Assessment of Heterosis for Selected Traits in Hybrid HEAR

by

Richard Douglas Cuthbert

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

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THE UNIVERSITY OF MANITOBA

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Abstract

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Summer oilseed rape with canola quality is one of the most important crops grown in western Canada, with the majority of the acreage seeded to hybrid cultivars. Although the phenomenon of hybrid vigor or heterosis is not completely understood, hybrid cultivars tend to possess greater vigor, increased seed yields, improved quality and better disease resistance. Previous studies have shown that crosses of summer oilseed rape can result in 40 to 120% high-parent heterosis for seed yield. Until recently, the development of hybrids in high erucic acid rapeseed (HEAR) has not been a viable option due to the limited genetic pool available. For this study twelve genetically and geographically diverse HEAR cultivars/strains (parents) were selected and crossed by full hand emasculation in a top-cross design to produce 45 F_1 hybrid combinations. Seven of the twelve parental lines were HEAR cultivars/strains developed by the University of Manitoba (UM) and the remaining five were proprietary European (EU) produced HEAR strains. Adequate seed was produced to evaluate the hybrids and parents in six environments in Manitoba during 2004 and 2005. Six agronomic traits (vigor, days to first flower, days to maturity, pre-harvest lodging, plant height, and seed yield) and six seed quality characteristics (oil concentration, protein concentration, sum of oil and protein concentration, erucic acid concentration and glucosinolate concentration) were

assessed in this study. Based on this assessment, mid-parent, high-parent and commercial heterosis estimates for each hybrid combination were calculated. General combining abilities of the parent cultivars/strains and specific combining abilities of the hybrid combinations for each agronomic and quality trait were also calculated. Differences between hybrids and parent cultivars/strains were easily visually distinguishable in field trials after emergence due to the higher vigor of the hybrids. Superior performing hybrids produced in this study displayed high-parent heterosis estimates for seed yield of up to 155% and commercial heterosis for seed yield of up to 107%. These superior performing hybrids were much taller and had considerably better lodging resistance than parental cultivars/strains. Although seed protein concentration was lower in the higher seed yield hybrids than in the parents, the oil concentration exceeded the parents. The top performing hybrids produced in this study were from UM x EU crosses, as predicted by pedigree and/or geographical diversity.

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1.0 Introduction

Summer oilseed rape production has grown dramatically in Canada during the past fifty years (Canola Council, 2006). Summer oilseed rape is well adapted to the temperate climate of the Canadian Prairies. Oil composition can be modified using conventional and transgenic approaches. The first rapeseed cultivars were moderately high in erucic acid, a fatty acid with 22 carbons and one double bond (C22:1), which can cause health problems when digested by animals. Therefore, these cultivars were better suited to industrial oil applications than edible oils. The need for a healthy oil for human consumption prompted breeders to develop rapeseed cultivars that are low in erucic acid content. The high protein content of the rapeseed meal was suitable for a livestock feed, however, the high glucosinolate content reduced palatability and interfered with thyroid function in non-ruminants (Greer, 1950). Lowering the glucosinolate content in the seed was another priority for breeders. Dr. Baldur Stefansson at the University of Manitoba was the first to successfully produce a rapeseed plant that had the desired oil and meal composition. This cultivar was registered in 1974 as "Tower". The improvements in quality of rapeseed resulted in the Canola Crushers of Western Canada naming the new commodity canola in 1979 to distinguish the low erucic acid content in the seed oil and the low glucosinolate content in the meal from the common rapeseed (Sernyk, 1982).

In subsequent years, major efforts were placed on breeding canola cultivars with improved agronomic traits to increase the productivity. Today, there are approximately 5.5 million hectares of canola grown in Western Canada, with the majority of this acreage comprised of hybrid canola cultivars (Statistics Canada, 2006). Hybrid cultivars can have

an advantage over open pollinated cultivars if they show higher seed yield and superior agronomic performance. Hybrids have been shown to out-yield open pollinated varieties by as much as 40 to 60 % due to heterosis (Semyk and Stefansson, 1983; Brandle and McVetty, 1989). Although the phenomenon of heterosis is still not clearly understood, two main theories as to why F_1 generation plants have tendency to out-perform the better parent have been put forth (Bernando, 2002). The first theory is overdominance (Shull, 1948). When two same species plants with different pedigree are cross-pollinated the progeny will be heterozygous at most loci (East, 1936; Shull, 1948). The different gene products from each locus together produce a more vigorous plant resulting in greater seed production (East, 1936; Shull, 1948). The second theory of heterosis is the dominance theory, which states that addition of multiple dominant alleles at many loci will produce a complementary effect (Davenport, 1908; Bruce, 1910; Keeble and Pellew, 1910).

The extent of heterosis in HEAR cultivars has not previously been documented. Many of the HEAR cultivars from the University of Manitoba are closely related genetically, with Hero, Mercury, Venus, Neptune, and Castor being sister lines with similar pedigree. More recent HEAR (MillenniUM01, MillenniUM02, and MillenniUM03) cultivars developed at the University of Manitoba have increased genetic diversity.

Over the past three decades, the original HEAR cultivars have been used for their high erucic acid oil content, and have resulted in many new HEAR cultivars with agronomics incorporated from commercial canola varieties. To achieve high heterosis levels in hybrid HEAR, another genetically distinct source of HEAR is required.

Significant heterosis has also been found for crosses of geographically separated oilseed rape cultivars (Brandle and McVetty, 1990).

Many specialty crops are produced under contract between producers and companies. Under these contracts, the producer will purchase Certified seed for the growing season and all seed which is harvested from this crop is delivered to the company which holds the contract. Hybrid cultivars are suitable for the contract system since hybrids that are grown again (F_2 generation), results in plants that segregate for many traits including vigor, flowering, disease resistance, height, lodging, maturity, and flowering.

The objectives of this research were to:

1) Develop HEAR hybrid crosses using HEAR cultivars/strains with diverse pedigrees and diverse geographical origin.
2) Assess the HEAR hybrids and HEAR cultivar/strains in replicated multi-location yield trials over two years.
3) From the yield trial data, estimate the mid- and high-parent and commercial heterosis for the selected agronomic and seed quality traits.
4) Also calculate general and specific combining abilities of the selected agronomic and seed quality traits for the HEAR parental cultivars/strains using the yield trial data.

2.0 Literature Review

2.1 History

2.1.1 Rapeseed

Rapeseed was first grown as early as 3000 BC by India and China (Prakash, 1980). During this time, oil from rapeseed was used as a fuel for oil lamps (Robbelen, 1991). Rapeseed acreage increased dramatically in Europe when its oil was discovered to be a high quality lubricant for steamship engines as it tended to adhere to metal surfaces even when submerged in water. The demand for this oil rose dramatically after the petroleum supplies were depleted during the Second World War. Prior to World War II, a handful of Canadian producers had begun to grow rapeseed on small acreages. When producers became aware of the petroleum shortage, seed increases were done and over the next three years, rapeseed acreage increased significantly. The cultivars produced in Canada at this time were known as "Polish rapeseed" or *Brassica campestris* species. Today these cultivars are referred to as *Brassica rapa*.

Additional rapeseed was purchased from United States seed companies to further expand production. These cultivars were the species *Brassica napus* which were originally obtained from Argentina and hence the name "Argentine rapeseed" was coined. The species *Brassica napus* was the result of an interspecific hybridization between *B. oleracea* and *B. rapa* with chromosome doubling to create viable fertile amphidiploids (Downey, 1983). Similar crosses between *B. nigra* and *B. campestris* to create *B. juncea* and between *B. nigra* and *B. oleracea* to create *B. carinata* have

occurred in nature. These interspecific hybridizations are represented in the triangle of U (Figure 2.1).

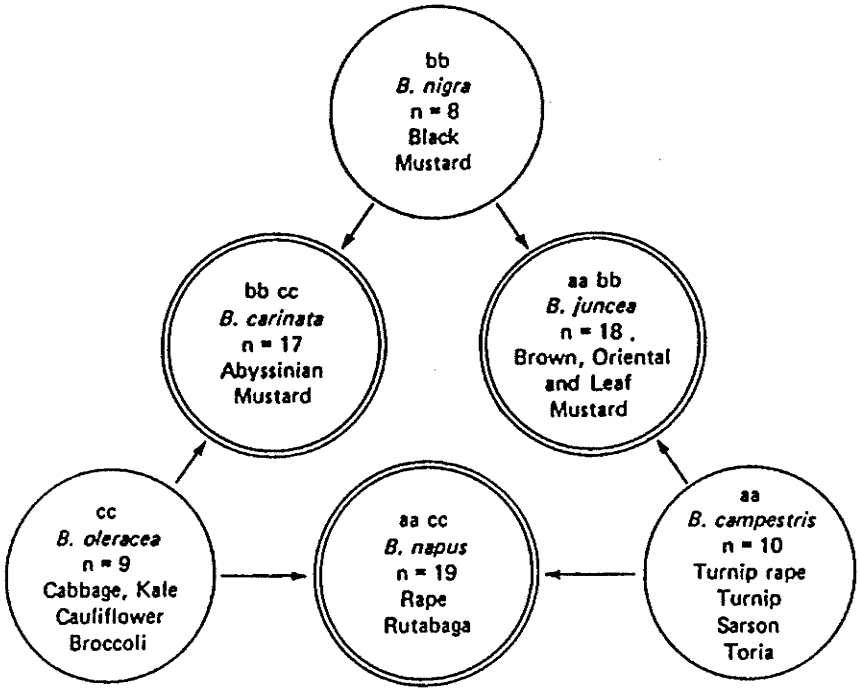

Figure 2.1: Triangle of U – Genomic and chromosome relationships of the *Brassica* species (Downey, 1983)

2.1.2 Canola and High Erucic Acid Rapeseed

Rapeseed oil was an excellent industrial oil for lubrication due to the moderately high erucic acid content in the seed (approximately 35%), however, the oil had detrimental effects on human health if consumed (Hulan *et al.*, 1975). The seed meal was also quite high in protein which was ideal for use as a livestock feed, however, the glucosinolate content in the seed was also high which caused palatability issues and enlarged thyroid glands (Beasley, 1999).

The need for a healthy, edible oil and good quality meal prompted breeders to develop rapeseed cultivars which were low in erucic acid content and low in

glucosinolate content in the seed. In 1974, Dr. Baldur Stephenson at the University of Manitoba was the first plant breeder in the world to successfully release a rapeseed cultivar named "Tower" that had the desired edible oil profile and was also low in seed glucosinolate content (Stefansson and Kondra, 1975). Cultivars which were low in both erucic acid and glucosinolates were termed "double low" and were described as "canola" in 1979 by the Canola Crushers of Western Canada to clearly distinguish them from rapeseed (Sernyk, 1982).

During the same period canola or double low oilseed rape lines were being developed, Dr. Baldur Stephenson recognized the usefulness of maintaining or improving the high erucic acid profile and began to lower the glucosinolate content of the seed meal while raising the erucic acid content of the oil (>50%). These lines were referred to as high erucic acid rapeseed (HEAR). By lowering the glucosinolate content in rapeseed, this created new uses for the meal mainly as a high protein livestock feed. With both the oil and meal being used, the economics of crushing HEAR greatly improved. New uses for erucic acid such as a slip agent in plastics and metal manufacturing have since been discovered (Katavic *et al.*, 2001).

The world's first HEAR cultivar released was Reston in 1982 (Alberta Agriculture, 1982) which was then followed by Hero in 1991 (Scarth *et al.*, 1991). Several new HEAR cultivars from the cross that produced Hero were released through the 1980's and early 1990's. Much of the University of Manitoba breeding efforts to develop new HEAR cultivars has used these cultivars as a source for high erucic acid content and low glucosinolate content.

As canola and HEAR acreages increased, breeding efforts were directed to improve the agronomics as well as the quality characteristics for end use processing. Today over 5.5 million hectares of *Brassica napus* are grown in Canada with the majority being hybrid cultivars. The majority of the canola and HEAR cultivars in production use a form of herbicide tolerance such as glyphosate (RoundUp Ready), glufosinate (Liberty Link) or imidazolinone (Clearfield) tolerance.

Today, HEAR in western Canada is a proprietary contract crop produced under contract to Bunge Canada. HEAR production acreage is relatively small when compared to canola, however, the area and volume of HEAR production is growing steadily in western Canada.

2.2 Oil Seed *Brassica napus* Quality Components

2.2.1 Seed Oil Concentration

The most valuable seed component in oilseed rape is the oil. Harvested seed is sold to processing companies which crush the seed to extract the oil and meal components. Since the value of the meal is approximately half the oil value, increasing the oil concentration of the seed is high priority for oilseed rape breeders. The majority (80 %) of the total seed oil is located in the cotyledons while the remainder is located in the endosperm (7 to 12 %) and seed coat (8 to 13%) (Downey *et al.*, 1975).

Development of seed oil is dependent on many factors including temperature and moisture during seed maturation, nitrogen availability, and genotype. Oilseed rape will produce high seed oil concentrations in cool, moist growing conditions with moderate rates of nitrogen (Downey, 1983). Seed oil concentration displays both additive and over

dominance gene action (Govil *et al.*, 1984) and has a narrow sense heritability of approximately 0.26 (Grami *et al.*, 1977a).

2.2.2 Protein Concentration

Protein concentration in the seeds of *Brassica* oilseed species is between 20 and 40% with the majority comprised of storage protein. Storage proteins play an important role as a nitrogen source for seedling germination and early seedling development. Differences in protein concentration between *Brassica* species are mainly due to genotype and environment effects.

Proteins are molecules comprised of a series of polypeptides made up of varying amounts of amino acids. Different configurations of amino acids within the polypeptides and orientation of the polypeptides make each protein unique for a certain function. Oilseed rape meal has an amino acid profile that compares favourably with soybean (*Glycine max*) meal (Clandinin *et al.*, 1986). Transcription of genes into RNA and translation of RNA into polypeptides is how proteins are synthesized. Narrow sense heritability associated with seed meal protein concentration is approximately 0.25 (Grami *et al.*, 1977a).

2.2.3 Sum of Oil and Protein Concentrations

Breeding for higher oil or protein concentrations independently is difficult because the narrow sense heritabilities of both are low. When oil and protein concentrations are considered together, the narrow sense heritability is much higher (0.33) compared to oil and protein concentrations (0.26 and 0.25 respectively) (Grami *et*

al., 1977a). The correlation between these two traits is strongly negative which indicates that selecting for increased concentrations of both traits simultaneously is the best approach (Robbelen, 1978).

2.2.4 Glucosinolates

After crushing oilseed rapeseed to extract oil, a high protein meal is produced that has a well-balanced amino acid composition suitable for use as a livestock feed. However, use of this meal as a livestock feed has been limited due to high levels of toxic sulphur containing compounds called glucosinolates (Bowland *et al.*, 1965). Glucosinolates are organic compounds that contain sulfur, nitrogen and a group derived from glucose. This central grouping has different aromatic and aliphatic side chains connected to the central carbon. When glucosinolates are consumed by animals, they are broken down by enzymatic degradation (myrosinase) which leads to the formation of isothiocynates, oxazolidine-2-thiones, thiocynates, and nitriles (Figure 2.2). These compounds cause reduced palatability of the feed and can also cause goiter in non-ruminant animals (Greer, 1950).

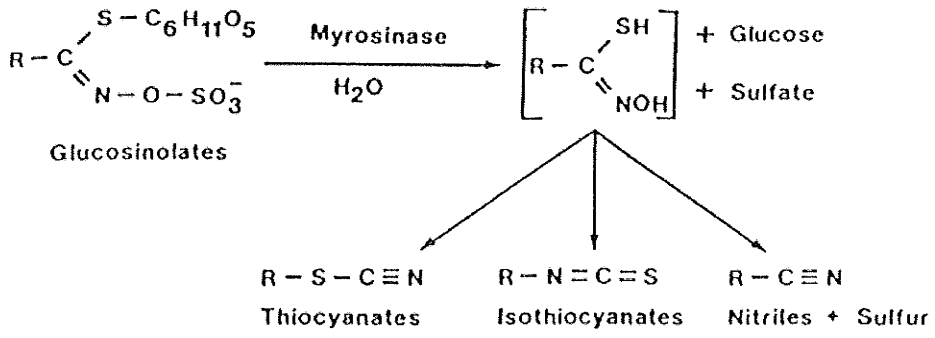

Figure 2.2: Chemical structure and enzymatic hydrolysis products of glucosinolates (Downey, 1983)

In 1967, a low glucosinolate Argentine oilseed rape cultivar was discovered ("Bronowski") through germplasm surveys. This cultivar was used by plant breeders as the source of valuable variation for low glucosinolate concentration to develop a new *B. napus* cultivar named "Tower" that only had approximately ten percent of the glucosinolate content found in normal rapeseed cultivars (Stefansson and Kondra, 1975). The reduction in glucosinolate concentration is due to a combination of three recessive alleles at three loci which limits the accumulation of the four aliphatic glucosinolates (Love, 1988). This glucosinolate reduction mechanism has been referred to as the "Bronowski block".

For a new cultivar to be registered by the Western Canada Canola/Rapeseed Recommending Committee (WCC/RRC) the glucosinolate content must not exceed 12 μmoles gram^{-1} of seed meal or must be lower than the mean of the check cultivars glucosinolate content (Canola Council of Canada, 2006). Current levels of glucosinolates in oilseed rape meal are not considered to have any impact on livestock (Clandinin *et al.*, 1986).

2.2.5 Erucic Acid Concentration

The fatty acid composition of the seed oil is as important economically as the concentration of seed oil. Oilseed rape oil is comprised of triglycerides with a glycerol backbone and three esterfied fatty acid chains. The fatty acid chains are constructed from carbon atoms and vary in length from 12 to 24 carbons long. The degree of saturation of the chains varies between different oilseed rape genotypes. The structure of fatty acids is

designated (carbon number):(number of double bonds). For example erucic acid is a 22:1 fatty acid. This means that there are 22 carbon atoms and 1 double bond.

Fatty acids with no double bonds are referred to as saturated. When double bonds are incorporated, the fatty acids are referred to as unsaturated. Mono-unsaturated fatty acids are fatty acid chains with a single double bond and fatty acid chains with more than one double bond within the chain are referred to as poly-unsaturated. The degree of saturation and the length of the fatty acid chain determines the viscosity of the oil. Short fatty acid chains with multiple double bonds will be much less viscous than a long fatty acid chain with no double bonds.

Table 2.1: Percent fatty acid composition of Canadian oils (Downey, 1990)

Fatty Acid	Formula	Oilseed Rape (HEAR)	Oilseed Rape (Canola)
Palmitic	C16:0	4.0%	4.7%
Steric	C18:0	1.5%	1.8%
Oleic	C18:1	17.0%	63.0%
Linoleic	C18:2	13.0%	20.0%
Linolenic	C18:3	9.0%	8.6%
Eicosenoic	C20:1	14.5%	1.9%
Erucic	C22:1	41.0%	0.0%

Erucic acid (22:1) biosynthesis involves a two-step chain elongation, with the addition of a two carbon fragment to oleic acid (C18:1) which forms eicosenoic acid (C20:1). Another two carbon fragment is added to the eicosenoic acid to form erucic acid (C22:1) (Jonsson, 1977). Canola cultivars which are low in erucic acid have a block in

the oil biosynthesis pathway that reduces elongation of the fatty acid chain after oleic acid to very low levels (< 2%) (Figure 2.3).

