = 1.7				stress = 1.5 genotype = 1.5 stress x genotype = 2.6			

Table 5.7. The effect of genotype, water stress and their interaction on yield components (total number of pods/plant, seeds /pod, 1000 seed weight) in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Total number of pods/plant				Seeds/pod				1000 seed weight (g)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	70	92	92	85	10.9	10.5	11.8	11.1	2.9	2.8	3.3	3.0
Muscon	59	74	80	71	8.9	7.7	11.1	9.3	3.6	3.5	4.2	3.8
Monty	34	35	45	38	18.8	19.0	19.7	19.2	3.5	3.5	3.9	3.6
Mean	54	67	72	64	12.9	12.4	14.2	13.2	3.3	3.3	3.8	3.5
LSD (P=0.05)	stress = 14 genotype = 14 stress x genotype = 24				stress = 0.9 genotype = 0.9 stress x genotype = 1.5				stress = 0.2 genotype = 0.2 stress x genotype = 0.3			

However, mean seed yield was significantly lower in Muscon compared to 887.1.6.1 and Monty.

5.3.11. Harvest Index

Harvest Index (HI) was significantly lower in severe stress treatment compared to mild stress and irrigated treatments (Table 5.6). HI of 887.1.6.1 and Muscon was not affected significantly by the water stress treatments but that of Monty was significantly lower in severe stress treatment than in mild stress or irrigated treatments (Table 5.6). HI of Monty was significantly higher than that of 887.1.6.1 and Muscon regardless of the stress treatment. HI did not differ significantly between 887.1.6.1 and Muscon in any stress treatment.

5.3.12. Yield components

Mean pod number/plant across genotypes was significantly higher in irrigated treatment compared to severe stress treatment (Table 5.7). Total number of pods/plant was not significantly affected by the water stress treatments in any genotype. Monty produced significantly less number of pods/plant compared to 887.1.6.1 or Muscon in all stress treatments. Total pods/plant between Muscon and 887.1.6.1 was not significantly different in any stress treatment.

Number of seeds/pod was significantly lower in severe stress treatment compared to irrigated treatment (Table 5.7). Number of seeds/pod of 887.1.6.1 and Monty was not affected by the water stress treatments but that of Muscon was significantly higher in the irrigated treatment than in the severe and mild stress treatments (Table 5.7). Monty produced significantly more seeds/pod than mustards in all stress treatments. Muscon produced significantly fewer seeds/pod under severe stress and mild stress treatments than 887.1.6.1, but in the irrigated treatment it produced a similar number of seeds/pod as 887.1.6.1.

1000 seed weight was significantly higher in the irrigated treatment than in the severe and mild stress treatments regardless of the genotype (Table 5.7). 1000 seed weight did not differ significantly between the severe and mild stress treatments in any genotype. Seeds of 887.1.6.1 were significantly smaller than seeds of Muscon and Monty in all stress treatments. Muscon and Monty produced seeds of similar size in severe and mild stress treatments. However, Muscon produced significantly heavier seeds than Monty in the irrigated treatment.

5.3.13. Radiation Use Efficiency

Mean radiation use efficiency (RUE) across genotypes for the period of 43 DAS to 127 DAS was significantly higher in mild stress treatment compared to severe stress and irrigated treatments (Table 5.8). Mean RUE was significantly higher in Muscon compared to 887.1.6.1 and Monty. RUE did not differ significantly between genotypes in mild stress and irrigated treatments. However, RUE of Muscon was significantly higher compared to that of 887.1.6.1 or Monty in the severe stress treatment.

5.3.14. Water Use Efficiency

Water Use Efficiency for dry matter production (WUE_{dm}) was significantly higher from mild stress treatment in all genotypes (Table 5.8). WUE_{dm} of 887.1.6.1 and Muscon was not significantly different between severe stress and irrigated treatments, however, that of Monty from severe stress was significantly higher than that from irrigated treatment. WUE_{dm} did not differ significantly between genotypes in the mild stress or irrigated treatments. However, WUE_{dm} of 887.1.6.1 and Muscon was significantly higher than Monty in the severe stress treatment.

Water Use Efficiency for grain production (WUE_{gr}) of all genotypes was significantly higher in the mild stress treatment compared to other stress treatments (Table 5.8). WUE_{gr} of 887.1.6.1 and Monty did not differ significantly between the severe stress and irrigated treatments. However, WUE_{gr} of Muscon was significantly higher in the severe stress than in the irrigated treatment. WUE_{gr} of genotypes did not differ significantly in the severe stress and irrigated treatments. However, WUE_{gr} of Monty under mild stress was significantly higher than that of Muscon.

5.3.15. Oil and Protein concentrations

Oil concentration of Muscon was not affected by stress treatments (Table 5.9). Oil concentration of 887.1.6.1 and Monty was significantly higher in the irrigated treatment than in severe and mild stress treatments. Oil concentration was significantly higher in Monty than in the mustards in all stress treatments. Oil concentration was significantly higher in 887.1.6.1 than Muscon in all stress treatments. Oil and protein concentration of the seed was inversely related.

Table 5.8. Radiation use efficiency (g/MJ), Water Use Efficiency for dry matter (WUE_{dm}) and Water Use Efficiency for grain (WUE_{gr}) production in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Radiation Use Efficiency (g/MJ)				Water Use Efficiency (dm) ($kg\ ha^{-1}\ mm^{-1}$)				Water Use Efficiency (gr) ($kg\ ha^{-1}\ mm^{-1}$)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	0.7	1.0	0.7	0.8	33.5	36.9	25.6	32.0	5.4	6.3	4.0	5.3
Muscon	1.2	1.0	0.9	1.1	31.6	34.8	23.7	30.1	4.7	5.3	2.7	4.2
Monty	0.6	0.9	0.8	0.7	22.7	32.5	18.9	24.7	4.5	7.7	3.4	5.2
Mean	0.8	1.0	0.8	0.9	29.4	34.7	22.7	28.9	4.8	6.4	3.4	4.9
LSD (P=0.05)	stress = 0.2 genotype = 0.2 stress x genotype = 0.4				stress = 4.5 genotype = 4.5 stress x genotype = 8.8				stress =1.4 genotype = 0.8 stress x genotype = 1.6			

Table 5.9. The effect of genotype, water stress and their interaction on seed oil and protein concentrations (%) in three genotypes of mustard and canola under three water stress treatments at Merredin in 2001.

