F2 Hybrid HEAR Agronomic and Seed Quality Studies

by

Tom Cyrus Bright

A Thesis Submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Department of Plant Science

University of Manitoba

Winnipeg

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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Abstract

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Canada is the world's largest producer of spring habit HEAR cultivars (McVetty et al., 1991). The currently grown HEAR cultivars, MillenniUM 03, Red River 1826 and Red River 1852 are open pollinated population cultivars. Even though there is no wholly adequate explanation to describe the phenomenon of hybrid vigor or heterosis, the seed yields of HEAR hybrids far exceed those of open pollinated population HEAR cultivars/strains. They also demonstrate greater vigor and better disease resistance. Hybrid cultivars/strains have many other advantages over open pollinated cultivars/strains such as larger seeds, enhanced oil and protein contents and superior agronomic performance. They produce bigger plants with more extensive root systems able to scavenge nutrients and moisture better. Recent studies have shown that crosses between different HEAR cultivars/strains can result in 40 to 100 % high-parent heterosis for seed yield. For this study two different types of HEAR hybrids were used including Conventional F2 HEAR hybrids and F2 Roundup Ready HEAR hybrids. These hybrids originated from crosses of genetically and geographically distinct HEAR cultivars/lines (parents). Seven of the twelve parental lines used in this study were HEAR strains developed by the University of the Manitoba (UM) and the rest were European (EU) strains. Adequate F2 HEAR hybrid seed was produced to assess the hybrids and parents in six environments in Manitoba during 2006 and 2007. All entries in all trials had agronomic parameters assessed during the growing season including vigor, days to

flower, days to maturity, lodging, plant height and seed yield. After harvest, six seed quality characteristics including oil concentration, protein concentration, sum of oil and protein concentration, meal protein concentration, erucic acid concentration and glucosinolate concentration were assessed in this study. Agronomic and seed quality studies in F2 HEAR hybrids will help characterize a novel approach to using HEAR hybrid seed efficiently. Three estimates of heterosis, mid-parent, high-parent and commercial heterosis for each F2 HEAR hybrid combination were calculated. As all F2 HEAR hybrids showed higher vigor than their parents, differences between hybrids and parental strains/cultivars were easily visually distinguishable in the F2 HEAR hybrid field trials. Conventional F2 HEAR hybrids displayed high-parent heterosis estimates for seed yield of up to 75 %, mid-parent heterosis for seed yield of up to 91 % and commercial heterosis for seed yield of up to 56 %. Furthermore, F2 Roundup HEAR hybrids displayed high-parent heterosis estimates for seed yield of up to 76 %, mid-parent heterosis for seed yield of up to 97 % and commercial heterosis for seed yield of up to 53 %. The levels of heterosis for seed yield observed in this study were half or more of the heterosis levels observed for the corresponding F1 HEAR hybrids. The levels of heterosis observed were sufficient to warrant further study of the use of F2 HEAR hybrids. In this study, F2 HEAR hybrids were much taller and had significantly better lodging resistance than their parents in all field trials. Conventional F2 HEAR hybrids displayed lower protein concentration and higher oil concentration than their parents. In contrast, F2 Roundup Ready HEAR hybrids displayed higher protein concentration and lower oil concentration. These two hybrid types were cross progeny from genetically distinct pools, so these differences were most likely genetics related.

1.0 Introduction

Rapeseed (*Brassica napus*) has been used for centuries throughout the world. First, oilseed rape was used as fuel in lamps in Asia and Europe. Oilseed rape then became a source of industrial lubricant. Finally, oilseed rape was improved in quality to produce an edible vegetable oil first in low erucic acid genotypes and then in low erucic acid, low glucosinolate genotypes. Baldur Stefansson at the University of Manitoba produced the world's first low erucic acid, low glucosinolate rapeseed variety "Tower" in 1974.

The trademark name "canola" was adopted by the Canola Council of Canada to distinguish the new, improved quality oilseed rape from the old one (McVetty and Brandle, 1989). Rapeseed has 35 to 40 % erucic acid oil, a fatty acid with 22 carbons and one double bond (C22:1), and high glucosinolate meal. High Erucic Acid Rapeseed (HEAR) has 50 to 55 % erucic acid oil (controlled by two dominant genes) and low glucosinolate (controlled by three recessive genes) meal. The currently grown HEAR cultivars, MillenniUM 03, Red River 1826 and Red River 1852 are open pollinated population cultivars. The Red River HEAR cultivars are the world's first HT (herbicide tolerant) HEAR cultivars.

Spring oilseed rape production has developed increasingly in western Canada (Scarth et al., 1991). Hybrid canola is quickly gaining in popularity compared to traditional open-pollinated population varieties. Significant heterosis for seed yield in oilseed rape has created interest in the development of hybrid cultivars. In western Canada, the total canola acreage planted to hybrids has more than doubled since 2000 (Statistics Canada, 2008). The demand for canola hybrids is expected to climb because of the yield and quality advantages that hybridization affords.

A hybrid results from a controlled cross of two genetically dissimilar parents. Only one parent provides pollen. The other produces the hybrid seed. The resulting hybrid plants are identical to one another and receive 50 % of their genes from the male parent and 50 % from the female parent. The production of hybrid canola has grown greatly with nearly 50 % of western Canada canola area planted to hybrid in 2008 (Statistics Canada, 2008). This is because of heterosis effects. Heterosis or hybrid vigor is the increased vigor, growth, size, yield, or function of a hybrid progeny over the parents that results from crossing genetically unlike organisms (Sleper and Poehlman, 2006). Practically, heterosis is the increase in vigor or growth of a hybrid progeny in relation to the better parent, referred to as the high-parent value. In canola for example, hybrids have been shown to have 40 to 60 % higher yield than their better parent (Grant and Beversdorf, 1985).

There are two theories that can explain this effect. The first theory suggests that hybrid vigor results from a group of favorable, dominant genes. Alleles that produce vigor and growth are dominant and recessive alleles are harmful or neutral. According to this idea, the F1 will have more favorable dominant alleles than either parent. This theory is called the Dominance theory (Sleper and Poehlman, 2006).

The second theory suggests that hybrid vigor is based on the fact that loci that are heterozygous contribute more to productivity than loci that are homozygous. In other words, the most vigorous hybrid plant is the one with the greatest number of heterozygous loci. This theory is called the Over-Dominance theory (Sleper and Poehlman, 2006).

Crosses between parents from different geographical areas resulted in hybrids with higher levels of heterosis than parents that had not been geographically separated (Moll et al., 1962). Crosses between Canadian and European *Brassica napus* cultivars/strains resulted in hybrids with generally higher yields (McVetty and Brandle, 1989).

In *Brassica napus* the heterosis range is between -10 and 140 % (McVetty and Brandle, 1989). Hybrid vigor and its qualities can not be easily predicted. They can only be determined through testing of the progeny for each parental combination. In spite of the fact that hybrid seeds have better yield and seed quality, it is difficult and expensive to produce hybrid *Brassica* seeds.

The objectives of this research were to:

1) Determine the performance of F2 HEAR hybrid strains/cultivars compared to open pollinated HEAR strains/cultivars in different locations over two years.

2) Estimate the mid-parent, high- parent and commercial heterosis for selected agronomic and seed quality traits for F2 HEAR hybrids.

3) Compare these assessments of heterosis in F2 HEAR hybrids to those seen in F1 HEAR hybrids.

Theoretically F2 HEAR hybrid seed retains half of the heterozygosity of the F1 HEAR hybrid and up to half of the heterosis observed in the F1 HEAR hybrid. If heterosis in the F1 HEAR hybrid is high, capturing half of this heterosis in F2 HEAR hybrid could be very useful.

The objectives of this research were to investigate the performance of F2 HEAR hybrid strains/cultivars as a means to reduce the amount of F1 HEAR hybrid seed that will be required for each new HEAR hybrid and significantly reduce the cost of seed for growers. Reducing the F1 HEAR hybrid seed quantity required will be possible since seed multiplication rates in *B. napus* are approximately 1000:1. Using much less expensive F2 HEAR hybrid seed may be possible since the level of heterosis for seed yield in the F2 HEAR hybrid strains/cultivars is in theory half of that seen in the F1 HEAR hybrid and therefore still of benefit to HEAR hybrid growers.

2.0 Literature Review

2.1 History and Biology

2.1.1 Rapeseed

The word "rape" in rapeseed finds its origin in the Latin word *rapum* which means turnip. Today the name rapeseed applies to the oilseeds of several species of the genus *Brassica*.

Brassica crops are among the oldest cultivated plants known to humans with written records dating back to 1500 BCE and archaeological evidence of its importance dating back to 5000 BCE (Tsunoda et al., 1980). During World War II, rapeseed oil was considered an essential lubricant because it could cling to water- and steam-washed metal surfaces better than any other oil. Since the naval ships and trains of the time were steam-powered, and with the European and Asian rape oil supplies cut off, Canada was asked to undertake production. The annual form of the *B. napus* species was introduced first, followed shortly by *B. campestris* (Downey, 1990). The four most widely cultivated species *B. napus*, *B. rapa*, *B. juncea*, and *B. oleracea* are all highly polymorphic and include oilseed crops, root crops, and vegetables crops such as Chinese cabbage, broccoli, and Brussels sprouts. The relationships among the cultivated species as shown in (Figure 2.1) were first clarified by Morinaga (1934) and verified by U (1935). *B. juncea, B. napus,* and *B. carinata* are amphidiploids species resulting from combining chromosomes sets of the low chromosome number species *B. nigra*, *B. oleracea* and *B. rapa*. *Brassica rapa* seems to have had the widest distribution historically. At least 2000 years ago it was distributed from northern Europe to China and Korea, with a primary center of diversity in the Himalayan region. *B. napus*, also known as rape or oilseed rape, is believed to have developed in the Mediterranean area where the wild forms of its ancestral species were sympatric.

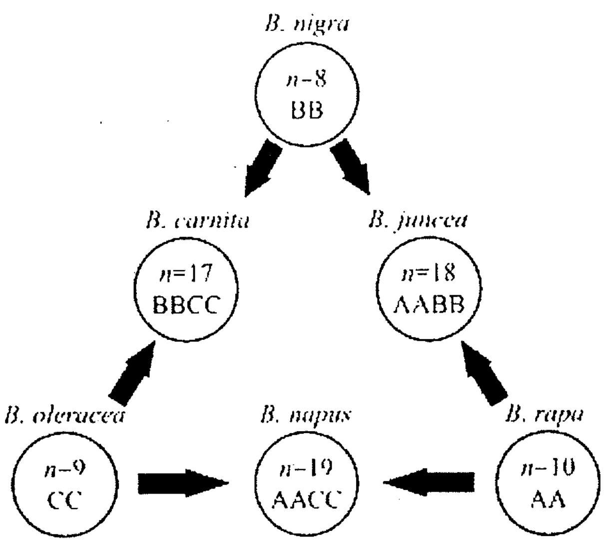

Figure 2.1: Triangle of U. Genomic and Chromosome Relationship of the *Brassica* Species (Downey, 1990)

Production of oilseed *B. napus* probably started in Europe during the middle ages where its oil was used as a lamp oil. Rapeseed breeding in Canada began shortly after the Second World War when H.J. Newfeld made selections from seed stocks introduced by Agriculture Canada from Argentina (Stefansson and Downey, 1995). The breeding program was continued at Saskatoon on small scale. In 1962 R.K. Downey began to devote himself full-time to breeding rapeseed. After 1966, B. Stefansson and F.W. Hougen, devoted most of their time to rapeseed breeding. The canola/rapeseed breeding programs continue at the University of Manitoba. Efforts to develop pollination control mechanisms that could be used to produce first generation hybrid cultivars have been underway since Shiga and Baba (1971) and Thompson (1972) reported on the cytoplasmic male sterility that occurs in many European rapeseed cultivars (Stefansson and Downey, 1995)

Canada's *Brassica* oilseed requirements are largely supplied by *Brassica napus* (97 %), *B. rapa* (2.5 %) and *B. juncea* or mustard (0.5 %). These species are also grown in different parts of the world. Winter type *B. napus*, which has higher yield than the spring type, is planted in most of Europe and in some parts of China. Spring type *B. napus* is produced in Canada, northern Europe and China. In Australia and the southeastern United States, where winters are mild enough, spring type *B. napus* can be grown as a fall-planted winter crop. Spring *B. rapa* is planted in Canada and is also grown in northern Europe, China and India. Spring types of *B. juncea* are dominant in India and are also grown to a limited extent in Canada and Europe primarily for condiment use. Worldwide production of rapeseed (including canola) increased to 46.4 million metric tons in 2005 which was the highest recorded total to date (Table 2.1).

	(million metric tones)
China	13.0
Canada	8.4
India	6.4
Germany	4.7
France	4.4
United Kingdom	1.9
Poland	1.4
Australia	1.1
World Total	46.4

Table2.1: Top Rapeseed Producers in 2005 (Food and Agriculture Organization, 2008)

B. napus is an annual herb with upright, bluish green stem. Its height is 0.8 to 1.5 m tall. Lower leaves are alternate, stalkless, 15 cm long and upper leaves are similar except for with the different size (9 cm long and 3 cm wide). Flowers are in branched clusters, pale yellow or cream color. *B. napus* flowers have 4 petals and 6 stamens. The fruit is a narrow silique, ascending, 3-5 cm long and roundish with a beak. The *B. napus* photosynthesis system is C3 which is lower efficiency than C4 plants such as corn. Oil seed rape is approximately 77 % self-pollinated under field conditions in western Canada (Rakow and Woods, 1987). Vectors for cross pollination are wind and/or insects.

2.1.2 Canola and High Erucic Acid Rapeseed

The requirement for a healthy, edible oil and good quality meal for livestock induced *Brassica* breeders to improve rapeseed cultivars. The term "canola" is a registered trademark of the Canadian Canola Association and refers to cultivars/strains of oilseed rape that produce seed oils with less than 2 % erucic acid (22:1) and meals with less than 20 μ mol of aliphatic glucosinolates per gram seed at 8.5 % moisture (Canola Council of Canada, 2008).

The development of the world's first canola-quality cultivars by plant breeders in Canada during the 1970s created a new, high-value oil and protein crop that has gained tremendous acceptance worldwide. *B. napus* canola was initially developed in Canada by Baldur Stefansson (Tower, 1974) while the world's first *B. rapa* canola cultivar was developed by Keith Downey (Tobin, 1977).

Oilseed rape (*Brassica* and related species, the *Brassicaceae*) is now the second largest oilseed crop in the world providing approximately 13 % of the world's supply. Two species, *Brassica napus* and *Brassica rapa* are increasingly important in world markets. Both species contain both spring and winter forms that are distinguished by vernalization requirement. Seeds of these species commonly contain 40 % or more oil and produce meals with 35 to 40 % protein.

The fatty acid composition of the oil is genetically controlled and has been successfully manipulated to produce different kinds of oil profile cultivars. Canola oil contains less than 2 % erucic acid, 5 to 8 % saturated fats, 60 to 65 % mono unsaturated fats and 30 to 35 % polyunsaturated fats. Canola oil is widely used as cooking oil, salad oil and in making margarine. It is highly recommended for health reasons because it has the lowest saturated fat content of all major edible vegetable oils.

The term "industrial rapeseed" refers to oilseed rape cultivars/strains that produce oils with 50 % or more erucic acid and seed meals that are either high or low in glucosinolate. Cultivars/strains with these characteristics are used primarily for non-edible purposes such as lubricants and hydraulic fluids. The seed meal is quite high in protein. Canola and the meal produced by high erucic acid, low glucosinolate rapeseed (HEAR) is also used as a meal for livestock (Scarth et al., 1991). The world's first high erucic acid, low glucosinolate rapeseed cultivar released was Reston in 1982 (Alberta Agriculture, 1982) while the second HEAR cultivar was Hero in 1991 (Scarth et al., 1991). A form of herbicide tolerance (HT) such as glyphosate (Roundup Ready) or glufosinate (Liberty Link) has been used in the majority of recent canola and HEAR cultivars. The University of Manitoba has produced Roundup Ready HEAR cultivars (Red River 1826 and Red River 1852) in 2006 (McVetty et al., 2006).

2.2 Oilseed Rape Quality Components

2.2.1 Oil Concentration

Oil is a valuable seed component in oilseed rape. Rapeseed is the third largest source of vegetable oil in the world. Rapeseed should be harvested at a moisture content of eight percent in the kernel. Lower moisture increases the possibility of shattering or damaging the kernel and any more moisture than eight percent will give the seed the chance of molding or deteriorating while in storage (Downey, 1983). Temperature during seed maturation, nitrogen availability and genotype are other factors which can affect the amount and quality of oil. Cool temperature with moderate rates of nitrogen is the best condition to produce higher seed oil concentrations (Downey, 1983). Oil concentration shows both additive and overdominance gene action (Govil et al., 1984). Plant breeders have paid particular attention to increasing the oil concentration of the seed since the oil is valued at 4 to 6 times the value of the meal.

2.2.2 Protein Concentration

Proteins are large organic molecules made of amino acid arranged in a linear chain and joined together by peptide bonds between the carboxyl and amino groups of proteins. The sequence of amino acids in a protein is defined by a gene and encoded in the genetic code. Narrow sense heritability for seed meal protein concentration is roughly 0.25 (Grami et al., 1977). Protein concentration of the seeds in oilseed rape species is between 20 and 40 %. There are different kinds of proteins in different species of rapeseed due to genetic effects.

2.2.3 Glucosinolates

Glucosinolates are a class of organic compounds that contain sulfur, nitrogen and a group derived from glucose. Glucosinolates well known for their toxic breakdown products which are water-soluble anions belonging to the glucosides. Every glucosinolate contains a central carbon atom which is bound via a sulfur atom to the glycone group and via a nitrogen atom to a sulfonated oxime group. In addition, the central carbon is bonded to a side group and different glucosinolates have different side groups.

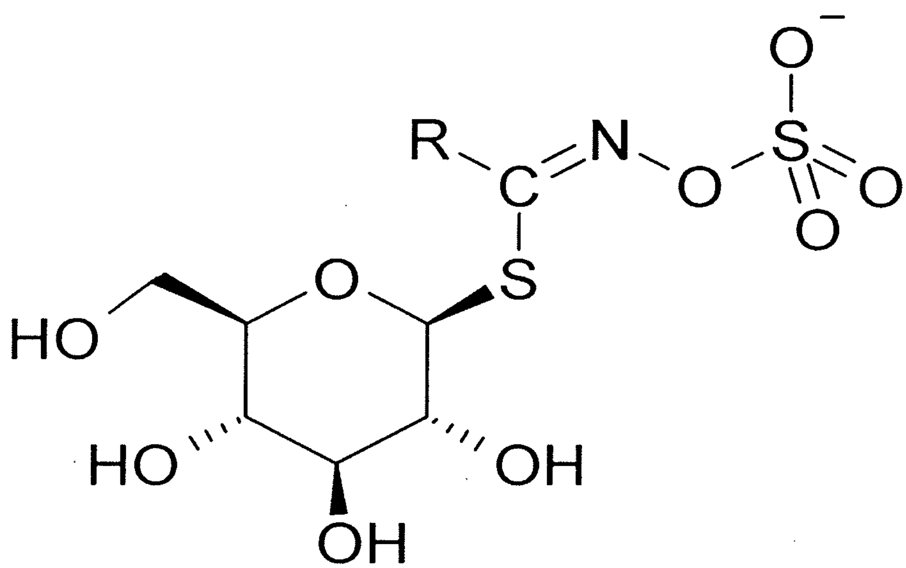

Figure 2.2: Chemical Structure of Glucosinolates (Downey, 1990)

About 120 different glucosinolates are known to occur naturally in plants. They are synthesized from certain amino acids.

The high protein meal in oilseed rapeseed left after extracting oil could be useful for livestock feed. However, use of this meal for livestock feed was not recommended due to high levels of toxic glucosinolates until plant breeders discovered a low glucosinolate Argentine rape strain named "Bronowski" (Stefansson and Downey, 1995).

Oil seed rape meal does not have any harmful effect on livestock if the glucosinolate content is lower than 12 μmoles per gram of seed meal (Canola Council of Canada, 2008).

2.2.4 Erucic Acid Concentration

Fatty acids are carboxylic acids with a long unbranched aliphatic tail (chain), which is either saturated or unsaturated. Fatty acids with no double bonds are referred to as saturated. The proportion of saturation of the chains differs between different *Brassica* species. The proportion of saturation and the length of the fatty acid chain are related to the viscosity of the oil. Short fatty acid chains with more double bonds will be much less viscous than a long fatty acid chain with no double bonds. If fatty acids have at least one double bound, the fatty acids are referred to as unsaturated. Erucic acid is a monounsaturated omega-9 fatty acid, denoted 22:1 ω-9.

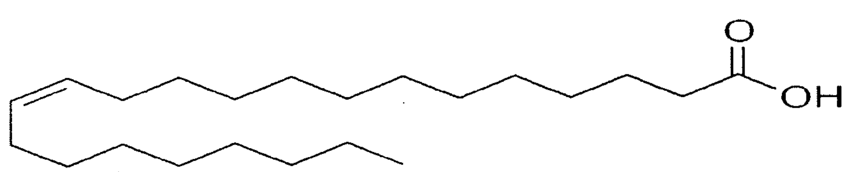

Figure 2.3: Chemical Structure of Erucic Acid (Taylor, 2003)

Nutritionists are interested in rapeseed oil because it is different from other edible vegetable oils in its fatty acid composition. Rapeseed oil contains significant amounts of the monoenoic fatty adds with 20 (eicosenoic) and 22 (erucic) carbon chains as opposed to the common carbon chain lengths of 16 and 18 carbon atoms found in most vegetable oils (Downey, 1990). In contrast to rapeseed oil, canola oil is low in erucic acid.