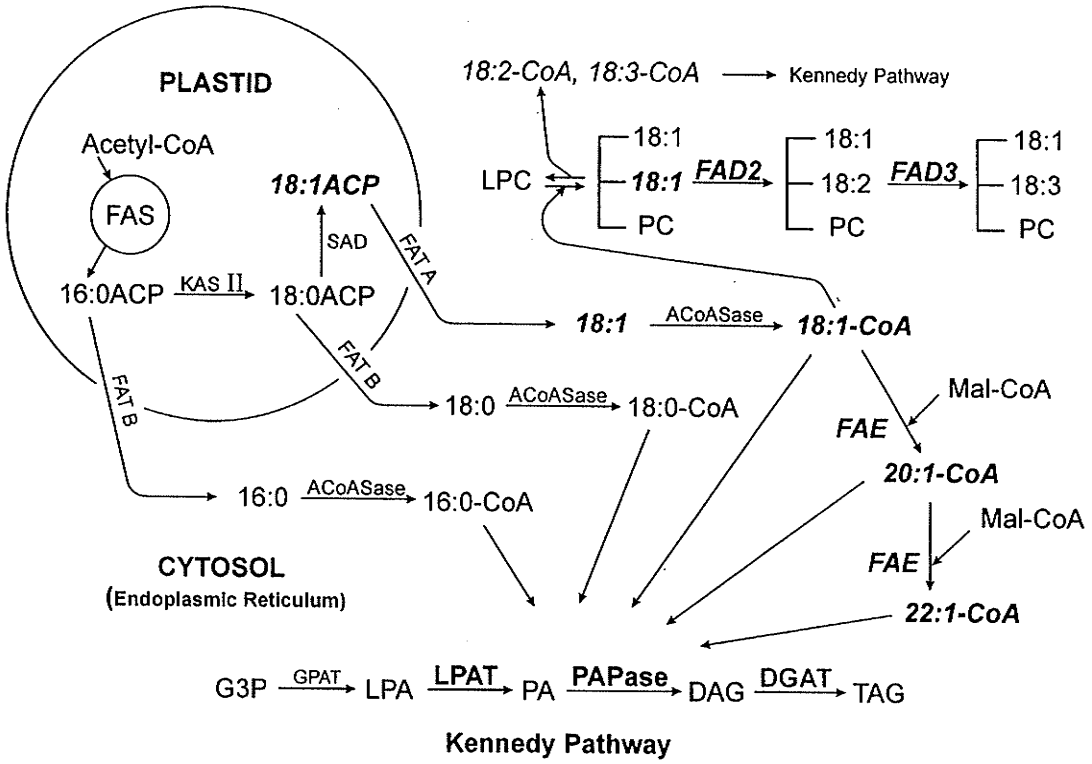

Figure 2.3: Oilseed rape lipid biosynthesis pathway (Taylor, 2003)

To date, no *Brassica* genotype has been identified with greater than 63% erucic acid concentration in the seed oil. A theoretical maximum of 66% is thought to be from physical limitations of only placing the erucic acid chain at positions Sn-1 and Sn-2 of the triglyceride glycerol molecule and not at the Sn-2 position during synthesis within the chloroplast (Tallent, 1972; Calhoun and Crane, 1975).

Brassica napus erucic acid biosynthesis is controlled multiple alleles at two gene loci with additive effects (Grami and Stefansson, 1977a; Harvey and Downey, 1964).

The alleles e, E^a, E^b, E^c, and E^d, at each loci contribute <1%, 10%, 15%, 30%, and 3.5% respectively (Siebel and Pauls, 1989). Selection of these alleles can result in erucic acid concentrations from less than 1 % to more than 60 % (Krzymanski and Downey, 1969).

2.3 Heterosis

A hybrid is the combination of two compatible parental lines which when crossed together may produce a superior plant (Bernardo, 2002). Some parental combinations will produce a hybrid which is more vigorous than the parents and will tend to produce more seed yield than the parents. This phenomenon known as hybrid vigor was named heterosis by Shull in 1914 (Shull, 1948). Shull was also the first to propose methods of exploiting heterosis for cultivar development (Shull, 1909). Although the exact mechanisms which result in heterosis are not fully understood, two main theories have been widely equally accepted.

2.3.1 Dominance Hypothesis

The complete dominance theory, originally proposed by Davenport (1908), Bruce (1910) and Keeble and Pellew (1910), states that heterosis is the result in the masking of unfavorable recessive alleles in the heterozygote (Bernardo, 2002). Mathematical formulas derived by Bruce in 1910 demonstrated that the hybrid family tended to have a lower proportion of recessive elements than the parental lines and assumed that dominance was positively correlated with vigor. Bruce concluded that the crossing of

two pure breeding lines results in a hybrid with a higher mean vigor than that of the parent breeds (1910).

The main objection to this hypothesis has been that if the proportion of dominant alleles controls hybrid vigor, then it should be possible to find a recombinant line in the F_2 population that performs equally well as the F_1 (Shull, 1911; East and Hayes, 1912). The second objection to this hypothesis is that traits measured in the F_2 population should be asymmetrical due to the 3:1 segregation ratio at each locus (Emerson and East, 1913; Jones, 1917; Bernardo, 2002). Both of these objections could be disregarded if a large number of loci are involved and also if linkage is involved (Jones, 1917; Bernardo, 2002).

2.3.2 Overdominance Hypothesis

Shull (1908) and East (1908) first suggested the overdominance hypothesis which states that heterosis is due to the superiority of the heterozygote over either homozygote (Bernardo, 2002). The hypothesis was later supported by Hull (1945). Linkage and multiple loci are not required for this hypothesis to be accepted as true.

2.3.3 General and Specific Combining Ability

Evaluating the contribution of an inbred line to a hybrid's performance can be difficult. Two measurements that aid in determining the contribution of an inbred line to a hybrid are general combining ability (GCA) and specific combining ability (SCA). General combining ability (GCA) is the average contribution that an inbred line makes in a series of pair-wise combinations while specific combining ability (SCA) is the average

contribution an inbred line makes to a specific pair-wise combination (Poehlman and Sleper, 1995). GCA evaluates the additive portion of genetic effects and SCA evaluates the non-additive portion of genetics effects (Poehlman and Sleper, 1995).

To calculate combining abilities, inbred lines are chosen and crossed to produce F_1 generation hybrids in every possible combination (diallel mating). Incomplete mating designs can be used, however, full crossing designs are desired. The hybrids are grown in field trials along with inbred lines and selected traits are evaluated. If five inbred lines (A, B, C, D, and E) were used to create hybrids, and A combined with B, C, D, and E better than any other inbred line, A would likely have high GCA. The inbred line which only combines well with another inbred line would likely have high SCA. High SCA genotypes depend on favorable genes that complement each other. Genotypes from distantly related populations will tend to combine to produce high yielding hybrids (Poehlman and Sleper, 1995).

Quite often breeders will have a large number of inbred lines to screen as potential parents for hybrid systems. If 50 lines were to be evaluated as possible parents for hybrids, the number of single-cross combinations (half diallel mating) is 1225. The number of crosses becomes difficult to manage when inbred lines are added. Testcrosses were introduced to help breeders quickly evaluate potential inbred lines. Heterogeneous genotypes that were known to be good combiners were crossed to potential inbred lines. If these lines produced high yielding F_1 populations, single crosses were carried out to determine the best specific combinations (Hallauer and Miranda, 1985)

2.3.4 Mid- and High-Parent Heterosis

Measuring heterosis is important to properly evaluating hybrids. Ideally a hybrid will produce a higher seed yield than the best parent line. The increased production of the hybrid over the best parent is referred to as high-parent heterosis. Another measurement used in evaluating hybrid performance is mid-parent heterosis. To determine mid-parent heterosis, seed yield of the hybrid is compared to the average seed yield of the two parent lines. High-parent heterosis found in spring oilseed rape for seed yield has been approximately 40 to 60 percent (Sernyk and Stefansson, 1983; Brandle and McVetty, 1989).

2.3.5 Commercial Heterosis

For a hybrid cultivar to be commercially viable, it is imperative that the seed yield advantage of the hybrid be much greater than the currently produced OP cultivar (Pandey and Zehr, 1999). To determine if a hybrid cross may be economically justified, the hybrid cross is compared to the current commercial OP cultivar (Pandey and Zehr, 1999). Hybrids which have a high positive commercial heterosis would be ideal to further develop.

2.4 Breeding Methods

2.4.1 Background

The breeding methods utilized by a breeder are heavily dependent on the crop type and whether the crop is self-pollinated or cross-pollinated. Mean outcrossing rates for *Brassica napus* have been shown to be from approximately 4.0 % on a plot-to-plot

basis and 21.0 % on a plant-to-plant basis (Cuthbert and McVetty, 2001). This range in outcrossing rates allows breeders to breed *B. napus* as a self or cross-pollinated crop with the most common breeding methods being pedigree breeding and hybrid breeding.

2.4.2 Pedigree Breeding

Pedigree breeding is the classical selection method used in plant breeding. This method is best described as a selection within an F_2 population produced from a planned cross of two genotypes (Hallauer and Miranda, 1985). These two genotypes will be from genetically diverse backgrounds, each with traits that would be desirable to combine into a single line.

Summer type oilseed rape cultivars or lines are normally crossed using hand emasculation techniques to produce F_1 seed. The time from planting to when a plant flowers and is ready to be crossed is approximately six weeks. Flowering can last from two to three weeks. After crossing is complete, any uncrossed branches are removed and crossed siliques are allowed to ripen. Approximately fifty F_1 seeds are grown in the greenhouse and each plant is covered with a glycine bag during flowering to ensure only self-pollination occurs. Seed is harvested for each F_1 plant. The F_2 seed from each F_1 plant is often seeded in short rows in the field. The F_2 seed could also be seeded in pots in the greenhouse again to evaluate single plants. Superior single plants are hand threshed often screened for seed quality components. Selected single plants are seeded as F_3 families. Traits such as seedling vigor, days to flower, plant height, days to maturity and pre-harvest lodging are measured throughout the growing season. This breeding cycle will continue until the F_6 generation, and will have produced up to fifty families.

Records of the identity of each plant or family and measured traits are maintained throughout each generation.

Preliminary yield trials will be seeded with the F_7 seed as well as disease nurseries. These trials will be grown at a single location with multiple replications. Agronomics and disease resistance will be measured throughout the growing season. Preliminary yield trials are harvested at maturity. Seed from yield trials will be screened for seed quality components such as oil, protein and glucosinolate concentrations. Seed from selected lines is combined from the replicates for use in advanced yield trials. Replicated advanced yield trials are planted in areas that represent the target growing regions for the final variety. Agronomics are again measured on the families throughout the growing season and the harvested seed is screened for seed quality components. Once families are selected for superior agronomics and seed quality traits, they are entered into the first and second years of official registration tests. Lines which perform well in registration tests are supported for registration and used for pedigreed seed production. A commercially produced cultivar can take up to twelve years to produce. Figure 2.4 depicts the flow of material in a pedigree selection breeding program.

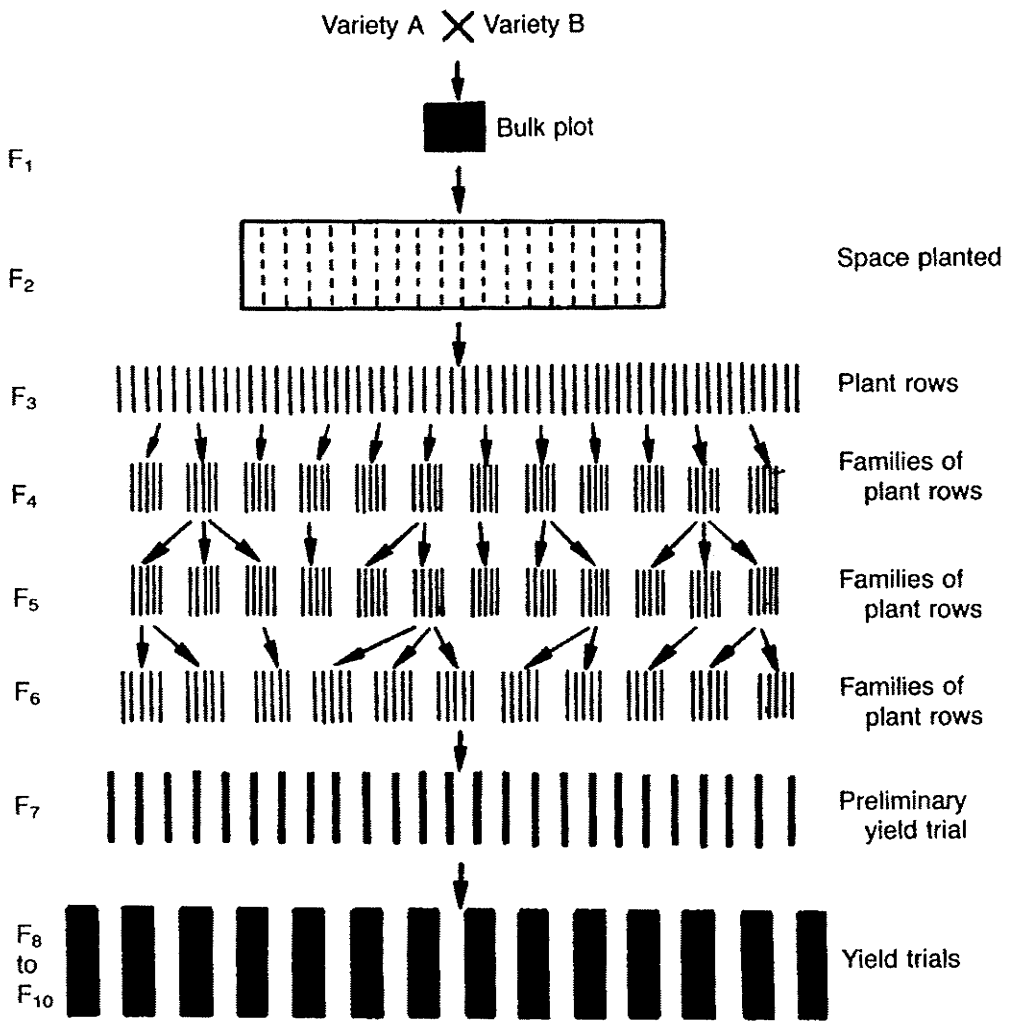

Figure 2.4: Pedigree selection breeding method (Poehlman and Sleper, 1995)

To reduce the time required to produce a commercially grown cultivar, breeders will often use winter nurseries for spring type material. Using winter nurseries can reduce the total time to approximately eight years by allowing two growing seasons per year. Pedigree selection breeding is a time consuming method, however, the costs are usually quite manageable for a breeding company or organization. Another advantage is the breeder will be able to evaluate families in a range of environments to allow selection of superior plants.

2.4.3 Hybrid Breeding

Unlike pedigree breeding where a breeder makes a cross between two lines, each with desired traits and grows the progeny of the cross for up to ten generations, hybrid breeding involves a cross between two compatible parents with the progeny grown by producers. Although this timeline seems much faster, significant effort is invested in creating the optimal female and male inbred parents. Shull in 1909 was the first to introduce breeding methods to exploit heterosis potential in maize (Shull, 1909). These methods resulted in the rapid expansion of the hybrid seed development for maize.

Parent selection is imperative in creating superior performing hybrids. To achieve maximum high-parent and commercial heterosis, genetically diverse inbred parents should be used in hybrid testing. Crossing similar pedigree lines will result in hybrids that perform, at best, equally well or poorer than the parents (Brandle and McVetty, 1989).

The production of large quantities of hybrid seed is the challenge of the industry. Controlling the male fertility of the female lines is required to ensure the desired cross occurs without the female selfing. Emasculation can be done by hand, or by genetics or chemical hybridizing methods (Simmonds, 1979). Hand emasculation of the anthers from rapeseed flowers on the female plant can become very tedious when producing large quantities of seed, however, for preliminary assessment of hybrid crosses which require small quantities of seed this method is extremely efficient. Once preliminary hybrid testing is complete and advanced inbred lines have been identified, a sterility system can be incorporated. Using sterility systems allows fast and efficient hybrid

production with minimal labour. Two widely used sterility systems are cytoplasmic male sterility and genic male sterility.

Cytoplasmic male sterility (CMS) involves both nuclear and cytoplasmic genes while genic male sterility (GMS) only involves nuclear genes. The CMS exploits the interaction between two cytoplasms (fertile and sterile) and usually a single dominant nuclear restorer gene or allele (McVetty, 1998). The male sterile A-line (female line) will have a sterile cytoplasm (*S*) and homozygous recessive at the nuclear loci *(rr)*. The male fertile R-line (restorer line) will have a fertile cytoplasm (*N*) and homozygous dominant at the nuclear loci *(RR)*. The male fertile B-line (maintainer line) will have a fertile cytoplasm (*N*) and homozygous recessive nuclear gene *(rr)*. These lines when crossed-pollinated will either maintain the female parent or produce male fertility restored hybrid seed which would be sold to producers (Figure 2.5).

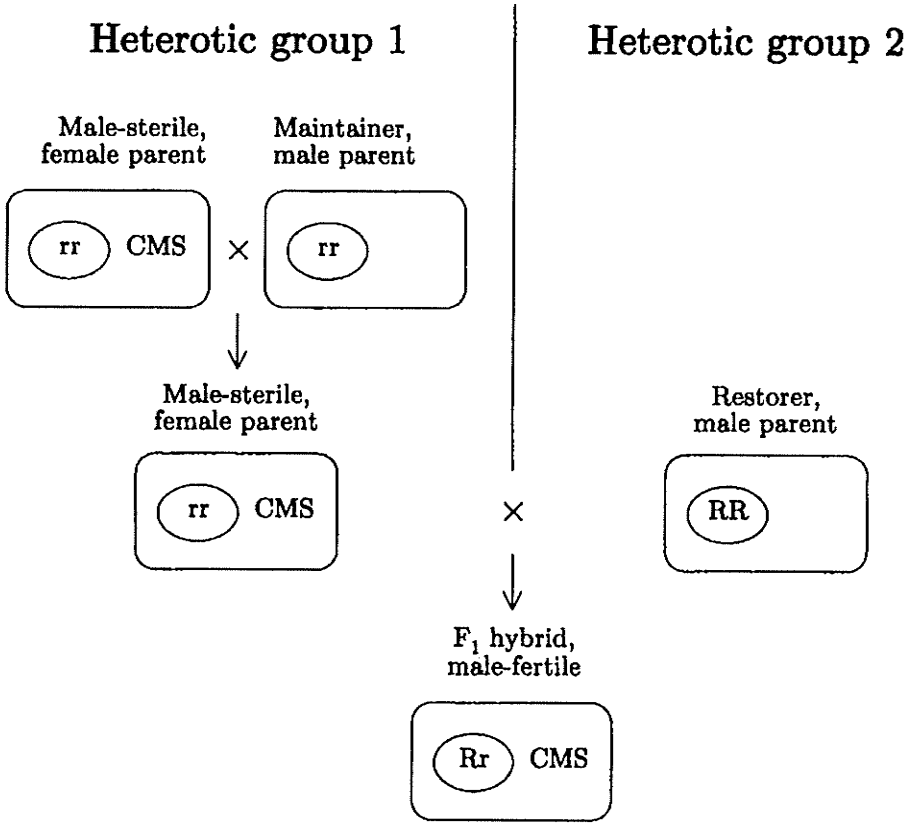

Figure 2.5: Hybrid seed production using a cytoplasmic male sterility system (Bernardo, 2002).

The main difference between cytoplasmic male sterility and genic male sterility is the lack of cytoplasmic effects on sterility. The GMS system relies on a single dominant gene to control fertility. The major drawback of this system is the inability to produce a pure breeding sterile female line. To be sterile, the plant must be homozygous recessive for the sterility gene (*rr*). Fertile plants must be removed from hybrid seed production fields by either manual removal or by exploiting a herbicide tolerance system (dominant herbicide tolerance allele tightly linked to the dominant fertility allele). The highest proportion of fertile to sterile plants that can be produced is one to one based on a test cross of a fertile heterozygote and sterile homozygous recessive (Sawhney, 1998).

The registration procedure for hybrids is very similar to open-pollinated populations. Once a company has demonstrated that a hybrid meets set agronomic and quality standards, it will be granted registration by the Western Canada Canola/Rapeseed Recommending Committee (WCC/RRC) (Canola Council of Canada, 2006).