Genotype	Oil concentration (%)				Protein concentration (%)			
	severe stress	mild stress	irrigated	Mean	severe stress	mild stress	irrigated	Mean
887.1.6.1	37.8	38.5	40.9	39.0	22.5	22.6	17.7	20.9
Muscon	36.5	36.6	36.7	36.6	28.1	26.2	22.5	25.6
Monty	40.1	41.4	48.8	43.4	23.3	22.7	16.3	20.8
Mean	38.1	38.8	42.1	39.7	24.6	23.8	18.8	22.4
LSD (P=0.05)	stress = 0.4 genotype = 0.4 stress x genotype = 0.7				stress = 0.9 genotype = 0.9 stress x genotype = 1.5			

Protein concentration of Muscon was lowest in the irrigated treatment and it significantly and progressively increased with increasing water stress in the mild and severe stress treatments (Table 5.9). Protein concentration of 887.1.6.1 and Monty in the irrigated treatment was significantly lower than in the mild and severe stress treatments, and they produced similar levels of protein in the mild and severe stress treatments.

5.4. DISCUSSION

Soil moisture stress during the post flowering period had a significant effect on water relations, growth, dry matter production and seed yield of mustard and canola. Seed yield significantly decreased with increasing soil moisture stress as a result of reduced total dry matter production and harvest index. Seed yield was strongly correlated with dry matter (r^2 = 0.70) and harvest index (r^2 = 0.55). Lower dry matter was associated with reduced LAI, total intercepted radiation and total water use under severe stress treatment. Dry matter was strongly correlated (P = 0.001) with water use (r^2 = 0.8) and intercepted radiation (r^2 = 0.9). Although the number of flowers produced over the flowering period was not affected significantly by stress treatments, the total number of pods/plant was less due to increased floral abortion. Number of seeds per pod and seed weight was also reduced under severe stress treatment.

Despite their similarity in phenology, the three genotypes used in this study have shown different morphological and physiological responses to soil moisture stress. Mustards produced significantly higher dry matter than Monty in all stress treatments, especially under severe stress. 887.1.6.1 and Muscon produced 36 % and 21 % higher dry matter compared to Monty under severe stress and 29 % and 18 % under irrigation respectively. Greater dry matter production of mustards was related to their higher water use and radiation use under severe stress and which in turn was associated with their superior physiological adaptation to increasing soil moisture stress. Percentage dry matter reduction in severe stress compared to irrigated treatment was strongly and negatively correlated (r^2 = -0.99) with osmotic adjustment in this study. Results agree with Kumar *et al.* (1984,1987); Singh *et al.* (1999), Niknam and Turner (2000), who found that the capacity for osmotic adjustment in mustard is greater compared to canola. Wright *et al.* (1996; 1997) reported that higher osmotic adjustment in mustard is in turn associated with higher dry matter production.

Osmotic adjustment may improve dry matter production as it (i) increases water use by stomatal adjustment, and increases soil moisture uptake by producing greater root biomass and root length density (Turner *et al.*, 1987; Ludlow and Muchow, 1990), (ii) allows stomata to remain partially open at progressively lower leaf water potentials and maintains positive photosynthetic activity (Ludlow, 1987), and (iii) maintains leaf area and reduces the rate of

leaf senescence by increasing both avoidance and tolerance of dehydration (Ludlow and Muchow, 1990).

Osmotic adjustment judged by difference in π_{sat} between severe stress and irrigated treatments in Monty was very poor compared to mustards (Figure 5.2 & Table 5.1). Between the two mustard genotypes, osmotic adjustment was more obvious in 887.1.6.1 than in Muscon. Plants with osmotic adjustment can maintain very low Ψ_l in response to increasing soil moisture stress (Turner et al., 2001). Leaf water potential was correlated with osmotic adjustment and the degree of association varied between genotypes in this study (Figure 5.7c). The coefficient of determination between Ψ_l and osmotic adjustment in 887.1.6.1, Muscon and Monty was 0.7, 0.3 and 0.1 respectively. Due to osmotic adjustment, leaf water potential (Ψ_l) in mustards was consistently lower than Monty in severe stress treatment (Figure 5.2). 887.1.6.1 maintained similar levels of Ψ_l to Muscon earlier, but at the end of the season Ψ_l in 887.1.6.1 was significantly lower compared to Muscon. This is related to the superior osmotic adjustment in 887.1.6.1 compared to Muscon.

The lowest water potential experienced by the last viable leaf (lethal water potential) is a key measure of dehydration tolerance (Sinclair and Ludlow, 1986). Dehydration tolerance is related to the degree of osmotic adjustment (Fowler and Ludlow, 1987). This indicates that 887.1.6.1 and Muscon have greater dehydration tolerance than Monty. Due to dehydration tolerance, leaves and other plant parts can survive longer during grain filling and therefore continue to supply carbon to developing seeds (Ludlow and Muchow, 1990). Plants avoid dehydration by maintaining cell turgor, this is in turn achieved by reducing water loss or reducing stomatal conductance and maintaining water uptake (Ludlow and Muchow, 1990). However, as stomata influence the influx of CO_2 into leaves, low stomatal conductance inevitably lowers photosynthetic rate, hence the usefulness of reduced stomatal conductance depends on a trade-off between the loss of production and the need to prevent dehydration (Ludlow and Muchow, 1990).