Fatty acid	Symbol	Rapeseed *Brassica napus*	*Brassica rapa*	Canola	Sunflower	Soybean
Palmitic	C16:0	4.0	4.9	4.7	7.2	11.5
Stearic	C18:0	1.5	1.6	1.8	4.1	3.9
Oleic	C18:1	17.0	33.0	63.0	16.2	24.6
Linoleic	C18:2	13.0	20.4	20.0	72.5	52.0
Linolenic	C18:3	9.0	7.6	8.6	0.0	8.0
Eicosenoic	C20:1	14.5	9.9	1.9	0.0	0.0
Erucic	C22:1	41.0	23.0	0.0	0.0	0.0

Table 2.2: Percent Fatty Acid Composition of Canadian Vegetable Oils (Downey, 1990)

Erucic acid biosynthesis is controlled by two genes with additive effects (Grami and Stefansson, 1977). Erucic acid biosynthesis consists of a two-step chain elongation as shown in (Figure 2.4). The change of oil composition from rapeseed to canola cultivars/strains which are low in erucic acid was achieved by genetically blocking the biosynthesis pathway which reduces elongation of the fatty acid chain after oleic acid to very low levels (Downey, 1990).

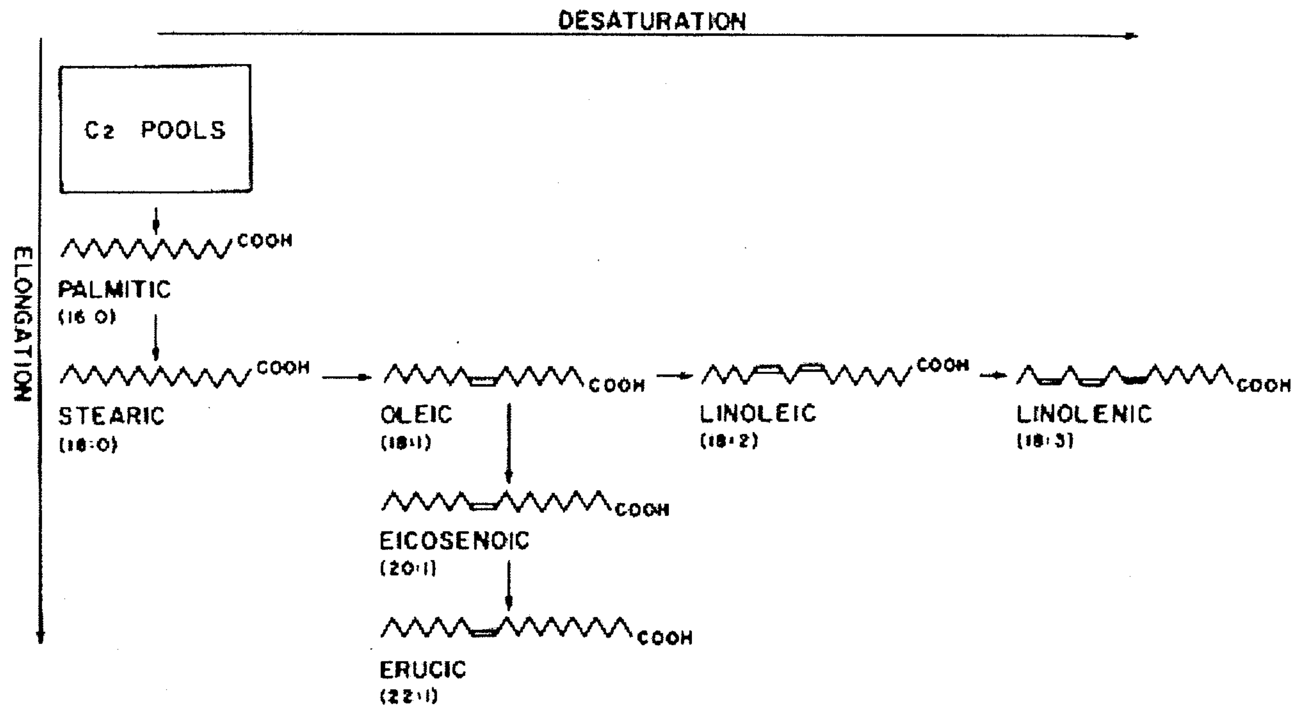

Figure 2.4: Biosynthetic Pathways of the Major Fatty Acids in Vegetable Oilseeds (Taylor, 2003)

2.2.5 Sum of Oil and Protein Concentrations

Increasing the concentration of oil in B*rassica napus* in the seed decreases the concentration of protein in the seed. Therefore, the correlation between protein and oil concentrations is negative (Robbelen et al., 1989). The sum of oil and protein is an unbiased measurement of seed quality. Plant breeders have had more success in breeding rapeseed for higher sum of oil and protein rather than for either higher oil or protein concentrations independently because the narrow sense heritability (the proportion of phenotypic variance that can be attributed to additive genetic variance) is higher (0.33) for the sum than for oil and protein concentrations 0.26 and 0.25 respectively (Grami et al., 1977).

2.3 Hybrid Breeding and Pollination Control System

A canola hybrid is the result of a cross between two genetically distinct lines of canola. Crosses between genetically distinct parental lines or population give rise to progeny that exhibit heterosis or hybrid vigor. Hybrids with a heterotic phenotype are in general more resistant to disease and insects, less susceptible to environmental stresses and have higher seed yield.

Previous research in the greenhouse showed that making hand crosses between two distantly related lines of canola resulted in yields that were up to 50 % higher than the better parent line. This increased yield is the result of heterosis or hybrid vigour. The more distantly related the parents, the greater the resulting hybrid vigour. However, producing hybrid seed by hand for large volumes of seed is economically impractical. Since *B. napus* is mainly self-pollinated, pollination of the parent lines must be controlled to make hybridization commercially feasible. Commercial F1 hybrid seeds of *Brassica* crops have been produced using self-incompatability since the 1930's. Male sterility in *Brassica* crops was not found until the 1950's (Tsunoda et al., 1980).

2.3.1 Definition of F1 Hybrids and Types

F1 hybrid means the first generation offspring of a cross between two individuals differing in one or more genes. The effectiveness of a breeding scheme depends on the breeder's ability to choose suitable parents and evaluate the progeny in the most appropriate sequence using techniques that are both efficient and accurate.

F1 hybrids types could be:

1) Open Pollinated Population x Open Pollinated Population (OPP x OPP).
2) Inbred Line x Inbred Line (IL x IL).
3) Doubled Haploid Line x Doubled Haploid Line (DH x DH).

Hybrid breeding schemes are:

1) Choosing two OPP, IL, or DH lines from two contrasting heterotic genes pools.
2) Putting in a pollination control system.
3) Making hybrid seeds commercially and then selling them.

2.3.2 Pollination Control Systems

Hybrid cultivars/strains have had their greatest utilization in cross-pollinated crops, such as corn. In recent years hybrid cultivars/strains are also being developed in crops which have both self and cross pollination, such as rapeseed. However, this selfing reduces the percentage of hybrid seed (hybridity) produced in hybrid seed production process. To overcome this problem and ensure that crosses occur only between the selected female and male lines, several forms of pollination control have been used to produce hybrid seed in plants (McVetty, 1998). These include manual emasculation, use of cytoplasmic male sterility system and use of genic male sterility system.

Although self-incompatibility may hinder the breeder's ability to self-pollinate and produce inbreds in self-incompatible species, it is being utilized to facilitate crossing of self-incompatible lines for the production of hybrid seed.

There are three different kinds of F1 hybrids and all of these F1 hybrids are self-fertile and can be selfed to generate F2 hybrid seed.

1) **Single cross F1 hybrids**

The single-cross system requires two self-incompatible, cross compatible inbreds and each homozygous for an S allele. This system has been developed in *Brassica* plants which have a sporophytic incompatibility system. The single cross system requires that a large amount of inbred seed be produced by bud pollination for commercial production. Also, bees can provide enough hybrid seed in *Brassica* plants.

INBRED A INBRED B

S1S1 X S2S2

↓

S1S2 Hybrid

Figure 2.5: Single Cross System (Sleper and Poehlman, 2006)

2) Double cross F1 hybrids

The double cross system increases the ratio of hybrid seed from a given amount of inbreed seed. The double cross system requires two isogenic, self-incompatible, cross-compatible lines of each inbred, each homozygous for a different incompatibility S allele as follows:

INBRED A		INBRED B		
S1S1 X S2S2		S3S3 X S4S4		
↓		↓		
S1S2	X	S3S4		
	↓			
S1S3	S1S4	S2S3	S2S4	Hybrids

Figure 2.6: Double Cross System (Sleper and Poehlman, 2006)

3) **Triple cross F1 hybrids**

To increase hybrid seed production in relation to inbred seed further, a triple cross system was proposed. The triple cross requires three homozygous genotypes for each inbred and permits one additional generation of seed increase.

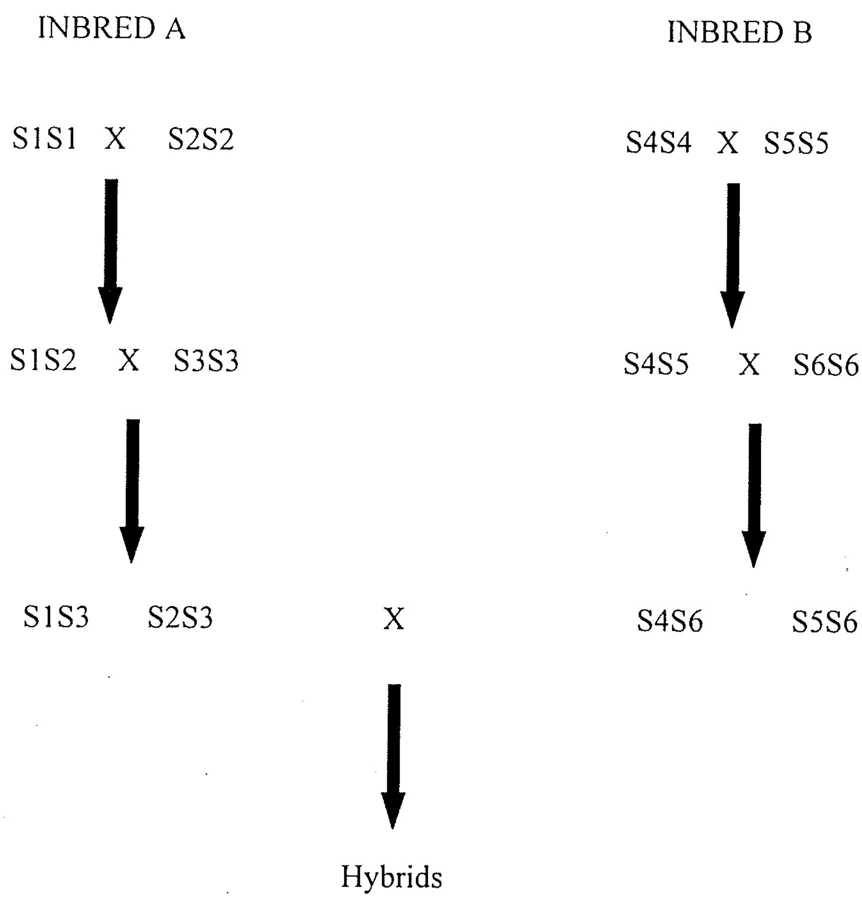

Figure 2.7: Triple Cross System (Sleper and Poehlman, 2006)

2.3.3 Cytoplasmic Male Sterility System

In *B. napus* use of cytoplasmic male sterility systems to develop the hybrid cultivars/strains is common. The development of hybrid cultivars/strains has been one of the essential factors contributing to increased crop productivity. Although all CMS sources can theoretically be developed into functional CMS systems, only a few have actually been developed to the point where commercial quantities of hybrid seed are being produced (McVetty, 1998). There are several reasons for this, including insufficient or unstable male sterility, difficulties with restoration systems, difficulties with seed production, and undesirable pleiotropic effects of the CMS pollination control system used. The majority of hybrids grown today are based on CMS as the pollination control mechanism (McVetty, 1998).

A long term sustained interest in CMS is related to the fact that it provides a possible mechanism of pollination control in plants to permit the easy production of commercial quantities of hybrid seed. A CMS system consists of a male-sterile line (the A-line), an isogenic maintainer line (the B-line) and a restorer line (the R-line).

A-Line: The male-sterile parent line in a cross used to produce hybrid seed. The A-line is the seed-producing line, commonly used with reference to production of hybrid rapeseed or corn.

B-line: The fertile counterpart, or maintainer of the A-line. The B-line does not have fertility restorer genes and is used as the pollen parent to maintain the A-line, commonly used with reference to production of hybrid rapeseed or corn.

R-line: The pollen parent line, containing fertility restoring gene(s), crossed with A-line in the production of hybrid seed in rapeseed or corn.

The *nap* CMS system in oilseed rape is unstable at moderate to high temperatures and therefore not commercially usable. Oilseed rape with the *ogu* CMS system growing at 12 °C or less displays chlorosis and generally poor growth. Oilseed rape hybrids produced using the *pol* CMS system performed significantly poorer than hybrids in a normal cytoplasm for seed yield, total dry matter, harvest index and oil content. Polima CMS A-lines are also temperature sensitive, reverting to partial male fertility at temperatures over 30 °C (McVetty, 1998).

2.3.4 Genic Male Sterility

Takag obtained a monogenic recessive male sterile mutant through gamma-ray irradiation of growing oil rape plants in 1970 (Tsunoda et al., 1980). Also, Heyne found male sterility in oilseed rape in 1973 (Tsunoda et al., 1980). Male sterility found in *Brassica* crops was in most cases inherited as a simple recessive gene (Tsunoda et al., 1980).

Male-sterile plants are potentially useful in hybrid programs because they eliminate the labor-intensive process of flower emasculation. The major problem with GMS is the maintenance of the male-sterile line. Normally, a GMS line (A-line) is maintained by backcrossing with the heterozygote (B-line), but the progeny produced are 50 % fertile and 50 % male sterile (Tsunoda et al., 1980). In the field, this creates the problem of removal of fertile plants (Tsunoda et al., 1980). For solving this problem, there are some suggestions. One proposal is to identify marker genes that are closely linked to ms genes and affects some vegetative characters, such as seed color and shape. Another one is to identify some visible pleiotropic effects of ms genes that would help sort out the male-sterile plants at an early stage. Also, the ability to manipulate male sterility in GMS lines by environmental or chemical methods is another desirable approach (Tsunoda et al., 1980).

A line: Male sterile (ms/ms), female parent

B line: Male fertile, maintainer, (Ms/ms), male parent

C line: Male fertile, (Ms/Ms), male parent

B x A	A x C
$\downarrow$	$\downarrow$
50 % Male fertile: 50 % Male sterile	F1 hybrid fertile

Figure 2.8: Genetic Male Sterility System (Tsunoda et al., 1980)

2.4 Hybrid Seed Production

The hybrid seed must have low contamination with seeds of different weeds or diseases such as *Sclerotina sclerotiorum*. Also, the genetic control of quality characters like erucic acid and glucosinolate content should be considered. The production of seed of hybrid varieties of oilseed needs special organization, which is basically similar to that of the seed production of conventional quality rapeseed varieties.

There are five steps:

1) Seed production is organized under full control of the breeder.

2) Multiplication fields have to be selected very carefully. They should have no contamination with volunteer plants of rape or other *Brassica* crops.

3) Farmers who are multiplying seed on contract have to work accurately. Only one variety per farm should be multiplied. Similar variety is grown on other fields of the farm or at least the multiplication fields have to be isolated well and combined first. A lot of seed can be transmitted by a combine, so combines must be thoroughly cleaned before use. Also, sowing must be done carefully, which includes cleaning of the drill.

4) As oilseed rape is a partially cross pollinated (allogamous) crop, minimum isolation distances of 100 m or more have to be observed.

5) The harvested seed should be dried and stored temporarily at the farms.

A random sample is taken and analyzed for the quality characters erucic acid and glucosinolate concentrations. If these values are within range, the dry seed has to be transported to the preparation plant where cleaning, preparation, germination tests, hybridity tests, storage, seed dressing and bagging are carried out.

The cost of pure clean hybrid seed is about 2.5 times that of conventional seed. Basically the production of the hybrid seed is similar to the multiplication of the CMS A-line. The production is carried out in crossing blocks by growing alternating strips of the seed parent and pollinator. For commercial hybrid seed production it is possible to have a ratio of seed parent: pollinator of 3:1 or even 4:1, 6:1 or 7:1 (Feistritzer and Kelly, 1987). As working male sterility systems are available, hybrid *B. napus* varieties have come onto the market.

The production of hybrid cultivars is also possible using a genetic male sterile system, provided enough cheap labor is available to rouge out the male fertile plants in the seed production fields before they flower. Such a system has been used in China but is not recommended in Western nations because of high labor costs (Robbelen et al., 1989).

There are only two steps of multiplication:

1) Multiplication of the lines which is done in the nursery of the breeder.
2) Production of hybrid seed which is done on contract by farmers.

2.5 Synthetics

By mixing seed of different *B. napus* lines or cultivars with good combining ability, synthetic cultivars can be produced which will utilize some of the seed yield heterosis expected from F1 hybrids. However, as the synthetic cultivar is multiplied through the Syn-1, -2, -3 generations, to produce sufficient seed for commercial sale, the level of heterozygosity changes. The low level of outcrossing (20 % to 30 %) between individual plants limits the degree of heterosis that can be utilized in synthetic cultivars.

2.6 Heterosis

Heterosis was first demonstrated in the early 20th century by George H. Shull and Edward M. East in corn (Sprague and Dudley, 1997). They defined heterosis as the increase in size or other valuable qualities in crossbred as compared to the pure biotypes. Not all traits in any crop show heterosis. Traits which show heterosis are:

Stand at emergence, vigor, days to flower, lodging, plant height, days to maturity, seed yield and stand at harvest (Sleper and Poehlman, 2006). Seed quality traits including oil, protein, glucosinolate and erucic acid concentration usually do not show heterosis because increases in one trait are offset by decreases in the other trait. For example, when we breed canola for higher oil content that means the percentage of other components in the seed such as protein is reduced.

There are two acceptable hypotheses explain the phenomenon of heterosis. The over dominance hypothesis states the combination of divergent alleles at a particular locus will result in a higher fitness in the heterozygote than in the homozygote. In other words, this theory explains hybrid vigor on the basis that loci that are heterozygous contribute more to productivity than loci that are homozygous.

The second hypothesis is called the general dominance hypothesis. According to this theory, alleles that contribute to vigor and growth are dominant, whereas the recessive alleles may be neutral, harmful, or deleterious to the individual. If the dominant alleles contributed to the hybrid by one parent complement those contributed by the other parent, the F1 will then have a more favorable combination than either parent. The two hypotheses will have different consequences on the gene expression profile of the individuals. If over-dominance is the main cause for the fitness advantages of heterosis, then there should be an over-expression of certain genes in the heterozygous offspring compared to the homozygous parents. On the other hand, if avoidance of deleterious recessive genes is the cause, then there should be fewer genes that are under-expressed in the heterozygous offspring compared to the parents. Furthermore, for any given gene, the expression should be comparable to the one observed in the best of the two parents (Sleper and Poehlman, 2006).

Plant breeders express the degree of hybrid vigor of an agronomic character in different ways:

1) The percentage increase over the better parent.

2) The percentage increase over the mid parent or average of the two parents.

3) The percentage increase over the best commercial cultivar currently grown.

2.7 Using F2 hybrids on farms

Many different crops such as cereals and oilseeds are produced under contract between seed producers and farmers. Farmers will purchase certified seed (F1 hybrids) for the growing season and then F1 hybrids that are grown again (F2 hybrids) can be still used by farmers. For example, F2 canola hybrids displayed 11% higher seed yield than their parents in Sweden (Engqvist and Becker, 1991). This estimate of heterosis for F2 canola hybrid was sufficient to justify the use of F2 canola hybrids

Parent versus F1 hybrids and F2 hybrids versus parents relationships were shown in Figure 2.9. Assuming a linear relationship between heterosis and inbreeding coefficient, the expected degree of heterosis in F2 is half that seen in the F1 due to the production of homozygous genotypes in the F2 (Sleper and Poehlman, 2006). Hybrid vigor and its qualities can not usually be predicted. They can only be established or proven through testing of the F1 and F2 for each parental combination. Hybrid vigor cannot be maintained at its maximum because it starts reducing with the first generation in which self-pollination may occur. The amount of heterosis is always of essential importance to a breeder. Evaluation of heterosis in the F1 generation is often a problem due to shortage of seed, however, this can be overcome by evaluating the F2.