To fulfill commercial production demands, large quantities of hybrid seed are produced from parents with a pollination control system incorporated.

3.0 Materials and Methods

3.1 Development of Hybrid Lines

3.1.1 Genetic Material Selection

The majority of spring HEAR cultivar development has occurred at the University of Manitoba (UM) with limited breeding effort in other companies. Seven UM HEAR cultivars or strains were selected on the basis of diverse pedigrees as well as superior agronomics and seed quality (Table 3.1). Five proprietary EU produced HEAR strains were also available for use (Table 3.1).

Table 3.1: Selected HEAR cultivars/strains and breeding origin for parents used in hybrid crosses

HEAR cultivar/strain	Breeding Origin
Castor	Canada
MillenniUM01	Canada
MillenniUM03	Canada
HR200	Canada
HR102	Canada
RRHR102 (glyphosate tolerant)	Canada
HR199	Canada
EU HEAR 1	EU
EU HEAR 2	EU
EU HEAR 3	EU
EU HEAR 4	EU
EU HEAR 5	EU

3.1.2 Crossing Scheme

The twelve genetically diverse HEAR cultivars or strains were initially arranged into a half diallel crossing scheme. To reduce the labour and greenhouse/growth room resources required to produce quantities of hybrid seed, cultivars or strains with a similar pedigree were not crossed. The removal of certain genetically similar cultivars or strains resulted in a topcross design (Figure 3.1). UM created material was used as females in crosses since the cytoplasmic effects were better understood. The topcross design was divided into three sets of crosses based on pedigree diversity and geographical diversity of the parents. The primary set of crosses were the UM x EU (international) crosses. These crosses were expected to produce the highest level of heterosis due to differences in pedigree and geographical diversity. The secondary set of crosses were the UM x UM (non-international) crosses. Most of the UM material was derived from a common ancestor and the level of pedigree diversity would not be as great as for the UM x EU crosses. Another non-international cross between EU x EU strains cross was also completed as they were the most genetically diverse EU strains.

Parent	Castor	MillenniUM 01	MillenniUM 03	HR200	HR102	RRHR102	HR199	EU HEAR 1	EU HEAR 2	EU HEAR 3	EU HEAR 4	EU HEAR 5
Castor				X	X			X	X	X		X
MillenniUM 01					X			X	X	X	X	X
MillenniUM 03				X	X			X	X	X	X	X
HR200					X	X	X	X	X	X	X	X
HR102						X	X	X	X	X	X	X
RRHR102							X	X	X	X	X	X
HR199								X	X	X	X	
EU HEAR 1												
EU HEAR 2												X
EU HEAR 3												
EU HEAR 4												
EU HEAR 5												

Figure 3.1: Hybrid HEAR topcross mating design

3.1.3 Greenhouse

During the 2003/2004 winter, the HEAR parental cultivars/strains were crossed to produce 45 F_1 populations. Due to the large number of hybrids that were to be produced, crossing was split into five groups of nine crosses each. Each crossing group consisted of seven females and three males. EU HEAR 1 and EU HEAR 3 were very late flowering lines, therefore the female parental strains were grown under cool temperatures (15° C day and 10° C night) in controlled environment rooms to prolong flowering periods and ensure flower synchronization of parents. Each female plant was pruned to remove all branches except the main raceme and two side branches. The female plant was then tagged with the cross information. Crossing was carried out in the greenhouses at the University of Manitoba using full hand emasculation of the female and bud pollination as the crossing technique.

Eight plants of each parental cultivar/strain were grown along with the female and male plants to produce selfed seed suitable for field trials. Before first flower, plants were covered with glycine bags to ensure cross pollination did not occur. When plants were mature, seed from each plant was hand harvested and packaged individually.

Due to thrip and/or aphid damage in the greenhouse during crossing, seed quantities produced for crosses 2, 3, 17, 26 and 34 were insufficient for more than one year of field trials (Appendix Table A5). These crosses were subsequently repeated during the winter of 2004/2005 to produce additional seed.

3.2 Hybridity Assessment

When producing hybrids, ensuring the hybridity of the seed lots is very important. With the introduction of single dominant herbicide tolerance genes, it has become much simpler to determine the hybridity of the hybrid seed lot. Hybrids which have a herbicide resistant male and a herbicide susceptible female, should be resistant to the herbicide. If the hybrid is not resistant, this may be due to the breakdown of the sterility system, outside pollen contamination or female self-pollination.

Spray-out testing for HR200xRRHR102 and HR102xRRHR102 hybrids was completed to assess hybridity. Three-hundred seedlings for each of these two crosses, HR200 x RRHR102 and HR102 x RRHR102, were sprayed along with 32 seedlings of the non-HT parent and 32 seedlings of the HT parent RRHR102 as checks. Seedlings were sprayed with Glyphosate at a rate of 1.2 l ha^{-1} at the three leaf stage and rated for either susceptibility (dead) or tolerance (alive) one week later.

3.3 Field Trials

3.3.1 Experimental Design

Field trials were arranged in an 8x8 lattice design with three replications grown at three locations in southern Manitoba in 2004 and 2005. The lattice design helps to reduce effects of soil heterogeneity by creating randomizations between replications that allows indirect comparisons of entries. Since the 8x8 lattice design requires 64 entries and only 57 hybrids and parental entries were produced, the Canadian parents were included in the design twice. Each micro-plot was one row by three meters long and

plots were spaced 80 cm apart to ensure that vigorous hybrids did not overgrow the adjacent the parental cultivars/strains. Field trials were planted at Thornhill, Portage la Prairie and Carman, MB during 2004 and 2005.

Plots were seeded with a Hege guided-belt cone seeder at a rate of 105 seeds per 3 meters for hybrids and 150 seeds per 3 meters for parents. Terbufos (5% granules) insecticide was banded 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.*). Seeding discs were set to place the seed at a depth of 3 cm.

During the 2004 growing season, planting was delayed to the end of May and beginning of June due to a heavy snowfall on May 10th and subsequent cool wet soil conditions. Carman was seeded May 28, Portage la Prairie was seeded June 3 and Thornhill was seeded June 9. Heavy rainfall shortly after planting caused soil compaction and very poor emergence at Carman. In contrast, seedling emergence in Portage la Prairie and Thornhill was excellent.

The field trials at Carman, Portage la Prairie and Thornhill in 2005 were all seeded on May 30. Adequate moisture at time of planting helped a quick, uniform emergence at Portage la Prairie and Thornhill. Excessive soil moisture at Carman again hindered emergence.

Granular fertilizer, 20-0-0-14, NPKS, was applied by broadcast spreader to Thornhill in 2004 and Carman in 2004 and 2005 at a rate of 111 kg ha^{-1}. Fertilizer was applied in the previous fall in Portage la Prairie and Thornhill 2005.

The Carman 2005 field trial was sprayed with a herbicide mix of Poast Ultra, Lontrel, and Muster on July 26 to control grassy and broadleaf weeds. The herbicide

mixture was applied using a bicycle wheel plot sprayer equipped with fan nozzles delivering 108 L ha^{-1} at 275 KPa. Manual weed removal was completed as required for the remaining field trials.

Moisture levels were higher than average in 2004 and 2005 for southern Manitoba. Total rainfall from May to October 2004 was approximately 371.8 mm and total snowfall in May 2004 was approximately 50.4 mm (Environment Canada, 2006). Total rainfall from May to October 2005 was higher than 2004 at approximately 524.6 mm. In June 2005, excessive rainfall (over 180 mm) caused flooding throughout southern Manitoba (Environment Canada, 2006). Rainfall from July to October 2005 was lower than the same period in 2004. Summer temperatures during 2004 were very cool and were much lower than average when compared to 2005. Mean temperature during May to October 2004 was approximately 12.4 °C and the mean 2005 temperature for the same period was approximately 14.3 °C (Environment Canada, 2006). The largest differences in temperatures between the two growing seasons were observed from May to August. September and October were similar in temperature between 2004 and 2005.

3.3.2 Agronomic Traits

Selected agronomic traits were measured on hybrid and parent strains at all locations. These agronomic traits included: vigor, number of days to flower, plant height, number of days to maturity, preharvest lodging and seed yield.

Vigor was measured on a scale from 1 to 5 and was measured at the 4 to 5 leaf stage. Rows which consisted of large plants covering a large ground area were rated as 5 while rows which consisted of small plants were rated as 1.

Number of days to flower from planting was measured when 50 percent of the plants in a row began to flower. The range of flowering times required measurements to be taken over several weeks.

Plant height was measured after flowering was completed. Five plants were randomly selected within each row and the height from the soil to the top of the plant was measured in centimeters using a two meter long measuring stick.

Maturity of each row was measured as the number of days from planting until the row was physiologically mature. A plant was said to be physiologically mature when the seeds in the middle of the main raceme showed approximately 30 to 40 % colour change to brown or black.

Lodging was measured at physiological maturity on a scale from 1 to 5. Plants that stood erect at maturity were scored as 1 while plants that lay on the ground were scored as 5. Intermediate scores were based on the angle of the row in relation to the ground.

At maturity, the entire above-ground plant material of each 3 m row was cut down by hand and tied together with sisal string. The bundle of plants from each row was stooked in the field and left until adequately dry for threshing by stationary thresher. Seed collected by the thresher was directed into paper bags. These bags of seed were placed on warm air driers at the University of Manitoba for approximately two weeks to adequately dry the seed.

Seed yield per row was measured on dry seed in grams. Based on the growing area of 2.4 m^2 for each row, seed yield was then converted into kg ha^{-1}.

3.3.3 Seed Quality Traits

Selected quality traits were measured on the seed produced from field trials in 2004 and 2005. Quality traits measured were: protein, oil, glucosinolate concentrations in the seed and erucic acid concentration in the oil.

Oil, protein and glucosinolate concentrations in the seed were measured using near-infrared reflectance (NIR) technology, using a Foss 6500 system (Daun *et al.*, 1994; DeClercq, 2005). Values for each measurement were adjusted to zero percent moisture.

The sum of oil and protein concentrations was completed by adding the NIR results for seed oil concentration and seed protein concentration. Protein content of the meal was determined by comparing the seed protein concentration to the total seed minus oil concentration.

Erucic acid concentration in the oil was determined by the International Organization for Standardization method reference number ISO 5508:1990 (E), Animal and vegetable fats and oils-Analysis by gas chromatography of methyl esters of fatty acids (DeClercq, 2005).

3.4 Statistical Analysis

Agronomic and quality measurements from the field trials in 2004 and 2005 were entered into spreadsheet files for use with Agrobase 97 software (Agrobase, 1997). Trials were analyzed separately as both a lattice design and a randomized complete block design (RCBD). Lattice designs can not be combined unless identical randomizations are

used for each location, therefore trials were combined as environments and analyzed as RCBD (Cochran and Cox, 1957). The model used was:

$$Y_{ikj} = \mu + \text{Entry}_i + \text{Rep}_k + \text{Environment}_j + e_{ikj}$$ where:

Where:

Y_{ikj} = trait

μ = population mean

Entry_i = 64 entries for each environment

Rep_k = replications within a environment

Environment_j = replications of the basic design

e_{ikj} = residual

Fatty acid analysis is a laborious and costly to conduct and often very little variation between replications is observed therefore a seed sample from a single replicate for each environment was tested for erucic acid concentration. The model used for erucic acid analysis is as follows:

$$Y_{ij} = \mu + \text{Entry}_i + \text{Environment}_{ij} + e_{ij}$$ where:

Where:

Y_{ij} = trait

μ = population mean

$Entry_i$ = 64 entries for each environment

$Environment_j$ = replications of the basic design

e_{ij} = residual

To determine if the mean hybrid performance was significantly different from the mean parent cultivar/strain performance, an unpaired t-test was calculated for each trait. The critical t-statistic used for these tests was 2.00 at 55 degrees of freedom and at 5% probability. Sub-means for the international hybrids (UM x EU) and the non-international hybrids (UM x UM and EU x EU) for each agronomic and seed quality trait were tested with a t-test to determine if there were any significant differences. The critical t-statistic for these tests was 2.01 at 43 degrees of freedom and at 5% probability.

The formula used was:

$$t = \frac{\overline{X_{hybrid}} - \overline{X_{parent}}}{S.E.D.}$$

Where:

t = test statistic

X_{hybrid} = overall mean of the hybrid combinations

X_{parent} = overall mean of the parent cultivars/strains

S.E.D. = standard error of the difference between two mean values

3.4.1 Heterosis Calculations

Based on the agronomic and seed quality traits measured, three heterosis estimates (mid-parent, high-parent and commercial) were calculated. The calculation of the mid-parent (MP) heterosis estimate used the following formula:

$$\frac{\overline{F_1} - \overline{MP}}{\overline{MP}} \times 100 = \% \text{ MP Heterosis}$$

Where:

F_1 = the mean of the hybrid combination

MP = mean of the two parental cultivars/strains of the F_1 hybrid combination

The calculation of the high-parent (HP) heterosis estimate used the following formula:

$$\frac{\overline{F_1} - \overline{HP}}{\overline{HP}} \times 100 = \% \text{ HP Heterosis}$$

Where:

F_1 = the mean of the hybrid combination

HP = mean of the better of the two parental cultivars/strains of the F_1 hybrid combination

The calculation of the commercial heterosis estimate used the following formula:

$$\frac{\overline{F_1} - \overline{Mill03}}{\overline{Mill03}} \times 100 = \%\ \text{Commercial Heterosis}$$

Where:

F_1 = the mean of the hybrid combination

Mill03 = mean of the cultivar "MillenniUM03"

3.4.2 Specific and General Combining Ability Calculations

Estimates of specific and general combining abilities were determined by using methods outlined by Simmonds (1979). The first step was to arrange the means of the parents and hybrids into the diallel mating design and calculate row and column totals for the crosses each parent was involved (Figure 3.2).

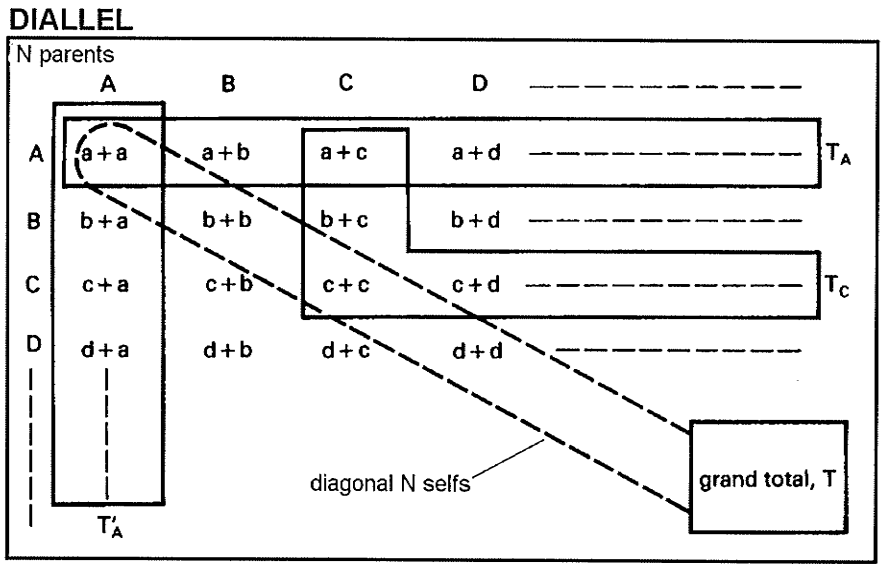

Figure 3.2: Mating patterns for estimation of combining abilities (Simmonds, 1979)

The next step was to calculate the GCA estimate for the parent. This was determined by dividing the parent total (T_A) by the number of crosses the parent was

involved and comparing this mean to the overall mean hybrid performance. Using the GCA estimates for each parent, expected means for each hybrid was calculated using the following formula:

$$X_{AB} = \tilde{X} + GCA_A + GCA_B + SCA_{AB}$$

Where:

X_{AB} = Observed hybrid performance

$\tilde{X}$ = Overall hybrid mean performance

GCA_A = General combining ability estimate for parent A

GCA_B = General combining ability estimate for parent B

SCA_{AB} = Specific combining ability estimate for hybrid AB

A regression of the expected (independent variable) and observed (dependent variable) hybrid means was calculated. The residual of each hybrid was the specific combining ability estimate for each hybrid.

4.0 Results and Discussion

4.1 Greenhouse Seed Production

Sufficient F1 seed was produced for all 45 hybrids to grow three locations of trials per year for two consecutive years 2004 and 2005 (Appendix Table A1, Appendix Table A2, Appendix Table A3, Appendix Table A4, and Appendix Table A5).

4.2 Hybridity Assessment

Two crosses involved a glyphosate tolerant (RRHR102) HEAR parent crossed to a conventional HEAR parent. For these crosses, the hybridity of the hand-crossed seed lots could be determined via herbicide tolerance proportions in F_1 seed lots. The hybridity levels in the hybrid seed for these two hand-crossed seed lots were very high (98.7 to 100%). The production of hand-crossed hybrid seed was very successful. It is presumed that the hybridity of all other hand-crossed hybrid seed lots was equally high.

4.3 Hybrid and Parent Strain Agronomic Trait Comparisons

Agronomic data from Thornhill and Portage la Prairie, Manitoba from 2004 and 2005 was analyzed using a randomized complete block design. Both the Carman, Manitoba 2004 and Carman, Manitoba 2005 trials displayed poor stand establishment due to soil crusting, missing plots due to flooding and substantial insect damage therefore they were harvested but not included in the agronomic trait analyses.

4.3.1 Seedling Vigor

After emergence, differences between hybrids and parents were easily distinguishable due to the higher vigor of the hybrids. Hybrids had a mean vigor rating of 4.1 for vigor with a maximum of 4.7 and a minimum of 3.4. Parents had a significantly lower mean rating than hybrids (3.4) with a maximum of 3.8 observed and a minimum of 3.3. Sernyk and Stefansson (1983) also observed higher seedling vigor for the hybrids. Differences between the UM x EU hybrids and UM x UM / EU x EU hybrids were not significant (Table 4.3.1).

In general, the UM x EU #3 hybrids had the highest seedling vigor, with vigor ratings of 4.0 or higher. Vigor displayed significant mid-parent, high-parent and commercial heterosis for most hybrids. UM x EU #4 hybrids had relatively low vigor. UM x UM hybrids had intermediate seedling vigor similar to the UM x EU #2 and EU #2 x EU #5 hybrids. Vigor was significantly correlated with a number of traits such as lodging, plant height, seed yield, seed oil concentration and seed protein concentration which indicated that high vigor hybrids tended be superior performing (Appendix Table B1).

EU # 3 was the highest general combiner parent with a GCA of 0.1 (Table 4.3.2). A positive GCA for seedling vigor indicated that a parent tended to contribute relatively more to a hybrid while a negative GCA indicated that a parent was detrimental to a hybrids seedling vigor. The lowest GCA parent was Castor with a GCA of -0.3 (Table 4.3.2). Specific combining abilities ranged from -0.4 to 0.6 (Table 4.3.3).