In leaves with osmotic adjustment, stomata remain partially open to progressively lower water potential. This stomatal adjustment has a positive effect on photosynthetic activity as it promotes continued water loss (Ludlow, 1987). Stomatal conductance is positively correlated

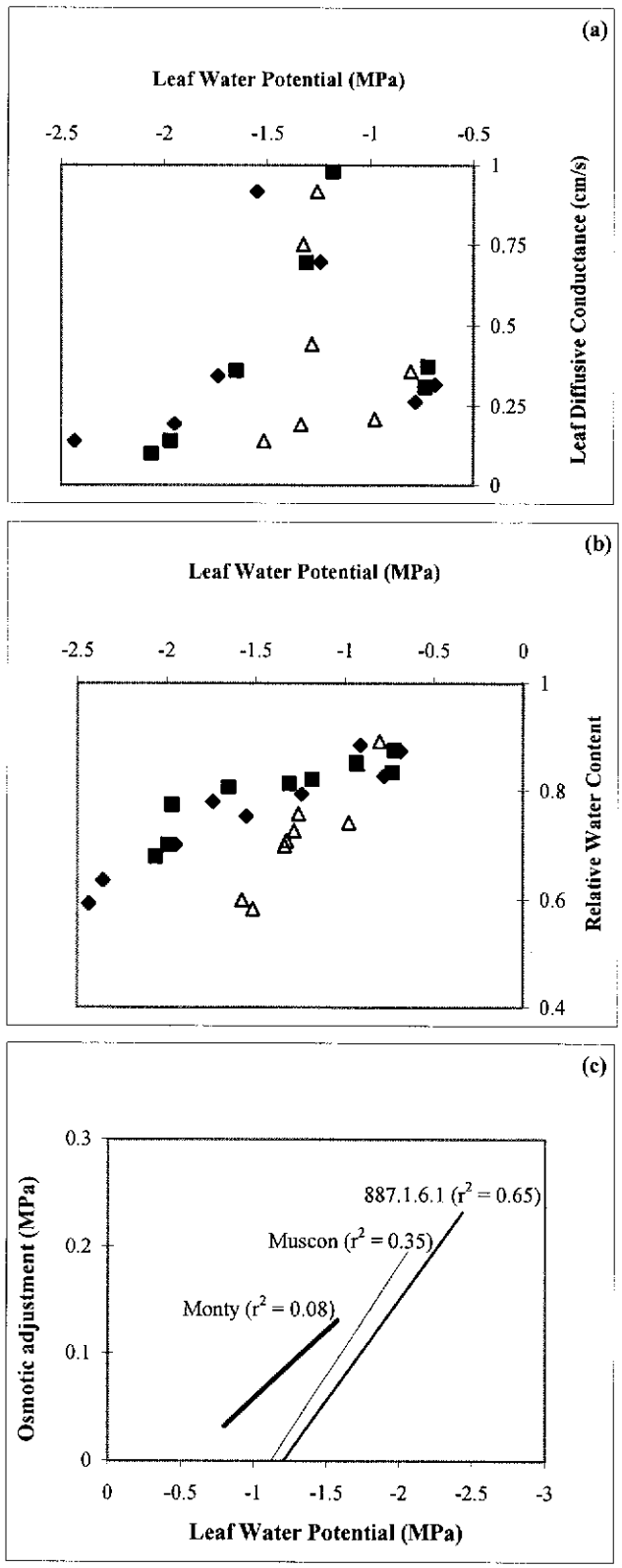

Figure 5.7. Association between (a) Leaf Water Potential (Ψ_l) and Leaf Diffusive Conductance (LDC), (b) Ψ_l and Relative Water Content (RWC), and (c) Ψ_l and Osmotic Adjustment, in two mustard genotypes (887.1.6.1 - ♦ and Muscon - ■) and a canola variety Monty- Δ under severe water stress at Merredin, WA in 2001.

with the degree of osmotic adjustment in *Brassica* species (Kumar *et al.*, 1984). Due to osmotic adjustment *B. juncea* genotypes can maintain relatively normal rates of transpiration as evidenced by high stomatal conductance under low leaf water potential (Kumar *et al.*, 1987). Similar observations were made in this study. 887.1.6.1 and Muscon were able to maintain stomatal activity at very low levels of Ψ_l compared to Monty (Figure 5.7a). Maintenance of some stomatal activity even at very low Ψ_l at the end of the season under severe water stress may have helped mustards continue leaf gas exchange for a longer period than Monty. This is the reason for a higher percentage increment in dry matter in mustards compared to Monty under severe stress.

Osmotic adjustment is also responsible for maintaining high RWC as Ψ_l decreases and thereby delaying leaf senescence and death (Turner, 1997). RWC and Ψ_l of last viable leaf of 887.1.6.1 was 59 % and –2.5 MPa, and that of Muscon was 68 % and –2.0 MPa respectively (Figure 5.7b). RWC and Ψ_l of last viable leaf of Monty was 58 % and –1.5 MPa, respectively. This indicates that at a given value of Ψ_l the mustards have greater RWC than canola. RWC is more closely related to tissue water deficits and is a measure of the plant's ability to extract water from the environment (Turner, 1997). Mustards can maintain higher RWC as they have the ability to extract more water from drying soils due to their superior osmotic adjustment. RWC or water potential at which leaves die (lethal values), express the degree to which plant parts can withstand desiccation. Low lethal water status refers to more negative water potentials and low RWC (Ludlow and Muchow, 1990). This indicates that, lethal water status of mustards is lower than that of Monty and that of 887.1.6.1 is lower than that of Muscon. Therefore, 887.1.6.1 is more tolerant to desiccation.

