AGRONOMIC AND GROWTH CHARACTERISTICS OF SPRING SPELT COMPARED TO COMMON WHEAT

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Agronomic and Growth Characteristics of Spring Spelt Compared to Common Wheat

Spelt wheat (Triticum aestivum L. emend. Thell) (spelta group) is an ancient hulled specialty wheat being grown on a limited scale as a fall-sown crop in Western Europe. Little is known about the agronomics and growth characteristics of spring spelt, a potential specialty wheat for western Canada. The main objectives of this study were to compare the yield potential and growth characteristics of spring spelt wheat to that of common spring wheat (Triticum aestivum L. emend. Thell) in central Saskatchewan, using growth analysis; to investigate the response of spring spelt to seeding date; to determine the role of spelt glumes on seedling emergence and establishment under adverse temperature and moisture conditions.

The seeding rate and growth analysis experiment was conducted in the field using two spring spelt cultivars (CDC Bavaria and PGR8801) and a common wheat cultivar (Katepwa) at four seeding rates ranging from 150 to 450 seeds/m^2 at Saskatoon, Saskatchewan, in 1995 and 1996. The response of spring spelt and common wheat to seeding date was measured from late April to early June under field conditions over two years. The role of spelt glumes on seed germination, seedling emergence and crop establishment was studied under field conditions at an early (late April) and a late (early June) date of seeding over two years. Seed germination, seedling establishment and seed water uptake were studied under controlled environment conditions at water potentials ranging from 0 to −1.8 MPa, at temperatures of 9, 16 and 23 °C.

The field studies indicate that spring spelt is able to produce a comparable grain yield to common wheat. The same seeding rate as common wheat (150 to 250 seeds/m^2) can be used for spring spelt wheat in central Saskatchewan. Spring spelt's leaf area index (LAI), leaf area duration (LAD) and crop growth rate (CGR) are approximately 51, 53 and 16 per cent higher than common wheat, giving rise to 24 per cent higher biological yield for spring spelt compared to that of common wheat. Optimal seeding date for spring spelt is late April to early May because with late seeding spring spelt's grain yield tends to decrease. Seedling establishment for spring spelt is lower and less stable compared to that of common wheat, though the variation in seedling establishment does not influence the final grain yield.

Controlled environment studies indicated that the glume of spring spelt wheat acts as an obstacle to water uptake, leading to an approximate 25 per slower water uptake rate compared to naked seeds. The glume has negative impact on seed germination and seedling emergence. The negative impact of the glume on seed water uptake, seed germination and seedling emergence increases under drought conditions. Thus, only under sufficiently wet soil conditions may using hulled seed as the propagule lead to comparable establishment of spring spelt relative to common wheat. In conclusion, spring spelt can be grown successfully in central Saskatchewan, producing a comparable grain yield to common wheat provided it is seeded before mid May.

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ABSTRACT

Spelt wheat (Triticum aestivum L. emend. Thell) (spelta group) is an ancient, hulled, specialty wheat which is presently grown on a limited scale as a fall-sown crop in Western Europe. Little is known about the agronomics and growth characteristics of spring spelt, a potential specialty wheat for western Canada. The main objectives of this study were to compare the yield potential and growth characteristics of spring spelt wheat to that of common spring wheat (Triticum aestivum L. emend. Thell) in central Saskatchewan, using growth analysis; to investigate the response of spring spelt to seeding date; and to determine the effect of the hulls of spelt on seedling emergence and establishment under adverse temperature and moisture conditions.

The seeding rate and growth analysis experiment was conducted in the field using two spring spelt cultivars (CDC Bavaria and PGR8801) and a common wheat cultivar (Katepwa) at four seeding rates ranging from 150 to 450 seeds/m^2 at Saskatoon, Saskatchewan, in 1995 and 1996. The response of spring spelt and common wheat to seeding date was measured from late April to early June under field conditions over two years. The role of spelt hulls on seed germination, seedling emergence and crop establishment was studied under field conditions using an early (late April) and a late (early June) date of seeding over two years. Seed germination, seedling establishment and seed water uptake were studied under controlled environment conditions at water potentials ranging from 0 to –1.8 MPa, at temperatures of 9, 16 and 23 °C.

The field studies indicated that spring spelt can produce grain yield comparable to common wheat. The same seeding rate as common wheat (150 to 250 seeds/m^2) can be used for spring spelt wheat in central Saskatchewan. Spring spelt has a higher leaf area index (LAI), leaf area duration (LAD) and crop growth rate (CGR) than common wheat, giving rise to 24 per cent higher biological yield for spring spelt compared to that of common wheat. Optimal seeding date for spring spelt is late April to early May; with later seeding spring spelt's grain yield tends to decrease. Seedling establishment for spring spelt is lower and less stable than common wheat, though this variation in seedling plant density does not influence the final grain yield.

Controlled environment studies indicated that the hull of spring spelt wheat acts as an obstacle to water uptake, leading to an approximate 25 per cent slower water uptake rate compared to naked seeds. The hull has negative impact on seed germination and seedling emergence. The negative impact of the hull on seed water uptake, seed germination and seedling emergence increases under drought conditions. Thus, only under sufficiently wet soil conditions may using hulled seed as the propagule lead to comparable establishment of spring spelt relative to common wheat. In conclusion, spring spelt can be grown successfully in central Saskatchewan, producing a comparable grain yield to common wheat provided it is seeded before mid-May.

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1.0 INTRODUCTION

Bread wheat (Triticum aestivum L. emend. Thell) and pasta wheat (Triticum turgidum L.) together constitute the staple food of about 35 per cent of the world's population, while providing about 20 per cent of the total calories consumed (Breiman and Graur, 1995). These wheats owe their vast cultivation areas to the existence of a wide range of cultivars with different adaptations and their numerous end-uses.

Spelt wheat is a sub-group of allohexaploid wheat, T. aestivum. A brittle spike and hulled seeds are characteristics of this primitive wheat. Spelt (as hulled seed) is used traditionally for feeding animals in Western Europe (Abdel-Aal *et al.*, 1998b). Spelt cultivars (after removing the hull) with different kernel texture characteristics can potentially be used for baking, making pita breads and flaked cereal (Abdel-Aal *et al.*, 1998a). Few studies have evaluated the establishment and productivity of fall-sown spelt in the marginal crop production areas of Western Europe (for example, Ruegger *et al.*, 1990a, b; Ruegger and Winzeler, 1993; Rimle, 1995). Fall-sown spelt has a grain yield comparable to common wheat under wet-cool growing conditions (Ruegger and Winzeler, 1993). An acceptable grain yield under the above-mentioned conditions has been attributed to the spelt's ability to establish and grow in cool environments (Nesbitt and Sammuel, 1995).

All reported studies on the growth, development, and production of spelt wheat have been conducted in Europe (Ruegger *et al.*, 1990a, b; Ruegger and Winzeler, 1993; Rimle, 1995, Schmid *et al.*, 1996). In that part of the world, a hulled kernel (Percival, 1921), along with a relatively low grain yield, has limited spelt's production to wet areas characterized by heavy and hilly soils (McFadden and Sears, 1946). Spelt's ability to establish under the above harsh soil conditions (Schmid *et al.*, 1996) seems to be the reason of its culture in that type of conditions.

During the past decade or two, there has been an increased interest in organic farming systems due, mainly, to ecological concerns and interest in health food products. The comparable grain yield of spelt wheat and common wheat under wet soil moisture conditions, along with the spelt's capability to withstand some diseases have attracted the attention of organic farmers in Europe. In Canada, too, ecological concerns (*e.g.* excessive application of pesticides) coupled with an interest in spelt as a specialty crop have increased interest in introducing spring spelt wheats to Canada.

Spelt wheat cultivars may need different agronomic practices than common spring wheat cultivars grown in western Canada. Spelt differs from common wheat in plant morphology. Spelt is a tall wheat with lax leaves and more vegetative growth compared to common wheat (Ruegger *et al.*, 1990b; Ruegger and Winzeler, 1993; Rimle, 1995), which might need a different seeding rate relative to spring wheats in Western Canada. Where spelt is grown in Europe, it is adapted to marginal crop production areas (mountainous areas with heavy poor soils) where common wheat does not perform well. The spelt hull might have a beneficial effect on seedling establishment under sub-optimal conditions. According to Nesbitt and Sammuel (1995), the thick, tough hulls of hulled wheats provide protection to the kernel especially in a heavy wet soil. If this is the case, it could increase the emergence rate with harsh seedbed conditions (e.g. an early seeding date). Spelt cultivars, adapted to cool and wet soil conditions, might establish and perform better than common wheat if seeded early. If this is true, spelt wheat might be able to use a longer growth period.

Because there are no reports of spring spelt wheat growth and productivity in western Canada, efforts to introduce this crop hinge on some basic agronomic investigations. Studies of appropriate seeding rate, seeding date and the impact of seed form (naked vs. hulled) on crop establishment will shed some light on the question of spring spelt wheat performance in central Saskatchewan. This study had three main objectives. The first objective was to compare the agronomic performance and growth characteristics of spring spelt and common wheat through growth analyses at different seeding rates. The second objective was to investigate the response of spelt wheat to seeding date. The third objective was to investigate the impact of the hulls of spelt on seedling emergence and establishment under adverse temperature and moisture conditions.

2 .0 LITERATURE REVIEW

2.1 History and Origin of Spelt Wheat

Current knowledge concerning the history of crops is somewhat incomplete (Helbaek, 1960). For example, the beginning of cultivation of naked hexaploid wheat is not fully understood. For spelt wheat, the situation is even more unclear, as both the genetic and geographical origins of this type of wheat are disputed.

The word "spelt" was used for the first time in an edict of the Emperor Diocletian, 301 A.D (Percival, 1921; McFadden and Sears, 1946). Spelt has been identified in the deposits of the second millennium B.C. in Europe (Helbaek, 1960). This was about three centuries after the Roman Empire expanded to the Rhine and Danube, and came into contact with the German tribes. The word "spelta" is believed to be of Saxon origin (McFadden and Sears, 1946).

Most researchers (Percival, 1921; McFadden and Sears, 1946; Kuckuck, 1959; Helbaek, 1960; Andrews, 1964; Kema, 1992b; Nesbitt and Sammuel, 1995) agree that spelt is an ancestral type of common wheat (*i.e.* naked common wheat was originated from spelt). According to these authors, a cross between emmer wheat (T. turgidum L.) and a wild relative, *i.e.* einkorn wheat (T. tauschii (Coss.) Schmal), resulted in the formation of allopolyploid hulled wheats. The same mode of spike articulation for spelt and the progeny of the above-mentioned hybridization is the best support for this claim (Nesbitt and Sammuel, 1995). Furthermore, because of the lack of free-threshing ability, spelt is assumed to be a primitive, undifferentiated prototype of these allopolyploid wheats (McFadden and Sears, 1946). Later, mutations and/or further hybridization led to the formation of free-threshing allopolyploid wheat.

Whether spelt has two separate origins in Persia and Europe, or a single origin in the Near East is disputed. McFadden and Sears (1946) concluded that, based on historical and linguistic evidence, a European origin (southeastern Europe) for spelt is inevitable while evidence is lacking for an alternative origin, *i.e.* southwest Asia. They argued that spelt arose due to chromosome doubling in natural hybrids of tetraploid wheat and goat grass (Aegilops squarrosa sensu auct) in southeastern Europe. From there, spelt was carried into central and western Europe. Here, it came into contact with a free-threshing tetraploid wheat, to form free-threshing hexaploid wheats by natural hybridization. McFadden and Sears (1946) maintained that if spelt is a progenitor of the free-threshing European hexaploid wheats, its derivation must not have happened until the beginning of the Bronze Age in Europe or even later. They pointed out that spelt's brittle rachis and hulled seeds caused a transitory culture status everywhere until free-threshing forms displaced it. Contrary to the above arguments, Kuckuck (1959) used his observation of a region in central Iran, namely Bakhtiari, with its culture of spelt to rule out a European origin for this wheat. He observed winter, summer and intermediate spelt types that had the same anatomical basis as the Swiss forms. Crossing Iranian and European spelts resulted in no segregation of spike characteristics. Kuckuck (1959) concluded that Iranian and European spelts have a common origin, the Fertile Crescent.