Table 4.3.1: Vigor and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Vigor (1-low to 5-high)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	3.8	11.1	7.1	8.4
2	MillenniUM01 x EU HEAR 1	4.3	20.7 *	20.1 *	22.8 *
3	MillenniUM03 x EU HEAR 1	4.5	29.3 *	28.6 *	30.1 *
4	HR200 x EU HEAR 1	3.8	13.5	9.4	10.7
5	HR102 x EU HEAR 1	4.3	21.5 *	19.4 *	25.1 *
6	RRHR102 x EU HEAR 1	4.1	15.9 *	15.3 *	17.9 *
7	HR199 x EU HEAR 1	3.8	10.3	7.1	8.4
8	Castor x EU HEAR 2	4.0	14.3 *	6.7	15.6 *
9	MillenniUM01 x EU HEAR 2	3.9	7.5	4.5	13.3
10	MillenniUM03 x EU HEAR 2	4.2	15.7 *	11.2	20.5 *
11	HR200 x EU HEAR 2	4.3	21.4 *	13.3 *	22.8 *
12	HR102 x EU HEAR 2	4.2	13.1 *	11.2	20.5 *
13	RRHR102 x EU HEAR 2	3.9	7.5	4.5	13.3
14	HR199 x EU HEAR 2	4.7	32.5 *	24.5 *	35.0 *
15	Castor x EU HEAR 3	4.6	40.9 *	40.9 *	32.4 *
16	MillenniUM01 x EU HEAR 3	4.3	25.2 *	20.1 *	22.8 *
17	MillenniUM03 x EU HEAR 3	4.4	31.7 *	27.7 *	27.7 *
18	HR200 x EU HEAR 3	4.1	25.5 *	25.5 *	17.9 *
19	HR102 x EU HEAR 3	4.2	21.3 *	15.0 *	20.5 *
20	RRHR102 x EU HEAR 3	4.2	22.8 *	17.8 *	20.5 *
21	HR199 x EU HEAR 3	4.7	42.6 *	41.5 *	35.0 *
22	MillenniUM01 x EU HEAR 4	3.5	0.6	-1.1	1.2
23	MillenniUM03 x EU HEAR 4	4.2	21.2 *	20.5 *	20.5 *
24	HR200 x EU HEAR 4	3.8	12.4	9.6	8.4
25	HR102 x EU HEAR 4	4.3	20.7 *	17.2 *	22.8 *
26	RRHR102 x EU HEAR 4	3.8	7.8	5.9	8.4
27	HR199 x EU HEAR 4	3.9	16.7 *	14.6 *	13.3
28	Castor x EU HEAR 5	3.5	4.9	2.3	1.2
29	MillenniUM01 x EU HEAR 5	4.1	17.2 *	15.3 *	17.9 *
30	MillenniUM03 x EU HEAR 5	4.3	23.5 *	22.8 *	22.8 *
31	HR200 x EU HEAR 5	3.8	14.8 *	12.0	10.7
32	HR102 x EU HEAR 5	4.1	15.8 *	12.6 *	17.9 *
33	RRHR102 x EU HEAR 5	4.3	24.4 *	33.2 *	25.1 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	3.4	5.2	5.2	-1.2
35	Castor x HR102	3.8	11.4	5.7	10.7
36	MillenniUM01 x HR102	4.2	16.4 *	15.0 *	20.5 *
37	MillenniUM03 x HR200	4.0	19.2 *	15.6 *	15.6 *
38	MillenniUM03 x HR102	4.0	12.9	10.3	15.6 *
39	HR200 x HR102	4.3	26.0 *	19.4 *	25.1 *
40	HR200 x RRHR102	4.2	22.8 *	17.8 *	20.5 *
41	HR200 x HR199	3.9	19.7 *	18.8 *	13.3
42	HR102 x RRHR102	4.3	20.9 *	19.4 *	25.1 *
43	HR102 x HR199	3.9	13.2	8.1	13.3
44	RRHR102 x HR199	3.8	12.0	8.2	10.7
45	EU HEAR 2 x EU HEAR 5	4.3	20.8 *	15.5 *	25.1 *
	UM x EU Mean	4.1 a	18.9	16.3	18.5
	UM x UM / EU x EU Mean	4.0 a	16.7	13.3	16.2
	Overall Hybrid Mean	4.1 s	18.3	15.5	17.9
	Max	4.7	42.6	41.5	35.0
	Min	3.4	0.6	-1.1	-1.2
Parents					
46	EU HEAR 1	3.5			
47	EU HEAR 2	3.8			
48	EU HEAR 3	3.3			
49	EU HEAR 4	3.4			
50	EU HEAR 5	3.4			
51	Castor	3.3			
52	MillenniUM01	3.5			
53	MillenniUM03	3.5			
54	HR200	3.3			
55	HR102	3.6			
56	RRHR102	3.5			
57	HR199	3.3			
	Overall Parent Mean	3.4 t			
	Max	3.8			
	Min	3.3			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

Table 4.3.2: General combining ability effects for selected agronomic traits measured from HEAR hybrids grown in four environments 2004 and 2005

Hybrid HEAR Parent	Vigor (1-low to 5-high)	Flower (d)	Maturity (d)	Lodging (1-erect to 5-flat)	Height (cm)	Yield (kg ha^{-1})
EU HEAR 1	-0.1	5.0	7.3	-0.8	16.3	348.2
EU HEAR 2	0.0	0.2	2.0	-0.1	3.2	102.4
EU HEAR 3	0.1	1.9	4.7	-0.6	12.9	322.6
EU HEAR 4	-0.3	-1.0	-2.5	0.5	-11.5	-648.8
EU HEAR 5	-0.1	-1.2	-3.5	0.2	-6.8	-364.9
Castor	-0.3	-0.2	-0.6	0.1	-3.2	-200.0
MillenniUM01	-0.1	-0.3	-0.5	0.3	-4.8	-277.6
MillenniUM03	0.0	-0.9	-0.5	0.2	-3.9	-61.2
HR200	-0.1	-0.1	-1.6	0.3	-6.2	-218.8
HR102	0.0	-0.6	-0.2	0.0	-1.9	53.8
RRHR102	-0.1	1.6	0.5	-0.2	6.6	-91.6
HR199	0.0	1.2	4.0	-0.4	6.7	164.8
Hybrid Mean	4.1	43.5	102.7	2.9	110.3	2328.0

Table 4.3.3: Specific combining ability effects for selected agronomic traits measured from HEAR hybrids grown in two environments during 2004 and 2005.

Cross #	Pedigree	Vigor (1-low to 5-high)	Flower (d)	Maturity (d)	Lodging (1-erect to 5-flat)	Height (cm)	Yield (kg ha^{-1})
1	Castor x EU HEAR 1	0.0	-0.1	4.5	-0.3	-0.3	196.0
2	MillenniUM01 x EU HEAR 1	0.2	1.1	5.4	-0.3	5.7	438.7
3	MillenniUM03 x EU HEAR 1	0.3	-0.7	3.3	-0.3	2.4	-32.5
4	HR200 x EU HEAR 1	-0.2	-0.7	3.2	0.1	1.6	440.7
5	HR102 x EU HEAR 1	0.1	-0.8	3.8	0.2	-2.6	19.5
6	RRHR102 x EU HEAR 1	0.1	0.7	4.7	-0.2	3.7	55.3
7	HR199 x EU HEAR 1	-0.4	1.6	5.7	-0.1	0.3	-52.6
8	Castor x EU HEAR 2	0.1	0.1	0.3	-0.1	2.0	-31.4
9	MillenniUM01 x EU HEAR 2	-0.2	0.1	0.3	-0.1	4.7	-52.3
10	MillenniUM03 x EU HEAR 2	-0.2	0.3	1.5	-0.4	2.2	-48.8
11	HR200 x EU HEAR 2	0.1	0.9	0.8	0.1	1.7	113.9
12	HR102 x EU HEAR 2	-0.1	0.4	2.6	-0.1	3.8	184.8
13	RRHR102 x EU HEAR 2	-0.2	0.7	3.3	0.0	0.1	-74.4
14	HR199 x EU HEAR 2	0.4	0.5	3.8	0.0	0.5	135.5
15	Castor x EU HEAR 3	0.6	-0.1	0.5	0.0	2.7	368.4
16	MillenniUM01 x EU HEAR 3	0.0	-0.5	0.9	0.3	-1.3	148.0
17	MillenniUM03 x EU HEAR 3	0.0	-0.6	0.5	0.0	-2.1	238.4
18	HR200 x EU HEAR 3	-0.1	-0.4	1.3	-0.1	0.0	205.2
19	HR102 x EU HEAR 3	-0.3	0.7	2.8	-0.2	4.5	286.6
20	RRHR102 x EU HEAR 3	-0.1	1.8	4.4	0.1	0.9	-77.8
21	HR199 x EU HEAR 3	0.3	-0.9	4.5	-0.2	2.1	11.7
22	MillenniUM01 x EU HEAR 4	-0.3	0.4	-3.4	-0.3	-0.9	-49.3
23	MillenniUM03 x EU HEAR 4	0.2	-0.4	-4.9	-0.1	4.1	361.5
24	HR200 x EU HEAR 4	0.0	0.9	-4.0	0.0	3.7	6.9
25	HR102 x EU HEAR 4	0.3	0.1	-5.4	-0.3	-0.1	84.8
26	RRHR102 x EU HEAR 4	0.0	0.6	-5.3	-0.1	1.2	322.3
27	HR199 x EU HEAR 4	0.0	-0.9	-5.1	0.3	-3.8	-125.9
28	Castor x EU HEAR 5	-0.3	0.9	-0.6	-0.2	3.9	81.2
29	MillenniUM01 x EU HEAR 5	0.1	0.1	-2.8	-0.2	-1.3	94.4
30	MillenniUM03 x EU HEAR 5	0.1	0.9	-1.2	-0.2	4.6	220.2
31	HR200 x EU HEAR 5	-0.1	0.7	-3.4	-0.2	0.4	5.1
32	HR102 x EU HEAR 5	-0.1	0.1	-2.1	-0.2	2.0	52.7
33	RRHR102 x EU HEAR 5	0.4	-1.0	-3.2	0.0	-0.4	106.2
34	Castor x HR200	-0.3	0.0	-1.8	0.4	-7.8	-609.4
35	Castor x HR102	-0.1	-0.8	-1.5	0.3	-5.3	-456.1
36	MillenniUM01 x HR102	0.0	-0.7	-1.0	0.3	-1.8	-112.6
37	MillenniUM03 x HR200	-0.1	-0.2	-1.7	0.2	2.0	-162.5
38	MillenniUM03 x HR102	-0.3	0.2	0.4	0.3	-2.6	-272.1
39	HR200 x HR102	0.2	0.0	-2.3	0.2	-0.5	-232.4
40	HR200 x RRHR102	0.3	-0.6	-2.8	0.0	-5.9	-310.1
41	HR200 x HR199	-0.1	-1.4	-2.5	0.2	-7.6	-264.7
42	HR102 x RRHR102	0.2	-1.0	-2.2	0.4	-6.3	-190.0
43	HR102 x HR199	-0.3	-1.4	-0.3	0.5	-7.2	-612.4
44	RRHR102 x HR199	-0.2	-1.6	-2.2	0.5	-7.1	-614.6
45	EU HEAR 2 x EU HEAR 5	0.2	0.6	1.3	-0.1	3.9	204.3

4.3.2 Days to Flower

HEAR hybrids on average flowered 43.5 days after planting, with a range from the earliest 41.2 days after planting and the latest 48.9 days after planting. The parent cultivars/strains had a significantly later mean than the hybrids (45.8 days) because EU #1 and EU #3 strains flowered on average 10 to 20 days later than all other strains. The range of parent flowering was from 42.1 to 63.1 days. International hybrids involving both UM and EU parents were significantly later than UM hybrids and EU hybrids (Table 4.3.4).

Mid-parent heterosis for days to flower for all of the UM x EU #1 and UM x EU #3 hybrids indicated that these hybrids were significantly earlier than the mean of their two parents. Three UM x UM hybrids and two UM x EU hybrids exhibited significant high-parent heterosis for days to first flower. Three UM x UM hybrids and three UM x EU hybrids exhibited significant commercial heterosis for early flowering. The current commercial cultivar, MillenniUM03, was very early to flower (42.9 days) which resulted in few hybrids demonstrating significantly high commercial heterosis. Grant and Beversdorf (1985) also found that *B. napus* hybrids tended to flower later than their parents. Days to flower was significantly correlated with many traits such as maturity, lodging, plant height, seed yield, seed oil concentration, seed protein concentration, sum of oil and protein concentrations, and erucic acid concentration (Appendix Table B1).

The best general combiner was EU #5 for advanced flowering with a GCA of 1.2 days while EU #1 was the poorest general combiner with a GCA of 5.0 days (Table 4.3.2). Hybrids using EU #5 as a parent flowered approximately 1.2 days earlier on

average while hybrids using EU #1 flowered approximately 5 days later on average. The specific combining abilities for all hybrids ranged from -1.6 to 1.8 (Table 4.3.3).

Table 4.3.4: Days to first flower and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Flower (d)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	46.2	-11.6 *	7.0	7.7
2	MillenniUM01 x EU HEAR 1	47.3	-9.1 *	10.5	10.4
3	MillenniUM03 x EU HEAR 1	45.2	-13.2 *	5.4	5.4
4	HR200 x EU HEAR 1	45.7	-13.0 *	4.3	6.5
5	HR102 x EU HEAR 1	45.3	-12.9 *	6.2	5.5
6	RRHR102 x EU HEAR 1	48.3	-10.2 *	4.4	12.5
7	HR199 x EU HEAR 1	48.9	-7.0 *	11.4	14.1
8	Castor x EU HEAR 2	43.0	-2.5 *	-0.4	0.3
9	MillenniUM01 x EU HEAR 2	42.9	-2.4 *	0.2	0.1
10	MillenniUM03 x EU HEAR 2	42.7	-3.0 *	-0.5	-0.5
11	HR200 x EU HEAR 2	43.8	-1.4	0.1	2.2
12	HR102 x EU HEAR 2	43.0	-1.9	0.9	0.3
13	RRHR102 x EU HEAR 2	44.9	-1.6	-0.4	4.8
14	HR199 x EU HEAR 2	44.3	-0.4	1.0	3.4
15	Castor x EU HEAR 3	44.1	-8.5 *	2.1	2.8
16	MillenniUM01 x EU HEAR 3	43.5	-9.4 *	1.6	1.5
17	MillenniUM03 x EU HEAR 3	43.0	-10.5 *	0.3	0.3
18	HR200 x EU HEAR 3	43.8	-9.6 *	0.1	2.2
19	HR102 x EU HEAR 3	44.6	-6.9 *	4.6	4.0
20	RRHR102 x EU HEAR 3	47.3	-4.9 *	2.3	10.2
21	HR199 x EU HEAR 3	44.3	-8.8 *	0.8	3.2
22	MillenniUM01 x EU HEAR 4	42.3	-1.7	-1.4	-1.5
23	MillenniUM03 x EU HEAR 4	41.2	-4.3 *	-4.0 *	-4.0 *
24	HR200 x EU HEAR 4	42.9	-1.3	-0.6	0.1
25	HR102 x EU HEAR 4	41.8	-2.5 *	-1.9	-2.4 *
26	RRHR102 x EU HEAR 4	43.9	-1.7	1.7	2.4
27	HR199 x EU HEAR 4	42.1	-3.3 *	-2.5 *	-1.9
28	Castor x EU HEAR 5	42.8	0.5	1.8	-0.1
29	MillenniUM01 x EU HEAR 5	41.9	-1.3	-0.4	-2.2 *
30	MillenniUM03 x EU HEAR 5	42.3	-0.3	0.6	-1.3
31	HR200 x EU HEAR 5	42.7	-0.6	1.4	-0.5
32	HR102 x EU HEAR 5	41.8	-1.4	-0.8	-2.6 *
33	RRHR102 x EU HEAR 5	42.2	-4.5 *	-2.3	-1.6
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	42.7	-1.9	-1.1	-0.5
35	Castor x HR102	41.6	-3.1 *	-2.5 *	-3.0 *
36	MillenniUM01 x HR102	41.5	-2.9 *	-2.6 *	-3.2 *
37	MillenniUM03 x HR200	42.0	-3.1 *	-2.0	-2.0
38	MillenniUM03 x HR102	42.1	-1.6	-1.3	-1.9
39	HR200 x HR102	42.4	-1.8	-0.5	-1.1
40	HR200 x RRHR102	43.4	-3.5 *	-0.8	1.3
41	HR200 x HR199	42.3	-3.6 *	-3.5 *	-1.5
42	HR102 x RRHR102	42.7	-3.9 *	0.1	-0.5
43	HR102 x HR199	41.9	-3.1 *	-1.7	-2.2 *
44	RRHR102 x HR199	43.3	-3.8 *	-1.3	1.1
45	EU HEAR 2 x EU HEAR 5	42.8	-1.9	1.6	-0.3
	UM x EU Mean	43.9 a	-5.2	1.6	2.5
	UM x UM / EU x EU Mean	42.4 b	-2.8	-1.3	-1.1
	Overall Hybrid Mean	43.5 s	-4.6	0.8	1.5
	Max	48.9	0.5	11.4	14.1
	Min	41.2	-13.2	-4.0	-4.0
Parents					
46	EU HEAR 1	61.3			
47	EU HEAR 2	45.1			
48	EU HEAR 3	53.2			
49	EU HEAR 4	43.2			
50	EU HEAR 5	42.1			
51	Castor	43.2			
52	MillenniUM01	42.8			
53	MillenniUM03	42.9			
54	HR200	43.8			
55	HR102	42.6			
56	RRHR102	46.2			
57	HR199	43.9			
	Overall Parent Mean	45.8 t			
	Max	61.3			
	Min	42.1			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.3.3 Days to Physiological Maturity

The parent cultivars had a wide range of maturities from 97.4 to 124.7 days while the HEAR hybrids had a narrower range of maturities from 97.5 to 110.1 days. Maturity had a strong positive correlation (0.84**) with days to flower (Appendix Table B1) which was also what Grant and Beversdorf reported in 1985. Maturity was also highly correlated with the same traits as days to flower (lodging, plant height, seed yield, seed oil concentration, seed protein concentration, sum of oil and protein concentrations, and erucic acid concentration) (Appendix Table B1). EU #1 and EU #3 matured approximately 20 days later than most other parent strains which lengthened the parental mean to 105.8 days. Comparing the parental mean days to maturity to the hybrid mean days to maturity of 102.7, no significant difference was observed (Table 4.3.5). No significant difference between the international hybrids and non-international hybrids was observed (Table 4.3.5).

Mid-parent heterosis was significant for days to maturity for the UM x EU #1 and EU #3 hybrids. This was due to EU #1 and EU #3 maturing very late and increasing the mid-parent mean maturity for the hybrid combination. A few UM x UM hybrids and HR199 x EU #4 had significantly earlier maturity than the mid-parent mean. No hybrids were observed to have significant high-parent heterosis for maturity. Four UM x EU hybrids and two UM x UM hybrids displayed significant commercial heterosis for days to maturity. Overall, HEAR hybrids were slightly later than their earlier parent which is also what Sernyk and Stefansson (1983) determined.

EU #5 was the best general combiner for advancing physiological maturity with a GCA of -3.5 days while EU #1 was the poorest general combiner with a GCA of 7.3

days, i.e. it delayed physiological maturity by an average of 7.3 days for the hybrids using EU #1 as a parent (Table 4.3.2). Specific combining abilities ranged from -5.4 to 5.7 days (Table 4.3.3).