Genotypes with high osmotic adjustment produce more root biomass and greater root length density and extract more soil water (Turner, 1986). Deeper roots were developed under severe stress in mustard compared to Monty (as evident from water extraction data, Figure 5.4) and this is related to higher WU in mustard compared to Monty (Table 5.4). Water Use Efficiency for dry matter production (WUE_{dm}) of Monty was significantly lower than that of mustards due to its lower dry matter production (Table 5.8). Osmotic adjustment has also been shown to reduce floral abortion (Turner, 1997; Turner *et al.*, 2001). Floral abortion was not affected

by stress in 887.1.6.1 and this may be related to its superior osmotic adjustment. Floral abortion was higher in Monty was related to its poor osmotic adjustment.

Osmotic adjustment maintains higher HI by increasing assimilates supply during seed filling, by reducing leaf senescence, by maintaining photosynthetic activity of remaining leaves, and by increased use of pre-anthesis assimilates in seed filling (Ludlow and Muchow, 1990). Osmotic adjustment that occurs late in the season has little benefit in maintaining high rates of photosynthesis when leaf growth has ceased and very little moisture is available in the soil. However, it could play a role in maintaining positive rates of photosynthesis at low leaf water potential (Leport *et al.*, 1999). Maintenance of even a low level of photosynthetic activity may be critical in providing energy required for translocating and transferring carbon and nitrogen from the leaves, stems and roots to the developing seed. HI of mustards was not affected by soil moisture stress, but that of Monty was significantly reduced by severe soil moisture stress (Table 5.6). Lower HI of Monty under severe soil moisture stress may be related to the reduction of the efficiency in remobilization of stored assimilates to the seeds and reduced photosynthetic activity resulting from poor osmotic adjustment. Yield reduction due to moisture stress compared to irrigated treatment in Monty was higher (42 %) than that of 887.1.6.1 (37 %) and Muscon (33 %). Yield reduction was negatively correlated (r^2 = - 0.55) with osmotic adjustment. The higher yield reduction in Monty may be related to its poor efficiency of conversion of dry matter to seeds under severe stress.

Despite the ability of mustards to adjust physiologically to increasing water deficit and to produce greater dry matter than Monty, seed yield of mustards and Monty were not significantly different (Table 5.6). High dry matter does not always translate into high seed yields. Partitioning of dry matter into seeds, and the ability of plants to redistribute reserves, are also necessary for high seed yield (Leport *et al.*, 1999). Although HI of Monty was reduced by severe stress it was higher than mustard in all stress treatments (Table 5.6). The poor ability of mustards to convert the dry matter into seed yield, as indicated by the lower harvest indices, was probably related to the failure in out yielding canola at any level of stress. Under severe stress, Monty plants were compact, shorter and had a maximum of five primary branches and no secondary branches (Table 5.3) compared to those under stress free treatment. More pods were borne on the main stem and some on primary branches and there

were no secondary pods (Figure 5.5). In contrast, plants of 887.1.6.1 were taller and had more primary and secondary branches (Table 5.3), hence a greater proportion of dry matter was wasted to maintain the larger vegetative structure. This indicates the relative inefficiency of mustard's dry matter partitioning into seeds. The ability of Monty to change its morphology under water stress could be the main reason for it producing the same seed yields as mustards, despite its poor physiological adjustment to drought.

Contrary to the findings of this study, a yield advantage of mustard over canola under severe moisture stress was reported previously (Wright *et al.*, 1995; 1996; Wright and Morgan, 1998; Niknam and Turner, 2000). This indicates the presence of another factor/s, which prevented the expression of higher yield potential of mustards under severe stress in this study. Two possible reasons could be the level of stress developed during the growing period and the similarity of the phenotypic stability of three genotypes used in this study. As the spring and summer of 2001 at Merredin was mild compared to long term averages, a sufficiently high level of stress may not have developed in the mustards to express a yield advantage over canola. As presented in Chapter 4, 887.1.6.1, Muscon and Monty have average phenotypic stability, so that they exhibit similar levels of response to changes in environments.

Soil moisture stress has a negative effect on oil concentration (Heenan and Armstrong, 1993; Jensen *et al.*, 1996; Hocking *et al.*, 1997; Blondel and Renard, 1999; Walton, 1999). Similarly, oil concentrations were reduced by severe soil moisture stress in this study (Table 5.9). As found previously (Blondel and Renard, 1999), oil and protein concentrations were negatively correlated and protein concentration increased with severe soil moisture stress (Table 5.9).

5.5. CONCLUSIONS

Increasing water stress in the post-flowering period significantly reduced seed yields, dry matter production, and HI in mustard and canola. Yield components such as pods/plant, seeds/pod and 1000 seed weight were also reduced by water stress.

Dry matter production of mustards was higher than that of canola under severe water stress and which in turn related to their superior osmotic adjustment.

Osmotic adjustment improved dry matter production in mustards as it;
(i) Allowed stomata to remain partially open at progressively lower leaf water potentials and maintained higher stomatal conductance,
(ii) Increased water use by stomatal adjustment, and increased soil moisture uptake by producing deeper roots, and
(iii) Maintained leaf area and reduced the rate of leaf senescence by increasing both avoidance and tolerance of dehydration and thereby increased radiation use and duration of dry matter production.

However the poor ability of mustards to convert their dry matter into seed yields, as indicated by the lower harvest indices, was probably related to the failure to out yield canola at any level of stress, despite their superior physiological adaptation. Morphological attributes such as short, compact plant stature, and reduced branching were the key traits contributing to higher yields in Monty under water stress conditions.