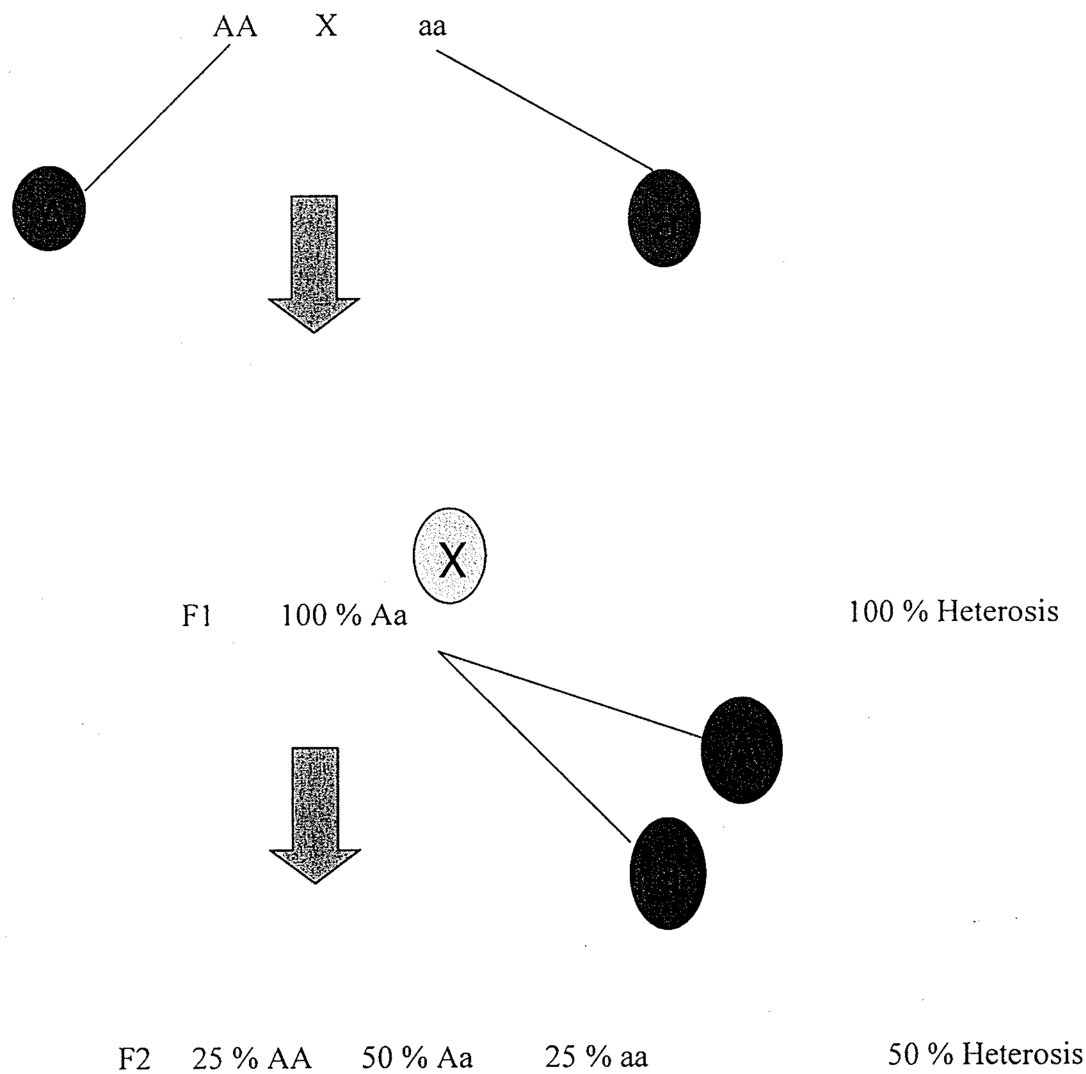

Figure 2.9: Heterozygosity and Hybrid Vigor in F1 and F2 Generations

2.8 Inbreeding Depression

Inbreeding consists of any system of mating that leads to an increase in homozygosity in the progeny. The most rapid approach to homozygosity in plants is through self-fertilization in which heterzygosity in a population of plants being reduced by one-half with each successive self-fertilization (Figure 2.9).

The main visible consequence of inbreeding in cross-pollinated species is loss in size and vigor in progeny plants as heterozygosity decreases. The decrease in vigor is largest following the first generation of inbreeding (Figure 2.9). The decline in vigor with inbreeding is known as inbreeding depression and results from increases in the frequency of homozygous loci with deleterious effects. Corn as a cross pollinated crop has very high inbreeding depression while canola in Western Canada has low inbreeding depression because it has just 3 % to 4 % cross pollination (McVetty et al., 2006).

In plants with heterozygous loci, the recessive deleterious allele is not expressed in the plant phenotype due to masking by the favorable, dominant allele. As homozygosity increases, many dominant alleles are lost and the deleterious effects of recessive alleles on the phenotype are expressed.

In contrast to hybrid vigor, the inbreeding of a normally cross-pollinated plant results in a loss of vigor of the individual plant, which can make it more susceptible to unfavorable environmental factors. The inbreeding effects on a normally cross-pollinated plant are the opposite of hybrid vigor in plants.

3.0 Materials and Methods

3.1 Genetic Background of HEAR Strains

In this research, seven HEAR strains/cultivars which were developed at the University of Manitoba (UM) and five European strains (EU) were chosen based on superior agronomics, seed quality and diverse pedigree. The HEAR cultivars/strains used were: Castor, MillenniUM 01, MillenniUM 03, HR 200, HR 102, RRHR 102 (glyphosate tolerant), HR 199, EU HEAR 1, EU HEAR 2, EUHEAR 3, EUHEAR 4, EUHEAR 5.

3.2 Crossing Scheme

F1 HEAR hybrid seeds were produced in the winter of 2003/2004 in the greenhouse at the University of Manitoba. The twelve genetically diverse HEAR strains or cultivars were arranged in a top crossing scheme. Crossing was accomplished by hand emasculation and bud pollination techniques. In this technique, the parental strains/cultivars were covered by bagging to prevent contamination. Then, the harvested seed was cleaned and packaged. Total F1 HEAR hybrids produced in the winter of 2003/2004 were 45 including 37 Conventional F1 hybrids and 8 F1 Roundup hybrids. In this research study 10 Conventional F1 HEAR hybrids and all 8 F1 Roundup HEAR hybrids were chosen. When sufficient F1 HEAR hybrid seed was produced, several hundred F1 plants were grown in isolation in the field and selfed to produce F2 HEAR hybrid seeds (Figure 3.1).

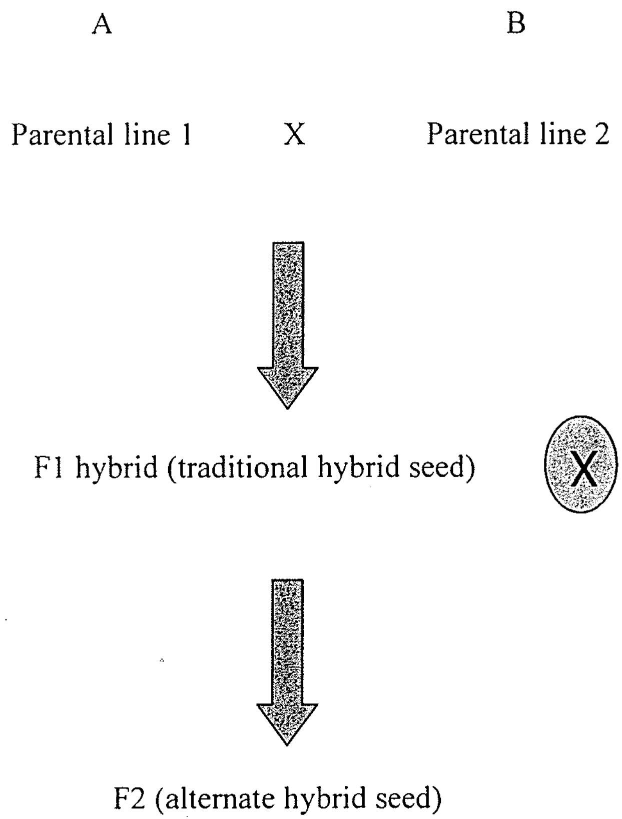

Figure 3.1: Crossing Scheme from Parental Strains to F2 Alternative Hybrid Seed

There were two different materials used in this research:

3.3 Conventional F2 HEAR Materials

Ten F2 hybrid HEAR strains and ten open pollinated population parents were used in this study (Table 3.1). Field trials were conducted at three locations (Winnipeg, Carman and Portage la Prairie) in 2006 and 2007. F2 HEAR hybrid field trial plots had six rows three m long with twenty cm row spacing. These were seeded with a Hege small plot belt-cone seeder. All F2 HEAR hybrid field trials were swathed and harvested using a Wintersteiger small plot combine. Seed collected was kept in paper bags. These bags of seed were placed on a warm air drier room at the University of Manitoba for at least fourteen days until the seeds were uniformly dry. All trials had agronomic parameters assessed during or after the growing season including vigor, days to flower, days to maturity, lodging, plant height and seed yield.

	PEDIGREE
F2	HR 200 x EU HEAR 1
F2	HR 102 x EU HEAR 3
F2	MillenniUM 03 x EU HEAR 3
F2	Castor x EU HEAR 3
F2	MillenniUM 01 x EU HEAR 1
F2	MillenniUM 01 x EU HEAR 3
F2	HR 200 x EU HEAR 3
F2	HR 102 x EU HEAR 2
F2	HR 199 x EU HEAR 2
F2	HR 199 x EU HEAR 1
P	Castor
P	MillenniUM 01
P	MillenniUM 03-1
P	MillenniUM 03-2
P	HR 200
P	HR 102
P	HR 199
P	EU HEAR 1
P	EU HEAR 2
P	EU HEAR 3

-P = Parental Strains/Cultivars
-F2 = Conventional F2 HEAR Hybrids

Table 3.1: Conventional F2 HEAR Hybrids and Parental Materials

3.4 F2 Roundup Ready (RR) HEAR Materials

In this study the hybrids possessed herbicide tolerance genes. The Roundup herbicide tolerance gene was provided only in the male parent. Therefore, the F2 hybrids segregated for herbicide tolerance and were not sprayed with Roundup in this study.

Eight F2 RR hybrid HEAR strains and twelve open pollinated population parents were used in this study (Table 3.2). F2 RR hybrid HEAR field trials were conducted at two locations (Carman, Portage la Prairie) in 2006 and 2007. F2 RR hybrid HEAR field trial plots had six rows with three m long with twenty cm row spacing. These were seeded with a Hege small plot belt-cone seeder. All F2 RR hybrid HEAR field trials were swathed and harvested using a Wintersteiger small plot combine. Seed collected was kept in paper bags. These bags of seed were placed on warm air driers at the University of Manitoba for at least fourteen days until seeds became uniformly dry. All trials had agronomic parameters assessed during or after the growing season including vigor, days to flower, days to maturity, lodging, plant height and seed yield.

	PEDIGREE
F2	RRHR 102 x EU HEAR 1
F2	RRHR 102 x EU HEAR 3
F2	HR 102 x RRHR 102
F2	RRHR 102 x EU HEAR 5
F2	RRHR 102 x EU HEAR 4
F2	RRHR 102 x HR 199
F2	HR 200 x RRHR 102
F2	RRHR 102 x EU HEAR 2
P	Red River 1852
P	EUHEAR 5
P	RRHR 102
P	Red River 1826
P	EU HEAR 4
P	MillenniUM 03
P	HR 200
P	HR 102
P	HR 199
P	EU HEAR 1
P	EU HEAR 2
P	EU HEAR 3

-P = Parental Strains/Cultivars
-F2 = F2 Roundup HEAR Hybrids

Table 3.2: F2 Roundup Ready HEAR Hybrids and Parental Materials

3.5 Field Trials

3.5.1 Experimental Design

Field trials were arranged in a Randomized Complete Block Design (RCBD) design at three locations in southern Manitoba in 2006 and 2007. Winnipeg, Carman and Portage locations were used for one set of hybrid trials while Carman and Portage locations were used for a second set of hybrid trials. Randomization of entries between replications in both years was useful for accurate comparisons of entries.

The F2 HEAR hybrid field trials had 4 replications. Terbufos (5 % granules) insecticide was mixed with the seed at a rate of 55.6 g a.i.ha^{-1} to control flea beetles (*Phyllotreta crucifera Goeze and P. striolata F.*). The seeding discs were set at a depth of 3 cm. The F2 HEAR hybrid field trials at Winnipeg were seeded on May 9, at Carman on May 20 and at Portage la Prairie on May 26 in 2006. The F2 HEAR hybrid trials at Winnipeg were seeded on May 15, at Carman on May 25 and at Portage la Prairie on May 27 in 2007. Seedling emergence at all locations was excellent due to adequate soil moisture and timely rains in both 2006 and 2007. Total rainfall from May to October 2006 was approximately 325.5 mm and total rainfall from May to October 2007 was approximately 310.5 mm (Environment Canada, 2008). Summer temperatures during 2006 were a little higher than 2007. Mean temperature during May to October in 2006 was roughly 17 °C and the mean temperature for similar period in 2007 was approximately 16 °C (Environment Canada, 2008). Temperatures were near average during July and August of 2006 and 2007, however, they were higher than average during May and June in both years. The largest differences in temperatures between the two growing seasons were observed in the June to September period.

Granular fertilizer, 20-0-0-14, NPKS, was applied by broadcast spreader to Winnipeg, Carman and Portage la Prairie in 2006 and 2007 at a rate of 111 kg ha^{-1} nitrogen. The Carman and Portage la Prairie field trials were sprayed with a herbicide mix of Poast Ultra, Lontrel and Muster on July 20 to control grassy and broadleaf weeds. The herbicide mixture applied using a bicycle wheel plot sprayer equipped with fan nozzles delivering 108 L ha^{-1} at 275 KPa. Also, manual weed removal was done as required for the remaining field trials.

3.5.2 Agronomic Traits

Vigor was based on how quickly ground was covered by the plants at the 4 to 5 leaf stage measured on a scale from 1 to 5. This rating was a visual one. Rows with large plants covering a large ground area were rated as 5 and rows with small plants were rated as 1. Number of days to flower was measured when 50 % of the plants in a row or plot had at least one open flower.

Number of days to maturity was measured when plants were visually physiological mature in each row or plot. Plants were considered physiological mature when 40 % to 50 % seed color change to yellowish brown occurred.

Lodging was measured at physiological mature on a scale from 1 to 5. Plants with an erect stem at maturity were rated as 1. The greater angle of the plants in relation to the ground, the more score of lodging. When the plants lay flat on the ground, they were scored as 5.

Plant height was measured at the physiological maturity. Several plants were randomly chosen within each row or plot and the height (from the soil to the very top of the plant) was measured in cm using a two meter long measuring stick. Seed yield per row or plot was measured in grams and then converted into kg ha^{-1}.

3.5.3 Seed Quality Traits

Oil, protein and glucosinolate concentrations in the seed were measured using near-infrared reflectance (NIR) technology and a Foss 6500 system (Daun et al., 1994; DeClercq, 2008). Oil and protein concentrations were measured at 0 % moisture and glucosinolate concentration was measured at 8.5 % moisture. The sum of oil and protein concentrations was calculated by adding seed oil concentration and protein concentration. Prom (Protein content of the meal) was calculated by subtracting the oil portion from total seed weight. Erucic acid concentration in the oil was measured by gas chromatography of methyl esters of fatty acids (DeClercq, 2008).

3.6 Statistical Analysis

These agricultural experiments were repeated at several locations for two years. This is necessary because the effects of factors might vary considerably from location to location as well as from year to year. Therefore, it is possible to determine the effects of environment (years and locations) on the entries.

Field trials were arranged in a Randomized Complete Block Design at each location. The individual trials were combined over locations and years after a heterogeneity test of error variances (Bartlett's test) was found to be non-significant. The analysis of combined parameters is essentially an extension of the analysis of variance applied to the simple randomized complete block experiments. However, it also involves the principle of the split-plot analysis as two error terms are required. One error term is needed to test locations, years and the interaction of locations and years. Another one is required to evaluate varieties and all the interactions that involve varieties. The raw data of agronomic parameters and seed quality in 2006 and 2007 were entered into Excel files to be analyzed by the SAS Mixed Procedure Program. Firstly, the analysis of data was done for each location and year separately. Then, the trials were combined over locations and years with each location/year termed an environment and analyzed as a split-plot (Cochran and Cox, 1957).

The model used was:

$Y_{ijk} = \mu + t_i + b_j + \text{environment}_k + e_{ijk}$

Letters are representing:

Y_{ijk} = each observation of the trait

μ = population mean

t_i = entries (i = 1 to 20)

b_j = the effect of the j'th replication within an environment, j =1 to 4

environment_k = replications over the experiment

e_{ijk} = residual

The t-test procedure was used to carry out a t-test with 95 % confidence intervals and alpha = 0.05 to compare means of hybrids and parents for each trait. This procedure determined if the hybrid mean was significantly different from the parent strain/cultivar mean.

3.6.1 Heterosis Assessments

Three different kinds of heterosis including mid-parent, high-parent and commercial heterosis were determined for agronomic and seed quality traits in this study.

For calculating the mid-parent (MP) heterosis, the mean of the F2 HEAR hybrid for each trait (F2) and the mean of the two parental strains/cultivars of the F2 HEAR hybrid for each trait (MP) were calculated.

Then, the following formula was used to calculate mid-parent heterosis:

$$\frac{\overline{F2} - \overline{MP}}{\overline{MP}} \times 100 = \%\ \text{Mid- Parent Heterosis}$$

For calculating the high-parent (HP) heterosis, the mean of the F2 HEAR hybrid for each trait (F2) and the mean of the better of the two parental strains/cultivars of the F2 hybrid for each trait (HP) were calculated.

Then, the following formula was used to calculate high-parent heterosis:

$$\frac{\overline{F2} - \overline{HP}}{\overline{HP}} \times 100 = \%\ \text{High- Parent Heterosis}$$

For calculating the commercial heterosis, the mean of the F2 HEAR hybrid for each trait (F2) and the mean of the commercial cultivar in the region (MillenniUM 03 or COM) were calculated.

Then, the following formula was used to calculate commercial heterosis:

$$\frac{\overline{F2} - \overline{COM}}{\overline{COM}} \times 100 = \%\ \text{Commercial Heterosis}$$

4.0 Results and Discussion

4.1 Agronomic Parameters

4.1.1 Seedling Vigor for Conventional F2 HEAR Hybrids

Conventional F2 HEAR hybrids displayed considerably higher vigor than parents and it was easy to distinguish the differences between hybrids and parents from the 4 to 5 leaf stage in these field trials. Conventional F2 HEAR hybrids had a mean vigor rating of (4.5) while parents had a significantly lower mean rating of (3.4) (Table 4.1).

Cuthbert (2006) used F1 HEAR hybrids from parents similar to the F2 HEAR hybrids used in this study. Cuthbert (2006) found that F1 HEAR hybrids displayed higher seedling vigor (4.0) than their parents (3.4). F2 HEAR hybrids displayed higher mean vigor (4.5) than the F1 HEAR hybrids (4.0) due to excellent soil moisture and optimum seeding date. Sernyk and Stefansson (1983) also observed high seedling vigor for F1 canola hybrids compared to canola parents.

MillenniUM 01 x EU HEAR 1 had the maximum vigor (4.9) while HR 199 x EU HEAR 1 had the minimum mean vigor (4.0) for Conventional F2 HEAR hybrids (Table 4.1). Crosses between EU #1, EU #3 and Manitoban cultivars/strains produced F2 HEAR hybrids with higher vigor than other F2 HEAR hybrids (Table 4.1).

Vigor displayed significant mid-parent, high-parent and commercial heterosis for all hybrids in the Conventional F2 HEAR hybrid field trials (Table 4.1). Cuthbert (2006) also found that vigor displayed significant mid-parent, high-parent and commercial heterosis for all hybrids in the F1 HEAR hybrid field trials.

Vigor was significantly correlated with a number of traits such as lodging ($r = -0.37$), yield ($r = 0.58$) and plant height ($r = 0.42$) which indicated that Conventional F2 HEAR hybrids with higher vigor were taller, had higher yield and lower lodging than Conventional F2 HEAR hybrids with lower vigor (Table 4.2).

Similarly, Cuthbert (2006) found that vigor was significantly correlated with a number of traits such as lodging, plant height and seed yield which indicated that F1 HEAR hybrids with higher vigor were taller, had higher yield and lower lodging than F1 HEAR hybrids with lower vigor. Cuthbert (2006) also found that vigor was significantly correlated with seed oil concentration and seed protein concentration in the F1 HEAR hybrid field trials.

Table 4.1: Mean Vigor and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	VIG (1-5)	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
5	MilleniUM 01 x EU HEAR 1	4.9	53.1 *	44.1 *	44.1 *
3	MillenniUM 03 x EU HEAR 3	4.8	43.3 *	41.2 *	41.2 *
8	HR 102 x EU HEAR 2	4.6	29.6 *	24.3 *	35.3 *
9	HR 199 x EU HEAR 2	4.6	26.0 *	24.3 *	35.3 *
7	HR 200 x EU HEAR 3	4.5	26.8 *	18.7 *	32.4 *
1	HR 200 x EU HEAR 1	4.4	29.4 *	16.0 *	29.4 *
4	Castor x EU HEAR 3	4.4	37.5 *	35.4 *	29.4 *
2	HR 102 x EU HEAR 3	4.3	28.4 *	26.5 *	26.5 *
6	MillenniUM 01 x EU HEAR 3	4.2	25.4 *	23.5 *	23.5 *
10	HR 199 x EU HEAR 1	4.0	21.2 *	10.3 *	17.6 *
Parents					
15	HR 200	3.8			
19	EU HEAR 2	3.7			
17	HR 199	3.6			
14	MillenniUM 03-2	3.5			
12	MillenniUM 01	3.4			
16	HR 102	3.4			
13	MillenniUM 03-1	3.3			
20	EU HEAR 3	3.3			
11	Castor	3.1			
18	EU HEAR 1	3.0			
Overall Hybrid Mean		4.5 †			
Overall Parent Mean		3.4			
Hybrids-Parents		1.1			

* - hybrids significant at p≤ 0.05

† - means of hybrids and parents are significantly different at p≤ 0.05

Table 4.2: Correlation Matrix for Selected Agronomic Traits and Seed Quality for Conventional F2 HEAR Hybrids Grown in Six Environments 2006 and 2007

	VIG (1-5)	FLR (days)	LOD (1-5)	HT (CM)	MAT (days)	YLD (kg ha^{-1})	Protein (g kg^{-1})	Oil (g kg^{-1})	GLU (μmolg^{-1} seed)	Prom (g kg^{-1})	Sum (g kg^{-1})	Er (%)
VIG												
FLR	-0.18											
LOD	-0.37*	0.06										
HT	0.42 *	0.08	-0.96 *									
MAT	-0.12	0.93 *	0.002	0.15								
YLD	0.58 *	-0.51 *	-0.89 *	0.88*	-0.40 *							
Protein	-0.17	-0.10	0.25	-0.25	-0.22	-0.83 *						
Oil	0.18	-0.05	-0.27	0.26	0.09	0.83 *	-0.95 *					
GLU	-0.08	0.16	0.15	-0.01	0.01	-0.24	0.48 *	-0.51 *				
Prom	-0.18	0.05	0.27	-0.26	-0.09	-0.47*	0.86 *	-0.55 *	0.51 *			
Sum	0.11	-0.24	-0.17	0.16	-0.13	0.59 *	-0.51 *	0.72 *	-0.31 *	-0.72 *		
Er	0.15	-0.56 *	0.003	-0.10	-0.48 *	0.21	0.001	0.07	-0.48 *	-0.07	0.15	

* - Correlation coefficient (r) significant at $p \leq 0.05$

* - N = 480

4.1.2 Seedling Vigor for F2 Roundup HEAR Hybrids

Differences between hybrids and parents were easily visually distinguishable from 4 to 5 leaf stage in the F2 Roundup HEAR hybrid field trials due to higher vigor. Cuthbert (2006) also found similar results in the F1 HEAR hybrid field trials.