Table 4.3.5: Days to physiological maturity and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments during 2004 and 2005

Cross #	Pedigree	Maturity (d)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	107.9	-4.4 *	6.9	5.8
2	MillenniUM01 x EU HEAR 1	108.8	-3.2 *	8.6	6.7
3	MillenniUM03 x EU HEAR 1	106.7	-5.9 *	4.6	4.6
4	HR200 x EU HEAR 1	106.4	-5.6 *	5.6	4.3
5	HR102 x EU HEAR 1	107.3	-5.2 *	5.6	5.2
6	RRHR102 x EU HEAR 1	108.3	-4.7 *	5.5	6.2
7	HR199 x EU HEAR 1	110.1	-5.2 *	2.4	7.9
8	Castor x EU HEAR 2	102.6	-2.1	1.6	0.6
9	MillenniUM01 x EU HEAR 2	102.6	-1.7	2.4	0.6
10	MillenniUM03 x EU HEAR 2	103.8	-1.4	1.8	1.8
11	HR200 x EU HEAR 2	102.9	-1.7	2.1	0.9
12	HR102 x EU HEAR 2	105.0	-0.1	3.3	2.9
13	RRHR102 x EU HEAR 2	105.8	0.2	3.1	3.7
14	HR199 x EU HEAR 2	107.0	-1.0	-0.5	4.9
15	Castor x EU HEAR 3	103.3	-7.9 *	2.3	1.3
16	MillenniUM01 x EU HEAR 3	103.8	-7.1 *	3.6	1.8
17	MillenniUM03 x EU HEAR 3	103.3	-8.3 *	1.3	1.3
18	HR200 x EU HEAR 3	103.9	-7.3 *	3.1	1.9
19	HR102 x EU HEAR 3	105.7	-6.1 *	4.0	3.6
20	RRHR102 x EU HEAR 3	107.5	-4.9 *	4.7	5.4
21	HR199 x EU HEAR 3	108.3	-6.2 *	0.7	6.2
22	MillenniUM01 x EU HEAR 4	101.5	1.6	1.9	-0.5
23	MillenniUM03 x EU HEAR 4	100.0	-0.8	0.4	-2.0
24	HR200 x EU HEAR 4	100.7	0.5	1.1	-1.3
25	HR102 x EU HEAR 4	99.6	-1.0	0.0	-2.4
26	RRHR102 x EU HEAR 4	99.8	-1.3	0.2	-2.2
27	HR199 x EU HEAR 4	100.7	-2.8 *	1.1	-1.3
28	Castor x EU HEAR 5	100.5	1.3	3.2	-1.5
29	MillenniUM01 x EU HEAR 5	98.3	-0.5	0.9	-3.6 *
30	MillenniUM03 x EU HEAR 5	99.9	0.2	2.6	-2.1
31	HR200 x EU HEAR 5	97.5	-1.6	0.1	-4.4 *
32	HR102 x EU HEAR 5	99.1	-0.4	1.7	-2.8 *
33	RRHR102 x EU HEAR 5	98.1	-1.9	-2.7	-3.8 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	99.7	-1.2	-1.1	-2.3
35	Castor x HR102	100.3	-1.0	-0.6	-1.7
36	MillenniUM01 x HR102	100.8	-0.1	0.6	-1.2
37	MillenniUM03 x HR200	99.8	-1.6	-1.0	-2.2
38	MillenniUM03 x HR102	102.2	0.4	0.5	0.2
39	HR200 x HR102	99.3	-1.9	-1.5	-2.6 *
40	HR200 x RRHR102	98.9	-2.8 *	-1.9	-3.0 *
41	HR200 x HR199	100.0	-4.0 *	-0.8	-2.0
42	HR102 x RRHR102	99.8	-2.3	-1.8	-2.2
43	HR102 x HR199	102.5	-2.0	0.8	0.5
44	RRHR102 x HR199	100.7	-4.2 *	-1.9	-1.3
45	EU HEAR 2 x EU HEAR 5	103.0	0.0	5.7	1.0
	UM x EU Mean	103.5 a	-2.9	2.5	1.5
	UM x UM / EU x EU Mean	100.6 a	-1.7	-0.2	-1.4
	Overall Hybrid Mean	102.7 s	-2.6	1.8	0.7
	Max	110.1	1.6	8.6	7.9
	Min	97.5	-8.3	-2.7	-4.4
Parents					
46	EU HEAR 1	124.7			
47	EU HEAR 2	108.6			
48	EU HEAR 3	123.4			
49	EU HEAR 4	99.6			
50	EU HEAR 5	97.4			
51	Castor	101.0			
52	MillenniUM01	100.2			
53	MillenniUM03	102.0			
54	HR200	100.8			
55	HR102	101.7			
56	RRHR102	102.7			
57	HR199	107.5			
	Overall Parent Mean	105.8 s			
	Max	124.7			
	Min	97.4			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.3.4 Plant Height

Parental strains used in this study ranged from approximately 90.6 to 143.8 cm in height while HEAR hybrids ranged from 93.3 to 132.9 cm. EU #1 and EU #3 were by far the tallest parents with plant heights over 140 cm while the remainder of the parents were between 90 and 112 cm. EU #1 and EU #3 strains skewed the parental mean height to 107.4 cm. The hybrids had a slightly narrower range of plant heights which resulted in a mean of 110.3 cm. No significant difference was detected between the parental and hybrid means for height, however, international hybrids were significantly taller than the non-international hybrids (Table 4.3.6). The shortest hybrid was Castor x HR200 (93.3 cm) and the tallest was RRHR102 x EU #1 (132.9 cm).

Very few hybrids were significantly taller than the mid-parent or high-parent values. These results are confirmed by Sernyk and Stefansson (1983) and Grant and Beversdorf (1985). The only hybrid significant for high-parent heterosis was MillenniUM03 x HR200 (102.5 cm). Many hybrids displayed significant levels of commercial heterosis since MillenniUM03 was one of the shorter parental strains. UM x EU #1, #2, and #3 were all significantly taller than MillenniUM03. Almost all the UM x UM hybrids were significantly taller than MillenniUM03.

Plant height was highly correlated with almost all agronomic and seed quality traits (Appendix Table B1). A notable strong positive correlation was between height and seed yield (0.89**) which indicated that taller hybrids produce more seed.

EU #1 had the highest GCA estimate of 16.3 cm while EU # 4 had the lowest GCA estimate of -11.5 cm (Table 4.3.2). Specific combining abilities ranged from -7.8 to 5.8 cm (Table 4.3.3).

Table 4.3.6: Plant height and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Height (cm)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	120.4	-1.4	-16.2	27.6 *
2	MillenniUM01 x EU HEAR 1	125.0	5.9 *	-13.0	32.5 *
3	MillenniUM03 x EU HEAR 1	122.5	2.9	-14.8	29.8 *
4	HR200 x EU HEAR 1	119.6	2.0	-16.8	26.7 *
5	HR102 x EU HEAR 1	119.2	-0.6	-17.1	26.3 *
6	RRHR102 x EU HEAR 1	132.9	3.9	-7.5	40.8 *
7	HR199 x EU HEAR 1	129.6	3.1	-9.9	37.3 *
8	Castor x EU HEAR 2	111.3	3.4	-2.9	17.9 *
9	MillenniUM01 x EU HEAR 2	112.5	8.8 *	-1.8	19.2 *
10	MillenniUM03 x EU HEAR 2	110.8	6.1 *	-3.3	17.4 *
11	HR200 x EU HEAR 2	108.3	5.6	-5.5	14.8 *
12	HR102 x EU HEAR 2	114.2	8.4 *	-0.4	21.0 *
13	RRHR102 x EU HEAR 2	117.9	4.1	2.9	24.9 *
14	HR199 x EU HEAR 2	118.3	6.6 *	3.3	25.4 *
15	Castor x EU HEAR 3	120.4	-0.4	-14.7	27.6 *
16	MillenniUM01 x EU HEAR 3	115.0	-1.5	-18.6	21.9 *
17	MillenniUM03 x EU HEAR 3	115.0	-2.4	-18.6	21.9 *
18	HR200 x EU HEAR 3	115.0	-0.8	-18.6	21.9 *
19	HR102 x EU HEAR 3	123.3	3.9	-12.7	30.7 *
20	RRHR102 x EU HEAR 3	127.1	0.3	-10.0	34.7 *
21	HR199 x EU HEAR 3	128.3	3.2	-9.1	36.0 *
22	MillenniUM01 x EU HEAR 4	94.2	0.6	-0.9	-0.2
23	MillenniUM03 x EU HEAR 4	100.0	5.6	5.3	6.0
24	HR200 x EU HEAR 4	97.5	5.1	2.6	3.3
25	HR102 x EU HEAR 4	97.5	2.1	1.5	3.3
26	RRHR102 x EU HEAR 4	106.3	2.6	-5.2	12.6 *
27	HR199 x EU HEAR 4	101.3	0.0	-5.8	7.3 *
28	Castor x EU HEAR 5	104.6	4.0	3.9	10.8 *
29	MillenniUM01 x EU HEAR 5	97.9	1.6	-2.5	3.8
30	MillenniUM03 x EU HEAR 5	104.6	7.4 *	4.1	10.8 *
31	HR200 x EU HEAR 5	98.3	2.9	-2.1	4.2
32	HR102 x EU HEAR 5	103.8	5.6	3.3	9.9 *
33	RRHR102 x EU HEAR 5	108.8	2.4	8.1	15.2 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	93.3	-2.4	-7.2	-1.1
35	Castor x HR102	99.6	1.3	-1.0	5.5
36	MillenniUM01 x HR102	101.7	8.0 *	5.9	7.7 *
37	MillenniUM03 x HR200	102.5	10.8 *	8.6 *	8.6 *
38	MillenniUM03 x HR102	101.7	6.8 *	5.9	7.7 *
39	HR200 x HR102	101.7	8.9 *	5.9	7.7 *
40	HR200 x RRHR102	103.8	2.4	-7.4	9.9 *
41	HR200 x HR199	102.1	3.0	-5.0	8.2 *
42	HR102 x RRHR102	107.1	2.9	-4.5	13.5 *
43	HR102 x HR199	106.3	4.4	-1.2	12.6 *
44	RRHR102 x HR199	113.8	3.6	1.5	20.5 *
45	EU HEAR 2 x EU HEAR 5	110.0	2.3	-4.0	16.6 *
	UM x EU Mean	112.8 a	3.1	-5.8	19.5
	UM x UM / EU x EU Mean	103.6 b	4.3	-0.2	9.8
	Overall Hybrid Mean	110.3 s	3.4	-4.3	16.9
	Max	132.9	10.8	8.6	40.8
	Min	93.3	-2.4	-18.6	-1.1
Parents					
46	EU HEAR 1	143.8			
47	EU HEAR 2	114.6			
48	EU HEAR 3	141.3			
49	EU HEAR 4	95.0			
50	EU HEAR 5	100.4			
51	Castor	100.6			
52	MillenniUM01	92.3			
53	MillenniUM03	94.4			
54	HR200	90.6			
55	HR102	96.0			
56	RRHR102	112.1			
57	HR199	107.5			
	Overall Parent Mean	107.4 s			
	Max	143.8			
	Min	90.6			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.3.5 Pre-Harvest Lodging

Overall HEAR hybrid and parental strain means were not significantly different for pre-harvest lodging ratings (2.9 and 3.1 respectively). The range of lodging ratings for both hybrids and parents were very similar (hybrid range – 1.7 to 3.8, parent range – 1.7 to 4.0). As with many other agronomic traits, EU #1 and EU #3 strains were superior in their ability to remain erect at harvest compared to other parental strains which raised the parental lodging mean lodging rating substantially. International hybrids were significantly better at remaining erect at harvest when compared to the UM x UM and EU x EU hybrids (Table 4.3.7). Lodging was highly negatively correlated (r = -0.95) with plant height which indicated that taller hybrids tended to remain standing at harvest significantly better than short hybrids (Appendix Table B1).

UM x EU #1 hybrids were significantly better than the mid-parent mean rating for lodging resistance. HEAR hybrids did not have significantly better lodging resistance than the higher rated parent. Many hybrids demonstrated high commercial heterosis estimates for lodging rating, a reflection of the poor lodging resistance displayed by MillenniUM03. Most hybrids that were significantly taller than MillenniUM03 were also significantly better than MillenniUM03 for lodging resistance.

EU #1 had the highest GCA lodging rating estimate of -0.8 (Table 4.3.2). The lowest general combiner was EU #4 with a lodging GCA of 0.5 (Table 4.3.2). Specific combining abilities ranged from -7.8 to 5.7 (Table 4.3.3).

Grant and Beversdorf (1985) determined that *B. napus* hybrids were generally poorer at resisting lodging than their parents due to higher seed yields. While this study reports minimal mid- or high-parent heterosis for lodging resistance, the significant and

relatively large commercial heterosis estimates indicated that HEAR hybrids stand significantly better than the current commercial HEAR cultivar, MillenniUM03.

Table 4.3.7: Pre-harvest lodging and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Lodging (1-erect to 5-flat)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	2.0	-26.1 *	0.0	-46.7 *
2	MillenniUM01 x EU HEAR 1	2.2	-27.7 *	8.5	-42.1 *
3	MillenniUM03 x EU HEAR 1	2.0	-30.4 *	0.0	-46.7 *
4	HR200 x EU HEAR 1	2.5	-14.2 *	25.0	-33.3 *
5	HR102 x EU HEAR 1	2.3	-17.8 *	16.5	-37.9 *
6	RRHR102 x EU HEAR 1	1.8	-29.4 *	-12.5	-53.3 *
7	HR199 x EU HEAR 1	1.7	-35.8 *	-16.5	-55.5 *
8	Castor x EU HEAR 2	2.8	-7.0	6.0	-24.5 *
9	MillenniUM01 x EU HEAR 2	3.1	-7.6	15.4	-17.9 *
10	MillenniUM03 x EU HEAR 2	2.7	-16.8 *	0.0	-28.8 *
11	HR200 x EU HEAR 2	3.3	0.0	21.7	-13.3 *
12	HR102 x EU HEAR 2	2.8	-13.2 *	3.0	-26.7 *
13	RRHR102 x EU HEAR 2	2.7	-5.2	0.0	-28.8 *
14	HR199 x EU HEAR 2	2.5	-14.8 *	-6.4	-33.3 *
15	Castor x EU HEAR 3	2.4	-4.8	44.9	-35.5 *
16	MillenniUM01 x EU HEAR 3	2.9	3.0	74.9	-22.1 *
17	MillenniUM03 x EU HEAR 3	2.6	-4.8	54.5	-31.2 *
18	HR200 x EU HEAR 3	2.5	-9.1	49.7	-33.3 *
19	HR102 x EU HEAR 3	2.2	-18.7 *	29.9	-42.1 *
20	RRHR102 x EU HEAR 3	2.2	-6.3	29.9	-42.1 *
21	HR199 x EU HEAR 3	1.8	-28.1 *	4.8	-53.3 *
22	MillenniUM01 x EU HEAR 4	3.4	-7.8	0.0	-8.8
23	MillenniUM03 x EU HEAR 4	3.5	-2.4	2.3	-6.7
24	HR200 x EU HEAR 4	3.8	3.4	9.6	0.0
25	HR102 x EU HEAR 4	3.2	-10.6	-7.3	-15.5 *
26	RRHR102 x EU HEAR 4	3.1	-3.4	4.1	-17.9 *
27	HR199 x EU HEAR 4	3.3	0.6	4.1	-11.2 *
28	Castor x EU HEAR 5	3.1	-4.0	2.7	-17.9 *
29	MillenniUM01 x EU HEAR 5	3.3	-7.1	8.3	-13.3 *
30	MillenniUM03 x EU HEAR 5	3.2	-6.1	5.7	-15.5 *
31	HR200 x EU HEAR 5	3.3	-4.8	8.3	-13.3 *
32	HR102 x EU HEAR 5	3.0	-10.0	0.0	-20.0 *
33	RRHR102 x EU HEAR 5	2.9	-2.0	-14.5	-22.1 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	3.8	3.5	9.8	0.0
35	Castor x HR102	3.4	-3.5	0.1	-8.8
36	MillenniUM01 x HR102	3.6	-6.6	-2.5	-4.5
37	MillenniUM03 x HR200	3.6	-5.5	-4.5	-4.5
38	MillenniUM03 x HR102	3.4	-7.8	-6.8	-8.8
39	HR200 x HR102	3.4	-8.8	-6.8	-8.8
40	HR200 x RRHR102	3.0	-11.6 *	1.4	-20.0 *
41	HR200 x HR199	3.1	-12.4 *	-3.8	-17.9 *
42	HR102 x RRHR102	3.1	-7.1	4.1	-17.9 *
43	HR102 x HR199	3.1	-10.3	-3.8	-17.9 *
44	RRHR102 x HR199	2.8	-8.1	-4.4	-24.5 *
45	EU HEAR 2 x EU HEAR 5	2.9	3.0	9.4	-22.1 *
	UM x EU Mean	2.7 a	-11.2	11.3	-27.6
	UM x UM / EU x EU Mean	3.3 b	-6.3	-0.6	-13.0
	Overall Hybrid Mean	2.9 s	-9.9	8.1	-23.7
	Max	3.8	3.5	74.9	0.0
	Min	1.7	-35.8	-16.5	-55.5
Parents					
46	EU HEAR 1	2.0			
47	EU HEAR 2	2.7			
48	EU HEAR 3	1.7			
49	EU HEAR 4	3.4			
50	EU HEAR 5	3.0			
51	Castor	3.4			
52	MillenniUM01	4.0			
53	MillenniUM03	3.8			
54	HR200	3.8			
55	HR102	3.7			
56	RRHR102	3.0			
57	HR199	3.2			
	Overall Parent Mean	3.1 s			
	Max	4.0			
	Min	1.7			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.3.6 Seed Yield

HEAR hybrids overall were significantly higher yielding for seed than their parental strains. The range of seed yields for parental strains was much smaller than for hybrids. The lowest yielding hybrid was Castor x HR199 (1388.9 kg ha^{-1}) and the highest yielding hybrid was HR102 x EU #3 (3162.3 kg ha^{-1}). The lowest yielding parent was EU #3 (1005.5 kg ha^{-1}) and the highest yielding parent strain was EU #2 (1897.8 kg ha^{-1}). The EU x EU hybrids were significantly higher seed yielding than the UM x UM and EU x EU hybrids (Table 4.3.8). These results indicate that both geographical diversity and genetic diversity are important characteristics of parental strains to consider when selecting parents for hybrid crosses to achieve optimal heterosis performance.

Almost all HEAR hybrids were significantly higher yielding than the mean of their parents and many of these hybrids were also significantly higher yielding than the better parent. The highest seed yield hybrids were from the UM x EU #1 and UM x EU #3 hybrids with mid- and high-parent heterosis estimates over 150% and commercial heterosis estimates over 100% (Table 4.3.8). These estimates of mid-parent and high-parent heterosis for seed yield at a minimum and in many cases, exceed the reports in studies previously conducted by Sernyk and Stefansson (1983), Brandle and McVetty (1989) and Grant and Beversdorf (1985).

UM x UM hybrids were generally short and did not resist lodging well which resulted in reduced seed yield (r = -0.85**) (Appendix Table B1). UM x EU #4 and UM x EU #5 hybrids were also very short, did not remain erect at harvest and were very early maturing. This combination of agronomic traits accounted for the some of the lower seed

yields. MillenniUM03 had a seed yield of approximately 1527.2 kg ha^{-1} which was significantly less than many hybrids in this study.

EU #1 was the best general combiner for seed yield with a GCA estimate of 348.2 kg ha^{-1} (Table 4.3.2). This strain was probably the best because it was tall, late maturing and remained erect at harvest. The lowest general combiner for seed yield was EU #4 with a GCA of -648.8 kg ha^{-1} (Table 4.3.2). Hybrids created with this strain were very short, very early maturing, and did not remain erect at harvest. SCA estimates were quite variable with a range from -614.6 to 440.7 kg ha^{-1} (Table 4.3.3). GCA and SCA estimates calculated for seed yield in this study are similar to those calculated for *B. napus* canola hybrids created by Grant and Beversdorf (1985).