If the geographical origin of spelt wheat is somewhere in the Fertile Crescent, then its emergence goes back to the beginning of agriculture. According to Helbaek (1960), hexaploid wheat emerged with the beginning of agriculture. He believes that wild emmer was forced, by man, to grow in specific environments, *i.e.* low latitudes, different from its original habitat. Mutations and selection in the new habitats yielded cultivated emmer, followed by hybridization with goat grass to form hexaploid wheat. The similarity of carbonized remains of emmer and spelt wheat creates difficulties in providing phylogenetic explanations on the origin of spelt. Therefore, spelt's distribution in time and space has not yet been ascertained (Nesbitt and Sammuel, 1995). Apart from disputes over spelt's origin, it seems that hulled wheats, including spelt, were mainly replaced by free-threshing wheats during the first millennium AD in Europe (Nesbitt and Sammuel, 1995). How cultivation of hulled wheats (including spelt) changed and finally ceased through time is not clear. According to Nesbitt and Sammuel (1995), economic pressure for increased productivity along with changes in culture and eating habits probably led to the selection of free-threshing wheats which respond better to increased inputs.

2.2 Taxonomic Status

The nomenclature and classification of spelt within the genus Triticum is not agreed upon (Beglinger, 1995). Bowden (1959) considered all known hexaploid wheats, including spelt, as subgroups of a single species, *i.e.* Triticum aestivum. Accordingly, an appropriate nomenclature for spelt wheat is Triticum aestivum (spelta. group) (Barnes and Beard, 1992). More recently, Cao (1997) confirmed the above nomenclature using RFLP and RAPD analyses. Nevertheless, even some of the most recent publications (*e.g.* Ruegger *et al.*, 1993; Beglinger, 1995; Rimle, 1995) have considered spelt wheat as a separate species, *i.e.* Triticum spelta.

2.3 Agronomic and Physiologic Attributes

Most of the available literature on growth characteristics depicts spelt as a hardy crop, relative to common wheat. Spelt wheat is one of the hardiest cereals in terms of resisting frost (Percival, 1921). The fact that hulled wheats are grown mainly in mountainous areas reflects their tolerance of poor growing conditions (high altitudes with high precipitations, heavy soils and cold winters), rather than their isolation (Nesbitt and Sammuel, 1995). The history of the appearance of spelt in Europe, for instance, shows that emmer wheat continued to be important in the lowlands of Western Europe, while spelt appeared in the uplands. Indeed, replacement of emmer wheat by spelt in Europe during the Bronze and Iron Age was a part of the expansion of agriculture onto poorer soils. Furthermore, spelt is known to possess natural defenses against fungal pathogens (Kema, 1992a and 1992b). Some spelt accessions show resistance to stem rust (McVey, 1990), as well as smut and bunt (Percival, 1921; Iordanskaya, 1996). Arseniuk *et al.* (1991) found no advantage of spelt over common wheat in reaction to Septoria nodorum.

The spike of spelt has a mode of disarticulation that differs from the rest of the hulled wheats in that the rachis breaks at the upper end instead of the lower end of the internode (Percival, 1921). A broad, hollow and weak rachis at the point of attachment of each spikelet creates an easy-breaking structure of the spike. The semi-brittle joints between the rachis internodes, along with the toughened hulls bring about the hulled character. Consequently, the product of a threshed spike consists of 21-32 per cent chaff, depending on the cultivar (Percival, 1921). Spelt wheat is usually taller than common wheat and lodges easily (Ruegger and Winzeler, 1993).

Comparing the responses of spelt and common wheat to limited water conditions, Cabeza *et al.* (1993) found a higher mortality in tillers of the spelt compared to the common wheat cultivars. Thus, the hardiness referred to as a characteristic of spelt might be true only when low temperatures and/or excess moisture are common, *i.e.* heavy soils. The photosynthetic rates for spelt and common wheat have been reported as comparable (Ruegger *et al.*, 1993), while another study showed that the photosynthetic rate of spring spelt was the lowest among hexaploid wheats (Khan and Tsunoda, 1970).

2.4 Quality Attributes

According to Percival (1921), the relatively low gluten content of spelt flour makes it valuable in production of confectioneries and pastry. In southern Germany, roasted spelt grain is used as a condiment in soups. Spelt wheat use in bread production, at the turn of the century, was mostly restricted to situations where it was milled along with bread wheat. Spelt wheat has a higher starch content than common wheat while having a similar protein content (Percival, 1921). Studies on wild and cultivated wheat accessions of all ploidy levels indicate that the lowest lysine content exists in T. aestivum sub groups aestivum and spelta, and T. turgidum var. durum (Waines *et al.*, 1986).

The information on nutritional characteristics and chemical composition of spelt wheat is contradictory (Cubadda and Marcconi, 1995). Some studies question the apparent end-use quality advantages attributed to spelt wheat (Ranhorta *et al.*, 1995; Ruegger and Winzeler, 1993). Comparing spelt with one common wheat cultivar, Ranhotra *et al.* (1995) provided evidence that spelt wheat is not superior to common wheat in terms of vitamins, protein, fiber and mineral content and digestibility. Lysine, which is the most deficient amino acid in wheat, was 28 per cent lower in spelt than in common wheat. Spelt's gluten content was similar to that of common wheat; it provides no advantage for individuals with sensitivity to gluten. Furthermore, spelt wheat had inferior baking quality compared to common wheat because of a shorter dough development time and poor mixing quality. The texture of bread from the spelt wheat was coarser than from common wheat. Accordingly, only if spelt is promoted as a specialty crop, where white bread standards would not apply, can it gain some acceptability. A slightly lower protein content of spelt than common wheat (11.8 *vs.* 12.5 per cent), was reported by Ruegger and Winzeler (1993).

More recent studies in western Canada have emphasized that the outcome of any quality comparison between spelt and common wheat depends on the cultivars examined (Abdel-Aal *et al.*, 1995 and 1997). CDC Bavaria and PGR8801 are two spelt accessions whose nutritional and compositional characteristics have proven to be different from those of the common wheat cultivar, Katepwa. Comparing five spring spelt accessions and one einkorn (T. monococum) with a common hard red spring wheat, Katepwa, and a durum wheat, Kyle, Abdel-Aal *et al.* (1995) established some differences in nutritional and compositional characteristics of spelt and common wheat. PGR8801 had higher soluble sugars, protein and ash than Katepwa and CDC Bavaria. CDC Bavaria had higher starch and fat content than Katepwa and PGR8801. CDC Bavaria and PGR8801 had less total and insoluble dietary fiber than Katepwa. The gluten content of PGR8801, CDC Bavaria and Katepwa was similar (77 per cent of total flour protein). In a recent study, Abdel-Aal *et al.* (1997) reported that spring spelt can have a comparable protein content to common wheat.

2.5 Cultivation Status

Most of the data about the agronomics of spelt wheat deals with fall-seeded spelt grown in Europe. It seems that the extent of cultivation of spelt wheat during the history of expansion of hexaploid bread wheat has been dependent on either the lack of an appropriate staple crop, a shortage of favorable environmental conditions for naked wheat, or an interest in using it as a specialty crop. According to Percival (1921) the greatest extent of its cultivation in the early 20th century was in Germany, where more than 314,000 ha, mostly in Bavaria, Wurtemberg, and Baden was planted to spelt wheat. Spelt wheat was cultivated before common bread wheat became prevalent in those regions. During the same period, Switzerland and Austria maintained the second and third positions, after Germany, in terms of area devoted to spelt, with 39,000, and 5,000 ha, respectively. No record of spelt wheat cultivation in Africa, India, China, or Persia was available at that time. Percival (1921) pointed out that the major obstacle to the expansion of spelt cultivation up to that time was the lack of an appropriate apparatus to remove the hull, rather than any environmental limitations. A recent report (Messmer *et al.*, 1996) indicates that spelt is currently cultivated on 2000 ha (approximately two per cent of the bread production area) of marginal land in Switzerland.

2.6 Relative Agronomic Performance of Spelt and Common Wheat

There are few reports in the literature on spelt wheat productivity. Almost all the available literature is related to the performance of spelt in Western Europe where it is cultivated as a marginal crop. There is, however, a general agreement between studies on a number of agronomic characteristics of spelt. A higher tillering rate (Ruegger *et al.*, 1990b; Ruegger and Winzeler, 1993; Rimle, 1995), along with taller plants (Ruegger and Winzeler, 1993; Beglinger, 1995; Rimle, 1995), later maturity (Beglinger, 1995; Rimle, 1995), larger grains (Ruegger *et al.*, 1990b; Beglinger, 1995; Rimle, 1995) and lower harvest index (Ruegger *et al.*, 1993; Beglinger, 1995; Rimle, 1995) than common wheat have been established as agronomic characteristics for fall-sown spelt cultivars. Ruegger *et al.* (1993) reported that harvest index of fall-sown spelt was 31 to 36 per cent compared to 43 to 44 per cent for winter wheat. A harvest index of 37 to 40 per cent has been reported for a number of spring wheat cultivars currently sown in western Canada (Hucl and Baker, 1988; Hucl, 1995). For some other growth and yield characteristics, reported comparisons between spelt and common wheat are contradictory (Schmid and Winzeler, 1990; Ruegger *et al.*, 1990b).

Almost all studies allude to the fact that growing under harsh conditions (wet-cool heavy soils) does not limit spelt productivity as much as the productivity of common wheat (Percival, 1921; Schmid *et al.*, 1996). According to Schmid and Winzeler (1990), spelt produces a higher number of spikes than common wheat. Ruegger *et al.* (1990b) noted that, due to higher tiller mortality, spelt produced the same number of spikes as common wheat. Common wheat and spelt produced a similar number of spikelets per spike, but an overall lower number of kernels per spike in spelt caused a lower grain yield compared to common wheat.

Ruegger *et al.* (1993) conducted a study on spelt wheat agronomic performance at low versus high altitudes, using low and high seeding rates. Overall, naked grain yield of spelt was lower than that of common wheat, but the magnitude of the difference at the high altitude was less than at the more favorable growing conditions at the low altitude. Hulled grain yield of spelt was greater than that of common wheat cultivars at the high altitude location only. Kernel size of spelt and common wheat did not differ significantly, while harvest index of spelt was always lower than that of common wheat (0.31-0.36 vs. 0.43-0.44). In another study (Ruegger and Winzeler, 1993) spelt produced a higher hulled grain yield at a high altitude than at a low altitude, while the overall (high and low altitude) hulled grain yield of spelt and common wheat were not significantly different. Yields of spelt and common wheat were not affected by seeding rate, and both showed a similar yield response to nitrogen fertilizer. A high spike yield at the low seeding rate compensated for a small number of spikes for both wheat types. Despite having a greater number of tillers, spelt produced a smaller number of spikes than common wheat, resulting in a comparable yield. A similar grain yield for spelt and common wheat was also reported by Rimle (1995), although spelt cultivars showed a greater yield stability than common wheat. According to Ruegger *et al.* (1990a), in an unfavorable year for cereal production, naked grain yield of spelt was higher than that of common wheat cultivars. In a favorable year, the naked grain yield of spelt was 20 per cent lower than that of common wheat. Hulled grain yield of spelt was always higher than the naked grain yield of common wheat. The authors related the yield stability of the spelt cultivars to their ability to produce a higher number of tillers along with heavier kernels than common wheat.

2.7 Seeding Date and Rate

Studies carried out on seeding rate of spelt are few in number and carried on fall-sown cultivars in Europe (Ruegger and Winzeler, 1993). No reports on seeding date of spring spelt are available. Ruegger and Winzeler (1993) studied two winter spelt and two winter common wheat cultivars at two seeding rates, 200 and 400 seeds/m^2 in Switzerland. The wheat types produced a similar grain yield at the two seeding rates, though a higher number of spikes was produced with the high seeding rate.

Results of early studies on spring common wheat in western Canada suggest that seeding spring wheat in early May and at a seeding rate of as low as 50 kg/ha is beneficial to productivity under the semi-arid environments which prevail on the prairies (Pelton, 1969; Larter *et al.*, 1971; Briggs and Aytenfisu, 1979). Increasing the seeding rate to 90-100 kg/ha and above did not improve grain yield and even decreased grain yield of spring wheat in central Alberta, southwestern Saskatchewan and Manitoba (Pelton, 1969; Larter *et al.*, 1971; Briggs and Aytenfisu, 1979). Seeding in late April and early May in Manitoba and central Alberta increased grain yield of spring wheat cultivars, compared to seeding in late May (Larter *et al.*, 1971; Briggs and Aytenfisu, 1979). Early seeding of spring cereals was recommended for Montana, Washington, and North Dakota (Black and Siddoway, 1977; Alessi *et al.*, 1979; Ciha, 1983).