F2 Roundup HEAR hybrids had a mean vigor rating of (4.2) while parents had a significantly lower mean rating of (3.2) (Table 4.3). RRHR 102 x EU HEAR 1 had the maximum (4.6) while RRHR 102 x EU HEAR 5 had the minimum (3.8) mean vigor in the F2 Roundup HEAR hybrid field trials. Crosses between EU #1, EU #3 and Manitoban strains/cultivars produced F2 Roundup HEAR hybrids with higher vigor than other F2 Roundup HEAR hybrids (Table 4.3).

Similarly, Cuthbert (2006) found that F1 HEAR hybrids displayed higher seedling vigor than parents. However, F2 HEAR hybrids displayed higher mean vigor (4.2) than F1 HEAR hybrids (4.1) due to excellent soil moisture, generally better environmental conditions and optimum seeding date. Sernyk and Stefansson (1983) also found that F1 canola hybrids displayed higher seedling vigor than parents.

Vigor displayed significant mid-parent, high-parent and commercial heterosis for all hybrids in the F2 Roundup HEAR hybrid field trials (Table 4.3). Cuthbert (2006) also found similar results in the F1 HEAR hybrid field trials.

Vigor was significantly correlated with a number of traits such as lodging ($r = -0.35$), yield ($r = 0.62$) and plant height ($r = 0.31$) which indicated that hybrids with higher vigor were taller, had higher yield and lower lodging than hybrids with lower vigor (Table 4.4). Cuthbert (2006) found that vigor was significantly correlated with a number of traits such as lodging, plant height and seed yield which indicated that F1 HEAR hybrids with higher vigor were taller, had higher yield and lower lodging than F1 HEAR hybrids with lower vigor. Cuthbert (2006) also found that vigor was significantly correlated with seed oil concentration and seed protein concentration in the F1 HEAR hybrid field trials.

Table 4.3: Mean Vigor and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	VIG (1-5)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	4.6	43.8 *	31.4 *	35.3 *
4	RRHR 102 x EU HEAR 3	4.4	29.4 *	12.8 *	29.4 *
1	RRHR 102 x EU HEAR 4	4.3	28.8 *	14.9 *	25.0 *
8	HR 102 x RRHR 102	4.2	40.0 *	35.5 *	23.5 *
7	HR 200 x RRHR 102	4.1	31.0 *	23.1 *	19.5 *
3	RRHR 102 x HR 199	4.0	48.1 *	37.9 *	17.6 *
5	RRHR 102 x EU HEAR 2	3.9	27.9 *	21.9 *	14.7 *
2	RRHR 102 x EU HEAR 5	3.8	35.7 *	31.0 *	11.8 *
Parents					
11	EU HEAR 3	3.9			
12	EU HEAR 4	3.7			
20	Red River 1852	3.6			
9	EU HEAR 1	3.5			
14	MillenniUM 03	3.4			
15	HR 200	3.3			
10	EU HEAR 2	3.2			
16	HR 102	3.1			
17	RRHR 102	2.9			
19	Red River 1826	2.9			
13	EU HEAR 5	2.7			
18	HR 199	2.5			
Overall Hybrid Mean		4.2 †			
Overall Parent Mean		3.2			
Hybrids-Parents		1.0			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

Table 4.4: Correlation Matrix for Selected Agronomic Traits and Seed Quality for Roundup F2 HEAR Hybrids Grown in Four Environments 2006 and 2007

	VIG (1-5)	FLR (days)	LOD (1-5)	HT (CM)	MAT (days)	YLD (kg ha^{-1})	Protein (g kg^{-1})	Oil (g kg^{-1})	GLU (µmolg^{-1} seed)	Prom (g kg^{-1})	Sum (g kg^{-1})	Er (%)
VIG												
FLR	-0.13											
LOD	-0.35*	0.40 *										
HT	0.31*	0.07	-0.89 *									
MAT	-0.10	0.90 *	0.32 *	0.02								
YLD	0.62*	-0.46 *	-0.86 *	0.79*	-0.31 *							
Protein	0.07	-0.07	-0.21	0.08	0.002	0.86 *						
Oil	-0.08	-0.17	0.16	-0.18	-0.22	-0.86 *	-0.94 *					
GLU	0.17	0.22	0.01	0.20	0.31 *	0.14	-0.31 *	0.39 *				
Prom	0.08	0.17	-0.16	0.18	0.22	0.43 *	0.50 *	-0.54 *	0.53 *			
Sum	-0.03	-0.24	0.01	-0.13	-0.25	0.69 *	0.74 *	-0.62 *	-0.32 *	-0.74 *		
Er	0.18	-0.45 *	-0.20	-0.09	-0.51 *	0.26	0.12	0.12	-0.43 *	-0.12	0.22	

* - Correlation coefficient (r) significant at $p \leq 0.05$

* - N = 320

4.1.3 Days to Flower for Conventional F2 HEAR Hybrids

F2 HEAR hybrids flowered on average (42.7) days after planting and parents flowered on average (43.7) (Table 4.5). The parental strains/cultivars had significantly later mean days to flower than the Conventional F2 HEAR hybrids because EU #1 and EU #3 strains flowered on average 10 to 15 days later than all other HEAR strains/cultivars.

The difference of days to flower between F2 HEAR hybrids and parents was statistically and practically significant. The lower number of days to flower is an important advantage especially for regions which have a shorter growing season. Cuthbert (2006) also found that F1 HEAR hybrids displayed significantly earlier mean days to flower than their parents. In contrast, Grant and Beversdorf (1985) found that *B. napus* hybrids tended to flower later than their parents.

The range of days to flowering for F2 HEAR hybrids was from (40.3) for HR 102 x EU HEAR 2 to (45.1) for HR 199 x EU HEAR 1 in the Conventional F2 HEAR hybrid field trials (Table 4.5). The parental strains/cultivars had wider range of days to flower from 40.4 to 55.9 days than F2 HEAR hybrids in the Conventional field trials. Since EU #1 and EU #3 strains flowered much later than all other strains/cultivars, crosses between EU #1, EU #3 and Manitoban strains/cultivars produced F2 HEAR hybrids with longer days to flower than other F2 HEAR hybrids (Table 4.5).

Mid-parent heterosis for days to flower for all Conventional F2 HEAR hybrids except for HR 199 x EU HEAR 2 was significantly earlier than the mean of their two parents. HR 200 x EU HEAR 3, HR 102 x EU HEAR 3 and HR 102 x EU HEAR 2 were the only three F2 HEAR hybrids that exhibited significant high-parent and commercial heterosis in the Conventional F2 HEAR hybrid field trials (Table 4.5). Cuthbert (2006) found significant mid-parent, high-parent and commercial heterosis for days to flower for some F1 HEAR hybrids.

Days to flower was significantly correlated with a number of traits such as yield (r = -0.51), maturity (r = 0.93) and erucic acid (r = -0.56) in the Conventional F2 HEAR hybrid field trials (Table 4.2). Cuthbert (2006) found that days to flower was significantly correlated with all agronomic and seed quality traits except for vigor and glucosinolate concentration for the identical set of F1 HEAR hybrids.

Cuthbert (2006) found that F1 HEAR hybrids on average flowered (43.8) days after planting. However, F2 HEAR Conventional hybrids showed earlier mean days to flower (42.7) than F1 HEAR hybrids due primarily to different environmental conditions.

Table 4.5: Mean Days to Flower and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	FLR (days)	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
10	HR 199 x EU HEAR 1	45.1	-6.2 *	11.7	9.2
4	Castor x EU HEAR 3	44.8	-5.3 *	10.5	8.5
6	MillenniUM 01 x EU HEAR 3	44.4	-6.3 *	9.2	7.4
1	HR 200 x EU HEAR 1	43.7	-9.9 *	5.8	5.8
5	MillenniUM 01 x EU HEAR 1	43.7	-9.3 *	7.5	5.7
9	HR 199 x EU HEAR 2	42.5	4.7	5.2	2.8
3	MillenniUM 03 x EU HEAR 3	41.1	-13.2 *	1.2	-0.5
7	HR 200 x EU HEAR 3	40.9	-14.3 *	-1.0 *	-1.0 *
2	HR 102 x EU HEAR 3	40.6	-14.6 *	-1.0 *	-1.7 *
8	HR 102 x EU HEAR 2	40.3	-1.5 *	-1.8 *	-2.5 *
Parents					
18	EU HEAR 1	55.9			
20	EU HEAR 3	54.1			
15	HR 200	41.5			
14	MillenniUM 03-2	41.2			
16	HR 102	41.0			
19	EU HEAR 2	40.7			
12	MillenniUM 01	40.6			
13	MillenniUM 03-1	40.6			
11	Castor	40.5			
17	HR 199	40.4			
Overall Hybrid Mean		42.7 †			
Overall Parent Mean		43.7			
Hybrids-Parents		-1.0			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.1.4 Days to Flower for F2 Roundup HEAR Hybrids

F2 Roundup HEAR hybrids flowered on average (42.4) days after planting and parents flowered on average (44.1) days after planting (Table 4.6). F2 Roundup HEAR hybrids had significantly earlier mean days to flower than the parental strains/cultivars because European strains #1 and #3 flowered on average 10 to 15 later than all other strains/cultivars. Cuthbert (2006) also found that the identical set of F1 HEAR hybrids displayed earlier mean days to flower (43.6) than their parents (45.8). In contrast, Grant and Beversdorf (1985) found that *B. napus* hybrids tended to flower later than their parents.

The range of hybrid flowering was from RRHR 102 x HR 199 (41.4) to RRHR 102 x EU HEAR 5 (43.0) in the F2 Roundup HEAR hybrid field trials (Table 4.6). The parental strains/cultivars had wider range of days to flower from 40.0 to 53.3 days after planting than F2 HEAR hybrids in the F2 Roundup HEAR hybrid field trials.

No high-parent and commercial heterosis for days to flower was observed in these field trials. However, a few hybrids displayed mid-parent heterosis for days to flower in these trials. Cuthbert (2006) found significant mid-parent, high-parent and commercial heterosis for days to flower for some F1 HEAR hybrids.

Days to flower was significantly correlated with a number of traits such as yield (r = -0.46), maturity (r = 0.90) and erucic acid (r = -0.45) in the F2 Roundup HEAR hybrid field trials (Table 4.4). F2 Roundup HEAR hybrids showed earlier mean days to flower than F1 HEAR hybrids (43.5). This can be an important advantage for F2 Roundup HEAR hybrids especially for which regions have shorter growing season.

Cuthbert (2006) found that days to flower was significantly correlated with all agronomic and seed quality traits except for vigor and glucosinolate concentration for the identical set of F1 HEAR hybrids.

Table 4.6: Mean Days to Flower and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	FLR (days)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
2	RRHR 102 x EU HEAR 5	43.0	0.4	0.7	3.6
4	RRHR 102 x EU HEAR 3	42.8	-10.9 *	0.1	3.1
1	RRHR 102 x EU HEAR 4	42.6	0.6	1.5	2.7
6	RRHR 102 x EU HEAR 1	42.6	-12.9 *	-0.2	2.7
8	HR 102 x RRHR 102	42.5	1.7	3.8	2.9
7	HR 200 x RRHR 102	42.4	2.6	6.1	2.3
5	RRHR 102 x EU HEAR 2	42.0	-1.9	-1.6	1.2
3	RRHR 102 x HR 199	41.4	-2.1	-1.0	-0.3
Parents					
11	EU HEAR 3	53.3			
20	Red River 1852	43.3			
13	EU HEAR 5	43.0			
19	Red River 1826	43.0			
10	EU HEAR 2	42.9			
9	EU HEAR 1	55.1			
17	RRHR 102	42.7			
12	EU HEAR 4	42.0			
18	HR 199	41.8			
14	MillenniUM 03	41.5			
16	HR 102	40.9			
15	HR 200	40.0			
Overall Hybrid Mean		42.4 †			
Overall Parent Mean		44.1			
Hybrids-Parents		-1.7			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.1.5 Days to Maturity for Conventional F2 HEAR Hybrids

Although Conventional F2 HEAR hybrids displayed higher days to maturity (94.7) than parents (94.3), the difference between hybrids and parents for days to maturity was not statistically and practically significant (Table 4.7). Cuthbert (2006) also found no significant difference between mean days to maturity of parents (105.8) and F1 HEAR hybrids (103.2). MilleniUM 01 x EU HEAR 1 had the maximum (97.5) days to maturity while HR 102 x EU HEAR 2 had the minimum (91.5) days to maturity (Table 4.7). The parental strains/cultivars had a wide range of maturities from 89.3 to 109.5 days while the Conventional F2 HEAR hybrids had a narrower range of maturities from 91.5 to 97.5 days. Since EU #1 and EU #3 matured approximately 15 to 17 days later than most other parental strains/cultivars, crosses between EU #1, EU #3 and Manitoban strains/cultivars produced F2 HEAR hybrids with longer days to maturity than other F2 HEAR hybrids (Table 4.7).

Days to maturity was significantly correlated with a number of traits such as yield (r = -0.40) and erucic acid concentration (r = -0.48) which indicated that lower days to maturity increased yield and erucic acid concentration in these trials (Table 4.7). Cuthbert (2006) found that days to maturity was significantly correlated with all agronomic and seed quality traits except for vigor and meal protein concentration for the identical set of F1 HEAR hybrids.

Days to maturity was also highly correlated to days to flower (r = 0.93) in the Conventional F2 HEAR hybrid field trials (Table 4.2). Grant and Beversdorf (1985) and Cuthbert (2006) also found days to maturity had a strong positive correlation with days to flower (r = 0.90) and (r = 0.89) respectively for F1 hybrids.

Mid-parent heterosis was significant for days to maturity for UM X EU #1 and UM X EU #3 hybrids in the Conventional F2 HEAR hybrid field trials (Table 4.7). This was because EU #1 and EU#3 had very late maturity. However, no Conventional F2 HEAR hybrids showed significant high-parent and commercial heterosis. Cuthbert (2006) found significant mid-parent and commercial heterosis for days to maturity for a few F1 HEAR hybrids. However, no F1 HEAR hybrids showed significant high-parent heterosis.

Table 4.7: Mean Days to Maturity and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	MAT (days)	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
5	MillenniUM 01 x EU HEAR 1	97.5	-2.0	9.1	7.0
1	HR 200 x EU HEAR 1	97.2	-2.9 *	7.1	6.7
6	MillenniUM 01 x EU HEAR 3	96.8	-1.6	8.3	6.2
10	HR 199 x EU HEAR 1	96.2	-4.7 *	4.0	5.6
2	HR 102 x EU HEAR 3	94.3	-4.8 *	3.8	3.5
3	MillenniUM 03 x EU HEAR 3	94.2	-5.1 *	3.5	3.4
7	HR 200 x EU HEAR 3	94.0	-5.1 *	3.6	3.1
4	Castor x EU HEAR 3	93.9	-5.0 *	3.8	3.1
9	HR 199 x EU HEAR 2	91.6	0.3	-1.0	0.5
8	HR 102 x EU HEAR 2	91.5	1.1	0.7	0.4
Parents					
18	EU HEAR 1	109.5			
20	EU HEAR 3	107.3			
17	HR 199	92.5			
14	MillenniUM 03-2	91.1			
13	MillenniUM 03-1	91.0			
16	HR 102	90.8			
15	HR 200	90.7			
11	Castor	90.5			
19	EU HEAR 2	90.2			
12	MillenniUM 01	89.3			
Overall Hybrid Mean		94.7			
Overall Parent Mean		94.3 ^{ns}			
Hybrids-Parents		0.4			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

4.1.6 Days to Maturity for F2 Roundup HEAR Hybrids

Although no significant differences were observed between Conventional F2 HEAR hybrids and parental strains/cultivars, F2 Roundup HEAR hybrids showed significantly shorter days to maturity (91.6) than parents (92.5) due to having different genetic sources (Table 4.8). Cuthbert (2006) found no significant difference between mean days to maturity of parents (105.8) and F1 HEAR hybrids (102.8).

RRHR 102 x EU HEAR 1 had the maximum (96.8) days to maturity while RRHR 102 x EU HEAR 4 had the minimum (88.3) days to maturity (Table 4.8). The parental strains/cultivars had a wide range of maturities from 87.8 to 108.5 days while the F2 Roundup HEAR hybrids had a narrower range of maturities from 88.3 to 96.8 days (Table 4.8).

Days to maturity was significantly correlated with a number of traits such as yield ($r = -0.31$), lodging ($r = 0.32$), glucosinolate ($r = 0.31$) and erucic acid ($r = -0.51$) concentrations in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) found that days to maturity was significantly correlated with all agronomic and seed quality traits except for vigor and meal protein concentration for the identical set of F1 HEAR hybrids. Days to maturity was also highly correlated to days to flower ($r = 0.90$) in the F2 Roundup HEAR hybrid field trials (Table 4.2). Grant and Beversdorf (1985) and Cuthbert (2006) also found days to maturity had a strong positive correlation with days to flower ($r = 0.90$) and ($r = 0.89$) respectively for F1 hybrids.

Mid-parent heterosis was significant for days to maturity for the UM X EU #1 and UM X EU #3 hybrids in the F2 Roundup HEAR hybrid field trials. However, no hybrids showed significant high-parent and commercial heterosis. Cuthbert (2006) found significant mid-parent and commercial heterosis for days to maturity for a few F1 HEAR hybrids. However, no F1 HEAR hybrids showed significant high-parent heterosis.

EU #1 and EU #3 matured approximately 20 days later than most other parental strains/cultivars (Table 4.8). Cuthbert (2006) also found EU #1 and EU #3 matured 20 days later than the parental strains/cultivars. Because EU #1 and EU #3 matured approximately 20 days later than most other parental strains/cultivars, crosses between EU #1, EU #3 and Manitoban strains/cultivars produced F2 HEAR hybrids with longer days to maturity than other F2 HEAR hybrids in the F2 Roundup HEAR hybrid field trials (Table 4.8).

Table 4.8: Mean Days to Maturity and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	MAT (days)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	96.8	-3.5 *	5.2	9.0
4	RRHR 102 x EU HEAR 3	94.8	-4.4 *	3.0	6.7
5	RRHR 102 x EU HEAR 2	91.5	0.8	2.2	3.0
7	HR 200 x RRHR 102	90.8	0.7	2.9	2.3
8	HR 102 x RRHR 102	90.7	-0.9	-0.3	2.1
3	RRHR 102 x HR 199	90.2	-1.7	-1.4	1.6
2	RRHR 102 x EU HEAR 5	89.6	-1.4	-0.2	0.9
1	RRHR 102 x EU HEAR 4	88.3	-1.8	0.6	-0.6
Parents					
9	EU HEAR 1	108.5			
11	EU HEAR 3	106.3			
17	RRHR 102	92.0			
18	HR 199	91.5			
16	HR 102	91.0			
13	EU HEAR 5	89.8			
10	EU HEAR 2	89.5			
14	MillenniUM 03	88.8			
19	Red River 1826	88.5			
15	HR 200	88.3			
20	Red River 1852	87.9			
12	EU HEAR 4	87.8			
Overall Hybrid Mean		91.6 †			
Overall Parent Mean		92.5			
Hybrids-Parents		-0.9			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.1.7 Plant Height for Conventional F2 HEAR Hybrids

Conventional F2 HEAR hybrids significantly displayed greater height than parents (Table 4.9). Conventional F2 HEAR hybrids had a mean height of (134 cm) and parents had a lower mean height of (118 cm) (Table 4.9).

Cuthbert (2006) found no significant differences between the parental strains/cultivars (107 cm) and F1 HEAR hybrids (115 cm) for height.

HR 199 x EU HEAR 1 had the maximum (143 cm) while HR 102 x EU HEAR 2 had the minimum mean height (126 cm) in the Conventional F2 HEAR hybrid field trials (Table 4.9). The parental strains/cultivars displayed height ranging from 112 to 127 cm while Conventional F2 HEAR hybrids displayed height ranging from 126 to 143 cm (Table 4.9).

European strains including EU #3, EU #1 and EU #2 were much taller than other parents (Table 4.9). Furthermore, crosses between EU #1, EU #3 and Manitoban strains/cultivars produced taller hybrids in these field trials (Table 4.9).