Table 4.3.8: Seed yield and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments during 2004 and 2005

Cross #	Pedigree	Yield (kg ha^{-1})	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	2819.9	103.7 *	71.9 *	84.7 *
2	MillenniUM01 x EU HEAR 1	2977.0	159.4 *	155.1 *	94.9 *
3	MillenniUM03 x EU HEAR 1	2744.6	106.7 *	79.7 *	79.7 *
4	HR200 x EU HEAR 1	3043.9	141.7 *	118.8 *	99.3 *
5	HR102 x EU HEAR 1	2923.4	101.4 *	64.7 *	91.4 *
6	RRHR102 x EU HEAR 1	2798.8	87.0 *	50.1 *	83.3 *
7	HR199 x EU HEAR 1	2973.8	103.9 *	66.2 *	94.7 *
8	Castor x EU HEAR 2	2321.3	31.2 *	22.3 *	52.0 *
9	MillenniUM01 x EU HEAR 2	2214.8	44.5 *	16.7	45.0 *
10	MillenniUM03 x EU HEAR 2	2457.1	43.5 *	29.5 *	60.9 *
11	HR200 x EU HEAR 2	2445.9	48.7 *	28.9 *	60.2 *
12	HR102 x EU HEAR 2	2817.6	53.4 *	48.5 *	84.5 *
13	RRHR102 x EU HEAR 2	2397.9	27.4 *	26.4 *	57.0 *
14	HR199 x EU HEAR 2	2890.7	56.8 *	52.3 *	89.3 *
15	Castor x EU HEAR 3	2964.0	124.1 *	80.7 *	94.1 *
16	MillenniUM01 x EU HEAR 3	2658.0	144.7 *	127.8 *	74.0 *
17	MillenniUM03 x EU HEAR 3	2987.2	135.9 *	95.6 *	95.6 *
18	HR200 x EU HEAR 3	2780.1	132.0 *	99.9 *	82.0 *
19	HR102 x EU HEAR 3	3162.3	127.5 *	78.2 *	107.1 *
20	RRHR102 x EU HEAR 3	2637.4	83.8 *	41.4 *	72.7 *
21	HR199 x EU HEAR 3	3009.8	115.4 *	68.2 *	97.1 *
22	MillenniUM01 x EU HEAR 4	1388.9	19.3	19.0	-9.1
23	MillenniUM03 x EU HEAR 4	2038.6	51.6 *	33.5 *	33.5 *
24	HR200 x EU HEAR 4	1510.0	18.3	8.6	-1.1
25	HR102 x EU HEAR 4	1888.7	28.7 *	6.4	23.7 *
26	RRHR102 x EU HEAR 4	1965.8	29.9 *	5.4	28.7 *
27	HR199 x EU HEAR 4	1800.4	22.0	0.6	17.9
28	Castor x EU HEAR 5	1918.4	30.5 *	17.0 *	25.6 *
29	MillenniUM01 x EU HEAR 5	1846.0	49.6 *	42.0	20.9
30	MillenniUM03 x EU HEAR 5	2210.6	56.4 *	44.8 *	44.8 *
31	HR200 x EU HEAR 5	1821.6	35.4 *	31.0	19.3
32	HR102 x EU HEAR 5	2169.9	41.1 *	22.3	42.1 *
33	RRHR102 x EU HEAR 5	2063.0	30.3 *	25.8	35.1 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	1388.9	-8.4	-15.3	-9.1
35	Castor x HR102	1843.0	7.9	3.9	20.7
36	MillenniUM01 x HR102	2100.8	42.8 *	18.4	37.6 *
37	MillenniUM03 x HR200	1989.0	36.3 *	30.2 *	30.2 *
38	MillenniUM03 x HR102	2180.2	32.1 *	22.9 *	42.8 *
39	HR200 x HR102	2045.9	29.3 *	15.3	34.0 *
40	HR200 x RRHR102	1807.8	11.0	-3.1	18.4
41	HR200 x HR199	2136.1	34.3 *	19.4 *	39.9 *
42	HR102 x RRHR102	2228.7	22.5 *	19.5 *	45.9 *
43	HR102 x HR199	2089.2	17.3	16.8	36.8 *
44	RRHR102 x HR199	1926.6	5.4	3.3	26.2 *
45	EU HEAR 2 x EU HEAR 5	2375.2	48.5 *	25.2 *	55.5 *
	UM x EU Mean	2443.9 a	72.3	50.9	60.0
	UM x UM / EU x EU Mean	2009.3 b	23.3	13.0	31.6
	Overall Hybrid Mean	2328.0 s	59.2	40.8	52.4
	Max	3162.3	159.4	155.1	107.1
	Min	1388.9	-8.4	-15.3	-9.1
Parents					
46	EU HEAR 1	1128.2			
47	EU HEAR 2	1897.8			
48	EU HEAR 3	1005.5			
49	EU HEAR 4	1161.5			
50	EU HEAR 5	1300.3			
51	Castor	1640.3			
52	MillenniUM01	1166.9			
53	MillenniUM03	1527.2			
54	HR200	1391.0			
55	HR102	1774.5			
56	RRHR102	1865.1			
57	HR199	1789.1			
	Overall Parent Mean	1470.6 t			
	Max	1897.8			
	Min	1005.5			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.4 Hybrid and Parent Strain Seed Quality Trait Comparisons

4.4.1 Oil Concentration

Mean oil concentration for the HEAR hybrids was significantly higher than for the parental strains (Table 4.4.1). Parental strains and hybrids both had large ranges of oil concentrations. The lowest oil concentration observed for hybrids and parents was approximately 450 g kg^{-1}. The hybrids had a much higher maximum oil concentration than the parental strains (533.3 and 515.8 g kg^{-1} respectively). The international hybrids were significantly higher for seed oil concentration than the non-international hybrids (Table 4.4.1).

Previous studies on *B. napus* canola hybrids by Grant and Beversdorf (1985) did not find significantly higher oil concentration for hybrids. Sernyk and Stefansson (1983) found that *B. napus* hybrids performed equally well for oil concentration to the parental strains. Many hybrids developed in this study had very high seed oil concentration (up to 533 g kg^{-1}). This study found that the high seed yield hybrids were also very high for seed oil concentration hybrids. The correlation coefficient between these two traits was 0.84** (Appendix Table B1).

Hybrids created from HR102 or HR200 with EU #1, EU #2 or EU#3 were consistently over 500 g kg^{-1}, they were significantly better than the high parent, and were also significantly better than MillenniUM03. The highest general combiners for oil concentration were EU #1, EU #2, EU #3 and HR102 with GCA estimates of 13.3, 12.7, 9.3, and 10.3 g kg^{-1} respectively (Table 4.4.2). While high GCA parental strains influenced the higher seed oil concentration of the hybrids they were used to create, many hybrid combinations had high seed oil concentrations despite low parental GCA values

(Table 4.4.3). RRHR102 x EU#4 had a SCA value of 15.1 g kg^{-1} despite the parent strains having low GCA estimates of 0.4 g kg^{-1} and -24.7 g kg^{-1} respectively (Table 4.4.3). The highest oil concentration hybrid, HR102 x EU #1, was created by parental strains with high GCA estimates and the hybrid also had the highest SCA estimate of 24.4 g kg^{-1}. This hybrid also was very high for seed yield at over 2900 kg ha^{-1}.

Table 4.4.1: Oil concentration and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Oil Conc. ($g\ kg^{-1}$)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	502.5	8.6 *	8.6 *	7.7 *
2	MillenniUM01 x EU HEAR 1	496.7	7.9 *	7.4 *	6.4 *
3	MillenniUM03 x EU HEAR 1	495.0	6.5 *	6.1 *	6.1 *
4	HR200 x EU HEAR 1	503.3	9.3 *	8.8 *	7.9 *
5	HR102 x EU HEAR 1	533.3	11.9 *	8.6 *	14.3 *
6	RRHR102 x EU HEAR 1	508.3	8.4 *	6.9 *	8.9 *
7	HR199 x EU HEAR 1	492.5	5.4 *	4.4 *	5.5 *
8	Castor x EU HEAR 2	487.5	-0.3	-5.5	4.5 *
9	MillenniUM01 x EU HEAR 2	502.5	3.2 *	-2.6	7.7 *
10	MillenniUM03 x EU HEAR 2	488.3	-0.6	-5.3	4.6 *
11	HR200 x EU HEAR 2	508.3	4.3 *	-1.5	8.9 *
12	HR102 x EU HEAR 2	507.5	0.8	-1.6	8.8 *
13	RRHR102 x EU HEAR 2	493.3	-0.5	-4.4	5.7 *
14	HR199 x EU HEAR 2	486.7	-1.4	-5.6	4.3 *
15	Castor x EU HEAR 3	489.2	5.2 *	4.6 *	4.8 *
16	MillenniUM01 x EU HEAR 3	494.2	6.8 *	5.7 *	5.9 *
17	MillenniUM03 x EU HEAR 3	507.5	8.7 *	8.6 *	8.8 *
18	HR200 x EU HEAR 3	501.7	8.3 *	7.3 *	7.5 *
19	HR102 x EU HEAR 3	511.7	6.8 *	4.2 *	9.7 *
20	RRHR102 x EU HEAR 3	496.7	5.4 *	4.5 *	6.4 *
21	HR199 x EU HEAR 3	494.2	5.2 *	4.8 *	5.9 *
22	MillenniUM01 x EU HEAR 4	450.0	-1.1	-1.7	-3.6
23	MillenniUM03 x EU HEAR 4	460.8	0.3	-1.3	-1.3
24	HR200 x EU HEAR 4	461.7	1.3	0.6	-1.1
25	HR102 x EU HEAR 4	473.3	0.3	-3.6	1.4
26	RRHR102 x EU HEAR 4	475.8	2.6 *	0.1	2.0
27	HR199 x EU HEAR 4	455.0	-1.5	-3.5	-2.5
28	Castor x EU HEAR 5	473.3	0.8	-0.7	1.4
29	MillenniUM01 x EU HEAR 5	469.2	0.4	-1.6	0.5
30	MillenniUM03 x EU HEAR 5	480.0	1.8	0.7	2.9 *
31	HR200 x EU HEAR 5	474.2	1.4	-0.5	1.6
32	HR102 x EU HEAR 5	489.2	1.1	-0.3 *	4.8 *
33	RRHR102 x EU HEAR 5	484.2	1.7	4.7	3.8 *
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	455.8	-1.0	-1.4	-2.3
35	Castor x HR102	481.7	1.1	-1.9	3.2 *
36	MillenniUM01 x HR102	478.3	0.8	-2.6	2.5 *
37	MillenniUM03 x HR200	477.5	3.2 *	2.3	2.3
38	MillenniUM03 x HR102	481.7	0.6	-1.9	3.2 *
39	HR200 x HR102	483.3	1.8	-1.5	3.6 *
40	HR200 x RRHR102	470.0	0.6	-1.1	0.7
41	HR200 x HR199	475.0	2.1	0.7	1.8
42	HR102 x RRHR102	486.7	0.7	-0.8	4.3 *
43	HR102 x HR199	477.5	-0.8	-2.7	2.3
44	RRHR102 x HR199	470.8	-0.6	-1.0	0.9
45	EU HEAR 2 x EU HEAR 5	484.2	-2.4	-6.1	3.8 *
	UM x EU Mean	489.3 a	3.6	1.7	4.9
	UM x UM / EU x EU Mean	476.9 b	0.5	-1.5	2.2
	Overall Hybrid Mean	486.0 s	2.8	0.9	4.1
	Max	533.3	11.9	8.8	14.3
	Min	450.0	-2.4	-6.1	-3.6
Parents					
46	EU HEAR 1	462.5			
47	EU HEAR 2	515.8			
48	EU HEAR 3	467.5			
49	EU HEAR 4	452.5			
50	EU HEAR 5	476.7			
51	Castor	462.5			
52	MillenniUM01	457.9			
53	MillenniUM03	466.7			
54	HR200	458.8			
55	HR102	490.9			
56	RRHR102	475.4			
57	HR199	471.7			
	Overall Parent Mean	471.6 t			
	Max	515.8			
	Min	452.5			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

Table 4.4.2: General combining ability effects for selected seed quality traits measured from HEAR hybrids grown in four environments 2004 and 2005

Hybrid HEAR Parent	Oil Conc. (g kg^{-1})	Protein Conc. (g kg^{-1})	PROM (g kg^{-1})	SUM (g kg^{-1})	GLUC (μmol g^{-1} seed)	Erucic Acid (%)
EU HEAR 1	13.3	-8.8	-4.9	4.3	-1.3	-3.5
EU HEAR 2	12.7	-6.1	1.7	7.8	3.2	-0.8
EU HEAR 3	9.3	-9.5	-10.0	-0.5	-1.4	-2.7
EU HEAR 4	-24.7	17.8	10.9	-6.7	1.0	0.2
EU HEAR 5	-7.1	-2.0	-10.8	-9.8	0.2	2.1
Castor	-7.1	2.5	-1.6	-4.9	1.8	-1.0
MillenniUM01	-7.6	9.0	9.9	1.5	2.7	-0.1
MillenniUM03	-3.8	3.5	3.5	-0.1	-1.0	1.2
HR200	-4.2	2.2	0.7	-1.5	-1.5	0.9
HR102	10.3	-6.5	-3.2	3.4	-0.7	0.7
RRHR102	0.4	-0.8	-0.9	-1.1	0.4	-1.8
HR199	-6.0	4.3	3.2	-0.6	1.9	-0.8
Hybrid Mean	486.0	244.3	474.7	730.1	17.3	54.0

Table 4.4.3: Specific combining ability effects for selected seed quality traits measured from HEAR hybrids grown in four environments 2004 and 2005

Cross #	Pedigree	Oil Conc. ($g\ kg^{-1}$)	Protein Conc. ($g\ kg^{-1}$)	PROM ($g\ kg^{-1}$)	SUM ($g\ kg^{-1}$)	GLUC ($\mu mol\ g^{-1}$ seed)	Erucic Acid (%)
1	Castor x EU HEAR 1	9.4	-5.6	-2.0	3.1	-2.5	-0.8
2	MillenniUM01 x EU HEAR 1	4.2	-4.9	-1.9	1.1	0.8	0.0
3	MillenniUM03 x EU HEAR 1	-1.5	-0.8	-2.6	-0.6	0.2	-0.3
4	HR200 x EU HEAR 1	7.2	-6.2	-7.4	0.7	-0.5	-0.2
5	HR102 x EU HEAR 1	21.9	-8.8	3.8	13.5	-0.2	0.3
6	RRHR102 x EU HEAR 1	7.4	-1.4	1.6	4.5	-0.6	-0.9
7	HR199 x EU HEAR 1	-1.7	0.7	0.2	0.6	0.3	0.3
8	Castor x EU HEAR 2	-5.0	0.8	-3.1	-4.4	0.8	0.6
9	MillenniUM01 x EU HEAR 2	10.6	-6.1	0.3	6.0	-0.8	0.5
10	MillenniUM03 x EU HEAR 2	-7.6	0.5	-4.6	-5.8	0.9	-1.3
11	HR200 x EU HEAR 2	12.7	-2.4	9.0	10.5	0.3	0.1
12	HR102 x EU HEAR 2	-3.4	-5.0	-9.9	-6.7	-1.1	-1.4
13	RRHR102 x EU HEAR 2	-7.1	2.5	-2.0	-3.1	0.5	-1.5
14	HR199 x EU HEAR 2	-7.0	3.8	-0.1	-3.7	0.0	-0.3
15	Castor x EU HEAR 3	0.3	1.0	1.1	1.2	-1.1	-0.5
16	MillenniUM01 x EU HEAR 3	5.9	-3.4	-0.4	1.6	-0.6	-0.4
17	MillenniUM03 x EU HEAR 3	15.2	-10.1	-6.2	5.6	-1.4	0.0
18	HR200 x EU HEAR 3	9.8	-7.9	-7.6	1.9	0.2	-0.7
19	HR102 x EU HEAR 3	4.4	-6.4	-11.4	-1.1	0.7	0.5
20	RRHR102 x EU HEAR 3	-0.1	1.9	3.9	2.5	-1.0	-1.0
21	HR199 x EU HEAR 3	4.1	-0.1	4.1	4.5	1.4	0.1
22	MillenniUM01 x EU HEAR 4	-2.3	0.7	-0.8	-3.1	1.8	0.4
23	MillenniUM03 x EU HEAR 4	4.5	-3.5	0.1	1.0	0.5	0.6
24	HR200 x EU HEAR 4	5.8	-3.1	-0.6	1.5	0.7	1.2
25	HR102 x EU HEAR 4	2.1	1.0	0.6	0.8	-0.7	0.6
26	RRHR102 x EU HEAR 4	15.1	-11.6	-5.7	2.7	-0.3	1.5
27	HR199 x EU HEAR 4	1.0	-3.6	-3.0	-3.6	-1.0	1.1
28	Castor x EU HEAR 5	1.9	2.4	5.3	3.5	0.3	0.3
29	MillenniUM01 x EU HEAR 5	-1.7	-0.3	-3.8	-2.7	-0.7	-0.4
30	MillenniUM03 x EU HEAR 5	5.1	-1.2	1.3	3.9	-0.3	-0.7
31	HR200 x EU HEAR 5	-0.3	0.1	-1.0	-2.3	0.0	-0.3
32	HR102 x EU HEAR 5	-0.6	4.9	6.8	1.3	0.8	-0.6
33	RRHR102 x EU HEAR 5	4.9	-3.4	-1.2	2.4	0.5	0.3
34	Castor x HR200	-18.8	14.6	9.5	-4.6	1.4	1.4
35	Castor x HR102	-8.2	6.1	3.2	-1.8	-1.0	0.9
36	MillenniUM01 x HR102	-11.0	9.3	8.2	-0.5	-0.9	-0.9
37	MillenniUM03 x HR200	-0.5	-1.5	-4.5	-5.0	1.5	0.1
38	MillenniUM03 x HR102	-11.6	8.4	6.7	-3.1	1.5	-0.9
39	HR200 x HR102	-9.6	7.2	2.7	-1.8	-0.4	-1.1
40	HR200 x RRHR102	-12.4	8.0	2.2	-4.0	0.2	1.1
41	HR200 x HR199	-0.7	1.7	6.6	2.0	0.0	0.1
42	HR102 x RRHR102	-11.0	5.4	0.9	-2.9	-1.0	0.8
43	HR102 x HR199	-13.5	9.2	6.2	-3.5	0.4	1.4
44	RRHR102 x HR199	-9.7	4.9	-0.2	-7.4	0.1	1.2
45	EU HEAR 2 x EU HEAR 5	-8.2	2.1	-4.4	-4.7	0.2	-1.4

4.4.2 Seed Protein Concentration

Mean hybrid seed protein concentration was significantly lower than the parent seed protein concentration mean (Table 4.4.4). The range of seed protein concentrations was very similar for hybrids and parent strains (hybrids – 220.0 to 273.3 g kg^{-1}, parent cultivars/strains – 228.3 to 269.2 g kg^{-1}). International hybrids were significantly lower than the non-international hybrids (242.0 g kg^{-1} and 250.6 g kg^{-1} respectively).

Sernyk and Stefansson in 1983 found that seed oil concentration and seed protein concentration were strongly negatively correlated. Grant and Beversdorf (1985) determined that negative heterosis for seed protein concentration was evident when comparing hybrids to parent strains. This study found a similar strong negative correlation of r = -0.94** (Appendix Table B1). Since many hybrids were high for oil concentration, the low hybrid mean seed protein concentration was likely.

The EU x EU hybrid was the only hybrid to have a significantly high mid-parent heterosis estimate for protein concentration. No significant heterosis estimates were observed for high-parent heterosis or commercial heterosis. The highest general combiner for seed protein concentration was EU #4 with a GCA of 17.8 g kg^{-1}. Hybrids created with EU #4 had approximately 18.0 g kg^{-1} more protein in the seed than the mean of all hybrids. The lowest GCA parental cultivar/strain was EU #2 (-9.5 g kg^{-1}).