Recent studies on seeding date of spring wheat suggest that relative yield with early versus late seeding is dependent, to a considerable extent, on the environment (Baker, 1990; Hucl, 1995). The grain yield of any seeding date is low if a period of severe drought coincides with a critical period of development. Seeding eight spring wheat cultivars in Central Saskatchewan after mid-May produced a higher grain yield than seeding in early May (Baker, 1982). Baker (1990) studied four semi-dwarf and five normal height spring wheat cultivars for their optimum seeding date. The highest grain yield was achieved, on average, with late May seeding dates. Cutforth *et al.* (1990) studied three Canada Prairie

Spring wheats and one Canada Western Red Spring wheat, Neepawa, over a range of seeding dates from late April to mid-June in Saskatchewan. They found that all cultivars had a near-constant grain yield when seeded from as early as possible to mid-May, while seeding later reduced grain yield. The only case in which late seeding increased grain yield was when an early spring drought was followed by a wet summer. Comparing four Canada Western Red Spring wheats under two contrasting seeding dates, Hucl (1995) found that delayed seeding decreased or increased grain yield, depending on the year. If reproductive development is delayed, due to late seeding, grain yield might increase or decrease depending on temperature and moisture regime during the growing season.

Eight spring wheat cultivars, representing a broad range of types, were compared over three seeding rates (Baker, 1982). The highest grain yield, on average, was achieved at the highest seeding rate, 430 seeds/m^2 (140kg/ha). Hucl and Baker (1990b) studied optimum seeding rate of a high tillering, low tillering and an oligoculm spring wheat cultivar. Seeding rates varied from 40 to 640 seeds/m^2. While seeding rate affected grain yield, the impact of seeding rate on the yield was dependent on year. In a dry hot year, for example, grain yield of all cultivars increased with seeding rate, while in a normal year, grain yield increased with seeding rates up to 320 seeds/m^2 only. Lafond (1994) studied a hard red wheat, a durum wheat, and a barley cultivar under zero-till management. He found that as seeding rates increased from 34 to 202 kg/ha, for wheat cultivars, and 27 to 161 kg/ha for barley, grain yield increased. A major portion of the increase in wheat grain yield was achieved with the increase in seeding rate from 34 to 70 kg/ha. A similar result was found under conventional fallow (Lafond and Derksen, 1996).

2.8 Germination and Establishment of Spelt Wheat

When harvested, spelt grain yield is mostly in the form of intact spikelets usually containing two and sometimes one or three kernels. Kernels are tightly enclosed in the hulls. Hulled kernels are often used for seeding purposes. Sowing this rather unique propagule seems to affect seedling establishment differently under differing field conditions. However, few detailed studies on the impact of the hull on germination and establishment of spelt are available. Ruegger and Winzeler (1993) reported that a higher number of plants were established for spelt than common wheat over a range of seeding rates. According to Percival (1921), the process of hull removal causes more than a 50 per cent decrease in germination of naked seeds, compared to hulled seeds.

In a study on seedling emergence of naked and hulled seeds under wet cool seedbed conditions, Riesen *et al.* (1986) found that per cent seedling emergence of hulled seeds was more than naked seeds. In this study, wet cool seedbed conditions were simulated by covering seeds with a three cm thick soil layer in a tray and the tray was filled with tap water and kept at 6/4 °C (day/night). The per cent of seedling emergence for winter wheat seeds was lower than that of naked and hulled seeds of the spelt wheat (2 vs. 21 and 29 per cent, respectively). Hulled spelt had lower infestations of soil-borne pathogens than naked spelt and winter wheat seed. Riesen *et al.* (1986) concluded that hulls protect the spelt seeds from fungal colonization. Ruegger *et al.* (1990c) reported a higher germination for hulled spelt seeds than naked seed of common wheat in a water logged soil. They observed a 40 per cent decrease in naked spelt seed germination, compared to hulled seeds, under field conditions. Under controlled conditions, the same germination was observed for hulled or naked spelt seed and common wheat seed when germinated under optimal conditions (Ruegger *et al.*, 1990c). Under cool-wet conditions, however, the presence of the hull produced a much higher germination than naked spelt or common wheat seed. Ruegger *et al.* (1990c) speculated that under favorable conditions, hulls reduced germination due mainly to a restricted uptake of oxygen and the competition of hull-inhabited microorganisms for oxygen.

Beglinger (1995) conducted a detailed study on the germination behavior of spelt wheat. A higher growth rate for the coleoptile of spelt wheat compared to that of common wheat was observed under laboratory conditions. This characteristic, along with a long coleoptile, would facilitate penetration of the spelt seedling through compacted soil in the field. According to Redmann and Qi (1992), seedling emergence of perennial grasses is positively affected by length of their coleoptiles when seeded in depth of a relatively dry soil. Beglinger (1995) did not elaborate on the mode of internode elongation and weather spelt's seedling emergence is through mesophile elongation or not. Beglinger (1995) did not give details of water uptake of different seed forms except that three hours of soaking led to an identical amount of water uptake for spelt and common wheat cultivars. A higher resistance to hypoxia of spelt than common wheat was observed when imitating low oxygen flow under laboratory conditions. Low oxygen flow condition was created by applying a gas mixture of 1 per cent O_2 and 99 per cent N_2 to jars containing spelt seeds (Schmid *et al.*, 1996). The seedling growth index of spelt was higher than that of common wheat. The difference between spelt and common wheat in seedling growth index increased with hypoxia. Beglinger (1995) concluded that hypoxia tolerance and rapid seedling growth are absolute necessities for germination in an atmosphere created by tight hulls.

2.9 Factors Involved in Seed Germination and Seedling Establishment

Seed germination involves the initiation of growth in a previously quiescent or dormant embryo (Bradford, 1990). Seed germination is initiated by water imbibition, which is the uptake of water by the dry seed. The movement of water into the seed is due to diffusion and capillary action (Woodstock, 1988). Seeds imbibe water by attraction of water by the cell wall and protoplasmic macromolecules such as proteins and polysaccharides (Woodstock, 1988). These constituents hold water by electrostatic forces, *i.e.* hydrogen bonds. The summation of osmotic and matric potential of a dry wheat seed reaches -400MPa (McDonald *et al.*, 1988) giving an enormous affinity between the seed and available water. Thus, the initial step of imbibition is independent of biological activities (Collis-George and Melville, 1975) and serves to saturate the pericarp by capillary movement (Becker, 1960). During the final step of the imbibition, biological activities, such as coleorhiza growth, hasten the imbibition rate. Thus, during imbibition, a rapid initial water uptake is followed by a plateau phase, and finally ends with a rapid water uptake due to radicle growth (Bradford, 1990). Since germination in its physiological sense is essentially complete with the initiation of embryo growth, the plateau phase that is coincident with little change in water content represents the main step in regulation of germination. Any promoting or inhibiting effects of internal (*e.g.* dormancy) or external (for example temperature and moisture status of the germination medium) factors on germination is through shortening or extension of the lag phase (Bradford, 1990).

The adverse impact of low soil water potential on imbibition rate and germination speed of different species has been established by a number of researchers (Lafond and Baker, 1986b; McDonald *et al.*, 1988; Qi and Redmann, 1993). Collis-George and Sands (1959 and 1962), Collis-George and Williams (1968), and Collis-George and Melville (1975 and 1978) have investigated the seed and soil water potential and soil-seed interactions and their impact on the outcome of imbibition, and in turn, germination under field conditions. In the early stages of water absorption, osmotic potential does not contribute much to the seed water potential because the seed storage material is not hydrolyzed and is mainly in the form of large grains (Collis-George and Melville, 1975). In a practical sense, seed has access only to vapor when it is embedded in a dry soil above a more moist soil layer (Collis-George and Melville, 1978). Since there is no effective liquid conductivity with the supply source, the hydraulic conductivity of the soil around the seed is negligible. Here, a water vapor pressure gradient leads to vapor transfer. Only if the water potential of the nearby supply source is less negative than the permanent wilting point, can sufficient imbibition and subsequently germination occur.

Seed, soil and seed-soil interaction characteristics aside, seeds must imbibe a minimum quantity of water before they proceed with germination. The threshold seed water content necessary for germination is not agreed upon (Bouaziz and Bruckler, 1989; Collis-George and Melville's, 1975). According to Bouaziz and Bruckler (1989), the non-limiting water range, where the impacts on seed imbibition and germination percentage are negligible, is 0 to -0.9 MPa. Germination is not ceased at water potentials up to -3 MPa. According to Bouaziz and Bruckler (1989), a typical wheat seed must reach a certain threshold of water content, *e.g.* 27%, in order to start germinating. In Collis-George and Melville's (1975) experiment, approximately, 68% moisture content of the wheat seed was necessary for germination at 20 °C, when seeds were exposed to a liquid water phase. When seeds were exposed to a pure vapor phase, Collis-George and Melville (1978) found that for 50% germination, a moisture content of 48 to 50 per cent was necessary. A vapor phase for water uptake often is the case under field conditions. An approximate 50 per cent, wet weight basis, seed moisture content was reported by Ashraf and Abu-Shakra (1978) as the threshold for germination of wheat. At water potentials more negative than -0.6 MPa, the water uptake rate decreased and the germination rate was slower. Cultivars differed in their rate of water uptake and rate of seed germination (Ashraf and Abu-Shakra, 1978). Furthermore, total germination decreased at water potentials more negative than -1.2 MPa. Sub-optimal temperatures (6.5 and 10.5 °C) did not reduce total germination. According to Naylor and Gurmu (1990), each species has a characteristic water potential below which the seed will not germinate; for wheat the minimum water potential lays between -0.7 and -1.2 MPa.

Some studies suggest that the impact of soil temperature on water imbibition and seed germination is greater than that of soil moisture. Studying the impact of varying temperature and moisture on water uptake and germination of winter wheat seed, Lafond and Fowler (1989) observed a greater impact of soil temperature, than soil water content, on seed water uptake rate and germination. With temperatures of up to 25 °C, the seed water content at germination decreased. With temperatures above 25 °C, water content increased, indicating that 25 °C is the optimal temperature for germination. Furthermore, water absorption by wheatgrass (Agropyron spp) seeds was directly proportional to temperature in the range of 4.5 to 27.8 °C (Keller and Bleak, 1970).

2.10 Growth Analysis

2.10.1 Approaches to Growth Analysis

After an annual plant is seeded, it loses weight for a short time after germination. The duration of this stage differs with plant species. Leaf differentiation of the seedling occurs during this period, leading to the loss in dry weight (Hunt, 1982). Newly differentiated leaves soon begin to assimilate. This development is followed by a period of rapid growth due to the unfolding of new leaves. With flowering, a major part of the assimilates is partitioned to the reproductive structures, slowing the rate of dry weight gain. With maturation, total dry weight accumulation ceases, while partitioning of reserves to the reproductive structures continues. Therefore, following an initial period of establishing a self-sufficient size, a constant assimilative efficiency leads to an increase in rate of dry mass accumulation (the exponential portion of growth) due to an increase in the amount of assimilative area. Eventually, a falling efficiency of assimilation leads to a linear period of growth. Finally, termination of growth leads to a leveling off of the growth curve. Together, the whole growth curve from the initial stage to maturity is sigmoidal.

Crop growth analysis is the analysis of change in mass or size during a specified period of time (Hunt, 1982; Gardner *et al.*, 1985). The amount or extent of growth during any specific time period is an outcome of the duration of that period and the rate of growth. The methodology of plant growth analysis started to develop in the 1920s with what is called the 'classical approach' initially proposed by Blackman (1919). Blackman (1919) suggested a constant index for plant growth based on the 'compound interest law'. Shortly thereafter, West *et al.* (1920) questioned the idea of a constant index for plant growth by emphasizing that growth rate is the increase in dry weight per unit time and it is determined by the amount of existing growing material and external factors. In higher plants all parts of the plant are not equally involved in forming new growth by cell division and assimilation. Therefore, West *et al.* (1920) concluded that when plant growth is related to its dry weight, growth is not related to the amount of actual growing material and the growth rate expressed per unit of dry weight does not remain constant throughout the growth period. Under these conditions, it is not possible to determine a constant index for plant growth even under constant external conditions. Furthermore, the effect of environmental factors cannot be easily determined. West *et al.* (1920) suggested the calculation of rates related to different units of plant weight based on frequent harvests throughout the life cycle. During the same period, concepts such as Relative Growth Rate (RGR) (the percentage rate at which the dry weight increases), Leaf Area Ratio (LAR) (the ratio of leaf area to plant dry weight) and Net Assimilation Rate (NAR) (the rate of increase in dry weight per unit leaf area) were developed. For each concept, the traditional approach to growth analysis included several measurements of changes in leaf area and plant weight and the calculation of averages of successive measurements. The main problem with the classical approach is that there are considerable fluctuations in estimation of RGR from harvest to harvest, due to deviations between the sample mean and the true population mean (Poorter, 1989).