Height displayed significant mid-parent, high-parent and commercial heterosis for all F2 HEAR hybrids (Table 4.9). Sernyk and Stefansson (1983) and Grant and Beversdorf (1985) also found significant mid-parent and high-parent heterosis for height in the F1 HEAR hybrid field trials. Cuthbert (2006) found significant mid-parent and high-parent heterosis for height for a few F1 HEAR hybrids. All Conventional F2 HEAR hybrids displayed significant commercial heterosis for height since cultivar MillenniUM 03 was short (118 cm) (Table 4.9). Cuthbert (2006) also found that all F1 HEAR hybrids displayed significant commercial heterosis for height since MillenniUM 03 was short (94 cm).

Height was significantly correlated with a number of traits such as lodging (r = -0.96), yield (r = 0.88) and vigor (r = 0.42) which indicated that taller hybrids had higher yield, vigor and lower lodging in the Conventional F2 HEAR hybrid field trials (Table 4.2). Similarly, Cuthbert (2006) found that a highly positive correlation was between height and seed yield (r = 0.89) which indicated that taller hybrids had higher yield. Cuthbert (2006) found that plant height was correlated with all other agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Table 4.9: Mean Plant Height and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	HT (cm)	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
10	HR 199 x EU HEAR 1	143	19.6 *	12.6 *	22.5 *
2	HR 102 x EU HEAR 3	141	16.4 *	24.4 *	20.2 *
3	MillenniUM 03 x EU HEAR 3	139	14.0 *	23.2 *	19.0 *
5	MillenniUM 01 x EU HEAR 1	137	12.3 *	20.7 *	16.6 *
4	Castor x EU HEAR 3	134	11.8 *	19.4 *	14.3 *
7	HR 200 x EU HEAR 3	132	9.6 *	16.0 *	12.9 *
6	MillenniUM 01 x EU HEAR 3	130	6.1 *	15.5 *	10.6 *
9	HR 199 x EU HEAR 2	129	10.4 *	12.7 *	10.1 *
1	HR 200 x EU HEAR 1	127	5.7 *	34.1 *	7.9 *
8	HR 102 x EU HEAR 2	126	7.6 *	12.7 *	7.9 *
Parents					
19	EU HEAR 3	127			
20	EU HEAR 1	126			
18	EU HEAR 2	121			
14	MillenniUM 03-2	120			
13	MillenniUM 03-1	118			
12	MillenniUM 01	117			
16	HR 102	114			
15	HR 200	114			
17	HR 199	113			
11	Castor	112			
Overall Hybrid Mean		134 †			
Overall Parent Mean		118			
Hybrids-Parents		16			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.1.8 Plant Height for F2 Roundup HEAR Hybrids

F2 Roundup HEAR hybrids displayed significantly greater height than parents (Table 4.10). F2 Roundup hybrids had a mean height of (134 cm) and parents had a lower mean height of (126 cm) (Table 4.10). Cuthbert (2006) found no significant differences between the parental strains/cultivars (107 cm) and F1 HEAR hybrids (112 cm) for height.

RRHR 102 x EU HEAR 3 had the maximum (146 cm) while HR 200 x RRHR 102 had the minimum mean height (127 cm) in the F2 Roundup HEAR hybrid field trials. The parental strains/cultivars displayed height ranging from 121 to 131 cm while F2 Roundup HEAR hybrids displayed height ranging from 127 to 146 cm (Table 4.10).

Cultivar Red River 1852 was the tallest among Manitoban strains/cultivars in both Roundup and Conventional field trials (Table 4.10). EU HEAR strains including EU #3 and EU #1 were much taller than other parents. Furthermore, crosses between EU #1, EU #3 and Manitoban strains/cultivars produced taller hybrids in these field trials (Table 4.10).

Height displayed significant mid-parent, high-parent and commercial heterosis for most hybrids. Most F2 HEAR hybrids displayed significant commercial heterosis since the cultivar MillenniUM 03 was relatively short (126 cm) in the F2 Roundup HEAR hybrid field trials. Sernyk and Stefansson (1983) and Grant and Beversdorf (1985) also found significant mid-parent, high-parent heterosis for height in canola hybrids.

Similarly, Cuthbert (2006) found significant mid-parent and high-parent heterosis for height for a few F1 HEAR hybrids.

Furthermore, Cuthbert (2006) also found that all F1 HEAR hybrids displayed significant commercial heterosis for height since the cultivar MillenniUM 03 was short (94 cm).

Height was significantly correlated with a number of traits such as lodging (r = -0.89), yield (r = 0.79) and vigor (r = 0.31) which indicated that taller F2 HEAR hybrids had higher yield, vigor and lower lodging in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) also found that height was significant correlation with lodging, yield and vigor for the identical set of F1 HEAR hybrids.

Table 4.10: Mean Plant Height and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	HT (cm)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
4	RRHR 102 x EU HEAR 3	146	16.2 *	14.2 *	16.2 *
6	RRHR 102 x EU HEAR 1	143	11.9 *	8.8 *	13.2 *
5	RRHR 102 x EU HEAR 2	135	6.7 *	5.3 *	6.4 *
2	RRHR 102 x EU HEAR 5	134	8.9 *	8.1 *	6.2 *
3	RRHR 102 x HR 199	130	4.8 *	4.8 *	3.3 *
8	HR 102 x RRHR 102	129	2.7	1.9	1.8
1	RRHR 102 x EU HEAR 4	128	2.9 *	2.2	1.7
7	HR 200 x RRHR 102	127	2.4	2.2	1.0
Parents					
9	EU HEAR 1	131			
11	EU HEAR 3	130			
20	Red River 1852	129			
10	EU HEAR 2	128			
19	Red River 1826	127			
14	MillenniUM 03	126			
16	HR 102	125			
12	EU HEAR 4	125			
15	HR 200	124			
18	HR 199	123			
17	RRHR 102	122			
13	EU HEAR 5	121			
Overall Hybrid Mean		134 †			
Overall Parent Mean		126			
Hybrids-Parents		8			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.1.9 Lodging for Conventional F2 HEAR Hybrids

Although Conventional F2 HEAR hybrids displayed lower lodging than parents, this difference was not statistically significant. F2 HEAR hybrids had a mean lodging rating of (2.5) while parents had a higher mean rating of (2.7) in the Conventional F2 HEAR hybrid field trials (Table 4.11).

Similarly, Cuthbert (2006) found no significant difference between F1 HEAR hybrids (2.7) and parents (3.1) for lodging. In contrast, Grant and Beversdorf (1985) found that *B. napus* hybrids were generally poorer at resisting lodging than their parents due to higher seed yields.

The range of lodging ratings for hybrids and parents were quite different. HR 199 x EU HEAR 2 had the maximum (2.9) while HR 200 x EU HEAR 3 had the minimum (2.1) mean lodging rating in the Conventional F2 HEAR hybrid field trials (Table 4.11). Cultivar MillenniUM 01 had the maximum (3.9) while strain EU HEAR 3 had the minimum (1.7) mean lodging rating (Table 4.11).

Crosses between EU #1, EU #3 and Manitoban strains/cultivars displayed lower lodging than the other Conventional F2 HEAR hybrids. Furthermore, EU# 3 and EU# 1 strains were superior in their ability to remain erect at harvest compared to the other parental strains/cultivars in these field trials. Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

Lodging displayed significant mid-parent heterosis for a few Conventional F2 HEAR hybrids but no high-parent heterosis for Conventional F2 HEAR hybrids (Table 4.11). Cuthbert (2006) also found significant mid-parent heterosis for a few F1 HEAR hybrids and no high-parent heterosis for F1 HEAR hybrids. However, all Conventional F2

HEAR hybrids displayed significant commercial heterosis estimates for lodging rating since the current commercial HEAR cultivar MilleniUM 03 displayed a poor lodging rating of (3.3) (Table 4.11). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids. All hybrids that were significantly taller than MillenniUM 03 also displayed better lodging resistance than cultivar MillenniUM 03 in the Conventional F2 HEAR hybrid field trials.

Lodging was significantly correlated with a number of traits such as yield (r = -0.89), vigor (r = -0.37) and height (r = -0.96) which indicated that hybrids with lower lodging were taller and demonstrated higher vigor and yield in these field trials (Table 4.2). Cuthbert (2006) found that lodging was significantly correlated with all agronomic and seed quality traits except for glucosinolate concentration for the identical set of F1 HEAR hybrids.

Table 4.11: Mean Lodging and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	LOD (1-5)	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
7	HR 200 x EU HEAR 3	2.1	-8.7	23.5	-34.4 *
4	Castor x EU HEAR 3	2.2	-13.7 *	29.4	-31.3 *
2	HR 102 x EU HEAR 3	2.3	15.0	35.3	-28.1 *
5	MillenniUM 01 x EU HEAR1	2.3	-20.7 *	21.1	-28.1 *
3	MillenniUM 03 x EU HEAR 3	2.4	-2.0	41.2	-25.0 *
10	HR 199 x EU HEAR 1	2.4	11.6	26.3	-25.0 *
1	HR 200 x EU HEAR 1	2.5	4.2	31.6	-21.9 *
8	HR 102 x EU HEAR 2	2.8	19.1	20.0	-12.5 *
6	MillenniUM 01 x EU HEAR 3	2.9	3.6	70.6	-9.4 *
9	HR 199 x EU HEAR 2	2.9	20.8	20.8	-9.4 *
Parents					
20	EU HEAR 3	1.7			
18	EU HEAR 1	1.9			
16	HR 102	2.3			
17	HR 199	2.4			
19	EU HEAR 2	2.4			
15	HR 200	2.9			
13	MillenniUM 03-1	3.2			
14	MillenniUM 03-2	3.3			
11	Castor	3.4			
12	MillenniUM 01	3.9			
Overall Hybrid Mean		2.5 ns			
Overall Parent Mean		2.7			
Hybrids-Parents		-0.2			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

4.1.10 Lodging for F2 Roundup HEAR Hybrids

F2 HEAR hybrids displayed lower lodging than parents in the F2 Roundup HEAR hybrid field trials. However, this difference was not statistically significant (Table 4.12). F2 HEAR hybrids had a mean lodging rating of (2.8) while parents had a higher mean rating of (2.9) in the F2 Roundup HEAR hybrid field trials (Table 4.12).

Similarly, Cuthbert (2006) also found no significant difference between F1 hybrids (2.7) and parents (3.1) for lodging. In contrast, Grant and Beversdorf (1985) found that *B. napus* hybrids were generally poorer at resisting lodging than their parents due to higher seed yields.

The range of lodging ratings for both hybrids and parents were very similar in the F2 Roundup HEAR hybrid field trials. HR 102 x RRHR 102 had maximum (3.3) while RRHR 102 x EU HEAR 1 had the minimum (1.9) mean lodging rating (Table 4.12). Cultivar MillenniUM 03 had the maximum (3.7) while strain EU HEAR 3 had the minimum (1.8) mean lodging in the F2 Roundup HEAR hybrid field trials (Table 4.12).

Lodging displayed significant mid-parent heterosis for only two hybrids RRHR 102 x EU HEAR 1 and RRHR 102 x EU HEAR 5 and displayed significant high-parent heterosis for only one hybrid RRHR 102 x EU HEAR 1 in the F2 Roundup HEAR hybrid field trials. Similarly, Cuthbert (2006) found that significant mid-parent heterosis for a few F1 HEAR hybrids and no high-parent heterosis for F1 HEAR hybrids. However, all hybrids displayed significantly high commercial heterosis estimates for lodging rating due to the poor lodging resistance displayed by the current commercial HEAR cultivar MillenniUM 03 in these field trials (Table 4.12). Cuthbert (2006) also found the similar results for the identical set of F1 HEAR hybrids.

Crosses between EU#1, EU#3 and Manitoban strains/cultivars displayed lower lodging rating than the other hybrids. EU# 3 and EU# 1 strains also demonstrated lower lodging compared to the other parental strains/cultivars in the F2 Roundup HEAR hybrid field trials. Cuthbert (2006) also found the similar results for the identical set of F1 HEAR hybrids.

Lodging was significantly correlated with a number of traits such as yield (r = -0.86), vigor (r = -0.35) and height (r = -0.89) which indicated that hybrids with lower lodging were taller and demonstrated higher vigor and yield in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) also found that lodging was significant correlation with height, yield and vigor for the identical set of F1 HEAR hybrids.

Also, lodging was significantly correlated with days to flowering (r = 0.4) and days to maturity (r = 0.32) in these field trials (Table 4.4). Cuthbert (2006) found that lodging was significantly correlated with all agronomic and seed quality traits except for glucosinolate concentration for the identical set of F1 HEAR hybrids.

Table 4.12: Mean Lodging and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	LOD (1-5)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	1.9	-24.0 *	-32.1 *	-48.6 *
4	RRHR 102 x EU HEAR 3	2.3	-2.1	27.8	-37.8 *
2	RRHR 102 x EU HEAR 5	2.8	-9.7 *	-3.4	-24.3 *
5	RRHR 102 x EU HEAR 2	2.8	3.7	55.6	-24.3 *
7	HR 200 x RRHR 102	3.0	-7.7	3.4	-18.9 *
1	RRHR 102 x EU HEAR 4	3.1	-3.1	6.9	-16.2 *
3	RRHR 102 x HR 199	3.2	12.3	14.3	-13.5 *
8	HR 102 x RRHR 102	3.3	4.8	13.8	-10.8 *
Parents					
11	EU HEAR 3	1.8			
9	EU HEAR 1	2.1			
10	EU HEAR 2	2.5			
19	Red River 1826	2.6			
20	Red River 1852	2.7			
18	HR 199	2.8			
17	RRHR 102	2.9			
13	EU HEAR 5	3.3			
16	HR 102	3.4			
12	EU HEAR 4	3.5			
15	HR 200	3.6			
14	MilleniUM 03	3.7			
Overall Hybrid Mean		2.8 ns			
Overall Parent Mean		2.9			
Hybrids-Parents		-0.1			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

4.1.11 Seed Yield for Conventional F2 HEAR Hybrids

F2 HEAR hybrids were significantly higher yielding (2182 kg ha^{-1}) than their parental strains/cultivars (1380 kg ha^{-1}) in the Conventional F2 HEAR hybrid field trials (Table 4.13). Cuthbert (2006) found that the identical set of F1 HEAR hybrids displayed significantly higher seed yield (2518 kg ha^{-1}) than their parents (1471 kg ha^{-1}).

The highest seed yield Conventional F2 HEAR hybrids displayed over 75 % high-parent, over 90 % mid-parent and over 50 % commercial heterosis estimates (Table 4.13). Conventional F2 HEAR hybrids demonstrated (as expected in theory) approximately half high-parent and commercial heterosis estimates observed in the identical set of F1 HEAR hybrids. Also, Conventional F2 HEAR hybrids displayed more than half mid-parent heterosis estimate observed in the identical set of F1 HEAR hybrids. These estimates of heterosis for Conventional F2 HEAR hybrids were sufficiently high to justify the use of Conventional F2 HEAR hybrids.

Cuthbert (2006) found that the highest yield F1 HEAR hybrids showed over 150 % mid-parent heterosis and high-parent heterosis and over 100 % commercial heterosis. Those estimates of mid-parent, high-parent and commercial heterosis for F1 HEAR hybrids for seed yield exceeded the reports in previous studies conducted by McVetty and Brandle (1989), Grant and Beversdorf (1985) and Sernyk and Stefansson (1983).

The range of seed yields for parental strains/cultivars was much smaller than for F2 HEAR hybrids. HR 200 x EU HEAR 1 had the maximum (2400 kg ha^{-1}) and MillenniUM 01 x EU HEAR 3 had the minimum (1931 kg ha^{-1}) mean seed yield in the Conventional F2 HEAR hybrid field trials (Table 4.13). Strain HR 199 had the maximum (1683 kg ha^{-1}) and EU HEAR 3 had the minimum mean seed yield (1009 kg ha^{-1}) in these field trials (Table 4.13).

All Conventional F2 HEAR hybrids were significantly higher yield than their better parental strain/cultivar (Table 4.13). As with many other agronomic parameters, crosses between EU#1, EU#3 and Manitoban strains/cultivars displayed higher yield than the other Conventional F2 HEAR hybrids.

Seed yield was significantly correlated with vigor ($r = 0.58$), days to flower ($r = -0.51$), lodging ($r = -0.89$), height ($r = 0.88$) and maturity ($r = -0.40$) which indicated that F2 HEAR hybrids with higher yield were much taller and had higher vigor, and lower lodging, days to flower and days to maturity in the Conventional F2 HEAR hybrid field trials (Table 4.2). Furthermore, yield was significantly correlated with protein ($r = -0.83$), oil ($r = 0.83$), meal protein ($r = -0.47$) and sum of oil and protein ($r = 0.59$) concentrations which indicated that F2 HEAR hybrids with higher yield had more oil and sum of oil and protein concentrations, and also had less protein, and meal protein concentrations in these field trials (Table 4.2). Cuthbert (2006) found that seed yield was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Seed yields displayed significant mid-parent, high-parent and commercial heterosis for all Conventional F2 HEAR hybrids (Table 4.13). Cuthbert (2006) found that seed yield displayed significant mid-parent, high-parent and commercial heterosis for many F1 HEAR hybrids in the F1 HEAR hybrid field trials.

Table 4.13: Mean Seed Yield and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	YLD (kg ha^{-1})	Mid-parent (%)	High-Parent (%)	Commercial (%)
Hybrids					
1	HR 200 x EU HEAR 1	2400	91.3 *	75.2 *	56.0 *
2	HR 102 x EU HEAR 3	2345	74.3 *	72.8 *	52.4 *
3	MillenniUM 03 x EU HEAR 3	2272	78.4 *	47.7 *	47.7 *
4	Castor x EU HEAR 3	2231	71.8 *	40.5 *	45.1 *
10	HR 199 x EU HEAR 1	2212	77.3 *	31.5 *	43.8 *
9	HR 199 x EU HEAR 2	2199	69.7 *	30.7 *	43.0 *
5	MillenniUM 01 x EU HEAR 1	2089	68.2 *	55.2 *	35.8 *
8	HR 102 x EU HEAR 2	2089	43.2 *	53.9 *	35.8 *
7	HR 200 x EU HEAR 3	2055	72.8 *	50.0 *	33.6 *
6	MillenniUM 01 x EU HEAR 3	1931	64.0 *	43.5 *	25.5 *
Parents					
17	HR 199	1683			
11	Castor	1588			
13	MillenniUM 03-1	1540			
14	MillenniUM 03-2	1538			
15	HR 200	1370			
16	HR 102	1357			
12	MillenniUM 01	1346			
19	EU HEAR 2	1235			
18	EU HEAR 1	1139			
20	EU HEAR 3	1009			
Overall Hybrid Mean		2182 †			
Overall Parent Mean		1380			
Hybrids-Parents		802			

* - hybrids significant at p≤ 0.05

† - means of hybrids and parents are significantly different at p≤ 0.05

4.1.12 Seed Yield for F2 Roundup HEAR Hybrids

F2 Roundup HEAR hybrids displayed significantly higher mean yield (1899 kg ha^{-1}) than their parental strains/cultivars (1315 kg ha^{-1}) (Table 4.14). McVetty and Brandle (1989), Grant and Beversdorf (1985) and Sernyk and Stefansson (1983) also found that F1 HEAR/canola hybrids displayed significantly higher mean seed yield than their parental strains /cultivars. Similarly, Cuthbert (2006) found that F1 HEAR hybrids displayed significantly higher méan yield (2301 kg ha^{-1}) than their parental strains/cultivars (1471 kg ha^{-1}) in the F1 HEAR hybrid field trials.

The range of seed yields for parental strains/cultivars was much smaller than for hybrids in the F2 Roundup HEAR hybrid field trials. RRHR 102 x EU HEAR 1 had the maximum (2499 kg ha^{-1}) while HR 200 x RRHR 102 had the minimum (1678 kg ha^{-1}) mean seed yield. Strain HR 199 had the maximum (1654 kg ha^{-1}) while strain EU HEAR 3 had the minimum (1003 kg ha^{-1}) mean seed yield in the F2 Roundup HEAR hybrid field trials (Table 4.14).

All F2 Roundup HEAR hybrids were significantly higher yield than their better parental strain/cultivar (Table 4.14). Also, crosses between EU #1, EU #3 and Manitoban strains/cultivars displayed higher yield than all other hybrids in these field trials. Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

Cuthbert (2006) found that the highest yielding F1 HEAR hybrids showed over 150 % mid-parent heterosis and high-parent heterosis and over 100 % commercial heterosis. F2 Roundup HEAR hybrids successfully demonstrated (as expected in theory) approximately half high-parent (76 %) and commercial heterosis (53 %) observed in the identical F1 HEAR hybrids (Table 4.14). Also, F2 Roundup HEAR hybrids displayed mid-parent heterosis (97 %) that was more than half the mid-parent heterosis observed in the identical F1 HEAR hybrids (Table 4.14). These estimates of heterosis for F2 Roundup hybrids were sufficiently high to justify the use of F2 Roundup HEAR hybrids.

Seed yield displayed significant mid-parent heterosis for all F2 Roundup HEAR hybrids. Also, seed yield showed significant high-parent and commercial heterosis for all F2 Roundup HEAR hybrids except for RRHR 102 x HR 199 (Table 4.14). Cuthbert (2006) found that seed yield displayed significant mid-parent, high-parent and commercial heterosis for many F1 HEAR hybrids in the F1 HEAR field trials.