Table 4.4.4: Protein concentration and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Protein Conc. (g kg^{-1})	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	232.5	-7.8	-9.4	-12.5
2	MillenniUM01 x EU HEAR 1	240.0	-7.1	-10.8	-9.7
3	MillenniUM03 x EU HEAR 1	238.3	-7.1	-10.3	-10.3
4	HR200 x EU HEAR 1	231.7	-8.2	-10.0	-12.8
5	HR102 x EU HEAR 1	220.0	-10.1	-11.1	-17.2
6	RRHR102 x EU HEAR 1	233.3	-6.8	-7.8	-12.2
7	HR199 x EU HEAR 1	240.8	-3.7	-4.6	-9.4
8	Castor x EU HEAR 2	241.7	-0.3	-5.8	-9.1
9	MillenniUM01 x EU HEAR 2	241.7	-2.8	-10.2	-9.1
10	MillenniUM03 x EU HEAR 2	242.5	-1.8	-8.8	-8.8
11	HR200 x EU HEAR 2	238.3	-1.9	-7.5	-10.3
12	HR102 x EU HEAR 2	226.7	-3.6	-6.4	-14.7
13	RRHR102 x EU HEAR 2	240.0	-0.3	-5.1	-9.7
14	HR199 x EU HEAR 2	246.7	2.6	-2.3	-7.2
15	Castor x EU HEAR 3	238.3	-5.0	-7.1	-10.3
16	MillenniUM01 x EU HEAR 3	240.8	-6.3	-10.5	-9.4
17	MillenniUM03 x EU HEAR 3	228.3	-10.6	-14.1	-14.1
18	HR200 x EU HEAR 3	229.2	-8.8	-11.0	-13.8
19	HR102 x EU HEAR 3	221.7	-9.0	-9.5	-16.6
20	RRHR102 x EU HEAR 3	235.8	-5.3	-6.8	-11.3
21	HR199 x EU HEAR 3	239.2	-3.8	-5.3	-10.0
22	MillenniUM01 x EU HEAR 4	273.3	2.6	1.5	2.8
23	MillenniUM03 x EU HEAR 4	263.3	-0.5	-0.9	-0.9
24	HR200 x EU HEAR 4	262.5	0.8	-0.3	-1.2
25	HR102 x EU HEAR 4	257.5	1.9	-2.2	-3.1
26	RRHR102 x EU HEAR 4	250.8	-2.8	-4.7	-5.6
27	HR199 x EU HEAR 4	264.2	2.4	0.3	-0.6
28	Castor x EU HEAR 5	247.5	1.4	-3.6	-6.9
29	MillenniUM01 x EU HEAR 5	251.7	0.5	-6.5	-5.3
30	MillenniUM03 x EU HEAR 5	245.0	-1.5	-7.8	-7.8
31	HR200 x EU HEAR 5	245.0	0.2	-4.9	-7.8
32	HR102 x EU HEAR 5	240.8	1.6	-0.5	-9.4
33	RRHR102 x EU HEAR 5	238.3	-1.7	-7.5	-10.3
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	264.2	2.8	2.6	-0.6
35	Castor x HR102	246.7	-1.1	-3.9	-7.2
36	MillenniUM01 x HR102	256.7	0.4	-4.6	-3.4
37	MillenniUM03 x HR200	249.2	-4.8	-6.2	-6.2
38	MillenniUM03 x HR102	250.0	-1.6	-5.9	-5.9
39	HR200 x HR102	247.5	-0.9	-3.9	-6.9
40	HR200 x RRHR102	254.2	-0.4	-1.3	-4.4
41	HR200 x HR199	253.3	-0.7	-1.6	-4.7
42	HR102 x RRHR102	242.5	-2.0	-4.1	-8.8
43	HR102 x HR199	251.7	1.8	-0.3	-5.3
44	RRHR102 x HR199	253.3	0.2	0.1	-4.7
45	EU HEAR 2 x EU HEAR 5	238.3	3.6 *	2.8	-10.3
	UM x EU Mean	242.0 a	-3.1	-6.4	-8.9
	UM x UM / EU x EU Mean	250.6 b	-0.2	-2.2	-5.7
	Overall Hybrid Mean	244.3 s	-2.3	-5.3	-8.1
	Max	273.3	3.6	2.8	2.8
	Min	220.0	-10.6	-14.1	-17.2
Parents					
46	EU HEAR 1	247.5			
47	EU HEAR 2	228.3			
48	EU HEAR 3	245.0			
49	EU HEAR 4	263.3			
50	EU HEAR 5	231.7			
51	Castor	256.7			
52	MillenniUM01	269.2			
53	MillenniUM03	265.8			
54	HR200	257.5			
55	HR102	242.1			
56	RRHR102	253.0			
57	HR199	252.5			
	Overall Parent Mean	251.0 t			
	Max	269.2			
	Min	228.3			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.4.3 Meal Protein Concentration

Another important measurement of protein concentration is protein concentration in the meal, that is the portion of the seed left after oil removed. HEAR hybrids had a mean meal protein concentration of 474.7 g kg^{-1} which was not significantly different from the parental mean meal protein concentration of 475.0 g kg^{-1}. The international hybrids were, however, significantly lower than the UM x UM and EU x EU hybrids (473.4 g kg^{-1}versus 478.3 g kg^{-1} respectively). The range of meal protein concentrations for hybrids and parents were very similar (hybrids – 451.7 to 494.2 g kg^{-1}, parent cultivars/strains – 440.8 to 498.4 g kg^{-1}) (Table 4.4.4).

HR200 x EU #2 was the only hybrid with significantly more meal protein than the mean of the parent strains. No significantly high heterosis estimates were observed for high-parent heterosis or commercial heterosis. The results for meal protein concentration are very similar to seed protein concentration. The highest GCA estimate for meal protein concentration was EU #4 with a GCA of 10.9 g kg^{-1}. Hybrids created with EU #4 had approximately 11.0 g kg^{-1} more protein in the meal than the mean of all hybrids.

Table 4.4.5: Meal protein concentration and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	PROM (g kg^{-1})	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	467.5	-0.3	-2.3	-6.2
2	MillenniUM01 x EU HEAR 1	478.3	0.0	-3.8	-4.0
3	MillenniUM03 x EU HEAR 1	471.7	-1.5	-5.3	-5.3
4	HR200 x EU HEAR 1	464.2	-1.0	-2.9	-6.9
5	HR102 x EU HEAR 1	471.7	0.7	-1.2	-5.3
6	RRHR102 x EU HEAR 1	471.7	0.3	-2.0	-5.3
7	HR199 x EU HEAR 1	474.2	1.4	-0.4	-4.8
8	Castor x EU HEAR 2	472.5	-0.4	-1.2	-5.2
9	MillenniUM01 x EU HEAR 2	486.7	0.6	-2.1	-2.3
10	MillenniUM03 x EU HEAR 2	475.8	-1.8	-4.5	-4.5
11	HR200 x EU HEAR 2	486.7	2.6 *	1.8	-2.3
12	HR102 x EU HEAR 2	464.2	-2.1	-2.8	-6.9
13	RRHR102 x EU HEAR 2	474.2	-0.4	-1.5	-4.8
14	HR199 x EU HEAR 2	480.0	1.4	0.8	-3.7
15	Castor x EU HEAR 3	465.8	-0.7	-2.6	-6.5
16	MillenniUM01 x EU HEAR 3	475.0	-0.7	-4.4	-4.7
17	MillenniUM03 x EU HEAR 3	463.3	-3.3	-7.0	-7.0
18	HR200 x EU HEAR 3	459.2	-2.1	-4.0	-7.9
19	HR102 x EU HEAR 3	451.7	-3.6	-5.4	-9.4
20	RRHR102 x EU HEAR 3	469.2	-0.3	-2.5	-5.8
21	HR199 x EU HEAR 3	473.3	1.1	-0.6	-5.0
22	MillenniUM01 x EU HEAR 4	494.2	1.0	-0.6	-0.8
23	MillenniUM03 x EU HEAR 4	489.2	-0.2	-1.8	-1.8
24	HR200 x EU HEAR 4	485.8	1.2	0.9	-2.5
25	HR102 x EU HEAR 4	483.3	0.8	0.3	-3.0
26	RRHR102 x EU HEAR 4	479.2	-0.5	-0.5	-3.8
27	HR199 x EU HEAR 4	485.8	1.4	0.9	-2.5
28	Castor x EU HEAR 5	469.2	2.1 *	-1.9	-5.8
29	MillenniUM01 x EU HEAR 5	470.8	0.4	-5.3	-5.5
30	MillenniUM03 x EU HEAR 5	470.0	0.1	-5.7	-5.7
31	HR200 x EU HEAR 5	465.0	1.2	-2.8	-6.7
32	HR102 x EU HEAR 5	469.2	2.2 *	-1.7	-5.8
33	RRHR102 x EU HEAR 5	463.3	0.5	-3.1	-7.0
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	484.2	1.2	1.2	-2.8
35	Castor x HR102	474.2	-0.8	-0.9	-4.8
36	MillenniUM01 x HR102	490.0	0.6	-1.4	-1.7
37	MillenniUM03 x HR200	475.0	-2.7	-4.7	-4.7
38	MillenniUM03 x HR102	482.5	-1.1	-3.2	-3.2
39	HR200 x HR102	475.8	-0.4	-0.5	-4.5
40	HR200 x RRHR102	477.5	-0.5	-0.8	-4.2
41	HR200 x HR199	485.8	1.8	1.6	-2.5
42	HR102 x RRHR102	472.5	-1.4	-1.8	-5.2
43	HR102 x HR199	481.7	1.0	0.9	-3.3
44	RRHR102 x HR199	477.5	-0.3	-0.8	-4.2
45	EU HEAR 2 x EU HEAR 5	462.5	1.5	-1.8	-7.2
	UM x EU Mean	473.4 a	0.0	-2.3	-5.0
	UM x UM / EU x EU Mean	478.3 b	-0.1	-1.0	-4.0
	Overall Hybrid Mean	474.7 s	0.0	-2.0	-4.7
	Max	494.2	2.6	1.8	-0.8
	Min	451.7	-3.6	-7.0	-9.4
Parents					
46	EU HEAR 1	459.2			
47	EU HEAR 2	470.8			
48	EU HEAR 3	460.0			
49	EU HEAR 4	481.7			
50	EU HEAR 5	440.8			
51	Castor	478.4			
52	MillenniUM01	497.1			
53	MillenniUM03	498.4			
54	HR200	478.3			
55	HR102	477.5			
56	RRHR102	481.3			
57	HR199	476.3			
	Overall Parent Mean	475.0 s			
	Max	498.4			
	Min	440.8			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.4.4 Sum of Oil and Protein Concentrations

Another important measurement of seed quality, especially for HEAR cultivar developers is the sum of oil concentration and seed protein concentration. Due to low individual heritabilities and the strong negative correlation of these two seed quality traits, selection is best conducted on the two traits simultaneously.

The hybrid mean sum of oil and protein concentration was significantly higher than the parent strain mean sum (730.1 g kg^{-1} versus 722.9 g kg^{-1}). The UM x EU hybrids were significantly higher than the UM x UM and EU x EU hybrids (Table 4.4.6).

Many UM x EU #1 and UM x EU #3 hybrids were significantly higher for sum of oil and protein concentration than the better parent strain and three of the EU x EU hybrid crosses were significantly better than MillenniUM03 (Table 4.4.6). This result indicates that increased oil and protein concentrations were possible and that it was easier to determine the superior hybrids by sum of protein and oil than of protein and oil separately. Grami and Stefansson (1977b) also concluded that selection for high sum of protein and oil concentration was more effective than selection for either protein or oil concentration alone.

Table 4.4.6: Sum of oil and protein concentrations and heterosis estimates for HEAR hybrids and HEAR cultivars/ strains grown in four environments 2004 and 2005

Cross #	Pedigree	SUM ($g\ kg^{-1}$)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	733.3	2.5 *	1.9 *	0.2
2	MillenniUM01 x EU HEAR 1	737.5	2.6 *	1.5 *	0.7
3	MillenniUM03 x EU HEAR 1	734.2	1.8 *	0.3	0.3
4	HR200 x EU HEAR 1	734.2	2.8 *	2.3 *	0.3
5	HR102 x EU HEAR 1	751.7	4.0 *	2.4 *	2.7 *
6	RRHR102 x EU HEAR 1	738.3	2.6 *	1.4 *	0.9
7	HR199 x EU HEAR 1	735.0	2.4 *	1.5 *	0.4
8	Castor x EU HEAR 2	729.2	-0.4	-2.1	-0.4
9	MillenniUM01 x EU HEAR 2	745.8	1.4 *	0.1	1.9 *
10	MillenniUM03 x EU HEAR 2	732.5	-0.8	-1.7	0.1
11	HR200 x EU HEAR 2	747.5	2.2 *	0.3	2.1 *
12	HR102 x EU HEAR 2	735.0	-0.6	-1.3	0.4
13	RRHR102 x EU HEAR 2	734.2	-0.3	-1.4	0.3
14	HR199 x EU HEAR 2	734.2	-0.1	-1.4	0.3
15	Castor x EU HEAR 3	726.7	1.5 *	1.0 *	-0.7
16	MillenniUM01 x EU HEAR 3	733.3	2.0 *	0.9	0.2
17	MillenniUM03 x EU HEAR 3	735.8	1.9 *	0.5	0.5
18	HR200 x EU HEAR 3	730.8	2.3 *	1.9 *	-0.2
19	HR102 x EU HEAR 3	732.5	1.3 *	-0.2	0.1
20	RRHR102 x EU HEAR 3	731.7	1.6 *	0.5	0.0
21	HR199 x EU HEAR 3	734.2	2.3 *	1.4 *	0.3
22	MillenniUM01 x EU HEAR 4	722.5	0.1	-0.6	-1.3
23	MillenniUM03 x EU HEAR 4	725.0	0.0	-1.0	-1.0
24	HR200 x EU HEAR 4	724.2	0.9 *	0.9 *	-1.1
25	HR102 x EU HEAR 4	728.3	0.3	-0.8	-0.5
26	RRHR102 x EU HEAR 4	725.8	0.4	-0.3	-0.9
27	HR199 x EU HEAR 4	720.0	-0.1	-0.6	-1.6
28	Castor x EU HEAR 5	720.0	0.9	0.1	-1.6
29	MillenniUM01 x EU HEAR 5	720.0	0.4	-0.9	-1.6
30	MillenniUM03 x EU HEAR 5	725.0	0.7	-1.0 *	-1.0
31	HR200 x EU HEAR 5	717.5	0.7	0.0	-2.0
32	HR102 x EU HEAR 5	725.8	0.7	-1.1	-0.9
33	RRHR102 x EU HEAR 5	722.5	0.6	0.4	-1.3
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	720.0	0.2	0.1	-1.6
35	Castor x HR102	727.5	0.1	-0.9	-0.6
36	MillenniUM01 x HR102	735.0	0.6	0.1	0.4
37	MillenniUM03 x HR200	724.2	-0.1	-1.1	-1.1
38	MillenniUM03 x HR102	730.8	-0.3	-0.5	-0.2
39	HR200 x HR102	730.8	0.7	-0.5	-0.2
40	HR200 x RRHR102	724.2	0.2	-0.6	-1.1
41	HR200 x HR199	730.8	1.4 *	0.9	-0.2
42	HR102 x RRHR102	730.0	-0.2	-0.6	-0.3
43	HR102 x HR199	730.0	0.1	-0.6	-0.3
44	RRHR102 x HR199	721.7	-0.6	-0.9	-1.4
45	EU HEAR 2 x EU HEAR 5	724.2	-0.3	-2.8	-1.1
	UM x EU Mean	731.0 a	1.2	0.1	-0.1
	UM x UM / EU x EU Mean	727.4 b	0.1	-0.6	-0.6
	Overall Hybrid Mean	730.1 s	0.9	-0.1	-0.3
	Max	751.7	4.0	2.4	2.7
	Min	717.5	-0.8	-2.8	-2.0
Parents					
46	EU HEAR 1	710.8			
47	EU HEAR 2	745.0			
48	EU HEAR 3	711.7			
49	EU HEAR 4	717.5			
50	EU HEAR 5	707.5			
51	Castor	719.6			
52	MillenniUM01	726.7			
53	MillenniUM03	732.1			
54	HR200	717.5			
55	HR102	734.2			
56	RRHR102	728.3			
57	HR199	724.2			
	Overall Parent Mean	722.9 t			
	Max	745.0			
	Min	707.5			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.4.5 Glucosinolate Concentration

HEAR hybrids had a significantly lower mean glucosinolate concentration (17.3 μmol g^{-1} seed) than the parent strain mean glucosinolate concentration (19.7 μmol g^{-1} seed). The sub-means of international and non-international hybrids were not significantly different which indicated that geographical origin did not have as much impact on glucosinolates as genetic diversity (Table 4.4.7). The glucosinolate concentration of all hybrid and parent cultivars/strains were high due to unusually long, cool and wet growing seasons during 2004 and 2005. Very few traits were significantly correlated with glucosinolate concentration (Appendix Table B1).

The range of glucosinolate concentration was quite variable for hybrids and parent strains. The parent with the highest glucosinolate concentration was Castor (26.9 μmol g^{-1} seed) and the lowest was HR200 (16.2 μmol g^{-1} seed). The hybrid range of glucosinolate concentrations was slightly lower. The highest glucosinolate concentration hybrid was Castor x EU #2 (22.2 μmol g^{-1} seed) and the lowest was MillenniUM03 x EU #3 (13.2 μmol g^{-1} seed). The highest GCA parent was HR200 with an estimate of -1.5 μmol g^{-1} seed. Generally, SCA effects were quite small (Table 4.4.3).

Even though the hybrids were higher in glucosinolate content than the acceptable limit for registration (12 μmol g^{-1} seed), the parent strain checks were also quite high. The current commercial cultivar, MillenniUM03 had a glucosinolate content of 17.7 μmol g^{-1} seed. Eleven UM x EU hybrids and two UM x UM hybrids were significantly lower than MillenniUM03 and might be acceptable for registration (Table 4.4.7). Of the eleven UM x EU hybrids, eight were also lower than the lower glucosinolate parent (Table 4.4.7).