The classical approach was challenged by the 'functional approach' in the 1960's. The development of the functional approach arose from the need to know the general trend of growth over time (Vernon and Alison, 1963; Hughes and Freeman, 1967; Radford, 1967). Therefore, a procedure based on frequent small harvests and employment of regression techniques was preferred to more infrequent but large harvests. The classical approach is characterized by infrequent large harvests. The functional approach is characterized by small frequent harvests. With small samples, the standard deviation of values for each harvest increases, compared to a larger harvest; but the information acquired over a long sampling period compensates for the large standard deviation. The advent of computers enabled researchers to fit curves to the growth data and led in turn to a widespread application of the `functional' approach (Poorter and Garnier, 1996). Two measurements, total dry weight and total leaf area, taken in the field from a single plant or a group of plants provide the raw data necessary for basic growth analysis measurements for either approach. The main difference between the two approaches is the frequency of measurements (Hunt, 1982). The functional approach is not free of pitfalls, however. The two main problems are the decision on the degree of the polynomial function and the statistical test for differences in RGR's (Poorter and Lewis, 1986; Poorter, 1989). Indeed, the basic assumption of the functional approach that the fitted growth function adequately describes the primary data is not realized in many practical cases.

Later, in the 1980's, shortcomings in the functional approach led to the suggestion of a so-called 'combined approach' for growth analysis. Researchers proposed that an algorithm should be applied that produces a minimum of unexplained residual, the smallest number of independent variables, and low order terms in the equation (Poorter and Lewis, 1986; Poorter, 1989). Poorter claimed that applying stepwise regression to use the simplest equation for RGR values, obtained by harvesting from a homogenous population of plants and by skipping one harvest each time, will resolve the shortcoming of the classical and functional approaches. Nevertheless, no agreement has been reached to date on an appropriate way to handle growth analysis data (Rowell and Walters, 1976; Gurevitch and Chester, 1986).

2.10.2 Analysis of Repeated Measurements

Growth analysis studies are associated with repeated measurements on the same experimental units. When several measurements over time are made on the same experimental unit, the final result is a number of values for each experimental unit. This is different from a situation where there is only one value or measure of 'outcome', as described by Gurevitch and Chester (1986), for each experimental unit. When having one value, analyzing that unit measure of outcome provides enough information about the treatment applied, while none of the assumptions of the analysis of variance are violated. With the former situation the experimenter is dealing with a set of dependent variables for assessing the performance or "outcome" in each experimental unit. A possible way of presenting the results is to analyze the data at each point separately along with graphical presentation. Presenting a graph and/or separate analysis for showing the effect of a treatment or procedure leads to a failure to obtain valuable information about the trends over time. It is also not possible to compare trends over time of the different treatments.

One of the basic assumptions of univariate analysis of data is that the measurements are independent of one another (Rowell and Walters, 1976; Steel and Torrie, 1980; LaTour and Miniard, 1983; Gurevitch and Chester, 1986). When an individual experimental unit is subjected to several measurements, there are often correlations among these measurements. This is the beginning point of the violation of the assumptions required by basic analyses of variance.

The above discussion suggests the need to employ a method to reduce each set of measurements on an experimental unit to a single weighted sum. Then, performing a univariate analysis on this weighted sum, as if it is the original measurement, will provide information that can be used to describe the trend over time or compare trends for different treatments. Orthogonal polynomial contrasts are suggested by some scientists for situations where a series of equal steps along an ordered scale are involved (Winer, 1971; Rowell and Walters, 1976; LaTour and Miniard, 1983; Gurevitch and Chester, 1986). In this approach, depending on the questions that an experiment has been conducted to answer, a list of contrasts on the repeated measurements is constructed. In other words, a set of linear functions of the variable over time is analyzed. In brief, treatment variation may be subdivided into linear, quadratic, *etc.* trend components by using orthogonal polynomials. Each component in an orthogonal set covers a different portion of the total variation, *i.e.* the components are additive (Winer, 1971).

2.10.3 Growth Analysis of Wheat

There is no detailed information on the growth aspects and growth analysis of spelt wheat. The only reference to growth characteristics of spelt is made by Ruegger *et al.* (1993), who reported a lower Leaf Area Index (LAI) for winter spelt than common wheat.

There is a close relationship between the green LAI value and the amount of light being intercepted by the plant and dry matter production increases with LAI (Shibles and Weber, 1965; Wilfong *et al.*, 1967). There is a point, *i.e.* optimum LAI (King and Evans, 1967), where an increase in LAI does not lead to a further increase in CGR (the increase in plant dry weight on a unit of land in a unit of time). Thus, maximum dry matter production is achieved at the optimum LAI. The optimum LAI for spring wheat is reported to be nine to ten (Watson *et al.*, 1963; King and Evans, 1967).

A CGR of 20 g m^{-2} d^{-1} is generally considered the average CGR of C_3 crops, which include wheat (Gardner *et al.*, 1985). In an artificial canopy of wheat, maximum CGR reached 30 g m^{-2} d^{-1} (King and Evans, 1967). Despite a close correlation between leaf area and plant dry matter (Aase, 1978), LAD is a more efficient expression of the photosynthetic capability of the plant than LAI because it takes into account both the magnitude of leaf area and its persistence over time (Helsel and Frey, 1978). Helsel and Frey (1978) found that the LAD for high-yielding oat (Avena sativa L.) cultivars was higher than that of a standard line. Baker and Gebeyehou (1982) concluded that LAD was closely associated with biological yield of two spring wheat and a barley cultivar. The relationship between LAD and yield is not limited to wheat and even cereals, as Kmec *et al.* (1998) found a linear relationship between yield and LAD of crambe (Crambe abyssinica Hochst. ex R. E. Fries). No reports are available on CGR and LAD of wheat under different seeding rates.

It is generally accepted that spelt wheat has lax leaves compared to common wheat (Percival, 1921; Ruegger and Winzeler, 1993; Begelinger, 1995; Rimle 1995). Some reports indicate that plant leaf angle affects productivity of cereal crops (Tanner *et al.*, 1966; Donald, 1968; Angus *et al.*, 1972; Walker *et al.*, 1988). Tanner *et al.* (1966) reported that the barley, wheat and oat cultivars with erect leaves had a higher yield than the cultivars with lax leaves. They concluded that the small grain cereals with erect leaves had a higher optimum leaf area index relative to those with lax leaves. According to Donald (1968, 1979), an ideal wheat or barley plant (for maximum productivity under ideal conditions) was one with small upright leaves. Angus *et al.* (1972) reported that with plant densities that produced a LAI of greater than four to five, barley cultivars with erect leaves outyielded those with lax leaves.

A number of studies indicate that final grain yield of cereals is little affected by the angle of leaf inclination (Austin *et al.*, 1976; Inner and Blackwell, 1983; Araus *et al.*, 1993). Austin *et al.* (1976) found that net carbon fixation by a winter wheat with erect leaves was greater than for a wheat with lax leaves, but the shortfall of the latter wheat was compensated for by a more effective translocation system during grain filling. They concluded that photosynthesis will be maximized when the leaves at the top portion of the plant are erect and those at the bottom portion are lax. Innes and Blackwell (1983) found that winter wheat cultivars with erect leaves produced a higher dry matter compared to those with lax leaves, but grain yield of both wheat types was similar. Tungland *et al.* (1987) reached a similar conclusion, where they found no difference in grain yield between barley cultivars differing in leaf inclination angle. Furthermore, barley cultivars differing in leaf angle responded similarly, in grain yield production, to seeding rate. Araus *et al.* (1993) reported that wheat lines differing in leaf inclination did not differ in yield. They found that wheat lines with erect leaves produced a higher number of spikes, but those lines with droopy leaves produced a greater number of kernels per spike and heavier kernels, resulting in yield component compensation. Furthermore, CGR at the 1-2 node and anthesis stages of erect and droop leaf types was similar.

2.11 Physiology of Wheat Grain Yield

Many developmental and physiological events throughout the life of a plant determine its grain yield (McMaster *et al.*, 1994). Wheat grain yield can be limited by both pre-anthesis (sink) and post-anthesis photosynthesis (source). Relative importance of source vs. sink is not fixed for any genotype, mainly because of its dependence on environmental factors (Fischer, 1975). While under stressful conditions a decrease in one or more yield components limits grain yield (*i.e.* sink limitation), under non-stress conditions a lack of sufficient assimilates to fill a large number of kernels (*i.e.* source limitation) often limits grain yield (Johnson and Kanemasu, 1982).

The source of assimilates that contributes to grain production can be from post-anthesis photosynthesis and stored pre-anthesis assimilates (Wardlaw, 1967; Fischer, 1979; Turner *et al.*, 1994; Palta *et al.*, 1994). Post-anthesis drought leads to an increase in contribution of pre-anthesis assimilates through increasing translocation from tillers bearing no spike (Palta et al., 1994) and the lower parts of the plant (Wardlaw, 1967) to kernels. The relative contribution of the stored pre-anthesis carbohydrates (mainly from labile carbohydrates in the stem and carbon skeleton of the leaf proteins) to kernel filling does not appear to exceed 10 (under well-watered conditions) to 23 per cent (under post-anthesis drought) of the final grain yield (Fischer, 1979). Kernel number increases with an increase in pre-anthesis growth. With the increase in pre-anthesis vegetative growth, however, soil water at anthesis decreases, leading to a decrease in source of assimilates available for kernel filling under limited rainfall conditions (Fischer and Kohn, 1966; Fischer, 1979; Turner *et al.*, 1994). Therefore, unless post-anthesis rainfall is sufficient for potential evapotranspiration, there is a trade-off between pre-anthesis and post-anthesis dry matter accumulation. Thus, under dry-land conditions an optimal level of vegetative growth is sought.

Area, duration and activity of the green tissue determine the amount of post-anthesis photosynthesis (Fischer and Kohn, 1966; Fischer, 1979). Drought, solar radiation and temperature influence post-anthesis photosynthate production. Drought influences kernel weight by altering the ratio of assimilates source:kernel (Fischer, 1979). If water is not limited, however, the sink strength affects the photosynthesis activity of the green tissues.

The three determinants of wheat grain yield are number of spikes per m^2, number of kernels per spike and kernel weight. Of the three components of wheat grain yield, spike number and kernel number are considered the major determinants (Middleton *et al.*, 1963; Lafond, 1994; McMaster *et al.*, 1994). Yield component compensation is a phenomenon normally observed between these components (Baker, 1966). Under conditions resulting in high tiller number per m^2, the spike number, and indirectly kernel number, is the major determinant of grain yield (Blue *et al.*, 1990). Under conditions resulting in low tiller number, kernel weight becomes more important in grain yield determination.

Both the number of kernels and the capacity of each kernel to utilise carbohydrates are important in determining the strength of the sink (Fischer and Kohan, 1966; Fischer, 1979). From the total assimilates produced post-anthesis, 20-30 per cent may be allocated to structural components of the spike and peduncle. Synthesis of lignin in the stem and stem respiration are important sinks for post-anthesis assimilates (Fischer, 1979).

In the Canadian prairies low rainfall during the growing season is a major reason for low wheat grain yields in many years (Campbell *et al.*, 1969). Environmental factors such as drought and high temperature have differing negative impacts on final wheat grain yield, depending on the stage at which the stress occurs (Fischer and Kohn, 1966; Langer and Ampong, 1970; Langer and Olugbemi, 1970; Wardlaw, 1971; Fischer, 1979; Entz and Fowler, 1988). The most sensitive period for each component coincides with the most rapid growth rate of that component (Entz and Fowler, 1988). Many experiments on the impact of stresses on sink-source relationships indicate that kernel number of the wheat spike is mainly determined before the anthesis and pre-anthesis events have minor impact on kernel filling and kernel weight (Fischer and Kohn, 1966; Langer and Ampong, 1970; Fischer, 1979). The critical period, when environmental factors such as drought, temperature and radiation have a large impact on kernel number, starts at about the booting stage and lasts until anthesis (Dubetz and Bole, 1973; Fischer, 1979; Singh, 1981; Entz and Fowler, 1990). The negative impact of environmental stress is through a reduction in dry matter accumulation and only if stress occurs suddenly at the flag leaf stage may it affect the reproductive organs. If drought or high temperature stress occurs at the double ridge formation stage of the plant growth, number of spikelets per spike is reduced (Langer and Ampong, 1970; Langer and Olugbemi, 1970; Wardlaw, 1971). Drought and high temperature during spikelet formation and anthesis can lead to reductions in kernel number per spike. Drought immediately after anthesis reduces kernel number per spike (Wardlaw, 1971). Reducing kernel number seems to be the most negative impact of drought and high temperature on final grain yield of wheat. The stresses can cause both damage to reproductive structures at the time of floret differentiation and alteration in allocation of carbohydrates to kernels at the onset of their formation after anthesis (Langer and Ampong, 1970; Langer and Olugbemi, 1970). Drought and high temperature after anthesis do not influence kernel number but they have negative impact on kernel weight (Day and Intalap, 1970; Langer and Ampong, 1970; Langer and Olugbemi, 1970; Entz and Fowler, 1988). However, kernel weight is not as closely related to grain yield as kernel number (Entz and Fowler, 1990).