Yield was significantly correlated with vigor ($r = 0.62$), days to flower ($r = -0.51$), lodging ($r = -0.86$), height ($r = 0.88$) and maturity ($r = -0.40$) which indicated that F2 Roundup HEAR hybrids with higher yield were much taller and had higher vigor, and also lower lodging, reduced days to flower and reduced days to maturity than other F2 Roundup HEAR hybrids in these field trials (Table 4.4). Furthermore, yield was significantly correlated with protein ($r = 0.86$), oil ($r = -0.86$), prom ($r = 0.43$) and sum of oil and protein ($r = 0.69$) which indicated that F2 Roundup HEAR hybrids with higher yield had more seed protein, more meal protein and a greater sum of oil and protein concentrations, and also had reduced oil concentration in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) found that yield was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Table 4.14: Mean Seed Yield and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	YLD (kg ha^{-1})	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	2499	96.6 *	75.9 *	53.1 *
4	RRHR 102 x EU HEAR 3	2102	73.4 *	47.9 *	28.7 *
5	RRHR 102 x EU HEAR 2	1857	40.8 *	30.7 *	13.7 *
2	RRHR 102 x EU HEAR 5	1840	34.9 *	29.5 *	12.7 *
8	HR 102 x RRHR 102	1807	18.2 *	10.4 *	10.7 *
7	HR 200 x RRHR 102	1719	18.4 *	15.9 *	5.3 *
1	RRHR 102 x EU HEAR 4	1690	34.6 *	19.0 *	3.5 *
3	RRHR 102 x HR 199	1678	9.2 *	1.5	2.8
Parents					
18	HR 199	1654			
16	HR 102	1637			
14	MillenniUM 03	1633			
15	HR 200	1484			
17	RRHR 102	1421			
13	EU HEAR 5	1306			
10	EU HEAR 2	1218			
19	Red River 1826	1125			
9	EU HEAR 1	1122			
20	Red River 1852	1091			
12	EU HEAR 4	1090			
11	EU HEAR 3	1003			
Overall Hybrid Mean		1899 †			
Overall Parent Mean		1315			
Hybrids-Parents		584			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2 Seed Quality Parameters

4.2.1 Oil Concentration for Conventional F2 HEAR Hybrids

Mean oil concentration for Conventional F2 HEAR hybrids (475 g kg^{-1}) was significantly higher than for the parental strains/cultivars (457 g kg^{-1}) (Table 4.15). Cuthbert (2006) also found that F1 HEAR hybrids from the same parents displayed significantly higher oil concentration (499 g kg^{-1}) than their parents (472 g kg^{-1}).

In contrast, a study of *B. napus* hybrids conducted by Grant and Beversdorf (1985) found no difference for oil concentration between F1 canola hybrids and parents. McVetty and Brandle (1989) and Sernyk and Stefansson (1983) also found that *B. napus* hybrids and parental strains/cultivars had similar oil concentration.

The ranges of oil concentration for both Conventional F2 HEAR hybrids and parental strains/cultivars were large (Table 4.15). HR 102 x EU HEAR 3 had the maximum (517 g kg^{-1}) while HR 199 x EU HEAR 2 had the minimum (451g kg^{-1}) mean oil concentration (Table 4.15). Strain HR 102 had the maximum (506 g kg^{-1}) while cultivar MillenniUM 01 had the minimum (430 g kg^{-1}) mean oil concentration in the Conventional F2 HEAR hybrid field trials (Table 4.15).

Crosses between EU #1, EU #2, EU #3 and Manitoban strains/cultivars produced HEAR hybrids which displayed higher oil concentration than the other hybrids in the Conventional F2 HEAR hybrid field trials (Table 4.15). Also, the hybrid produced from the cross between EU #3 and HR 102 displayed over (500 g kg^{-1}) oil concentration that was significantly higher than the high-parent values in these field trials (Table 4.15). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

Oil concentration was significantly correlated with sum of oil and protein concentration (r = 0.72), protein concentration (r = -0.95), seed yield (r = 0.83), glucosinolate concentration (r = -0.51) and meal protein concentration (r = -0.55) in the Conventional F2 HEAR hybrid field trials (Table 4.2). The correlation coefficient between oil concentration and seed yield (r = 0.83) suggests that the high seed yield Conventional F2 HEAR hybrids were also very high for seed oil concentration (Table 4.2). Cuthbert (2006) found that oil concentration was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Oil concentration displayed significant mid-parent and high-parent heterosis for many F2 HEAR hybrids in the Conventional field trials (Table 4.15). As the cultivar MillenniUM 03 had relatively low oil seed concentration, all Conventional F2 HEAR hybrids except for HR 199 x EU HEAR 2 displayed significant commercial heterosis (Table 4.15). Cuthbert (2006) also found that oil concentration displayed significant mid-parent, high-parent and commercial heterosis for many F1 HEAR hybrids in the F1 HEAR field trials.

Table 4.15: Mean Oil Concentration and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Oil ($g\ kg^{-1}$)	Mid-parent (%)	High-parent (%)	Commercial (%)
Hybrids					
2	HR 102 x EU HEAR 3	517	8.6 *	2.2	15.6 *
3	MillenniUM 03 x EU HEAR 3	493	10.3 *	10.1 *	10.1 *
7	HR 200 x EU HEAR 3	485	9.3 *	8.8 *	8.4 *
8	HR 102 x EU HEAR 2	485	-1.8	-4.3	8.4 *
1	HR 200 x EU HEAR 1	472	2.3	-1.9	5.4 *
6	MillenniUM 01 x EU HEAR 3	468	6.8 *	4.9 *	4.6 *
5	MillenniUM 01 x EU HEAR 1	463	1.6	-3.7	3.5 *
4	Castor x EU HEAR 3	461	3.8 *	3.4 *	3.1 *
10	HR 199 x EU HEAR 1	461	-1.1	-4.1	3.1 *
9	HR 199 x EU HEAR 2	451	-3.2	-6.1	1.0
Parents					
16	HR 102	506			
19	EU HEAR 2	481			
18	EU HEAR 1	481			
17	HR 199	452			
13	MillenniUM 03-1	447			
14	MillenniUM 03-2	447			
20	EU HEAR 3	446			
11	Castor	442			
15	HR 200	441			
12	MillenniUM 01	430			
Overall Hybrid Mean		475 †			
Overall Parent Mean		457			
Hybrids-Parents		18			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.2 Oil Concentration for F2 Roundup HEAR Hybrids

Mean oil concentration for F2 Roundup HEAR hybrids (476 g kg^{-1}) was significantly lower than for the parental strains/cultivars (492 g kg^{-1}) (Table 4.16). In contrast, Conventional F2 HEAR hybrids displayed higher mean oil concentration than parents. This was due to different genetic differences between Conventional and Roundup hybrids and parents used in this study. McVetty and Brandle (1989) found that *B. napus* hybrids and parental strains/cultivars had similar oil concentration. Cuthbert (2006) found that the same F1 HEAR hybrids displayed significantly higher oil concentration (486 g kg^{-1}) than their parents (471 g kg^{-1}).

The ranges of oil concentration for both F2 Roundup HEAR hybrids and parental strains/cultivars were large (Table 4.16). HR 102 x RRHR 102 had the maximum (508 g kg^{-1}) while RRHR 102 x EU HEAR 3 had the minimum (433 g kg^{-1}) mean oil concentration (Table 4.16). Cultivar Red River 1852 had maximum (534 g kg^{-1}) and strain EU HEAR 1 had the minimum (459 g kg^{-1}) mean oil concentration in the F2 Roundup HEAR hybrid field trials (Table 4.16). Cultivar Red River 1852 displayed the maximum mean oil (534 g kg^{-1}) among parents and F2 hybrids in both Conventional and Roundup HEAR hybrid field trials (Table 4.16).

Oil concentration was significantly correlated with sum of oil and protein concentration ($r = -0.62$), protein concentration ($r = -0.94$), seed yield ($r = -0.86$), glucosinolate concentration ($r = 0.39$) and meal protein ($r = -0.54$) concentration in the F2 Roundup HEAR hybrid field trials (Table 4.4).

This study found that the high seed yield F2 Roundup HEAR hybrids were low for seed oil concentrations as these two traits was highly negatively correlated as well (r = -0.86) in these field trials (Table 4.4). Cuthbert (2006) found that oil concentration was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Oil concentration displayed significant mid-parent, high-parent and commercial heterosis for few F2 hybrids in the F2 Roundup HEAR hybrid field trials (Table 4.16). Cuthbert (2006) also found significant mid-parent, high-parent and commercial heterosis for some F1 HEAR hybrids in the F1 HEAR hybrid field trials.

The F2 HEAR hybrid from the cross between two Manitoban strains HR 102 x RRHR 102 displayed the highest oil concentration. Crosses between EU #5, EU #2 and Manitoban strains/cultivars also displayed higher oil concentration than other F2 hybrids in the F2 Roundup HEAR hybrid field trials (Table 4.16).

Table 4.16: Mean Oil Concentration and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Oil ($g\ kg^{-1}$)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
8	HR 102 x RRHR 102	508	9.1 *	7.5 *	6.9 *
2	RRHR 102 x EU HEAR 5	497	0.8	-3.3	4.6 *
5	RRHR 102 x EU HEAR 2	491	0.2	-3.1	3.2 *
6	RRHR 102 x EU HEAR 1	485	0.1	-2.4	2.1
3	RRHR 102 x HR 199	478	-0.6	-2.3	0.5
1	RRHR 102 x EU HEAR 4	472	-1.3	-2.2	-0.8
7	HR 200 x RRHR 102	447	-7.3	-9.1	-6.0
4	RRHR 102 x EU HEAR 3	433	-10.6	-12.7	-8.9
Parents					
20	Red River 1852	534			
16	HR 102	514			
10	EU HEAR 2	506			
13	EU HEAR 5	497			
11	EU HEAR 3	496			
19	Red River 1826	492			
15	HR 200	492			
18	HR 199	489			
12	EU HEAR 4	483			
14	MillenniUM 03	475			
17	RRHR 102	473			
9	EU HEAR 1	459			
Overall Hybrid Mean		476			
Overall Parent Mean		492 †			
Hybrids-Parents		-16			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.3 Protein Concentration for Conventional F2 HEAR Hybrids

Mean protein concentration for Conventional F2 HEAR hybrids (252 g kg^{-1}) was significantly lower than for the parental strains/cultivars (264 g kg^{-1}) (Table 4.17). Cuthbert (2006) also found that the identical F1 HEAR hybrids (235 g kg^{-1}) displayed significantly lower protein concentration than their parents (251 g kg^{-1}). Grant and Beversdorf (1985) also found that F1 canola hybrids demonstrated lower protein concentration than their parents.

The range of protein concentration for F2 HEAR hybrids and parental strains/cultivars was very similar in the Conventional F2 HEAR hybrid field trials (Table 4.17). HR 199 x EU HEAR 2 had the maximum (271g kg^{-1}) while HR 102 x EU HEAR 3 had the minimum (229 g kg^{-1}) mean protein concentration. Cultivar MillenniUM 01 had maximum (283 g kg^{-1}) and strain HR 102 had the minimum (229 g kg^{-1}) mean protein concentration in these field trials (Table 4.17).

Protein concentration was significantly correlated with a number of traits such as sum of oil and protein concentration ($r = -0.51$), oil concentration ($r = -0.95$), seed yield ($r = -0.83$), glucosinolate concentration ($r = 0.48$) and meal protein concentration ($r = 0.86$) in the Conventional F2 HEAR hybrid field trials (Table 4.2). Cuthbert (2006) found that protein concentration was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids.

Protein concentration displayed significant mid-parent heterosis only for the HR 199 x EU HEAR 1 (Table 4.17). No significant high-parent and commercial heterosis were observed for F2 HEAR hybrids in these field trials. Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

Table 4.17: Mean Protein Concentration and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Protein ($g\ kg^{-1}$)	Mid-parent (%)	High-parent (%)	Commercial (%)
Hybrids					
9	HR 199 x EU HEAR 2	271	1.8	-1.0	-1.2
5	MillenniUM 01 x EU HEAR 1	266	1.3	-6.1	-3.0
10	HR 199 x EU HEAR 1	266	3.0 *	-3.0	-3.2
6	MillenniUM 01 x EU HEAR 3	261	-4.1	-8.0	-5.0
1	HR 200 x EU HEAR 1	254	-1.6	-7.6	-7.3
4	Castor x EU HEAR 3	250	-6.8	-9.3	-9.0
3	MillenniUM 03 x EU HEAR 3	242	-9.5	-11.8	-11.8
7	HR 200 x EU HEAR 3	241	-10.1	-12.5	-12.3
8	HR 102 x EU HEAR 2	239	-1.4	-6.3	-13.0
2	HR 102 x EU HEAR 3	229	-6.5	-12.1	-16.6
Parents					
12	MillenniUM 01	283			
11	Castor	275			
15	HR 200	275			
14	MillenniUM 03-2	275			
13	MillenniUM 03-1	274			
17	HR 199	274			
20	EU HEAR 3	260			
19	EU HEAR 2	255			
18	EU HEAR 1	242			
16	HR 102	229			
Overall Hybrid Mean		252			
Overall Parent Mean		264 †			
Hybrids-Parents		-12			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.4 Protein Concentration for F2 Roundup HEAR Hybrids

Mean protein concentration for F2 HEAR hybrids (249 g kg^{-1}) was significantly higher than for the parental strains/cultivars (242 g kg^{-1}) in the F2 Roundup HEAR hybrid field trials (Table 4.18). In contrast, Conventional F2 HEAR hybrids displayed lower mean protein concentration than parents. This was due to different genetic diversity of Conventional and Roundup hybrids. Grant and Beversdorf (1985) found that F1 canola hybrids displayed lower protein concentration than their parents. Cuthbert (2006) found also that the identical F1 HEAR hybrids (244 g kg^{-1}) displayed significantly lower protein concentration than their parents (251 g kg^{-1}).

The range of protein concentration for F2 Roundup HEAR hybrids was larger than parental strains/cultivars. RRHR 102 x EU HEAR 3 had the maximum (277 g kg^{-1}) while HR 102 x RRHR 102 had the minimum (226 g kg^{-1}) mean protein concentration (Table 4.18). Strain HR 200 had maximum (252 g kg^{-1}) while cultivar Red River 1852 had the minimum (227 g kg^{-1}) mean protein concentration in the F2 Roundup HEAR hybrid field trials (Table 4.18).

Protein concentration was significantly correlated with a number of traits such as sum of oil and protein concentration ($r = 0.74$), oil concentration ($r = -0.94$), seed yield ($r = 0.86$), glucosinolate concentration ($r = -0.31$) and meal protein concentration ($r = 0.50$) in the F2 Roundup HEAR hybrid field trials (Table 4.4).

Cuthbert (2006) found that protein concentration was significantly correlated with all agronomic and seed quality traits for the identical set of F1 HEAR hybrids. The correlation coefficient between protein concentration and seed yield ($r = 0.86$) suggests that the high seed yield F2 Roundup HEAR hybrids were also very high for seed protein concentration (Table 4.4)

A strong, negative correlation (-0.94) between oil and protein concentrations was observed in this study. Sernyk and Stefansson (1983) also found that seed oil concentration and seed protein concentration were strongly, negatively correlated.

Since F2 Roundup HEAR hybrids displayed significantly higher mean protein concentration than their parents, they also demonstrated significantly lower mean oil concentration than their parents.

Protein concentration displayed significant mid-parent, high-parent and commercial heterosis for some F2 Roundup HEAR hybrids (Table 4.18). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

Table 4.18: Mean Protein Concentration and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Protein ($g\ kg^{-1}$)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
4	RRHR 102 x EU HEAR 3	277	15.6 *	11.4 *	12.2 *
7	HR 200 x RRHR 102	262	4.8 *	4.0 *	6.3 *
1	RRHR 102 x EU HEAR 4	254	3.5 *	2.0	2.8
3	RRHR 102 x HR 199	248	0.5	-0.1	0.7
6	RRHR 102 x EU HEAR 1	243	-2.8	-3.4	-1.4
5	RRHR 102 x EU HEAR 2	242	1.8	-2.7	-1.9
2	RRHR 102 x EU HEAR 5	239	-1.6	-3.8	-3.1
8	HR 102 x RRHR 102	226	-9.1	-9.1	-8.4
parents					
15	HR 200	252			
9	EU HEAR 1	252			
16	EU HEAR 4	249			
17	RRHR 102	249			
14	MillenniUM 03	247			
18	HR 199	246			
12	EU HEAR 3	242			
19	Red River 1826	241			
13	EU HEAR 5	237			
20	EU HEAR 2	232			
11	HR 102	230			
10	Red River 1852	227			
Overall Hybrid Mean		249 †			
Overall Parent Mean		242			
Hybrids-Parents		7			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.5 Meal Protein Concentration for Conventional F2 HEAR Hybrids

Protein concentration in the meal or the portion of the seed left after oil removed is one of the important measurements of seed quality. The quality of livestock feed is primarily evaluated based on meal protein concentration.

Mean meal protein concentration for Conventional F2 HEAR hybrids (524.5 g kg^{-1}) was significantly lower than for the parental strains/cultivars (542.7 g kg^{-1}) (Table 4.19). Cuthbert (2006) found that F1 HEAR hybrids displayed no significant higher mean meal protein concentration than their parents for the identical set of F1 HEAR hybrids.

HR 199 x EU HEAR 2 had the maximum (548.5 g kg^{-1}) while HR 102 x EU HEAR 3 had the minimum (482.8 g kg^{-1}) mean meal protein concentration in the Conventional F2 HEAR hybrid field trials (Table 4.19).

Meal protein concentration was significantly correlated with a number of traits such as sum of oil and protein concentration ($r = -0.72$), oil concentration ($r = -0.55$), seed yield ($r = -0.47$), glucosinolate concentration ($r = 0.51$) and protein concentration ($r = 0.86$) in these field trials (Table 4.2). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids. Also, meal protein concentration was significantly correlated with lodging and height for F1 HEAR hybrids. However, meal protein concentration was not correlated with sum of oil and protein for the identical set of F1 HEAR hybrids in these field trials.

HR 199 x EU HEAR 2 was the only F2 HEAR hybrid which displayed significant mid-parent heterosis (Table 4.19). No significant high-parent heterosis was observed for Conventional F2 HEAR hybrids. As MillenniUM 03 displayed relatively good meal protein concentration, meal protein concentration displayed no significant commercial heterosis for Conventional F2 HEAR hybrids (Table 4.19).

Cuthbert (2006) found that meal protein concentration displayed significant mid-parent heterosis for a few F1 HEAR hybrids. No significant high-parent and commercial heterosis was observed for the identical set of F1 HEAR hybrids.

Table 4.19: Mean Meal Protein Concentration and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Prom ($g\ kg^{-1}$)	Mid-parent (%)	High-parent (%)	Commercial (%)
Hybrids					
9	HR 199 x EU HEAR 2	549	2.8 *	0.1	-0.8
10	HR 199 x EU HEAR 1	539	1.0	-1.6	-2.5
4	Castor x EU HEAR 3	539	-3.1	-3.4	-2.5
5	MillenniUM 01 x EU HEAR1	537	-1.4	-5.7	-2.8
6	MillenniUM 01 x EU HEAR 3	532	-5.3	-6.6	-3.7
1	HR 200 x EU HEAR 1	528	-1.9	-5.4	-4.4
8	HR 102 x EU HEAR 2	515	1.7	-0.8	-6.8
7	HR 200 x EU HEAR 3	515	-7.4	-7.8	-6.8
3	MillenniUM 03 x EU HEAR 3	507	-8.3	-8.4	-8.2
2	HR 102 x EU HEAR 3	483	-7.8	-12.9	-12.7
Parents					
12	MillenniUM 01	570			
15	HR 200	559			
11	Castor	558			
20	EU HEAR 3	554			
14	MillenniUM 03-2	553			
13	MillenniUM 03-1	553			
17	HR 199	548			
18	EU HEAR 1	519			
19	EU HEAR 2	519			
16	HR 102	494			
Overall Hybrid Mean		524.5			
Overall Parent Mean		542.7 †			
Hybrids-Parents		-18.2			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.6 Meal Protein Concentration for F2 Roundup HEAR Hybrids

Mean meal protein concentration for F2 Roundup HEAR hybrids (523.6 g kg^{-1}) was significantly higher than for the parental strains/cultivars (507.5 g kg^{-1}) (Table 4.20). In contrast, Conventional F2 HEAR hybrids showed lower mean meal protein concentration than parental strains/cultivars. This was due to genetic differences between Conventional and Roundup hybrids and parents used in this study.

RRHR 102 x EU HEAR 3 had the maximum (567 g kg^{-1}) and RRHR 102 x EU HEAR 2 had the minimum (492 g kg^{-1}) mean meal protein concentration in the F2 Roundup HEAR hybrid field trials (Table 4.20).

Meal protein concentration displayed significant mid-parent, high-parent and commercial heterosis for a few Roundup F2 HEAR hybrids (Table 4.20). Cuthbert (2006) found that meal protein concentration displayed significant mid-parent for a few F1 HEAR hybrids. No significant high-parent and commercial heterosis was observed for the identical set of F1 HEAR hybrids.

Meal protein concentration was significantly correlated with a number of traits such as sum of oil and protein concentration ($r = -0.74$), oil concentration ($r = -0.54$), seed yield ($r = 0.43$), glucosinolate concentration ($r = 0.53$) and protein concentration ($r = 0.50$) in these field trials (Table 4.4). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids. Also, meal protein concentration was significantly correlated with lodging and height for F1 HEAR hybrids. However, meal protein concentration was not correlated with sum of oil and protein for the identical set of F1 HEAR hybrids.