CHAPTER 6

GENERAL DISCUSSION

Experiments presented in this thesis were undertaken to study adaptation of mustard in the Mediterranean-type environments of south Western Australia with the hypothesis that mustard would be better adapted to these environments compared to canola due to mustards reputed ability to tolerate soil moisture stress. The hypothesis was sustained on the evidence presented in this thesis. Seed yield of high yielding mustard genotypes (887.1.6.1 and 82 No 22-98) used in this study are more stable across varying environmental conditions compared to high yielding canola genotype, Monty. However, mustards did not out yield canola in any experiment despite their superior physiological adaptation to water stress conditions. Objectives of this discussion are therefore, to explain the characteristics of mustards that make them superior or equal to canola, and to suggest the favorable characteristics that can be combined with the above characteristics to improve mustard yields in short season, low rainfall environments.

Phenology had a significant contribution to yield potential and its stability of mustard and canola. Earlier flowering genotypes of mustard (82 No 22-98, 887.1.6.1 and Muscon) and canola (Monty) produced higher seed yields in all experiments compared to later flowering mustards (JM 25 and JM 33) and canola (Oscar). Despite the variation in times of sowing, maturity occurred at similar times across all sowing treatments and genotypes due to increased soil moisture and high temperature stresses at the end of the season. Therefore, early sown crops had a longer post-anthesis duration, as did the earlier flowering genotypes. Since longer post-anthesis duration always resulted higher dry matter production and eventually higher seed yields, early flowering genotypes yielded better in all experiments. Duration to flowering was significantly correlated (r^2 = 0.49) with seed yield at Mullewa. However, duration to flowering was not significantly correlated with seed yield or final dry matter at Northam or Merredin. These results indicate that earlier flowering was more important at Mullewa for higher seed yields where the season was shorter and rainfall was lower, especially in the post-anthesis period compared to Merredin and Northam.

Early flowering may not always leads to increases in seed yield. Consequently, developmental plasticity is more important in environments with variable rainfall (Turner *et al.*, 2001). Days to flowering were not significantly affected by times of sowing at Northam in all genotypes except in late maturing JM 29 (Chapter 3). However, at Merredin this was observed only in very early maturing Muscon and 82 No 22-98 (Chapter 4). All other genotypes adjusted their growth duration with the changes in environment at Merredin. Due to developmental plasticity, 887.1.6.1 and Monty were able to respond to a longer and wetter season in 2001 at Merredin and produced higher seed yields. However, being more stable and determinate, Muscon and 82 No 22-98 lack the capacity to respond to the favorable season. Drought induced early maturity in 887.1.6.1 and Monty was also advantageous and they were able to produce similar yields as Muscon and 82 No 22-98 in late sowings. Early maturity in Muscon and 82 No 22-98 and development plasticity in 887.1.6.1 and Monty could be reasons for their higher yield potential and average phenotypic stability.

Phenology of the low yielding and mid maturing genotypes Oscar, JM 33 and JM 25 and the late maturing JM 29 was also highly responsive to environmental changes. Their flowering occurred relatively late in a longer growing duration (early sowing) and vice versa in shorter growing duration (late sowing). This suggests that they were sensitive to photoperiod, although the effect was not measured in this study. They flowered earlier in later sowings when environments were warmer and days were longer. Therefore, they produced yields similar to early maturing genotypes in late sowings. Seed yield was highest in Oscar and JM 33 when sown early at Northam, despite their late flowering due to low temperatures and shorter days during vegetative phase. Post-anthesis duration was not reduced due to late flowering in Oscar, JM 33 and JM 25, at Northam where season is longer. Oscar, JM 33 and JM 25 had sufficient time to complete seed development before terminal drought sets in at Northam. However, dry matter and seed yield in Oscar, JM 33 and JM 25 was lower in early sowings at Merredin. Late flowering and maturity reduced post-anthesis duration in Oscar, JM 33 and JM 25 at Merredin where growing season is shorter and rainfall is lower.

Dry matter production was clearly related to seed yields. Seed yields of mustard and canola were strongly correlated with final above ground dry matter production at Northam ($r^2 = 0.93$) and at Merredin ($r^2 = 0.90$ and 0.88 in 2000 and 2001 respectively). Post-anthesis dry matter

was strongly correlated with seed yield compared to pre-anthesis dry matter in both years at Merredin (Table 4.13) indicating the relative importance of post-anthesis dry matter for higher seed yield. Dry matter production is a function of water use (Passioura, 1977), radiation use (Monteith, 1977), and crop growth rate and post-anthesis duration (Duncan et al., 1978). Some genotypes, which have genetic potential for rapid early growth or early vigour, have higher rate of canopy closure. Therefore, efficient water use is possible with genotypes having early vigour. Early vigour also has a positive influence on yield potential due to increased radiation interception and eventually due to accumulation of sufficient pre-anthesis biomass to support seed development under sub optimal temperatures and radiation levels (Ludlow and Muchow, 1990).

Principal component biplots for seed yield revealed that mustard genotypes, 887.1.6.1, 82 No 22-98 and Muscon had rapid early growth (early vigour) under relatively lower temperature compared to JM 25, JM 33, Monty and Oscar (Chapter 4). Due to their slower early growth Oscar, Monty, JM 25, and JM 33 required relatively longer pre-anthesis periods to produce higher dry matter compared to 887.1.6.1, 82 No 22-98 and Muscon. This was confirmed in the detailed canopy development, dry matter production and partitioning study undertaken at Merredin. Due to its rapid early growth, 82 No 22-98 had a greater leaf area index and intercepted more PAR and eventually produced more dry matter at Merredin. However, optimum temperatures must be met for Oscar and JM 33 for early rapid growth and to produce similar levels of dry matter as in 82 No 22-98, as observed in 2001 at Merredin. Rapid early growth was more advantageous in low rainfall environments and in short growing seasons or late sowings.