3.0 MATERIALS AND METHODS

3.1 Seeding Rate Experiment

3.1.1 Cultivars, Agronomic Measurements and Growth Analysis

The objective of this study was to evaluate the agronomic performance of spring spelt wheat cultivars and their growth characteristics relative to common wheat utilizing different seeding rates. CDC Bavaria and PGR8801 and the common wheat cultivar Katepwa were sown at seeding rates of 150, 250, 350 and 450 naked seeds/m^2 (approximately 55, 92, 130 and 167 kg ha^{-1}, respectively, for Katepwa). Naked spelt seeds were used in this experiment to effectively control number of seeds sown. The two spelt cultivars have a spring growth habit (P. J. Hucl, personal communication). CDC Bavaria is a spring-type spelt of European origin. CDC Bavaria is adapted to the Dark Brown soil zone of Saskatchewan and is resistant to common bunt but susceptible to stem rust (P. J. Hucl, personal communication). CDC Bavaria has soft kernels and is susceptible to lodging. PGR8801 was obtained from Plant Gene Resources of Canada and is identified in the USDA as PI428177. The latter is a spring spelt, which has hard kernels and is resistant to lodging. Katepwa, a backcross derivative of Neepawa with resistance to stem rust, is a hard red spring wheat widely adapted to the Canadian prairies (Campbell and Czarnecki, 1987). Therefore, it was used as a check cultivar in this experiment as well as in the following experiments. The above seeding rates were tested because, in the literature, the optimal seeding rate for common wheat in western Canada varies from 50 to 160 kg/ha (Baker, 1982; Hucl and Baker, 1990b; Lafond, 1994). Seeds were sown on 3 May in 1995 and 2 May in 1996 at a soil depth of 3-4 cm. The seeding date reflects recommendations for the Canadian prairies (Pelton, 1969; Larter *et al.*, 1971; Briggs and Aytenfisu, 1979). The soil type was a Bradwell clay loam. The study was conducted at the Seed Farm, University of Saskatchewan, Saskatoon (52 °N Lat, 104 °W Long) in both years. Ammonium phosphate (11-55-0) was drilled in with the seed at a rate of approximately 50 kg ha^{-1} (Lafond and Baker, 1986a; Hucl, 1995). All field experiments were conducted on fallowed land.

Each experimental unit, *i.e.* plot, consisted of 24 rows, each 3.6 m long, spaced 0.3 m apart. Weekly measurements were carried out on above-ground biomass and leaf area over a 12-wk period in 1995 and 14-wk period in 1996. Sampling continued from 30 May to 15 August in 1995 and from 29 May to 28 August in 1996. At each harvest, a 1-m section of plants was cut at ground level from two rows. Measuring leaf area of the whole sample would have resulted in the extension of the measurement period and consequently wilting of the leaves. Therefore, only a portion of the harvested sample was used for leaf area measurements. The samples were weighed immediately after harvesting and one quarter (weeks 1-3 and 9-12 for 1995, and 1-3 and 12-14 for 1996) or one eighth (weeks 4-8 for 1995 and 4-11 for 1996) of the harvested sample was stored immediately in a plastic bag and used for determining LAI. The bagged materials were stored at 10 °C during the leaf area measurement period. The remainder of the sample was oven-dried for 48 h at 80 °C, and then weighed, to determine dry matter production. Final aboveground dry matter yield per ha (DM) was estimated using the last sample in each year. A 0.25-m long border of standing plants was left between harvested areas. Leaf areas (LAI) were measured by a LI-3000A Portable Area Meter (LI-COR-INC. 4421 Superior Street, P.O. Box 4425, Lincoln, Nebraska). Green leaves were detached from stems of the sample and passed through the instrument to estimate the LAI.

Average leaf area index (LAIave, $m^2 m^{-2}$), leaf area duration (LAD, wk $m^2 m^{-2}$) and crop growth rate (CGR, g m^{-2} day^{-1}) were estimated based on the weekly measurements. From the 12 and 14 LAI estimates obtained for each plot in 1995 and 1996, respectively, an average was calculated, excluding the last two harvests. The last two harvests were not included because plants were approximately at the physiological maturity stage at this time and in some plots virtually no green leaves were present. A good approximation of the amount of the assimilatory system of the canopy during crop growth is the integral of the LAI over the growth period (Radford, 1967). For each field plot, LAI values were plotted against time. The area under the curve was used for estimating LAD (Dunphy *et al.*, 1984; Kmec *et al.*, 1998). The area was estimated by integrating the curve (Major, 1977) between the first (first week of June) and last measurements (early August and mid-August in 1995 and 1996, respectively).

It is generally accepted that total dry matter production of any crop is related to the rate of dry matter production during the linear growth phase (Gardner *et al.*, 1985). Furthermore, if one calculates the slope of the best fitting line during this period, the slope of the line is, in fact, the rate of dry matter accumulation for this period, *i.e.* Crop Growth Rate. The linear portion of the curve for each year was selected. The linear portion of the curve corresponded with the six weeks from the 20^{th} June to the end of July for both years of the study. A regression line was fitted to the linear portion and the regression coefficient was used for calculating CGR.

Leaf angle (mean foliage tilt angle) was estimated (Welles and Norman, 1991) at the flag leaf stage (the 7-leaf stage for the spelt cultivars) on 23 June and 22 June in 1995 and 1996, respectively. Leaf angle was determined nondestructively using a LAI-2000 Plant Canopy Analyzer (LI-COR, Inc., P.O.Box 4425, 4421 Superior Street, Lincoln, Nebraska 68504, USA). This instrument consists of an optical sensor and a control box. The sensor contains an optical filter to restrict sensed radiation to wavelengths below 490 nm and the data received by the sensor are recorded by the control box that calculates mean inclination angle of the foliage (Welles and Norman, 1991). The basic technique involves a pair of measurements of sky brightness, one from a leveled (skywards) sensor above the canopy and the second measurement taken (by leveling the sensor) beneath the canopy. The leaf angle value for each plot was an average of five measurements.

Five plants in each plot of the second seeding rate (250 seeds/m^2) of CDC Bavaria and Katepwa were tagged in 1996. Growth stage determinations (Haun, 1973) were carried out on the main stem of the tagged plants on a weekly basis until anthesis. After anthesis, development of the plants was assessed based on the Feekes (Large, 1954) scale.

In 1996, the Belgian Lodging Index (Oplinger *et al.*, 1985) for each plot was determined, using the formula:

$$LI = S \times I \times 0.2 \quad \text{(Eq. 3.1)}$$

In this formula S = area of surface lodged (1 = no lodging, 9 = totally lodged), I = intensity of lodging (1 = completely upright, 5 = completely flat), and 0.2 = factor used in order to obtain an index in the range of 0.2 (no lodging) to 9.0 (completely lodged).

Seedling, tiller and spike number per m^2 were measured using two labeled rows each 0.5 m in length (Hucl and Baker, 1988). Tiller mortality percentage was calculated in the following manner :

(Tiller number-Spike number) x 100/Tiller number

Spikelets/spike, kernels/spike, spikelet yield, and spike yield were determined using 10 randomly harvested spikes from each plot. Plant height was measured from the ground level to the top of the awns. Grain yield was estimated by combine harvesting four intact rows of each plot. Since spelt is traded in the hulled seed form (Ruegger *et al.*, 1990a; Ruegger and Winzeler, 1993), spelt yield was presented in the hulled form and compared to the grain yield (naked) of common wheat for this experiment and other field experiments. Kernel weights were determined from a 500-kernel subsample. Harvest index was determined for each plot based on the 12th (1995) or 14th (1996) harvest. Harvest index based on naked grain yield was calculated for each plot as naked grain yield divided by the sum of grain yield, chaff, and straw and expressed as a percentage. For determining harvest index (based on naked grain yield) in spelt cultivars, hulled grains were passed through a de-awning machine three to four times.

3.1.2 Experimental Design and Statistical Methods

The experimental design was a randomized complete block with four replications, repeated over two years. The treatment design was a factorial with three levels of cultivar and four levels of seeding rate.

The main objective of repeating agricultural experiments is to include a wide range of environmental conditions. This increases the level of confidence about the reliability of the results for upcoming years or a wider range of locations. If inferences are to be made beyond the levels of the variable that has been chosen as a treatment, then effects of that variable must be considered as random effects. When years and locations are considered as random effects, the basic assumption is that the chosen years and locations are random samples of the up-coming years or all possible locations. This assumption too often is not met. Since there is no control over replications and years, they are usually assumed as random effects. However, as LaMotte (1983) argues, in some cases there is no clear cut answer to the question of whether treatment effects are random or fixed. Under these circumstances, the decision should be based on inferential objectives and the credibility of the designation. In this experiment, inferences are limited to the years 1995 and 1996. Year effects were assumed to be fixed. Furthermore, interactions of year and other factors are fixed. Therefore, except for replications, the rest of the factors were assumed to be fixed effects. Since the same set of cultivars and seeding rates were used in both years, cultivars and seeding rates were crossed with years. Furthermore, the error term (residuals) is always nested. When treatment effects include both fixed and random effects, the correspondent statistical model will be a mixed model. The statistical model was:

Y= Year Replication (Y) Cultivar Year*Cultivar Seeding rate Year*Seeding rate Cultivar*Seeding rate Year*Cultivar*Seeding rate Error.

When an experiment is conducted under different environmental conditions, care must be taken to meet the assumptions of the analysis of variance, when an ANOVA is used for analyzing data. These assumptions include: an additive effect of the environment and treatment effects, experimental errors which are random, independent, and normally distributed around zero, along with a common variance. The latter assumption often is not met (Cochran and Cox, 1957). In order to determine if the error variances of two years were homogeneous, Bartlett's test (Steel and Torrie, 1980) was carried out. The variances for years were heterogeneous for harvest index and LAD. In order to ensure that the F-tests for year x cultivar, year x seeding rate, and year x cultivar x seeding rate interactions in harvest index and LAD were not affected by heterogeneity in the error variances, F-tests for the above traits were performed using both 33 and 66 degrees of freedom for the denominator (Cochran and Cox, 1957; section 14.22). The observed F did not fall within the limits of the two F-tests for each trait. Thus, analyses of variance were combined over years and the pooled variance was used as an error term for performing the F-tests and mean comparison for all agronomic and growth analysis traits. The F-test for year effect was performed using Replication (Year) as an error term. The SAS General Linear Model (GLM) procedure (SAS Institute Inc., Cary, NC, 1988) was used for analyzing all data. The Least Significant Difference (LSD) test was used to determine the statistical differences between those means with significant F-test values. Meaningful orthogonal contrasts were used to carry out comparisons such as Katepwa versus spelt and CDC Bavaria versus PGR8801. The response to seeding rate was evaluated using orthogonal polynomial contrasts.

3.2 Seeding Date Experiment

The objective of this study was to investigate the response of spring spelt to seeding date. The spelt wheat cultivar CDC Bavaria and common wheat cultivar Katepwa were used in this study. Seeding dates covered a six-week period from late April to early June, in one-week intervals in 1995 and 1996. April 24, May 2, 8, 16, 23, and 29, were the six dates of seeding in 1995. May 1, 9, 15, 23, 29 and June 6 were the six dates of seeding in 1996. These seeding dates were tested mainly because early May is recommended as the optimal seeding date for spring common wheat in Canadian prairies (Pelton, 1969; Larter *et al.*, 1971; Briggs and Aytenfisu, 1979). A seeding rate of 250 seeds/m^2 was used. Naked seeds of the spelt wheat were used for this study because of the importance of having uniform seeding rates and also difficulty in seeding using current seeders. Seeding depth, location of the experiment, and fertilizer were as in section 3.1. Seedling, tiller, spike, kernel, and spikelet number, kernel weight, and grain yield, were determined as described in 3.1.