Table 4.20: Mean Meal Protein Concentration and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Prom ($g\ kg^{-1}$)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
4	RRHR 102 x EU HEAR 3	567	9.9 *	7.4 *	8.0 *
7	HR 200 x RRHR 102	553	6.8 *	4.9 *	5.5 *
1	RRHR 102 x EU HEAR 4	528	1.2	0.2	0.7
3	HR 199 x RRHR 102	522	0.5	-1.0	-0.5
2	RRHR 102 x EU HEAR 5	515	-0.1	-2.4	-1.9
6	RRHR 102 x EU HEAR 1	509	-4.7	-5.9	-2.9
8	HR 102 x RRHR 102	503	-0.8	-4.7	-4.1
5	RRHR 102 x EU HEAR 2	492	-3.7	-6.8	-6.2
Parents					
9	EU HEAR 1	541			
17	RRHR 102	527			
14	MillenniUM 03	525			
12	EU HEAR 4	517			
18	HR 199	511			
15	HR 200	508			
19	Red River 1826	508			
11	EU HEAR 3	504			
13	EU HEAR 5	503			
10	EU HEAR 2	494			
16	HR 102	486			
20	Red River 1852	466			
Overall Hybrid Mean		523.6 †			
Overall Parent Mean		507.5			
Hybrids-Parents		16.1			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.7 Sum of Oil and Protein Concentration for Conventional F2 HEAR Hybrids

The mean sum of oil and protein concentration for Conventional F2 HEAR hybrids (727 g kg^{-1}) was significantly higher than for the parental strains/cultivars (721 g kg^{-1}) (Table 4.21). Cuthbert (2006) also found that F1 HEAR hybrids displayed significantly higher mean sum of oil and protein concentration (734 g kg^{-1}) than their parents (723 g kg^{-1}) for the identical set of F1 HEAR hybrids. HR 102 x EU HEAR 3 had the maximum (746 g kg^{-1}) while Castor x EU HEAR 3 had the minimum (711 g kg^{-1}) mean sum of oil and protein concentration (Table 4.21). Crosses between EU #1, EU #3 and Manitoban strains/cultivars produced a higher mean sum of oil and protein concentration than for other hybrids in the Conventional F2 HEAR hybrid field trials (Table 4.21). Cuthbert (2006) also found similar results for the identical set of F1 HEAR hybrids.

This study indicated that increased oil and protein concentrations were possible and it was more accurate and desirable criterion to determine the superior hybrids by sum of oil and protein concentration than of protein and oil concentration separately. Grami and Stefansson (1977) also found that selection for sum of protein and oil concentration was more effective than selection for either protein or oil concentration individually.

Sum of oil and protein concentration was significantly correlated with a number of traits such as oil ($r = 0.72$), meal protein ($r = -0.72$), protein ($r = -0.51$) and glucosinolate concentration ($r = -0.31$) in these field trials. Cuthbert (2006) found that sum of oil and protein concentration was significantly correlated with all agronomic and quality traits except for meal protein and glucosinolate concentration for the identical set of F1 HEAR hybrids.

Sum of oil and protein was also significantly correlated with seed yield (r = 0.59) for Conventional F2 HEAR hybrids (Table 4.2). Cuthbert (2006) also found that sum of oil and protein was significantly correlated with seed yield (r = 0.65) for the identical set of F1 HEAR hybrids.

Sum of oil and protein concentration displayed significant mid-parent, and commercial heterosis for a few Conventional F2 HEAR hybrids (Table 4.21). No significant high-parent heterosis was observed for Conventional F2 HEAR hybrids (Table 4.21). Cuthbert (2006) found that sum of oil and protein concentration displayed significant mid-parent, high-parent and commercial heterosis for a few F1 HEAR hybrids.

Table 4.21: Mean Sum of Oil and Protein Concentration and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Sum ($g\ kg^{-1}$)	Mid-parent (%)	High-parent (%)	Commercial (%)
Hybrids					
2	HR 102 x EU HEAR 3	746	3.5 *	1.4	3.4 *
3	MilleniUM 03 x EU HEAR 3	734	2.9 *	1.8	1.8
5	MilleniUM 01 x EU HEAR 1	729	1.5	0.9	1.0
6	MilleniUM 01 x EU HEAR 3	728	2.6	2.1	1.0
10	HR 199 x EU HEAR 1	726	0.3	0.1	0.7
1	HR 200 x EU HEAR 1	726	0.9	0.5	0.6
7	HR 200 x EU HEAR 3	726	2.0	1.3	0.6
8	HR 102 x EU HEAR 2	723	-1.6	-1.7	0.2
9	HR 199 x EU HEAR 2	723	-1.1	-1.7	0.1
4	Castor x EU HEAR 3	711	-0.2	-0.9	-1.5
Parents					
16	HR 102	736			
19	EU HEAR 2	735			
17	HR 199	726			
18	EU HEAR 1	722			
14	MilleniUM 03-2	722			
13	MilleniUM 03-1	721			
11	Castor	717			
15	HR 200	716			
12	MilleniUM 01	713			
20	EU HEAR 3	706			
Overall Hybrid Mean		727 †			
Overall Parent Mean		721			
Hybrids-Parents		6			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.8 Sum of Oil and Protein Concentration for F2 Roundup HEAR Hybrids

Increasing the concentration of protein frequently results in the concentration of oil being reduced in the seed. This is because protein and oil are highly negatively correlated and also individually have low heritability (Grami and Stefansson, 1977). That is why plant breeders are interested in selecting for sum of oil and protein concentration and why they consider the sum of oil and protein as a good measurement for evaluating seed quality.

Mean sum of oil and protein for F2 HEAR hybrids (725 g kg^{-1}) was significantly lower than for the parental strains/cultivars (734 g kg^{-1}) in the F2 Roundup HEAR hybrid field trials (Table 4.22). In contrast, Conventional F2 HEAR hybrids displayed higher sum of oil and protein than the parental strains. This was due to genetic differences between Conventional and Roundup hybrids and parents used in this study.
Cuthbert (2006) also found that F1 HEAR hybrids displayed significantly higher mean sum of oil and protein concentration (729 g kg^{-1}) than their parents (723 g kg^{-1}) for the identical set of F1 HEAR hybrids.

RRHR 102 x EU HEAR 1 had the maximum (750 g kg^{-1}) while RRHR 102 x EU HEAR 3 had the minimum (696 g kg^{-1}) mean sum of oil and protein concentration in the F2 Roundup HEAR hybrid field trials (Table 4.22). The mean sum of oil and protein for cultivar Red River 1852 (766 g kg^{-1}) was the maximum observed among all F2 HEAR hybrids and parental strains/cultivars in all field trials (Table 4.22).

Sum of oil and protein concentration was significantly correlated with a number of traits such as oil (r = -0.62), meal protein (r = -0.74), protein (r = 0.74) and glucosinolate concentration (r = -0.32) in the F2 Roundup HEAR hybrid field trials. Cuthbert (2006) found that sum of oil and protein concentration was significantly correlated with all agronomic and quality traits except for meal protein and glucosinolate concentration for the identical set of F1 HEAR hybrids. Sum of oil and protein was also significantly correlated with yield (r = 0.69) for F2 Roundup HEAR hybrids (Table 4.4). Cuthbert (2006) also found that sum of oil and protein was significantly correlated with seed yield (r = 0.65) for the identical set of F1 HEAR hybrids.

RRHR 102 x EU HEAR 1 was the only F2 HEAR hybrid which displayed significant mid-parent, high-parent and commercial heterosis in the F2 Roundup HEAR hybrid field trials (Table 4.22). Cuthbert (2006) found that sum of oil and protein concentration displayed significant mid-parent, high-parent and commercial heterosis for a few F1 HEAR hybrids.

Table 4.22: Mean Sum of Oil and Protein Concentration and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Sum ($g\ kg^{-1}$)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	750	4.8 *	4.0 *	3.9 *
5	RRHR 102 x EU HEAR	734	0.9	0.1	1.6
3	RRHR 102 x HR 199	726	-0.2	-1.2	0.6
1	RRHR 102 x EU HEAR 4	725	0.3	0.1	0.4
2	RRHR 102 x EU HEAR 5	724	-0.4	-1.3	0.3
7	HR 200 x RRHR 102	723	-1.2	-2.7	0.2
8	HR 102 x RRHR 102	723	-2.5	-5.2	0.1
4	RRHR 102 x EU HEAR 3	696	-3.9	-4.3	-3.7
Parents					
20	Red River 1852	766			
16	HR 102	763			
15	HR 200	744			
18	HR 199	735			
13	EU HEAR 5	734			
10	EU HEAR 2	733			
19	Red River 1826	732			
11	EU HEAR 3	727			
12	EU HEAR 4	724			
14	MillenniUM 03	722			
17	RRHR 102	721			
9	EU HEAR 1	710			
Overall Hybrid Mean		725			
Overall Parent Mean		734 †			
Hybrids-Parents		-9			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.9 Glucosinolate Content for Conventional F2 HEAR Hybrids

The mean glucosinolate concentration for Conventional F2 HEAR hybrids (16 $\mu molg^{-1}$ seed) was significantly lower than for the parental strains/cultivars (18.8 $\mu molg^{-1}$ seed) (Table 4.23). Cuthbert (2006) also found that F1 HEAR hybrids (17 $\mu molg^{-1}$ seed) displayed significantly lower mean glucosinolate concentration than their parents (19.7 $\mu molg^{-1}$ seed).

The glucosinolate concentration of all F1 HEAR hybrids (17 $\mu molg^{-1}$ seed) and parental strains/cultivars (19.7 $\mu molg^{-1}$ seed) were higher than Conventional F2 HEAR hybrid and parental cultivars/strains due to long, cool and wet growing seasons during 2004 and 2005. Therefore, environmental conditions could affect seed quality including glucosinolate concentration.

The range of glucosinolate concentration was quite variable for Conventional F2 HEAR hybrids and parental strains/cultivars. HR 199 x EU HEAR 2 had the maximum (18.2 $\mu molg^{-1}$ seed) while HR 200 x EU HEAR 3 had the minimum (13.3 $\mu molg^{-1}$ seed) in the Conventional F2 HEAR hybrid field trials (Table 4.23). The parent with the highest mean glocosinolate concentration was cultivar Castor (23.6 $\mu molg^{-1}$ seed) and the lowest was strain HR 200 (16.1 $\mu molg^{-1}$ seed) in the Conventional F2 HEAR hybrid field trials (Table 4.23). Cuthbert (2006) also found that the parent with the highest mean glocosinolate concentration was Castor (26.9 $\mu molg^{-1}$ seed) and the lowest was HR 200 (16.2 $\mu molg^{-1}$ seed) for the identical set of F1 HEAR hybrids.

Glucosinolate concentration was significantly correlated with a number of traits such as oil ($r = -0.51$), sum of oil and protein ($r = -0.31$), protein ($r = 0.48$), meal protein ($r = 0.51$), and erucic acid ($r = -0.48$) concentration in the Conventional F2 HEAR hybrid field trials (Table 4.2). Cuthbert (2006) also found that glucosinolate concentration was significantly correlated with a number of traits such as oil, protein, meal protein for the identical set of F1 HEAR hybrids.

Glucosinolate concentration displayed significant mid-parent for all Conventional F2 HEAR hybrids. Also, glucosinolate concentration displayed significant high-parent and commercial heterosis for most Conventional F2 HEAR hybrids (Table 4.23). Cuthbert (2006) found that glucosinolate concentration displayed significant mid-parent, high-parent and commercial heterosis for a few F1 HEAR hybrids.

Both the Conventional F2 HEAR hybrids and their parents had higher glucosinolate concentration than the acceptable limit for registration (12 $\mu molg^{-1}$ seed). Even the commercial cultivar MillenniUM03 showed on average (17.45 $\mu molg^{-1}$ seed) glucosinolate concentration which was higher than acceptable limit (Table 4.23).

Table 4.23: Mean Glucosinolate Content and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Glucosinolate ($\mu molg^{-1}$ seed)	Mid-parent (%)	High-parent (%)	Commercial (%)
7	HR 200 x EU HEAR 3	13.3	-22.4 *	-17.4 *	-22.2 *
1	HR 200 x EU HEAR 1	13.4	-22.1 *	-16.8 *	-21.6 *
3	MillenniUM 03 x EU HEAR 3	14.2	-19.5 *	-17.0 *	-17.0 *
2	HR 102 x EU HEAR 3	15.2	-14.1 *	-11.6 *	-11.1 *
8	HR 102 x EU HEAR 2	15.6	-19.4 *	-9.3 *	-8.8 *
4	Castor x EU HEAR 3	16.3	-22.0 *	-10.4 *	-4.7 *
6	MillenniUM 01 x EU HEAR 3	17.5	-13.8 *	-3.8 *	2.3
10	HR 199 x EU HEAR 1	17.9	-7.3 *	-2.2	4.7
5	MillenniUM 01 x EU HEAR1	18.1	-11.1 *	-1.1	5.8
9	HR 199 x EU HEAR 2	18.2	-12.9 *	-7.6 *	6.4
15	HR 200	16.1			
14	MillenniUM 03-2	17.1			
16	HR 102	17.2			
13	MillenniUM 03-1	17.8			
20	EU HEAR 3	18.2			
18	EU HEAR 1	18.3			
17	HR 199	19.7			
19	EU HEAR 2	20.6			
12	MillenniUM 01	22.4			
11	Castor	23.6			
Overall Hybrid Mean		16 †			
Overall Parent Mean		18.8			
Hybrids-Parents		2.8			

* - hybrids significant at $p \leq 0.05$

† - means of hybrids and parents are significantly different at $p \leq 0.05$

4.2.10 Glucosinolate Content for F2 Roundup HEAR Hybrids

F2 Roundup HEAR hybrids were not different for glucosinolate concentration (17.2 $\mu molg^{-1}$ seed) compared to the parental strains/cultivars (17.3 $\mu molg^{-1}$ seed) (Table 4.24). In contrast, Conventional F2 HEAR hybrids displayed significantly lower mean glucosinolate concentration than the parental strains. Cuthbert (2006) found that F1 HEAR hybrids (17 $\mu molg^{-1}$ seed) displayed significantly lower mean glucosinolate concentration than their parents (19.7 $\mu molg^{-1}$ seed).

The range of glucosinolate concentration was quite wide for hybrids and parental strains in the F2 Roundup HEAR hybrid field trials (Table 4.24). The parent with the highest mean glocosinolate concentration was HR 199 (21.8 $\mu molg^{-1}$ seed) while the lowest was cultivar Red River 1826 (9.5 $\mu molg^{-1}$ seed).

Cuthbert (2006) also found that the parent with the highest mean glocosinolate concentration was cultivar Castor (26.9 $\mu molg^{-1}$ seed) and the lowest was strain HR 200 (16.2 $\mu molg^{-1}$ seed) for the identical set of F1 HEAR hybrids. RRHR 102 x EU HEAR 2 had the maximum (21.1 $\mu molg^{-1}$ seed) while RRHR 102 x EU HEAR 3 had the minimum (14.2 $\mu molg^{-1}$ seed) glucosinolate concentration (Table 4.24).

Glucosinolate concentration was significantly correlated with a number of traits such as oil ($r = 0.39$), sum of oil and protein ($r = -0.32$), protein ($r = -0.31$), meal protein ($r = 0.53$), erucic acid ($r = -0.43$) concentration, and days to maturity ($r = 0.31$) in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) also found that glucosinolate concentration was significantly correlated with a number of traits such as oil, protein, meal protein for the identical set of F1 HEAR hybrids.

Glucosinolate concentration displayed significant mid-parent, high-parent and commercial heterosis for some F2 Roundup HEAR hybrids (Table 4.24). Cuthbert (2006) also found that glucosinolate concentration displayed significant mid-parent, high-parent and commercial heterosis for a few F1 HEAR hybrids. Even though F2 Roundup HEAR hybrids displayed higher glucosinolate concentration than the acceptable limit for registration (12 $\mu molg^{-1}$ seed), the parent cultivar check MillenniUM03 showed (15.7 $\mu molg^{-1}$ seed) glucosinolate concentration which was higher than acceptable limit (Table 4.24).

Table 4.24: Mean Glucosinolate Content and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Glucosinolate ($\mu molg^{-1}$ seed)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
4	RRHR 102 x EU HEAR 3	14.2	-22.6 *	-24.9 *	-9.6 *
7	HR 200 x RRHR 102	14.9	-18.0 *	-21.2 *	-5.1 *
8	HR 102 x RRHR 102	15.6	-16.1 *	-14.8 *	-0.6
6	RRHR 102 x EU HEAR 1	16.6	-10.3 *	-12.2 *	5.7
2	RRHR 102 x EU HEAR 5	17.5	-2.2	-7.4 *	11.5
1	RRHR 102 x EU HEAR 4	18.1	-7.2 *	-10.0 *	15.3
3	RRHR 102 x HR 199	19.2	-5.5 *	-11.7 *	22.3
5	RRHR 102 x EU HEAR 2	21.1	4.2	-2.3	34.4
Parents					
19	Red River 1826	9.5			
20	Red River 1852	11.5			
14	MillenniUM 03	15.7			
13	EU HEAR 5	16.9			
15	HR 200	17.4			
11	EU HEAR 3	17.8			
9	EU HEAR 1	18.1			
16	HR 102	18.3			
17	RRHR 102	18.9			
12	EU HEAR 4	20.1			
10	EU HEAR 2	21.6			
18	HR 199	21.8			
Overall Hybrid Mean		17.2 ns			
Overall Parent Mean		17.3			
Hybrids-Parents		-0.1			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

4.2.11 Erucic Acid Concentration for Conventional F2 HEAR Hybrids

Conventional F2 HEAR hybrids were not different for erucic acid concentration (52.2 %) than the parental strains/cultivars (52.5 %) (Table 4.25). Cuthbert (2006) also found that there was no significant difference between F1 HEAR hybrids (52.3 %) and their parents (51.8 %) for mean erucic acid concentration for the identical set of F1 HEAR hybrids.

Similar ranges of erucic acid concentrations were observed for F2 HEAR hybrids and parental strains/cultivars in the Conventional F2 HEAR hybrid field trials. The parent with the highest mean erucic acid concentration was cultivar MillenniUM 03 (55.9 %) and the lowest was strain EU HEAR 1 (48.1 %). MillenniUM 03 x EU HEAR 3 had the maximum (53.9 %) while Castor x EU HEAR 3 had the minimum (49.3 %) erucic acid concentration in these field trials.

Erucic acid concentration was significantly correlated with a number of traits such as days to flower (r = -0.56), days to maturity (r = -0.48) and glucosinolate concentration (r = -0.48) in the Conventional F2 HEAR hybrid field trials (Table 4.2). Cuthbert (2006) found that erucic acid concentration was significantly correlated with all agronomic and seed quality traits except for vigor and glucosinolate concentration for the identical set of F1 HEAR hybrids.

Conventional F2 HEAR hybrids MillenniUM 03 x EU HEAR 3 and HR 102 x EU HEAR 3 displayed statistically significant mid-parent heterosis (Table 4.25). However, no significant high-parent heterosis was observed in the Conventional F2 HEAR hybrid field trials (Table 4.25). Since the commercial cultivar

MillenniUM 03 demonstrated the highest erucic acid concentration, there was no significant commercial heterosis observed for Conventional F2 HEAR hybrids.

Cuthbert (2006) found that erucic acid concentration displayed significant mid-parent heterosis for a few F1 HEAR hybrids. Only one hybrid displayed statistically significant high-parent heterosis for the identical set of F1 HEAR hybrids. No significant commercial heterosis was observed for the identical set of F1 HEAR hybrids.

Table 4.25: Mean Erucic acid Concentration and Heterosis Estimates for Conventional F2 HEAR Hybrids and Parental Strains/Cultivars Grown in Six Environments 2006 and 2007

Entry	Pedigree	Erucic Acid (%)	Mid-parent (%)	High-parent (%)	Commercial (%)
Hybrids					
3	MilleniUM 03 x EU HEAR 3	53.9	2.4 *	-3.3	-3.4
2	HR 102 x EU HEAR 3	53.8	3.5 *	-1.4	-3.5
8	HR 102 x EU HEAR 2	52.8	0.0	-3.3	-5.4
1	HR 200 x EU HEAR 1	52.7	2.4	-3.9	-5.5
9	HR 199 x EU HEAR 2	52.7	-0.8	-4.7	-5.5
7	HR 200 x EU HEAR 3	52.6	0.8	-4.2	-5.8
6	MillenniUM 01 x EU HEAR3	51.5	1.9	-0.3	-7.7
10	HR 199 x EU HEAR 1	51.2	-0.9	-7.4	-8.2
5	MillenniUM 01 x EU HEAR1	51.2	2.6	-0.9	-8.2
4	Castor x EU HEAR 3	49.3	0.9	-0.3	-11.7
Parents					
13	MillenniUM 03-1	55.9			
14	MillenniUM 03-2	55.8			
17	HR 199	55.3			
15	HR 200	54.9			
16	HR 102	54.6			
12	MillenniUM 01	51.7			
19	EU HEAR 2	51.0			
20	EU HEAR 3	49.4			
11	Castor	48.3			
18	EU HEAR 1	48.1			
Overall Hybrid Mean		52.2			
Overall Parent Mean		52.5 ns			
Hybrids-Parents		-0.3			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

4.2.12 Erucic Acid Concentration for F2 Roundup HEAR Hybrids

F2 Roundup HEAR hybrids were not different for erucic acid concentration (52.7 %) than the parental strains/cultivars (52.4 %) (Table 4.26). Cuthbert (2006) also found that there was no significant difference between F1 HEAR hybrids (53 %) and their parents (51.8 %) for mean erucic acid concentration for the identical set of F1 HEAR hybrids.

Similar ranges of erucic acid concentrations were observed for F2 Roundup HEAR hybrids and parental strains/cultivars. The parent with the highest mean erucic acid concentration was cultivar MillenniUM 03 (55.0 %) and the lowest was strain EU HEAR 5 (50.0 %). RRHR 102 x EU HEAR 1 had the maximum (53.9 %) while RRHR 102 x EU HEAR 3 had the minimum (50.0 %) erucic acid concentration in the F2 Roundup HEAR hybrid field trials.