Final above ground dry matter did not differ significantly between genotypes in late and very late sowings at Northam. However, in the low rainfall environment at Merredin final above ground dry matter in late sowings was significantly higher in mustards compared to canola. Mustards (887.1.6.1 and Muscon) produced higher dry matter than Monty under severe water stress treatment (Chapter 5) indicating mustard has the ability to produce greater dry matter under soil moisture stress compared to canola. Greater dry matter production in mustards under soil moisture stress is related to their superior physiological adjustments. Mustard leaves had higher turgor pressure than those of canola under severe soil moisture deficit,

leading to longer leaf area duration (Wright *et al.*, 1996; 1997; Wright and Morgan, 1998). Osmotic adjustment in mustard is greater compared to canola (Kumar *et al.*, 1984; 1987; Wright *et al.*, 1996; 1997; Kumar and Singh, 1998; Wright and Morgan, 1998). Due to osmotic adjustment, mustard can maintain high leaf water potential and consequently, maintain relatively normal rates of transpiration as evidenced by high stomatal conductance (Kumar *et al.*, 1987). As shown in Chapter 6, osmotic adjustment improved dry matter production in mustards by allowing stomata to remain partially open at progressively lower leaf water potentials and by maintaining higher stomatal conductance and photosynthesis (not measured in this study). It also increased both avoidance and tolerance of dehydration, maintained leaf area, reduced the rate of leaf senescence and consequently maintained greater photosynthetic activity for a longer period. Osmotic adjustment increased soil water uptake from deeper layers that in turn increased water use and dry matter production.

According to Principal Component Analysis and Finlay-Wilkinson Analyses (Chapter 4), genotypes used in this study can be grouped into three. The first includes high yielding mustards (887.1.6.1, 82 No 22-98, and Muscon) and canola (Monty), which showed average phenotypic stability. The second includes low yielding mustards (JM 25 and JM 33), and the third includes low yielding canola (Oscar). Therefore, it is difficult to discuss the yield difference between species (mustard vs canola) in this study. However, mean seed yield across environments studied was higher in mustard genotypes 887.1.6.1 and 82 No 22-98 than canola genotype, Monty. Monty was more sensitive to environmental changes compared to 887.1.6.1 and 82 No 22-98, hence produced lower yields in more stressful conditions resulted from low rainfall, high temperature and later sowings. As an example, seed yield of Monty is lower compared to 887.1.6.1 and 82 No 22-98 at Merredin in 2000 and Newdegate in 2000 and 2001 (Tables 4.6 and 4.7). However, in the detail experiment conducted to study the effect of water stress on mustard and canola, 887.1.6.1 and Monty produced statistically similar yields. This indicates that 887.1.6.1 and Monty performed equally in better environments. 887.1.6.1 produced higher average seed yield compared to Monty across varying environmental conditions, as its seed yield is more stable. This may be a reason for the apparent differences in observed in the two studies (Chapters 4 and 5). In both studies Muscon produced lower yield compared to Monty.

Although high yielding mustards produced greater dry matter under severe soil moisture stress conditions, they did not have the ability to out yield canola in any experiment or at any site. This was also observed in severe water stress treatment imposed by excluding rainfall after flowering by using rainout shelters. Possible reason for this includes the differences in canopy structure, dry matter partitioning and yield components between mustard and canola genotypes used in the present investigations.

Harvest index in mustard was more stable across times of sowings and was not affected significantly by soil moisture stress. However, HI in mustard was always lower compared to that of canola. Although mustards produce more dry matter compared to canola, it has not been translated into higher seed yields due to inherited lower efficiency of dry matter conversion in mustards. This could be a reason for mustard not out yielding canola, despite its ability to produce greater dry matter.

Furthermore, yield structure of the two species differed in that canola has fewer pods and more seeds per pod than mustard. Wright *et al.* (1995) found that over 98 % of the variation in seed yield in mustard and canola could be accounted for by the variation in seed number/plant which is a function of the number of pods /plant and the number of seeds per pod. This does not imply that variation in seed weight is unimportant in seed yield. As seed weight is more stable over a wide range of environments, factors that influence seed number are likely to be more important in adaptation and maintenance of high yield under water limiting environments (Wright *et al.*, 1995). Figure 6.1 shows the yield components in mustard and canola as influenced by times of sowing and water stress treatments. Under soil moisture stress, pod numbers in mustard reduced significantly compared to canola. Therefore, canola has a slight advantage in seed number/plant due to its higher number of seeds per pod under soil moisture stress. Differences in yield structure almost entirely cancel each other out under soil moisture stress resulting in canola and mustard plants producing similar seed numbers. Since seed weight is more stable, seed yields in mustards and canola were similar under soil moisture stress.