Speed of emergence was estimated by calculating the coefficient of velocity (CV), using data collected from daily counts of emerged seedlings:

$$CV = 100[\Sigma N_i]/[\Sigma N_i T_i] \quad \text{(Eq. 3.2)}$$

In this equation, N_i is the number of seeds emerged on day $_i$ while T_i is the number of days from sowing (Kotowski, 1926). The coefficient of velocity is the reciprocal of mean time to germination or emergence multiplied by 100. Increase in number of germinated seeds and/or decrease in number of days required to reach a certain number of germinated seeds increases the CV value.

Growing degree-days (GDD) were estimated using 5 °C as the base temperature. Environment Canada data collected at the Saskatoon Airport was used for estimating the GDD. Degree-days for each day were calculated by subtracting the base temperature from the mean daily temperature. When the mean daily temperature was not greater than the base temperature, the GDD was set as equal to zero (Cao and Moss, 1991a,b). Estimates of GDD were used to compare heading of spelt and common wheat. In addition to estimating days to 50% spike emergence, days to physiological maturity were determined using complete loss of green color of the hulls (Hanft and Wych, 1982) for each plot.

In order to compare the developmental pattern of spelt and common wheat, the development of the apical meristem between Haun stages (Haun, 1973) 2.0 to 6.0 was studied in 1996, using a microscope with a 12.5x magnification. The objective of this experiment was to determine whether spelt and common wheat differ in terms of time to reach the double-ridge stage. The fourth (May 29) and fifth (June 6) seeding dates were chosen for this purpose. Starting at the 2.0-3.0 Haun stage, five randomly selected plants (five plants per plot) of the two cultivars were harvested periodically (at 2-4 day intervals). Freshly harvested plants were brought to the laboratory where the main culm of each plant was dissected and the stage of development of the growing point or young spike was recorded using a 12.5x-magnification binocular microscope.

The experimental design was a four-replicate split plot RCBD, repeated over two years. Seeding dates were assigned to the main plots and cultivars to subplots. Each plot consisted of eight rows, each 3.6 m in length, spaced 0.3 m apart. As in the seeding rate experiment, since inferences are limited to only these two years, year effects were assumed to be fixed. Furthermore, interactions of year and other factors are fixed. Therefore, except for replications, the rest of the factors were assumed to be fixed effects. Since we have used the same set of cultivars at six seeding dates, ranging from late April to early June, in both years, cultivars and seeding dates were crossed with years. The statistical model was :

Y= Year Replication(Year) Seeding date Replication*Seeding date(Year)
Year*Seeding date Cultivar Year*Cultivar Cultivar*Seeding date
Year*Cultivar*seeding date Error.

The SAS General Linear Model (GLM) procedure (SAS Institude Inc., Cary, NC, 1988) was used for analyzing all data. Mean square of Replication(Year) was used as denominator for F-tests related to year effects. The mean Square of Replication*Seeding date(Year) was used as denominator, *i.e.* error a, for F-tests related to seeding date and year*seeding date effects. The error mean square was used as denominator, *i.e.* error b, for F-tests related to cultivar, year*cultivar, cultivar*seeding date, year*cultivar*seeding date effects. For comparisons involving different cultivars at different seeding dates, a synthetic mean square was calculated and Satterthwaite (1946) approximation was used to estimate an appropriate denominator and degrees of freedom. Bartlett's test for homogeneity of variances (Steel and Torrie, 1980) was conducted. For velocity of emergence, kernel weight and days to maturity the test detected a significant variation between errors for the two years. In order to ensure that the F-tests for year x cultivar, year x seeding date, and year x cultivar x seeding date interactions in the latter traits were not affected by the heterogeneity of the error variances, F-tests for the above traits were performed using degrees of freedom of one year and the pooled error for the denominator (Cochran and Cox, 1957; section 14.22). The observed F value did not fall within the limits of the two F-tests for each trait. Thus, analyses of variance for all characteristics were combined over years and the pooled variances were used as error terms for performing the F-tests and mean comparisons. The Least Significant Difference (LSD) test was used to determine the statistical differences between those means with significant F-test values. Orthogonal polynomial contrasts were employed to partition the variances due to seeding dates.

3.3 Seed Form Effects on Crop Establishment and Yield Traits

The objective of this study was to investigate if the hulls of spring spelt influence seedling establishment under field conditions at contrasting seeding dates. Naked and hulled seeds of the spelt cultivars CDC Bavaria and PGR8801 in addition to the naked seeds of the common wheat cultivar Katepwa were evaluated for potential seedling establishment differences. The term 'seed form' is used to describe naked and hulled seeds of the two spelt cultivars and the naked seeds of the common wheat cultivar. Naked seeds of spelt wheat were obtained by passing hulled kernels through a custom-built de-awning machine. A weighed sample of each of the two spelt seed lots was obtained. These samples were dehulled and the number of kernels in each sample determined. Based on the ratio of kernel number to hulled sample weight, hulled seed weight equivalent to the number of seeds required for each plot was estimated. An early seeding date (April 24 in 1995 and May 1 in 1996) and a late seeding date (May 29 in 1995 and June 6 in 1996) were used. These extreme seeding dates were tested because there are some reports on a protective role of the hull on sown seeds of winter spelt under wet-cool soil conditions in western Europe (Riesen *et al.*, 1986; Ruegger and Winzeler, 1993). The site of the study, seeding rate, seeding depth, fertilizer application, plot size and row spacing, assessment of agronomic characteristics, seedling, spike, kernel, and spikelet number, kernel weight, and grain yield were as described in 3.2. Speed of emergence was estimated as described in section 3.2.

The experimental design was a randomized complete block with four replications, repeated over two years. Replications were nested within seeding dates. All factors, with the exception of replication, were considered as fixed. The statistical model was:

Y = Year Replication (Year Seeding date) Seeding date Year*Seeding date Seed form Year*Seed form Seeding date*Seed form Year*Seeding date*Seed form Error.

Bartlett's test for homogeneity of variances indicated that error variances for the two years were not homogenous for spikes/m^2, kernels/spike, spikelets/spike, and grain yield. In order to ensure that the F-tests for year x seed form, year x seeding date, and year x seed form x seeding date interactions for the latter traits were not affected by heterogeneity in the error variances, F-tests for the above traits were performed using degrees of freedom of one year and the pooled error for the denominator (Cochran and Cox, 1957; section 14.22). The observed F value did not fall between the limits of the two F-tests for any trait. Thus, analyses of variance for all traits were combined over years and the pooled variances were used as error terms for performing the F-tests and mean comparisons. Year, seeding date, and year x seeding date interaction effects were tested against the mean square for the replication (year seeding date). Seed form, year x seed form, seeding date x seed form, and year x seeding date x seed form interaction effects were tested with the mean square for the pooled error. Protected Least Significant Difference (LSD) tests were used to compare means. Meaningful orthogonal contrasts were used to carry out specific comparisons with regard to different seed forms, *i.e.* naked vs. hulled seed form of the spelt cultivars, two seed forms of the two spelt cultivars vs. common wheat and CDC Bavaria vs. PGR8801.

3.4 Controlled Environment Experiments

The objective of these experiments was to evaluate the impact of the spelt hull on spelt seed germination and seedling establishment under controlled environment conditions. The impact of hulls on water uptake by the spelt seed relative to naked seed of common wheat was also investigated.

3.4.1 Preliminary Seed Germination Experiment

Two preliminary experiments were performed on those seed forms which were used in the field and will be used in indoor seed germination and seedling emergence experiments. The main purpose of these experiments was to assess possible difference between naked and hulled seeds of spelt wheat and between common and spelt wheats in level of germination and velocity of germination under controlled conditions. Some reports (Clarke and DePauw, 1989) indicate that mechanical threshing enhances germination of wheat. However, some other reports indicate that improper harvesting methods (*e.g.* high cylinder speed of the combine) reduces seedling emergence and grain yield of hard red spring wheat (Bourgeois *et al.*, 1996). Therefore, assessing the possibility of abrasion, and its impact on germination due to mechanical dehulling the spelt was of interest.

Two spelt wheat cultivars, CDC Bavaria and RGR8801, and a common wheat cultivar, Katepwa, were studied. For spelt cultivars, three types of seed were used; dehulled by hand, dehulled by machine, and hulled. Comparison of germination for hand-dehulled and machine-dehulled spelt seeds would reveal any probable impact of mechanical threshing on seed germination. Dehulling by machine took place by passing a spelt seed lot, obtained from combine harvesting, through a rubber belt de-awning machine three times. For naked seeds of spelt cultivars and common wheat, 50 intact seeds were placed on two layers of Whatman No. 1 filter paper in each petri dish. For hulled seeds of spelt cultivars, 50 spikelets were placed on two layers of Whatman No. 1 filter paper in each petri dish. After adding 10 ml water, petri dishes were placed in an incubator at 4 °C, in darkness. After five days petri dishes were transferred to 18 °C in darkness. Germination was measured at 24 h intervals. Seeds with a radicle of at least 10 mm in length were considered germinated. After each counting, germinated seeds were discarded. A coefficient of velocity of germination was calculated using the equation:

$$CV = 100[\Sigma N_i]/[\Sigma N_i T_i] \quad \text{(Eq. 3.3)}$$

For this study N_i was the number of germinated seeds on day i. T_i was days after incubation at 18 °C. All methods and materials for the two preliminary experiments were the same, except that in the second experiment for hulled seeds of spelt, the number of spikelets was adjusted to provide 50 seeds per petri dish. Following the addition of water, dishes were immediately transferred to 18 °C. The experimental design for each experiment was a completely random design with four replications.

3.4.2 Seed Germination of Spring Spelt Relative to Common Wheat

The germination percentage and germination velocity of differing seed forms of wheat was assessed under contrasting water regimes and temperatures. Naked and hulled seeds of each spelt cultivar and naked seeds of the common wheat cultivar Katepwa were used as the five treatments. In the following (tables of ANOVA and tables of means), 'seed form' will be used as a collective name for naked and hulled seeds of the two spelt cultivars and the naked seeds of the common wheat Katepwa. Preliminary experiments indicated that there was no significant impact of dehulling method on spelt seed germination (section 4.4.1). Thus, naked seeds obtained by mechanical dehulling were used in all germination experiments. Polyethylene Glycol 8000 MW (PEG 8000) was used for establishing water potentials. Target water potentials were achieved by dissolving PEG 8000 (BDH Inc., Toronto) in distilled water in accordance with Michel (1983). Water potentials were verified with a Vapor Pressure Osmometer Model 5500 (Wescor Inc., Logan, Utah). The literature (Ashraf and Abu-Shakra, 1978; Naylor and Gurmu, 1990) indicate that water potentials of approximately -0.5 to -1.0 MPa limit the germination rate and germination percentage of wheat. Therefore, in addition to distilled water, three osmotic potentials, -0.6, -1.2, and -1.8 MPa were used in this study. Fifty naked seeds of spelt wheat and common wheat, and 25 spikelets of spelt wheat were used as experimental units. Seeds were placed on two layers of Whatman No. 1 filter paper in 9-cm petri dishes. After equilibration at the desired temperature, 10 ml of the solution was added to each petri dish. In order to maintain the water potentials as stable as possible throughout the experiment, petri plates were wrapped with clear plastic wrap and immediately incubated in the dark at the desired temperature. Temperatures of 9, 16, and 23 °C were used in this experiment. The highest temperature (23 °C) is near the optimum for common wheat germination (Lafond and Fowler, 1989). In this experiment, the three temperatures were used as representative of late April, mid May, and late May-early June field conditions at Saskatoon. The number of germinated seeds was recorded every 8 h at 23 °C. At 9 and 16 °C, however, germination was recorded at 12-hour intervals. After three days from the onset of germination, counts were made at 24h intervals. Germination was recorded over a 14-day period for the low (9 °C) and intermediate (16 °C) temperatures, and for a 10-day period at the high temperature (23 °C). A seed with a visible radicle was considered as germinated. Germinated seeds were discarded after each recording. Germination percentage and velocity of germination were estimated as described in section 3.4.1.

The experimental design was completely random using a split-plot lay-out with three replications. The three temperatures were assigned to main plots. The experiment was carried out using two incubators. Three replications of three temperatures were assigned to incubators at random. A factorial of five seed forms and four water potentials was assigned to sub-plots in each temperature. The statistical model was:

Y= Temperature Replication*Temperature Seed form Water potential Seed form*Water potential Temperature*Seed form Temperature*water potential Temperature*Seed form* Water potential Error.