Erucic acid concentration was significantly correlated with a number of traits such as days to flower (r = -0.45), days to maturity (r = -0.51) and glucosinolate concentration (r = -0.43) in the F2 Roundup HEAR hybrid field trials (Table 4.4). Cuthbert (2006) found that erucic acid concentration was significantly correlated with all agronomic and seed quality traits except for vigor and glucosinolate concentration for the identical set of F1 HEAR hybrids.

Only F2 HEAR RRHR 102 x EU HEAR 1 displayed statistically significant mid-parent heterosis in the F2 Roundup HEAR hybrid field trials (Table 4.26). No significant high-parent heterosis was observed in the F2 Roundup HEAR hybrid field trials (Table 4.26). Since commercial cultivar MillenniUM 03 demonstrated the highest erucic acid concentration, there was no significant commercial heterosis observed for F2 Roundup HEAR hybrids.

Cuthbert (2006) found that erucic acid concentration displayed significant mid-parent heterosis for a few F1 HEAR hybrids. Only one hybrid was displayed statistically significant high-parent heterosis for the identical set of F1 HEAR hybrids. No significant commercial heterosis was observed for the identical set of F1 HEAR hybrids.

Table 4.26: Mean Erucic acid Concentration and Heterosis Estimates for F2 Roundup HEAR Hybrids and Parental Strains/Cultivars Grown in Four Environments 2006 and 2007

Entry	Pedigree	Erucic Acid (%)	Mid- Parent (%)	High-parent (%)	Commercial (%)
Hybrids					
6	RRHR 102 x EU HEAR 1	54.3	5.4 *	2.6	-1.3
7	HR 200 x RRHR 102	54.0	1.5	1.0	-1.8
1	RRHR 102 x EU HEAR 4	53.2	3.1	0.6	-3.3
5	RRHR 102 x EU HEAR 2	52.5	-0.7	-0.8	-4.5
3	RRHR 102 x HR 199	52.4	0.0	-1.0	-4.8
2	RRHR 102 x EU HEAR 5	52.2	1.5	-1.3	-5.0
8	HR 102 x RRHR 102	52.2	-3.0	-4.6	-5.1
4	RRHR 102 x EU HEAR 3	51.0	-2.4	-3.5	-7.2
Parents					
14	MillenniUM 03	55.0			
16	HR 102	54.7			
15	HR 200	53.5			
20	Red River 1852	53.0			
17	RRHR 102	52.9			
19	Red River 1826	52.9			
10	EU HEAR 2	52.8			
18	HR 199	51.8			
11	EU HEAR 3	51.7			
12	EU HEAR 4	50.3			
9	EU HEAR 1	50.1			
13	EU HEAR 5	50.0			
Overall Hybrid Mean		52.7 ns			
Overall Parent Mean		52.4			
Hybrids-Parents		0.3			

* - hybrids significant at $p \leq 0.05$

ns - means of hybrids and parents are not significantly different at $p \leq 0.05$

Table 4.27: Summary Mean Agronomic, Seed Quality Traits and Heterosis Estimates for Conventional F1 and F2 HEAR Hybrids

Agronomic and Seed Quality Traits	Conventional F1 HEAR hybrids				Conventional F2 HEAR hybrids			
		Heterosis				Heterosis		
	Mean traits	High-parent (%)	Mid-parent (%)	Commercial (%)	Mean Traits	High-parent (%)	Mid-parent (%)	Commercial (%)
Seedling Vigor (1-5)	4	15.7	19.3	18.4	4.5	26.4	32.1	31.5
Days to Flower (days)	43.8	0.9	-4.5	1.7	42.7	4.7	-7.6	3.4
Days to Maturity (days)	103.2	1.8	-2.6	0.7	94.7	4.3	-3.0	3.9
Plant Height (cm)	115	-4.2	3.9	16.7	134	19.1	11.4	14.2
Lodging (1-5)	2.7	7.7	-10.3	-21.1	2.5	-31.2	-34.2	-22.3
Seed Yield (kg ha^{-1})	2518	72.1	93.6	60.4	2182	50.1	71.1	41.9
Oil Concentration (g kg^{-1})	499	0.9	2.9	4.3	475	0.9	3.7	6.3
Protein Concentration (g kg^{-1})	235	-2.3	-2.8	-7.9	252	-7.8	-3.4	-8.2
Meal Protein Concentration (g kg^{-1})	468	-2.0	0.0	-4.7	525	-5.3	-3.0	-5.1
Sum of Oil and Protein Concentration (g kg^{-1})	734	-0.1	0.9	-0.3	727	0.4	1.1	0.8
Glucosinolate Content (μmolg^{-1} seed)	17	-1.8	-9.2	-1.4	16	-5.8	1.8	15.1
Erucic Acid Concentration (%)	52	-1.5	3.1	-4.2	52	-3.0	1.3	-6.5

Table 4.28: Summary Mean Agronomic, Seed Quality Traits and Heterosis Estimates for F1 and F2 Roundup HEAR Hybrids

Agronomic and Seed Quality Traits	F1 Roundup HEAR hybrids				F2 Roundup HEAR hybrids			
		Heterosis				Heterosis		
	Mean traits	High-parent (%)	Mid-parent (%)	Commercial (%)	Mean traits	High parent (%)	Mid-parent (%)	Commercial (%)
Seedling Vigor (1-5)	4.1	15.4	19.1	18.2	4.2	26.1	35.6	22.1
Days to Flower (days)	43.6	0.8	-4.6	1.6	42.4	1.2	-3.1	2.3
Days to Maturity (days)	102.8	1.8	-2.6	0.7	91.6	1.5	-1.5	3.1
Plant Height (cm)	112	-4.4	3.6	16.6	134	5.9	7.1	6.2
Lodging (1-5)	2.7	8.1	-9.6	-20.7	2.8	-21.5	-27.7	-15.5
Seed Yield (kg ha^{-1})	2301	34.9	59.7	48.2	1899	12.5	27.1	20.9
Oil Concentration (g kg^{-1})	486	0.9	2.8	4.1	476	0.9	3.7	6.3
Protein Concentration (g kg^{-1})	244	-5.3	-2.3	-8.1	249	-7.8	-3.4	-8.2
Meal Protein Concentration (g kg^{-1})	473	-2.0	0.0	-4.7	524	-5.3	-3.0	-5.1
Sum of Oil and Protein Concentration (g kg^{-1})	729	-0.1	0.9	-0.3	725	1.1	0.4	0.8
Glucosinolate Content (μmolg^{-1} seed)	17	-1.8	-9.2	-1.4	17	-5.8	1.8	15.1
Erucic Acid Concentration (%)	53	-1.3	3.2	-4.1	53	1.3	-3.0	-6.5

5.0 General Discussion and Conclusions

This research was the first F2 Hybrid High Erucic Acid Rapeseed Agronomic and Seed Quality Study done at the University of Manitoba. This study was conducted at several locations in 2006 and 2007 to assess heterosis for selected traits for F2 HEAR hybrids and observe if F2 HEAR hybrids were a desirable alternative for traditional F1 HEAR hybrids. All the F2 HEAR hybrids used in this study had been previously grown in 2004 and 2005 as F1 HEAR hybrids and assessed for agronomic and seed quality traits. Since the same parental cultivars/strains were grown in both F1 and F2 HEAR hybrid field trials, it was possible to determine the extent of heterosis for all traits for both F1 and F2 HEAR hybrids and then compare these levels to that expected from genetic considerations.

Conventional F1 HEAR hybrids and F1 Roundup HEAR hybrids demonstrated up to 155 % high-parent heterosis, 159 % mid-parent heterosis and 107 % commercial heterosis for seed yield when compared with their parents (Cuthbert, 2006). Conventional F2 HEAR hybrids displayed up to 75 % high-parent heterosis, 91 % mid-parent heterosis and 56% commercial heterosis for seed yield (Table 4.13). Furthermore, F2 Roundup HEAR hybrids showed up to 76 % high-parent heterosis, 97 % mid-parent heterosis and 53 % commercial heterosis for seed yield when compared with their parents (Table 4.14). The high-parent, mid-parent and commercial heterosis estimates for seed yield for all F2 HEAR hybrids were compared to those estimates of mid-parent, high-parent and commercial heterosis for seed yield for F1 HEAR/canola hybrids reported in previous studies conducted by McVetty and Brandle (1989), Sernyk and Stefansson (1983) and Grant and Beversdorf (1985). The levels of heterosis for seed yield in the F2

HEAR hybrids grown in this study frequently exceeded the values reported in the literature for F1 HEAR/canola hybrids.

All F2 HEAR hybrids with high seed yields were very vigorous in early seedling development in comparison with the parental strains/cultivars. All F2 HEAR hybrids were also significantly higher yielding than the better parental strain/cultivar in both Conventional and Roundup field trials (Table 4.13 and Table 4.14).

Days to flower was highly correlated with days to maturity. Height was also highly correlated with lodging and yield in F1 HEAR hybrid (grown in 2004 and 2005) and both Conventional and Roundup F2 HEAR hybrid field trials (Table 4.2 and Table 4.4). The high yield F1 HEAR hybrids (grown in 2004 and 2005) and F2 HEAR hybrids were later flowering and later maturing than other hybrids. Superior performing F1 HEAR and F2 HEAR hybrids were much taller and had considerably lower lodging than other F1 and F2 HEAR hybrids.

All F2 HEAR hybrids (Conventional and Roundup) significantly displayed higher mean vigor than parents and the differences between hybrids and parents from 4 to 5 leaf stage were visually distinguishable in all field trials. Although F1 HEAR hybrids (grown in 2004 and 2005) displayed higher mean seedling vigor than their parents, F2 HEAR hybrids showed even better mean vigor than F1 HEAR hybrids due to excellent soil moisture and optimum seeding date (Table 4.27 and Table 4.28).

All F2 HEAR hybrids displayed significantly earlier mean days to flower than the parental strains/cultivars because EU #1 and EU #3 strains flowered on average 10 to 15 days later than all other strains/cultivars. Although F1 HEAR hybrids demonstrated significantly earlier mean days to flower than the parental strains/cultivars, F1 HEAR hybrids showed longer days to flower than all F2 HEAR hybrids since planting was delayed and F1 HEAR hybrids showed poor emergence due to higher moisture levels than average in 2004 and 2005 (Table 4.27 and Table 4.28) (Cuthbert, 2006).

Conventional F2 HEAR hybrids displayed no significant difference from their parents for mean days to maturity and glucosinolate concentration. Conventional F2 HEAR hybrids demonstrated significantly higher mean oil concentration and sum of oil and protein concentration than parental strains/cultivars. Conventional F2 HEAR hybrids demonstrated significantly lower mean protein concentration and meal protein concentration than parental strains/cultivars. In contrast, F2 Roundup HEAR hybrids displayed opposite results for these parameters because these two hybrid types were cross progeny from genetically distinct pools.

All F2 HEAR hybrids and F1 HEAR hybrids (grown in 2004 and 2005) displayed no significant difference versus parental strains/cultivars for erucic acid concentration (Table 4.27 and Table 4.28). All Conventional F2 HEAR hybrids and F2 Roundup HEAR hybrids were significantly taller than parental strains/cultivars. Conventional F2 HEAR hybrids and F2 Roundup HEAR hybrids showed lower lodging than parental strains/cultivars. However, the difference between F2 HEAR hybrids and their parents for lodging was not statistically significant.
Furthermore, no significant difference was displayed between F1 HEAR hybrids (grown in 2004 and 2005) and parental strains/cultivars for both height and lodging traits.

Crosses between EU #1, EU #3 and Manitoban strains/cultivars displayed higher yield, vigor, later days to flower and days to maturity than the other HEAR hybrids in F1 HEAR hybrid field trials (grown in 2004 and 2005) and both Conventional and Roundup

F2 HEAR hybrid field trials. Also, all HEAR hybrids produced by crosses between EU #1, EU #3 and Manitoban strains/cultivars were taller and demonstrated lower lodging than other hybrids in F1 HEAR hybrid field trials (grown in 2004 and 2005) and both Conventional and Roundup F2 HEAR hybrid field trials.

Vigor, height and yield displayed significant mid-parent, high-parent and commercial heterosis for all F2 HEAR hybrids (Conventional and Roundup). Sernyk and Stefansson (1983) and Grant and Beversdorf (1985) also found significant mid-parent, high-parent heterosis for F1 HEAR/canola hybrids for those three agronomic parameters.

Cultivar Red River 1852 displayed maximum oil and sum of oil and protein concentration among all parental strains/cultivars and F2 HEAR hybrids. Cultivar Red River 1852 was the tallest among Manitoban strains/cultivars in both Roundup and Conventional field trials. Also, commercial cultivar MillenniUM 03 showed maximum erucic acid concentration among all parental strains/cultivars and F2 HEAR hybrids.

The disease resistance of the F2 HEAR hybrids used in this study was not evaluated. However, the Manitoban HEAR cultivars/strains were rated R to blackleg and contained one or more dominant blackleg genes. Even though there may have been segregation for blackleg resistance gene in F2 HEAR hybrid field trials, there were not observed any serious disease problems in all F2 HEAR hybrid field trials.

The F2 HEAR hybrids still have higher yield satisfactory phenology and seed quality compared to the Open Pollinated Population (OPP) HEAR cultivars/strains they will replace. The levels of heterosis observed were sufficient to warrant further study of the use of F2 HEAR hybrids (Table 4.27 and Table 4.28).

F1 HEAR hybrid seeds are difficult to produce and more expensive (about 2.5 times) than F2 HEAR hybrids to buy. When producing F1 HEAR hybrids, at least 50 % of seed will be lost due to insufficient cross pollination, pollen contamination, environment and heat stress. However, F2 HEAR hybrids are easier and faster to produce. When producing F2 HEAR hybrids, at least 90 % of expected seed will be produced.

Based on the results of this study, there was no significant difference between F2 HEAR hybrids and their parents for erucic acid concentration. Cuthbert (2006) also found that there was no significant difference between F1 HEAR hybrids and their parents for erucic acid concentration. Therefore, producers can use F2 HEAR hybrids as a reasonable alternative to F1 HEAR hybrids.

Using F2 HEAR hybrids can bring a promising future for agriculture and rewarding developments for the HEAR industry since this research study benefits farmers, seed producers and industries. The future study will be the assessment of heterosis for agronomic and seed quality traits in F3 HEAR hybrids to find that whether F3 hybrids will display acceptable level of heterosis for selected traits.

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7.0 Appendix

Appendix 7.1: Analysis of Variance for Vigor for F2 Conventional

Source	DF	Sum of Squares	Mean Square	Expected Mean Square
YearLoc	5	1.3	0.3	Var (Residual) +20 Var (Rep (YearLoc)) +Q (YearLoc,YearLoc*Entry)
Entry	19	114.5	6.0	Var (Residual) + Q (Entry,YearLoc*Entry)
YearLoc*Entry	95	42.6	0.4	Var (Residual) + Q (YearLoc*Entry)
Rep (YearLoc)	18	13.3	0.7	Var (Residual) + 20 Var (Rep (YearLoc))
Residual	342	163.5	0.5	Var (Residual)

Appendix 7.2: Analysis of Variance for Vigor for F2 Roundup

Source	DF	Sum of Squares	Mean Square	Expected Mean Square
YearLoc	3	5.8	1.9	Var (Residual) + 20 Var (Rep (YearLoc)) +Q (YearLoc,YearLoc*Entry)
Entry	19	125.1	6.6	Var (Residual) + Q (Entry,YearLoc*Entry)
YearLoc*Entry	57	21.10	0.4	Var (Residual) + Q (YearLoc*Entry)
Rep (YearLoc)	12	32.1	2.7	Var (Residual) + 20 Var (Rep (YearLoc))
Residual	228	121.9	0.5	Var (Residual)

Appendix 7.3: Analysis of Variance for Days to Flower for F2 Conventional

Source	DF	Sum of Squares	Mean Squares
YearLoc	5	1.2	0.2
Entry	19	8946.2	470.9
YearLoc*Entry	95	41.8	0.4
Rep (YearLoc)	18	13.3	0.7
Residual	342	186.0	0.5

Appendix 7.4: Analysis of Variance for Days to Flower for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	0.1	0.03
Entry	19	5331.8	280.6
YearLoc*Entry	57	4	0.1
Rep (YearLoc)	12	1.5	0.1
Residual	228	37.2	0.2

Appendix 7.5: Analysis of Variance for Days to Maturity for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	3.9	0.8
Entry	19	13269	698.4
YearLoc*Entry	95	48.7	0.5
Rep (YearLoc)	8	12.4	0.7
Residual	342	243.6	0.7

Appendix 7.6: Analysis of Variance for Days to Maturity for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	0.009	0.003
Entry	19	9926.2	522.4
YearLoc*Entry	57	0.1	0.003
Rep (YearLoc)	12	39.7	3.3
Residual	228	119.5	0.5

Appendix 7.7: Analysis of Variance for Plant Height for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	674.6	135.0
Entry	19	29497	1552.5
YearLoc*Entry	95	7191.0	75.7
Rep (YearLoc)	18	1047.8	58.2
Residual	342	17033	49.8

Appendix 7.8: Analysis of Variance for Plant Height for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	52.7	17.6
Entry	19	12132	638.5
YearLoc*Entry	57	1011.3	17.7
Rep (YearLoc)	12	583.4	48.6
Residual	228	5797.8	25

Appendix 7.9: Analysis of Variance for Seed Yield for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	63.5	12.7
Entry	19	46305206	2437116
YearLoc*Entry	95	1671.4	17.6
Rep (YearLoc)	18	366.1	20.3
Residual	342	6710.6	19.6

Appendix 7.10: Analysis of Variance for Seed Yield for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	84.5	28.2
Entry	19	36409021	1916264
YearLoc*Entry	57	3171	55.6
Rep (YearLoc)	12	246.3	20.5
Residual	228	6176.3	27.1

Appendix 7.11: Analysis of Variance for Lodging for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	2.0	0.4
Entry	19	69.4	3.7
YearLoc*Entry	95	26.6	0.3
Rep (YearLoc)	18	7.3	0.4
Residual	342	117.3	0.3

Appendix 7.12: Analysis of Variance for Lodging for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	7.2	2.4
Entry	19	53.5	2.8
YearLoc*Entry	57	8.2	0.1
Rep (YearLoc	12	2.7	0.2
Residual	228	44.3	0.2

Appendix 7.13: Analysis of Variance for Oil Concentration for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	6190.7	1238.1
ENTRY	19	244073	12846
YearLoc*ENTRY	95	64553	679.6
Rep (YearLoc)	18	510.3	28.3
Residual	342	19518	57.1

Appendix 7.14: Analysis of Variance for Oil Concentration for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	2924.3	974.8
ENTRY	19	160897	8468.3
YearLoc*ENTRY	57	3398.5	59.6
Rep (YearLoc)	12	209.	17.5
Residual	228	10738	47.1

Appendix 7.15: Analysis of Variance for Protein Concentration for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	3169.4	633.9
ENTRY	19	127577	6714.6
YearLoc*ENTRY	95	23835	250.9
Rep (YearLoc)	18	554.2	30.8
Residual	342	19321	56.5

Appendix 7.16: Analysis of Variance for Protein Concentration for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	1148.8	382.9
ENTRY	19	43835	2307.1
YearLoc*ENTRY	57	22019	386.3
Rep (YearLoc)	12	424.8	35.4
Residual	228	18249	80.0

Appendix 7.17: Analysis of Variance for Meal Protein for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	6190.7	1238.1
ENTRY	19	244073	12846
YearLoc*ENTRY	95	64553	679.5
Rep (YearLoc)	18	510.3	28.3
Residual	342	19518	57.1

Appendix 7.18: Analysis of Variance for Meal Protein for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	2924.3	974.8
ENTRY	19	160897	8468.3
YearLoc*ENTRY	57	3398.5	59.6
Rep (YearLoc)	12	209.5	17.5
Residual	228	10738	47.1

Appendix 7.19: Analysis of Variance for Sum of Oil and Protein for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	550.6	110.1
ENTRY	19	39188	2062.5
YearLoc*ENTRY	95	31699	333.7
Rep (YearLoc)	18	670.0	38.9
Residual	342	19234	56.2

Appendix 7.20: Analysis of Variance for Sum of Oil and Protein for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	7700.1	2566.7
ENTRY	19	78650	4139.5
YearLoc*ENTRY	57	32185	564.7
Rep (YearLoc)	12	335.4	28.0
Residual	228	21245	93.2

Appendix 7.21: Analysis of Variance for Glucosinolate Content for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	280.4	56.1
ENTRY	19	8245.8	434.0
YearLoc*ENTRY	95	995.2	10.5
Rep (YearLoc)	18	141.4	7.9
Residual	342	1612.4	4.7

Appendix 7.22: Analysis of Variance for Glucosinolate Content for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	11.9	4.0
ENTRY	19	8987.0	473.0
YearLoc*ENTRY	57	1772.8	31.1
Rep (YearLoc)	12	124.2	10.3
Residual	228	2763.6	12.1

Appendix 7.23: Analysis of Variance for Erucic Acid Concentration for F2 Conventional

Source	DF	Sum of Squares	Mean Square
YearLoc	5	84.1	16.8
ENTRY	19	1285.0	67.6
YearLoc*ENTRY	95	114.4	1.2
Rep (YearLoc)	6	0.9	0.2
Residual	114	112.3	1.0

Appendix 7.24: Analysis of Variance for Erucic Acid Concentration for F2 Roundup

Source	DF	Sum of Squares	Mean Square
YearLoc	3	40.0	13.3
Entry	19	308.1	16.2
YearLoc*Entry	57	432.9	7.6
Rep (YearLoc)	4	0.8	0.2
Residual	76	277.5	3.7