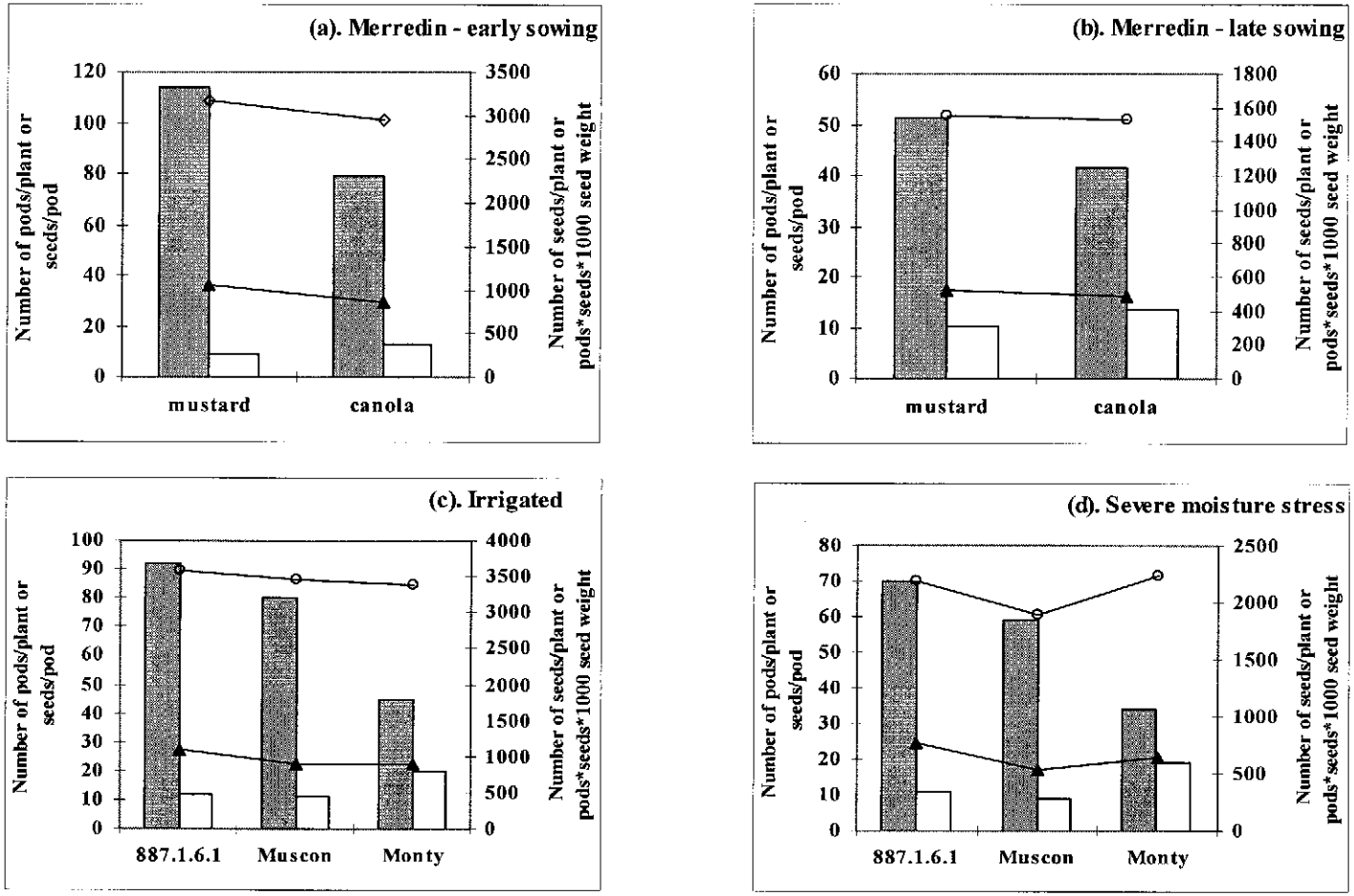

Figure 6.1. The effect of times of sowing (a & b) and water stress treatments (c & d) on yield components of mustard and canola at Merredin. Average number of pods/plant (solid histogram), number of seeds/pod (open histogram), number of seeds/plant (▲) and number of pods x seeds x 1000 seed weight/plant (○).

In summary, following characteristics of mustards can be identified as those contributed to superior or equal performances to canola.

1. Agronomic advantages - Early vigour (vigorous seedling growth, rapid ground covering ability), and the feasibility of direct harvesting due to non-shattering pods
2. Shorter pre-anthesis phase and longer post-anthesis phase
3. Developmental plasticity to adjust growth cycle according the varying environmental conditions
4. Greater dry matter production particularly under stress conditions resulting from low rainfall, high temperature and later sowings
5. Superior physiological adjustments to water stress conditions.

Despite all these advantages currently available mustard genotypes do not produce higher yields compared to canola due to their inferior yield component structure and lower efficiency of conversion of dry matter to seeds, as indicated by lower harvest indices.

Therefore, it is concluded that to take advantage of the stress tolerance of mustard the efficiency of conversion of biomass to seed yield must be increased. During the last few decades substantial-breeding efforts have occurred in the development of canola varieties adapted to various environments in Australia. However, to date very limited breeding efforts have been directed for the improvement of mustard in Australia. Further breeding and selection in mustard is required to modify its morphology and yield component, probably through the selection of compact, shorter statured genotypes with reduced branching. Mustard plants with more pods and pods with more seeds will lead to higher seed yields. Early generation (F_2 or F_3) materials from such breeding programs should be evaluated in key target environments in order to identify genotypes suitable for specific environments. This would result in mustard genotypes that are better adapted to the stressful conditions of the low rainfall, short season Mediterranean-type environments of south Western Australia. Although mustards produced more protein than canola; most of the mustard genotypes had lower oil contents than canola except 887.1.6.1. Development of mustard lines similar to 887.1.6.1 will also improve the value of mustard as an oilseed crop. The mechanisms underlying mustard's greater dry matter production, particularly photosynthetic activity under water stress require further investigation. More specific agronomic research on mustard is required to further improve yield and oil concentration in this crop.

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APPENDICES

A 1. Seed yield (t/ha), final above ground dry matter (t/ha) and harvest index (%) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, WA in 2000 growing season.