The temperature*replication interaction mean square was used as the denominator (error a) for F-tests, contrasts, or mean comparisons related to temperature. The error mean square, *i.e.* error b, was used for F-tests, contrasts, and mean comparisons related to seed form, water potential, and their interaction. For comparisons involving different cultivars at different seeding dates, a synthetic mean square was calculated and Satterthwaite (1946) approximation was used to estimate an appropriate denominator and degrees of freedom. The Least Significant Difference (LSD) test was used to determine the statistical differences between those means with significant F-test values. Response of final germination and velocity to temperature and water potential was evaluated using orthogonal polynomial contrasts.

3.4.3 Water Uptake by the Seed

Three wheat cultivars (CDC Bavaria, PGR8801, and Katepwa) were included in the experiment. Dehulling method, seed forms, osmotic solutions, osmotic potentials were similar to those described in 3.4.2. In the following (tables of ANOVA and tables of means), 'seed form' will be used as a collective name for naked and hulled seeds of the two spelt cultivars and the naked seeds of the common wheat Katepwa. Twenty naked seeds of the three cultivars, and 10 spikelets for the spelt wheat cultivars were used as an experimental unit. After weighing, seeds were placed on two layers of Whatman No. 1 filter paper in 9 cm petri dishes. Following equilibration at the desired temperature, 8 ml of the appropriate osmotic solution or distilled water was added to each petri dish. In order to prevent moisture loss during the study, each petri dish was wrapped with clear plastic wrap. Petri dishes were immediately incubated in the dark at the desired temperature for the planned length of time. Stability of the osmotic potential stability during long periods of incubation was verified by vapor pressure osmometer. Temperatures of 9, 16, and 23 °C were used in this experiment. For the lowest temperature, 11 measurement times were used. Measurement intervals were 1, 2, 4, 8, 16, 28, 40, 64, 88, 120, and 168 h of incubation. For the 16 and 23 °C treatments, 10 and nine measurement times were used, respectively. Following each measurement, seeds were removed from the petri dishes and blotted dry using paper towels. Blotted seeds were immediately weighed using an electronic precision analytical balance (Model ER-180A, A & D Company, Tokyo, Japan) with 0.1 mg precision. For hulled seeds of spelt wheat, blotted spikelets were weighed, dehulled by hand, and the naked seeds were weighed immediately. Seeds for each experimental unit were oven dried, at 130 °C, for 20 h, then cooled in a desiccator and reweighed for determination of seed moisture content on a dry weight basis (g water per g dry tissue). For one replication, only, wet and oven dry weight of the hull for hulled seeds of spelt cultivars was measured.

At the highest temperature and in distilled water, dehulled seeds of the spelt cultivars started germinating after 28 h of incubation. The data for seed water content during the first 16 h of incubation for three replicates of each temperature-seed form-water potential combination were used to fit a linear model to imbibition time. The rate of water uptake was thus estimated and subjected to ANOVA.

When at least three seeds in each petri dish had germinated, this was considered the start of germination, and the time to reach this stage was recorded. Furthermore, seed water content at this stage was determined and used in analysing per cent seed moisture content (seed dry weight basis) necessary for germination. The experimental and treatment design, statistical model, statistical procedures, F-tests, mean comparisons and contrasts were similar to those described in 3.4.2.

3.4.4 Seedling Establishment of Spring Spelt Relative to Common Wheat

In order to verify the results of the water uptake and germination experiments, a controlled seedling emergence experiment was conducted. A silt-loam soil was used as the germination medium. Soil pH, measured by a Portable digital pH meter (Canlab, Model 607), was 6.8. The soil was passed through a 5.2 mm sieve. The soil water content at the target water potentials was determined using a pressure-plate apparatus. A 4500 g oven-dry equivalent amount of air-dried soil was double bagged in plastic. The five target water potentials were -0.01, -0.033, -0.5, -1.0 and -1.5 MPa. Distilled water was added to give the desired soil water content for each soil water potential as determined by the pressure plate apparatus. After thoroughly mixing water with the soil, each double-bagged sample was equilibrated (for 48h) to the temperature at which germination was to be evaluated. The three temperatures used in this experiment were 9, 16 and 23 °C. Relative humidity was maintained at 60%. During the equilibration period, the soil was mixed twice in order to ensure that the water was uniformly distributed within the soil. At the end of the equilibration period, each soil sample was mixed again and approximately 700 g was placed in a 15 cm plastic pot. After compacting the soil, 50 naked seeds of the spelt and common wheat cultivars, or 25 spikelets of hulled seeds of spelt were placed on the soil surface and then were covered with a 2.5-cm thick layer of the correspondent soil. Pots were immediately wrapped in plastic bags and transferred to the desired temperature in darkness in a growth chamber (Conviron E8H, Asheville, NC). The arrangement of pots in each growth chamber was random. For each water potential at each temperature, one pot was filled with the correspondent soil, plastic wrapped, and placed in the growth chamber in order to check the stability of the water potential. Samples were taken twice during the germination period from the latter pot, weighed, oven dried, reweighed, and soil water content was compared with the initial water content. Emergence was initially recorded at 12h intervals. Later, emergence records were taken on a daily basis. Emergence was recorded for 21, 17, and 14 days for 9, 16 and 23 °C temperatures, respectively. Per cent seedling emergence and velocity of seedling emergence were estimated as described at section 3.3.

The experimental layout was a split-plot design, using temperatures as the main plot. Since three growth chambers were used, replicates of each main plot, *i.e.* temperature, were arranged in such a way that each replication was in a different growth chamber. While the main plot design was a randomised complete block design of three blocks, a factorial of seed form (five types) and water potential (five levels) was the sub-plot factor. Replication was considered a random effect. The statistical model was:

Y= Replication Temperature Replication*Temperature Seed form Water potential Seed form*Water potential Temperature*Seed form Temperature*Water potential Temperature*Seed form* Water potential Error.

The remainder of the statistical and analytical procedures were similar to those described in 3.4.2.

4.0 RESULTS

4.1 Seeding Rate Experiment

4.1.1 Environmental Conditions During Field Experiments

The two growing seasons during which experiments on seeding rate, seeding date, and seeding method were carried out differed markedly for precipitation (Table 4.1). The first year (1995) was characterised by a lower than average precipitation during the early part of the growing season. Precipitation was 66 and 49 per cent lower than average during May and June, respectively. During July and August, however, precipitation was 40 and 130 per cent higher than normal, respectively, leading to a slightly higher than normal precipitation during the four-month growing period. The second year was characterised by a higher than normal precipitation for most of the growing season. Precipitation was 33, 59, and 97 per cent higher than normal in May, June, and July, respectively, leading to a markedly higher than normal precipitation during the four-month period. Precipitation was 50 per cent lower than normal in August. Precipitation during January-April in these two years was also different (Appendix A). In 1995 precipitation during the above period was higher than average (89 vs. 65 mm) while in 1996 precipitation was slightly different from average (69 vs. 65 mm). Temperatures for the two years were not markedly different from the long-term average, except for May, 1996, which was approximately 3 °C cooler than the long term average.

Table 4.1 Synopsis of meteorological data for the 1995-1996 growing seasons at Saskatoon Airport[1].

Month	Temperature (°C)			Precipitation (mm)		
	1995[2]	1996[2]	30 year average	1995[2]	1996[2]	30 year average
May	-1.2	-3.1	11.5	-29.2	14.5	44.2
June	1.2	-0.3	16.2	-30.8	37.4	63.4
July	-1.7	-1.0	18.6	23.4	56.2	58.0
August	-1.9	0.7	17.4	47.8	-18.4	36.8
May-Aug	-0.9	-0.9	15.9	11.2	89.7	202.4

[1]Environment Canada data.
[2]Deviations from the 30 year (1961-1990) average were used for the two years.

4.1.2 Phenology of Spring Spelt Relative to Common Wheat

The study of Haun stage (preanthesis) and Feekes stage (after anthesis) development of the main stem in CDC Bavaria and Katepwa showed that there is a continuous difference in the development of the two cultivars from the seven-leaf stage to maturity (Table 4.2). For Katepwa and CDC Bavaria, seven and eight leaves (including the flag leaf) were formed on the main stem, respectively. From the seedling stage to 7-leaf stage, both cultivars had the same number of leaves on the main stem, according to the weekly measurements. Thus, the difference in number of leaves and developmental stages occurred after the 7-leaf stage. Spike emergence (9.5) in Katepwa was coincident with flag leaf formation (7.8) in CDC Bavaria. By the time Katepwa was ready for harvest (14 August), CDC Bavaria was at the mid-dough stage. Maturity in CDC Bavaria (end of August) was two weeks later than that of Katepwa.

Table 4.2 Main stem developmental stages of CDC Bavaria and Katepwa seeded at 250 seeds/m^2 in 1996*.

Date	Katepwa	CDC Bavaria
May 29	2.2	2.2
June 6	3.6	3.5
June 12	5.0	4.7
June 19	5.9	5.7
June 26	6.8	6.8
July 3	9.5	7.8
July 11	10.7 Anthesis complete	10 Inflorescence not fully emerged
July 18	Early milk	11.6 Anthesis half-way
July 24	Early dough	Water ripe
July 31	Soft dough	Late milk
August 7	End of dough stage	Early dough
August 14	Caryopsis dry	Soft dough
August 21	Over ripe	Hard dough
August 28		Caryopsis dry

*Haun scale was used through anthesis, followed by the Feekes scale.

4.1.3 Lodging Status of the Plots

In 1996 the Belgian lodging index of CDC Bavaria ranged from 5.6, at low seeding rates, to 8.0, at higher seeding rates, averaging 6.4 (Appendix B). The index for PGR8801 ranged from 0.4, at low seeding rates, to 1.8, at high seeding rates, averaging 0.8. No lodging was observed for Katepwa.

4.1.4 Statistical Analysis of Agronomic Traits and Growth Analysis Factors

Year effects were significant for all agronomic traits except for plants/m^2 kernels/spike and 1000-kernel weight (Tables 4.3 and 4.4). Cultivar effects were significant for all agronomic traits. For plants/m^2, spikes/m^2, kernel weight, tiller mortality, hulled grain yield and harvest index a majority of the variation due to the cultivar effects arose from differences between the spelt cultivars and the common wheat.

Table 4.3 Analysis of variance (Mean Squares) for tillers/m^2, spikes/m^2 (Spk/m^2), tiller mortality (Mortality) and kernels/spike (Krnl/spk) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	Tillers/m^2	Spk/m^2	Mortality	Krnl/spk
Year (Y)	1	1950000**	65500**	672.0	2.34
Replication (Y)	6	34000**	1550	270.8**	14.58**
Cultivar(C)	2	264000**	254000**	5531.6**	79.40**
Katepwa vs. Bavaria & PGR	1	2020	475000**	9116.3**	26.55**
Bavaria vs. PGR	1	526000**	33200**	1947.0**	132.25**
Seeding rate (R)	3	138000**	33800**	204.2*	107.10**
Linear	1	385000**	95900**	418.1**	320.13**
C*R	6	17400	3040	52.8	3.51
C*R Linear	1	1000	5650	10.6	4.11
Y*C	2	37400*	39700**	135.4	121.80**
Y*R	3	2260	5060	258.6*	8.50
Y*C*R	6	1640	2600	31.4	1.89
Error	66	7540	2600	63.8	2.76
CV (%)		13.2	11.4	26.0	6.9

* F test significant at the 0.05 level of probability.

** F test significant at the 0.01 level of probability.

Only for tillers/m^2 and kernels/spike did a majority of the variation arise from differences between the two spelt cultivars. For spikes/m^2, tiller mortality, hulled grain yield and harvest index, the difference between the two spelt cultivars accounted for part of the variation. Seeding rate effects were statistically significant for all agronomic traits, with the exception of 1000-kernel

Table 4.4 Analysis of variance (Mean Squares) for 1000-kernel weight (Kw), hulled grain yield (Yield) and harvest index (HI) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	Kw	Yield (MS x 10^{-3})	HI
Year (Y)	1	0.1	985000**	618.14**
Replication (Y)	6	9.6	3340**	15.02**
Cultivar(C)	2	800.4**	67000**	1577.94**
Katepwa vs. Bavaria & PGR	1	1589.3**	128000**	3083.21**
Bavaria vs. PGR	1	11.6	6940**	72.68**
Seeding rate (R)	3	3.8	6940**	10.29**
Linear	1	4.2	18300**	26.04**
C*R	6	12.1	1590	6.27*
C*R Linear	1	3.1	1380	21.72**
Y*C	2	20.1	9340**	17.16**
Y*R	3	8.9	5890**	1.31
Y*C*R	6	8.9	875	1.91
Error	66	13.0	984	2.75
CV (%)		8.3	7.0	4.3

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.

weight. Of all (first, second and third order) orthogonal polynomial contrasts, only the first order polynomials were statistically significant. With the exception of 1000-kernel weight, a linear response to the seeding rate was detected for all traits. Cultivar by year interactions were statistically significant for all agronomic traits, with the exception of plants/m^2, 1000-kernel weight, and tiller mortality. Interaction of year by seeding rate was statistically significant only for hulled grain yield and tiller mortality. Interaction of cultivar by seeding rate was statistically significant only for harvest index. Orthogonal polynomials indicated that the linear component of the interaction was significant for the harvest index. The three-factor interaction was not statistically significant for any of the traits. Tables of analyses of variance and means for plants/m^2, spikelets/spike, kernels/spikelet, spike yield, spikelet yield and plant height are presented in the Appendices C1 and C2.