Table 4.4.7: Glucosinolate content and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	GLUC (μmol g^{-1} seed)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	14.8	-35.5 *	-21.7 *	-16.5 *
2	MillenniUM01 x EU HEAR 1	18.8	-12.2 *	0.0	6.6
3	MillenniUM03 x EU HEAR 1	14.8	-18.7 *	-16.0 *	-16.0 *
4	HR200 x EU HEAR 1	13.7	-22.0 *	-15.7 *	-22.6 *
5	HR102 x EU HEAR 1	14.8	-19.3 *	-16.7 *	-16.5 *
6	RRHR102 x EU HEAR 1	15.3	-18.8 *	-18.7 *	-13.7 *
7	HR199 x EU HEAR 1	17.7	-9.0	-6.2	0.0
8	Castor x EU HEAR 2	22.2	-9.1 *	1.1	25.5
9	MillenniUM01 x EU HEAR 2	21.4	-6.8	-2.3	21.3
10	MillenniUM03 x EU HEAR 2	19.8	-0.2	11.8	11.8
11	HR200 x EU HEAR 2	18.7	-2.1	15.2	5.7
12	HR102 x EU HEAR 2	18.0	-9.2	1.6	1.9
13	RRHR102 x EU HEAR 2	20.6	1.2	9.8	16.5
14	HR199 x EU HEAR 2	21.5	2.6	7.5	21.7
15	Castor x EU HEAR 3	16.1	-28.2 *	-10.3	-9.0
16	MillenniUM01 x EU HEAR 3	17.4	-17.0 *	-2.8	-1.4
17	MillenniUM03 x EU HEAR 3	13.2	-26.0 *	-25.4 *	-25.4 *
18	HR200 x EU HEAR 3	14.3	-16.0 *	-11.6	-18.9 *
19	HR102 x EU HEAR 3	15.5	-13.0 *	-12.5 *	-12.3 *
20	RRHR102 x EU HEAR 3	14.8	-19.1 *	-17.2 *	-16.0 *
21	HR199 x EU HEAR 3	18.7	-1.5	4.2	5.7
22	MillenniUM01 x EU HEAR 4	22.0	0.9	12.4	24.5
23	MillenniUM03 x EU HEAR 4	17.3	-6.9	-1.9	-1.9
24	HR200 x EU HEAR 4	17.1	-4.6	5.4	-3.3
25	HR102 x EU HEAR 4	16.3	-12.4 *	-7.8	-7.6
26	RRHR102 x EU HEAR 4	17.8	-7.4	-5.3	0.5
27	HR199 x EU HEAR 4	18.5	-6.5	-5.5	4.7
28	Castor x EU HEAR 5	18.8	-12.8 *	15.3	6.6
29	MillenniUM01 x EU HEAR 5	18.8	-7.1	14.8	6.1
30	MillenniUM03 x EU HEAR 5	15.7	-7.8	-4.0	-11.3 *
31	HR200 x EU HEAR 5	15.6	-4.2	-3.9	-11.8 *
32	HR102 x EU HEAR 5	17.1	0.4	4.6	-3.3
33	RRHR102 x EU HEAR 5	17.8	1.2	9.5	0.5
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	18.4	-14.5 *	13.6	4.3
35	Castor x HR102	16.8	-24.9 *	-5.4	-5.2
36	MillenniUM01 x HR102	17.8	-15.0 *	0.2	0.5
37	MillenniUM03 x HR200	16.0	-5.5	-1.3	-9.4
38	MillenniUM03 x HR102	16.7	-5.8	-5.6	-5.6
39	HR200 x HR102	14.3	-15.5 *	-11.6	-18.9 *
40	HR200 x RRHR102	15.9	-8.9	-1.8	-9.9
41	HR200 x HR199	17.2	-5.2	5.9	-2.8
42	HR102 x RRHR102	15.4	-15.4 *	-12.9 *	-12.7 *
43	HR102 x HR199	18.3	-2.8	3.5	3.8
44	RRHR102 x HR199	19.0	-1.9	1.3	7.6
45	EU HEAR 2 x EU HEAR 5	20.1	5.0	23.0	13.7
	UM x EU Mean	17.4 a	-10.5	-2.8	-1.5
	UM x UM / EU x EU Mean	17.2 a	-9.2	0.7	-2.9
	Overall Hybrid Mean	17.3 s	-10.2	-1.9	-1.8
	Max	22.2	5.0	23.0	25.5
	Min	13.2	-35.5	-25.4	-25.4
Parents					
46	EU HEAR 1	18.8			
47	EU HEAR 2	21.9			
48	EU HEAR 3	17.9			
49	EU HEAR 4	19.6			
50	EU HEAR 5	16.3			
51	Castor	26.9			
52	MillenniUM01	24.0			
53	MillenniUM03	17.7			
54	HR200	16.2			
55	HR102	17.7			
56	RRHR102	18.8			
57	HR199	20.0			
	Overall Parent Mean	19.7 t			
	Max	26.9			
	Min	16.2			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

4.4.6 Erucic Acid Concentration

HEAR hybrids were not significantly different in erucic acid concentration than the parent strains (Table 4.4.8). Similar ranges of erucic acid concentrations were observed for hybrids and parent strains. The hybrid with the highest mean erucic acid concentration was HR200 x EU #5 (57.0%) and the lowest was RRHR102 x EU #1 (49.1%). The parent strain with the highest erucic acid concentration was EU #5 (56.5%) and the lowest was EU #1 (45.1%). The international hybrids were not significantly different than the non-international parents (Table 4.4.8).

Seed yield and erucic acid concentration was found to have a negative correlation of r = -0.77** (Appendix Table B1). The higher seed yield hybrids (UM x EU #1 and EU #3) were observed to be lower in erucic acid concentration. UM x EU #4 hybrids had significantly higher erucic acid concentration than the mean erucic acid concentration mid-parent value. Only one hybrid was significantly higher for erucic acid concentration than the better parent. No significant commercial heterosis was found for erucic acid concentration in hybrids in this study. The parent strains used in this study were all at least 50% for erucic acid concentration which would indicate that all parents were identical in the alleles at the two loci which confer erucic acid concentration. It was reasonable to conclude that the hybrids would be identical to the parental genotype for these alleles.

The highest GCA parent strain was the current commercial cultivar MillenniUM03 (1.2 %). EU #1 and EU #3 parental strains were the lowest general combiners with GCA estimates of -3.5 and -2.7 % respectively. Generally, SCA effects were quite small (Table 4.4.3).

Table 4.4.8: Erucic acid concentration and heterosis estimates for HEAR hybrids and HEAR cultivars/strains grown in four environments 2004 and 2005

Cross #	Pedigree	Erucic Acid (%)	Mid-Parent (%)	High-Parent (%)	Commercial (%)
UM x EU Hybrid Crosses					
1	Castor x EU HEAR 1	50.0	6.1 *	1.8	-11.3
2	MillenniUM01 x EU HEAR 1	51.5	3.9	-4.6	-8.6
3	MillenniUM03 x EU HEAR 1	52.3	3.1	-7.2	-7.2
4	HR200 x EU HEAR 1	52.2	3.5	-6.4	-7.3
5	HR102 x EU HEAR 1	52.5	4.8 *	-4.7	-6.8
6	RRHR102 x EU HEAR 1	49.1	1.5	-5.1	-12.8
7	HR199 x EU HEAR 1	51.2	2.7	-6.3	-9.1
8	Castor x EU HEAR 2	53.7	6.4 *	3.5	-4.7
9	MillenniUM01 x EU HEAR 2	54.4	2.7	0.7	-3.5
10	MillenniUM03 x EU HEAR 2	53.7	-0.7	-4.6	-4.6
11	HR200 x EU HEAR 2	54.9	1.9	-1.7	-2.6
12	HR102 x EU HEAR 2	53.1	-0.6	-3.5	-5.7
13	RRHR102 x EU HEAR 2	50.9	-1.7	-1.9	-9.6
14	HR199 x EU HEAR 2	52.9	-0.6	-3.2	-6.0
15	Castor x EU HEAR 3	50.9	5.8 *	3.8	-9.6
16	MillenniUM01 x EU HEAR 3	51.8	2.5	-4.0	-8.0
17	MillenniUM03 x EU HEAR 3	53.3	3.1	-5.3	-5.3
18	HR200 x EU HEAR 3	52.4	1.7	-6.2	-7.0
19	HR102 x EU HEAR 3	53.4	4.4 *	-3.1	-5.2
20	RRHR102 x EU HEAR 3	49.7	0.6	-3.9	-11.7
21	HR199 x EU HEAR 3	51.7	1.6	-5.4	-8.2
22	MillenniUM01 x EU HEAR 4	55.2	11.8 *	2.3	-2.0
23	MillenniUM03 x EU HEAR 4	56.5	11.6 *	0.2	0.2
24	HR200 x EU HEAR 4	56.8	12.9 *	1.8	0.9
25	HR102 x EU HEAR 4	56.0	12.2 *	1.8	-0.5
26	RRHR102 x EU HEAR 4	54.8	13.5 *	5.9 *	-2.8
27	HR199 x EU HEAR 4	55.3	11.1 *	1.1	-1.9
28	Castor x EU HEAR 5	55.9	6.0 *	-1.0	-0.7
29	MillenniUM01 x EU HEAR 5	56.0	1.3	-1.0	-0.7
30	MillenniUM03 x EU HEAR 5	56.8	0.7	0.6	0.9
31	HR200 x EU HEAR 5	57.0	1.5	0.8	1.2
32	HR102 x EU HEAR 5	56.4	1.1	-0.2	0.2
33	RRHR102 x EU HEAR 5	55.2	2.0	-1.1	-2.0
UM x UM / EU x EU Hybrid Crosses					
34	Castor x HR200	56.0	6.8 *	0.4	-0.6
35	Castor x HR102	55.3	6.2 *	0.4	-1.9
36	MillenniUM01 x HR102	54.2	-0.5	-1.5	-3.7
37	MillenniUM03 x HR200	56.6	0.9	0.4	0.4
38	MillenniUM03 x HR102	55.4	-0.6	-1.7	-1.7
39	HR200 x HR102	54.9	-0.9	-1.6	-2.5
40	HR200 x RRHR102	55.0	2.2	-1.5	-2.4
41	HR200 x HR199	54.8	-0.8	-1.8	-2.7
42	HR102 x RRHR102	54.4	1.9	-1.2	-3.4
43	HR102 x HR199	56.0	2.0	1.6	-0.7
44	RRHR102 x HR199	53.6	0.7	-2.0	-4.9
45	EU HEAR 2 x EU HEAR 5	54.4	0.4	-3.7	-3.3
	UM x EU Mean	53.6 a	4.2	-1.7	-4.9
	UM x UM / EU x EU Mean	55.0 a	1.5	-1.0	-2.3
	Overall Hybrid Mean	54.0 s	3.5	-1.5	-4.2
	Max	57.0	13.5	5.9	1.2
	Min	49.1	-1.7	-7.2	-12.8
Parents					
46	EU HEAR 1	45.1			
47	EU HEAR 2	51.9			
48	EU HEAR 3	47.1			
49	EU HEAR 4	44.8			
50	EU HEAR 5	56.5			
51	Castor	49.1			
52	MillenniUM01	54.0			
53	MillenniUM03	56.3			
54	HR200	55.8			
55	HR102	55.1			
56	RRHR102	51.7			
57	HR199	54.7			
	Overall Parent Mean	51.8 s			
	Max	56.5			
	Min	44.8			

* - hybrids significant at $p \leq 0.05$

a,b - means of UM x EU hybrids and UM x UM / EU x EU hybrids followed by the same letter are not significantly different at $p \leq 0.05$

s,t - means of hybrids and parents followed by the same letter are not significantly different at $p \leq 0.05$

5.0 General Discussion and Conclusions

Hybrids with higher seed yields were very vigorous in early seedling development and in the development of crop canopy in comparison to the parent cultivars/strains used in this study. The higher yielding hybrids were later flowering and later maturing than all UM cultivars/strains, however, they were much earlier than the very late flowering and maturing EU #1 and EU #3 strains. Superior performing hybrids were much taller and had considerably better lodging resistance than the UM cultivars/strains.

The very high heterosis levels for seed yield (approximately 159% mid-parent, 155% high-parent, and 107% commercial heterosis), obtained for the best HEAR hybrids are much higher than previously reported in the literature. Previously reported maximum high-parent heterosis seed yield in spring *B. napus* hybrids were 40% for Sernyk and Stefansson (1983), 120% Brandle and McVetty (1989) and 72% for Grant and Beversdorf (1985) supports the results found in this study.

While the top 10 seed yield hybrids were lower than the parent strains for seed protein concentration, the oil concentration was higher with little change in the sum of oil and protein concentrations. Meal protein concentration showed that parents and hybrids did not differ significantly in actual protein within the meal portion of the seed. Many hybrids had lower glucosinolates than the parent strains, which improves meal quality. Erucic acid concentration of the superior yielding hybrids was generally lower than the parent strains but was nevertheless over 50% for almost all hybrids with the exception of two hybrids involving the glyphosate tolerant parent (RRHR102).

There were several superior performing hybrids produced in this study. HR102 x EU #3 had a very high seed yield with high vigor, good standability, was acceptable for maturity and also had superior seed quality traits. Another superior performing HEAR hybrid was HR102 x EU #1 which had similar agronomics to HR102 x EU #3 but also had very high seed oil concentration. HR199 x EU #3 was also a superior yielding hybrid with very high vigor, exceptional standability, good maturity, and acceptable seed quality traits.

Hybrid HEAR cultivars offer the promise of significantly higher seed yields combined with satisfactory performance for all agronomic traits, superior performance for oil content and adequate performance for protein content and erucic acid content. There appear to be many beneficial attributes and few detrimental attributes associated with HEAR hybrids.

The disease resistance of the HEAR hybrids used in this study was not evaluated but the HEAR cultivars or strains from the UM all rated R to blackleg and contain one or more dominant blackleg resistance genes, suggesting that the HEAR hybrids could also have adequate blackleg resistance.

Based on the results of this study, further development of hybrid HEAR cultivars appears fully justified. The estimates of GCA and SCA for each agronomic and quality trait will be helpful in predicting the optimal single-cross HEAR hybrids to be developed as soon as a satisfactory pollination control system is available for use in hybrid HEAR seed production.

The next step in HEAR hybrid research will be to incorporate a pollination control system such as Male Sterile Lembke (MSL), a presumed genetic genetic

pollination control system (GMS), or a CMS pollination control system (*mur* or *ogu* INRA) into selected HEAR strains. Using female lines which are good general combiners for many traits may be a good choice economically because the cost of producing male sterile (female lines) can be quite expensive. Female lines that can be used for many crosses will have much more use in a hybrid breeding program.

The pollination control system will facilitate production of much larger quantities of hybrid HEAR seed and allow these hybrids to be grown in multi-row, multi-replicate, multi-location yield trials to more fully assess their agronomic and seed quality performance. The HEAR hybrids should also be screened for disease resistance/tolerance to blackleg, sclerotinia and fusarium. Hybrids with good disease resistance should be selected for further screening. Another important objective for HEAR hybrid development will be to incorporate herbicide tolerance genes into the parental strains to produce herbicide tolerant HEAR hybrids that will be appealing to producers.

6.0 Literature Cited

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7.0 Appendix

7.1 Appendix A

Appendix Table A1: Seed quantities for University of Manitoba x EU HEAR hybrids produced during the 2003/2004 winter

Cross #	Female		Male	Weight (g)	TSW (g)	Total Seeds
1	Castor	X	EU HEAR 1	7.90	2.95	2680
2	MillenniUM01	X	EU HEAR 1	2.75	3.86	713
3	MillenniUM03	X	EU HEAR 1	7.69	3.55	2166
4	HR200	X	EU HEAR 1	11.77	3.83	3076
5	HR102	X	EU HEAR 1	10.63	4.54	2344
6	RRHR102	X	EU HEAR 1	7.64	2.49	3067
7	HR199	X	EU HEAR 1	8.57	2.86	2997
8	Castor	X	EU HEAR 2	7.69	3.53	2180
9	MillenniUM01	X	EU HEAR 2	12.74	3.73	3412
10	MillenniUM03	X	EU HEAR 2	18.13	3.69	4910
11	HR200	X	EU HEAR 2	10.61	3.69	2878
12	HR102	X	EU HEAR 2	16.61	4.13	4025
13	RRHR102	X	EU HEAR 2	17.77	2.66	6670
14	HR199	X	EU HEAR 2	15.86	4.16	3817
15	Castor	X	EU HEAR 3	14.41	3.69	3899
16	MillenniUM01	X	EU HEAR 3	13.60	4.06	3354
17	MillenniUM03	X	EU HEAR 3	4.33	3.88	1117
18	HR200	X	EU HEAR 3	9.75	3.67	2658
19	HR102	X	EU HEAR 3	14.62	3.35	4366
20	RRHR102	X	EU HEAR 3	10.26	2.58	3983
21	HR199	X	EU HEAR 3	14.87	4.39	3386
22	MillenniUM01	X	EU HEAR 4	13.71	3.86	3555
23	MillenniUM03	X	EU HEAR 4	12.58	3.93	3202
24	HR200	X	EU HEAR 4	15.87	4.41	3602
25	HR102	X	EU HEAR 4	13.92	4.80	2899
26	RRHR102	X	EU HEAR 4	5.75	2.95	1949
27	HR199	X	EU HEAR 4	14.45	4.90	2950
28	Castor	X	EU HEAR 5	11.75	3.27	3599
29	MillenniUM01	X	EU HEAR 5	14.46	3.42	4226
30	MillenniUM03	X	EU HEAR 5	10.20	3.23	3162
31	HR200	X	EU HEAR 5	12.90	3.87	3334
32	HR102	X	EU HEAR 5	13.49	4.21	3201
33	RRHR102	X	EU HEAR 5	11.49	2.79	4120

Appendix Table A2: Seed quantities for UM x UM hybrids produced during the 2003/2004 winter

Cross #	Female		Male	Weight (g)	TSW (g)	Total Seeds
34	Castor	X	HR200	7.42	3.68	2015
35	Castor	X	HR102	15.85	3.76	4213
36	MillenniUM01	X	HR102	13.82	4.13	3347
37	MillenniUM03	X	HR200	9.23	3.68	2506
38	MillenniUM03	X	HR102	10.17	3.83	2653
39	HR200	X	HR102	18.22	3.99	4568
40	HR200	X	RRHR102	10.40	3.66	2842
41	HR200	X	HR199	9.70	3.91	2481
42	HR102	X	RRHR102	14.27	3.87	3684
43	HR102	X	HR199	14.77	3.62	4076
44	RRHR102	X	HR199	11.57	2.81	4118

Appendix Table A3: Seed quantities for EU HEAR x EU HEAR hybrids produced during the 2003/2004 winter

Cross #	Female		Male	Weight (g)	TSW (g)	Total Seeds
45	EU HEAR 2	X	EU HEAR 5	11.21	3.91	2865

Appendix Table A4: Seed quantities produced from selfed parents during the 2003/2004 winter

Cross #	Female	Male	Weight (g)	TSW (g)	Total Seeds
46	EU HEAR 1	SELFED	5.73	2.02	2838
47	EU HEAR 2	SELFED	9.10	2.14	4258
48	EU HEAR 3	SELFED	18.85	1.68	11228
49	EU HEAR 4	SELFED	14.50	2.62	5544
50	EU HEAR 5	SELFED	10.65	2.34	4561
51	Castor	SELFED	23.44	1.84	12720
52	MillenniUM01	SELFED	14.15	2.38	5934
53	MillenniUM03	SELFED	14.55	2.12	6847
54	HR200	SELFED	35.95	2.09	17173
55	HR102	SELFED	13.55	2.15	6314
56	RRHR102	SELFED	14.15	1.54	9215
57	HR199	SELFED	10.45	1.86	5623

Appendix Table A5: Seed quantities for hybrids produced during the 2004/2005 winter

Cross #	Pedigree	2004 Seed (g)	2004/2005 Seed Increase (g)	Total Seed (g)
2	MillenniUM01 x EU HEAR 1	0.00	10.75	10.75
3	MillenniUM03 x EU HEAR 1	4.33	4.23	8.56
17	MillenniUM03 x EU HEAR 3	0.67	24.39	25.06
26	RRHR102 x EU HEAR 5	2.96	17.68	20.64
34	Castor x HR200	3.94	25.99	29.93

7.2 Appendix B

Appendix Table B1: Correlation matrix for selected agronomic traits and seed quality traits for HEAR hybrids grown in four environments 2004 and 2005

	Vigor (1-low to 5-high)	Flower (d)	Maturity (d)	Lodging (1-erect to 5-flat)	Height (cm)	Yield (kg ha^{-1})	Oil Conc. (g kg^{-1})	Protein Conc. (g kg^{-1})	PROM (g kg^{-1})	SUM (g kg^{-1})	GLUC (μmol g^{-1} seed)	Erucic Acid (%)
Vigor												
Flower	0.06											
Maturity	0.24	0.84 **										
Lodging	-0.36 *	-0.83 **	-0.85 **									
Height	0.40 **	0.85 **	0.89 **	-0.95 **								
Yield	0.55 **	0.66 **	0.82 **	-0.85 **	0.89 **							
Oil Conc.	0.43 **	0.56 **	0.67 **	-0.68 **	0.74 **	0.84 **						
Protein Conc.	-0.42 **	-0.52 **	-0.58 **	0.70 **	-0.73 **	-0.84 **	-0.94 **					
PROM	-0.27	-0.29	-0.24	0.51 **	-0.47 **	-0.56 **	-0.54 **	0.79 **				
SUM	0.37 *	0.47 **	0.65 **	-0.47 **	0.58 **	0.65 **	0.82 **	-0.59 **	0.02			
GLUC	-0.19	-0.20	-0.05	0.20	-0.17	-0.29	-0.34 *	0.39 **	0.45 **	-0.09		
Erucic Acid	-0.27	-0.83 **	-0.86 **	0.85 **	-0.90 **	-0.77 **	-0.64 **	0.60 **	0.33 *	-0.54 **	0.15	

* $r = 0.294$ at $p \leq 0.05$, $df = 43$, ** $r = 0.380$ at $p \leq 0.01$, $df = 43$