Genotype	Seed yield (t/ha)				Final above ground dry matter (t/ha)				Harvest Index			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean
887.1.6.1	1.5	0.8	0.6	1.0	6.2	4.1	2.7	4.3	24	20	21	22
JM 25	1.1	0.7	0.4	0.7	5.1	3.4	2.1	3.5	21	20	17	20
JM 33	0.8	0.4	0.3	0.5	4.7	2.9	2.1	3.2	16	14	14	15
Muscon	1.1	1.1	0.6	0.9	5.7	4.4	3.3	4.5	18	24	20	20
82 No 22- 98	1.1	0.9	0.5	0.8	5.3	3.7	3.0	4.0	20	23	18	20
Monty	1.4	0.8	0.4	0.8	4.3	2.9	1.9	3.0	32	28	18	26
Oscar	0.9	0.4	0.2	0.5	3.3	2.0	1.4	2.3	26	17	13	19
Mean	1.1	0.7	0.4	0.8	4.9	3.3	2.4	3.5	22	21	17	20
LSD (P = 0.05)	TOS = 0.4 VAR = 0.2 TOS X VAR = 0.5 VAR / Same levels of TOS = 0.4				TOS = 1.0 VAR = 0.6 TOS X VAR = 1.3 VAR / Same levels of TOS = 1.1				TOS = 5 VAR = 3 TOS X VAR = 6 VAR / Same levels of TOS = 4			

A 2. Seed yield (t/ha), final above ground dry matter (t/ha) and harvest index (%) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, WA in 2001 growing season.

Genotype	Seed yield (t/ha)				Final above ground dry matter (t/ha)				Harvest Index			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean
887.1.6.1	1.7	0.8	0.2	0.9	10.0	4.6	1.9	5.5	17	19	11	16
JM 25	0.8	0.5	0.2	0.5	7.0	4.7	2.0	4.6	12	9	10	10
JM 33	0.9	0.7	0.3	0.6	7.7	5.0	2.4	5.0	12	13	11	12
Muscon	1.2	0.4	0.2	0.6	9.2	3.9	2.5	5.2	13	11	9	11
82 No 22- 98	1.1	0.9	0.3	0.8	7.5	4.2	3.2	5.0	15	22	10	15
Monty	1.5	0.5	0.3	0.8	6.7	3.8	2.2	4.2	23	14	13	17
Oscar	1.8	0.7	0.1	0.9	7.5	4.2	1.4	4.4	23	18	5	15
Mean	1.3	0.7	0.2	0.7	7.9	4.3	2.2	4.8	16	15	10	14
LSD (P = 0.05)	TOS = 0.1 VAR =0.2 TOS X VAR = 0.3 VAR / Same levels of TOS = 0.3				TOS = 0.5 VAR = 0.9 TOS X VAR = 1.4 VAR / Same levels of TOS = 1.5				TOS = 3 VAR = 3 TOS X VAR = 6 VAR / Same levels of TOS = 6			

A 3. Yield components (Pods/plant, Seeds/pod and 1000 seed weight) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, WA in 2000 growing season.

Genotypes	Pods/ plant				Seeds/pod				1000 seed weight			
	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean	Early (16 May)	Mid (9 June)	Late (30 June)	Mean
887.1.6.1	12	8	7	9	12	12	16	13	2.6	2.5	2.5	2.5
JM 25	11	8	6	8	10	12	14	12	2.7	2.5	2.8	2.7
JM 33	12	9	8	10	8	9	9	9	2.6	2.3	2.5	2.5
Muscon	10	9	7	8	11	9	10	10	3.3	3.1	3.1	3.2
82 No 22- 98	11	9	8	10	9	8	11	9	3.2	3.1	3.1	3.1
Monty	7	6	5	6	17	19	20	19	3.4	3.2	2.8	3.1
Oscar	6	5	4	5	17	19	20	18	3.2	2.9	2.8	3.0
Mean	10	8	7	8	12	12	14	13	3.0	2.8	2.8	2.9
LSD (P = 0.05)	TOS = 1 VAR = 1 TOS X VAR = 2 VAR / Same levels of TOS = 2				TOS = 2 VAR = 2 TOS X VAR = 4 VAR / Same levels of TOS = 4				TOS = 0.2 VAR = 0.1 TOS X VAR = 0.3 VAR / Same levels of TOS = 0.3			

A 4. Yield components (Pods/plant, Seeds/pod and 1000 seed weight) in seven genotypes of mustard and canola sown at three times (early, mid, late) at Merredin, WA in 2001 growing season.

Genotypes	Pods/ plant				Seeds/pod				1000 seed weight			
	Early (24 May)	Mid (15 June)	Late (13 July)	Mean	Early (24 May)	Mid (15 June)	Late (13 July)	Mean	Early (24 May)	Mid (15 June)	Late (13 July)	Mean
887.1.6.1	11	10	6	9	10	10	10	10	2.7	3.0	3.0	2.9
JM 25	8	10	7	9	10	9	9	9	3.1	2.7	3.6	3.1
JM 33	10	11	9	10	8	7	8	8	3.0	2.8	2.8	2.9
Muscon	10	7	6	8	7	8	7	7	4.2	4.0	4.3	4.2
82 No 22- 98	11	9	7	9	7	8	8	8	3.9	4.1	3.7	3.9
Monty	7	6	7	6	19	18	17	18	3.5	3.2	3.1	3.3
Oscar	8	7	5	7	18	11	17	16	3.3	3.0	3.4	3.2
Mean	9	9	7	8	11	10	11	11	3.4	3.2	3.4	3.3
LSD (P = 0.05)	TOS = 2 VAR = 2 TOS X VAR = 3 VAR / Same levels of TOS = 3				TOS = 1 VAR = 2 TOS X VAR = 3 VAR / Same levels of TOS = 3				TOS = 0.4 VAR = 0.5 TOS X VAR = 0.8 VAR / Same levels of TOS = 0.9			

LIST OF PUBLICATIONS FROM THE THESIS

Gunasekera, C.P.; Martin, L.D.; Walton, G.H. and Siddique, K.H.M. (2000). Adaptation of Indian mustard (*Brassica juncea* L.) in the Mediterranean environment of South Western Australia. In "*Oilseed Crop Updates- 2000*", Technical Information for Agribusiness, Agriculture Western Australia. Perth, WA, pp. 17-18.

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