Year and cultivar effects were statistically significant for all growth analysis variables (Table 4.5 and 4.6). For all variables, a majority of variation

Table 4.5 Analysis of variance (Mean Squares) for leaf angle, LAIave and LAD of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	Leaf angle	LAIave	LAD
Year(Y)	1	4802.5*	34.1413**	6594.70**
Replication (Y)	6	418.0**	0.2831**	31.75*
Cultivar (C)	2	1120.5**	3.9118**	467.00**
Katepwa vs. Bavaria & PGR	1	2120.0**	7.1033**	853.83**
Bavaria vs. PGR	1	121.0	0.7204	80.17**
Seeding rate (R)	3	30.6	0.0432*	2.19
Linear	1	4.6	0.1258**	6.07
C*R	6	38.9	0.0301	4.18*
C*R Linear	1	119.0	0.0978	14.63
Y*C	2	107.3	0.7213**	131.32**
Y*R	3	72.0	0.0492*	7.66**
Y*C*R	6	58.0	0.0108	1.65
Error	66	41.8	0.0153	1.63
CV(%)		9.6	8.2	7.9

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.

Table 4.6 Analysis of variance (Mean Squares) for CGR and total aboveground dry matter (DM) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	CGR	DM (MS x 10^{-5})
Year(Y)	1	2915.96**	8194**
Replication (Y)	6	19.42**	40**
Cultivar (C)	2	83.04**	105**
Katepwa vs. Bavaria & PGR	1	149.13**	169**
Bavaria vs. PGR	1	16.94*	40*
Seeding rate (R)	3	48.67**	7
Linear	1	126.31**	18
C*R	6	4.74	21
C*R Linear	1	2.34	23
Y*C	2	25.77*	82**
Y*R	3	1.96	24
Y*C*R	6	2.30	14
Error	66	2.72	9
CV(%)		9.0	10.8

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.

due to cultivar arose from differences between spelt and common wheat. For LAD, CGR and final aboveground dry matter (DM) a small portion of the variation due to cultivar arose from differences between the two spelt cultivars. Seeding rate effects were significant for LAIave and CGR. For the latter variables, a significant linear response to seeding rate was detected. Cultivar x seeding rate interaction was significant for LAD. Year x cultivar interactions were significant for all variables with the exception of leaf angle. Year x seeding rate interactions were significant for LAIave and LAD.

The number of tillers and spikes per m^2, tiller mortality, and grain yield in 1995 were lower than in 1996, while the reverse was true for harvest index (Table

4.7 and 4.8). The spelt cultivars had lower plants/m^2, spikes/m^2, kernels/spike and harvest index than common wheat but higher 1000-kernel weight, tiller mortality and hulled grain yield, when averaged over years and seeding rates and contrasted with Katepwa. PGR8801 spelt wheat had higher tillers/m^2 and spikes/m^2 and greater hulled grain yield than CDC Bavaria (Table 4.7). The reverse was true for kernels/spike and harvest index. When averaged over cultivars and years, plant, tiller and spikes/m^2 and tiller mortality increased linearly with seeding rate, while

Table 4.7 Means for tillers/m^2, spikes/m^2 (Spk/m^2), kernels/spike (Krnl/Spk) and 1000-kernel weight (Kw) of three wheat cultivars at four seeding rates and two years.

Source	Tillers/m^2 (no)	Spks/m^2 (no)	Krnl/spk (no)	Kw (g/1000)
Year				
1995	515	362	23.76	43.3
1996	800	527	24.08	43.4
Cultivar				
CDC Bavaria	563	372	24.98	45.8
PGR8801	745	418	22.11	46.7
Katepwa	664	544	24.66	37.6
LSD (0.05)	43	25	0.83	1.8
Seeding rate (seeds/m^2)				
150	558	394	26.50	43.9
250	638	438	24.58	43.0
350	710	466	23.03	43.3
450	723	480	21.57	43.2
LSD (0.05)	50	29	0.96	2.1^{ns}

^{ns} H_0 was not rejected for the trait.

Table 4.8 Means for tiller mortality (Mortality), hulled grain yield (Yield) and harvest index (HI) of three wheat cultivars at four seeding rates and two years.

Source	Mortality (%)	Yield (kg ha^{-1})	HI (%)
Year			
1995	28.1	3450	41.50
1996	33.4	5470	36.42
Cultivar			
CDC Bavaria	32.1	4620	36.02
PGR8801	43.2	4820	33.89
Katepwa	17.0	3950	46.98
LSD(0.05)	4.0	144	0.83
Seeding rate (seeds/m^2)			
150	26.8	4690	39.67
250	30.6	4440	39.36
350	33.6	4430	38.36
450	32.0	4290	38.45
LSD(0.05)	4.6	180	0.96

kernels/spike, hulled grain yield and harvest index decreased with seeding rate. Comparison of the year means, averaged over cultivars and seeding rates, indicated that LAIave, LAD, CGR and DM were higher in 1996 than 1995 while the reverse was true for the leaf angle (Table 4.9). Spelt had higher LAIave, LAD, and CGR than common wheat, while the reverse was true for leaf angle. LAIave increased and CGR decreased linearly with seeding rate.

Where none of the cultivar x year and cultivar x seeding rate interactions or seeding rate x year interaction was statistically significant, Tables of the interactions for agronomic traits and growth analysis factors are presented in

Table 4.9 Means for leaf angle, LAIave, LAD, CGR and total aboveground dry matter (DM) of three wheat cultivars at four seeding rates and two years.

Source	Leaf angle (°)	LAIave	LAD (wk m^2 m^{-2})	CGR (g $m^{-2}d^{-1}$)	DM (kg ha^{-1})
Year					
1995	74.8	0.907	7.95	12.78	6023
1996	60.6	2.100	24.52	23.81	11866
Cultivar					
CDC Bavaria	63.0	1.802	19.46	18.66	8990
PGR8801	65.8	1.590	17.23	19.69	9492
Katepwa	74.3	1.119	12.02	16.53	8350
LSD(0.05)	3.2	0.062	0.64	0.82	482
Seeding rate (seeds/m^2)					
150	67.9	1.454	15.95	19.61	9143
250	67.7	1.484	16.01	18.78	8940
350	66.3	1.530	16.42	18.52	8974
450	69.0	1.546	16.56	16.28	8720
LSD(0.05)	3.7^{ns}	0.071	0.74^{ns}	0.94	560^{ns}

^{ns} H_0 was not rejected for the trait.

Appendices C5-C16. All cultivars had higher tillers/m^2 in 1996 compared to 1995 (Table 4.10). A relatively smaller response of CDC Bavaria to year compared to the other cultivars led to a significant year x cultivar interaction for tillers/m^2. A similar trend was observed for spikes/m^2.

Kernels/spike of the spelt wheats was higher in 1996 than in 1995 (Table 4.11). Kernels/spike of Katepwa in 1996 was lower than in 1995, leading to a significant year x cultivar interaction. The only yield component that did not change with year for all cultivars was kernel weight.

Table 4.10 Means for tillers/m^2 and spikes/m^2 of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa in two years.

Year	Tillers/m^2			Spikes/m^2		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(no)			(no)	
1995	459	576	509	328	327	431
1996	667	914	818	416	509	657
LSD (0.05)[1]		61			36	

[1] LSD for comparing cultivar x year interaction for each trait.

Hulled grain yield of the spelt cultivars and grain yield of Katepwa were higher in 1996 compared to 1995 (Table 4.12). Grain yield in 1996 was 1.44, 1.64 and 1.72-fold of that in 1995 for CDC Bavaria, PGR8801 and Katepwa, respectively. Due to the above differences in the magnitude of increase in the yield, the rank of the cultivars changed. All cultivars had a lower harvest index in

Table 4.11 Means for kernels/spike (Krnl/spk) and 1000-kernel weight (Kw) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa in two years.

Year	Krnl/spk			Kw		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(no)			(g/1000)	
1995	23.4	21.1	26.7	45.5	47.5	37.0
1996	26.5	23.1	22.6	46.1	45.8	38.2
LSD (0.05)[1]		1.2			2.6^{ns}	

[1] LSD for comparing cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

1996 compared to 1995. A greater decrease in harvest index for Katepwa compared to that of the spelt cultivars, led to a cultivar by year interaction.

Harvest indices of the spelt wheat cultivars did not change with seeding rate (Table 4.12). Harvest index of Katepwa, however, decreased with seeding rate, leading to a significant cultivar x seeding rate interaction. Harvest index of Katepwa was higher than that of the spelt cultivars, irrespective of seeding rate. Neither plants/m^2, tillers/m^2, nor yield components (spikes/m^2, kernel weight and kernels/spike) responded differently to seeding rate across years (Appendices C11-C14). Hulled grain yield for all seeding rates was higher in 1996 relative to 1995 but the amount of increase in grain yield was higher with the high seeding rates (Appendix C13).

Table 4.12. Means for hulled grain yield (Yield) and harvest index (Hi) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates in two years.

Source	Yield			HI		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
Seeding rate (seeds/m^2)		(kg ha^{-1})			(%)	
150	4980	5090	4010	36.5	34.0	48.5
250	4400	4870	4040	36.8	33.5	47.8
350	4640	4690	3950	35.5	33.5	46.1
450	4460	4610	3790	35.2	34.6	45.5
LSD (0.05)[1]		310^{ns}			1.7	
Year						
1995	3790	3650	2900	38.0	36.1	50.3
1996	5450	5990	4990	34.0	31.6	43.6
LSD (0.05)[2]		220			1.2	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
[2] LSD for comparing cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

A significant cultivar x seeding rate interaction for LAD arose due, likely, to a decrease in LAD of CDC Bavaria compared to an increase in LAD of Katepwa with increasing seeding rate (Table 4.13). The LAIave and LAD in 1996 were higher than in 1995 for all cultivars. The smaller response for the common wheat, Katepwa, relative to the spelt cultivars led to a significant cultivar x seeding rate interaction. In both years CDC Bavaria had the highest LAIave and LAD, followed by PGR8801 and Katepwa. The CGR in 1996 was higher than in

Table 4.13. Means for LAIave and LAD of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates in two years.

Source	LAIave			LAD		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
Seeding rate ($seeds/m^2$)					($wk\ m^2\ m^{-2}$)	
150	1.84	1.53	1.00	20.17	16.83	10.85
250	1.79	1.57	1.10	19.30	16.88	11.86
350	1.81	1.62	1.16	19.42	17.59	12.26
450	1.77	1.65	1.22	18.98	17.60	13.11
LSD(0.05)[1]		0.12[ns]			1.28	
Year						
1995	1.11	0.91	0.70	9.85	7.93	6.01
1996	2.49	2.27	1.54	29.08	26.52	17.98
LSD(0.05)[2]		0.09			0.90	

[1]LSD for comparing cultivar x seeding rate interaction for each trait.
[2]LSD for comparing cultivar x year interaction for each trait.
[ns] H_0 was not rejected for the trait.

1995 for all cultivars (Table 4.14). A smaller increase for CDC Bavaria than for the other cultivars, however, led to a significant year x cultivar interaction. Spelt wheats had a similar CGR in 1995, which was higher than that of Katepwa. PGR8801 had a higher CGR than the other cultivars in 1996. CGR values were lower in 1995 (10.5-14.2 g m^{-2} d^{-1}) than in 1996 (22.6-25.7 g m^{-2} d^{-1}). The highest and lowest increases occurred for Katepwa and CDC Bavaria, respectively. Another biologically important change in CGR's for the two years was a change in the rank of the cultivars. The DM in 1996 was higher than in 1995 for all cultivars. The highest and lowest DM's in 1995 were produced by CDC Bavaria and Katepwa, respectively. The DM of PGR8801 in 1996 was higher than DM of CDC Bavaria and Katepwa, leading to a significant year x cultivar interaction.

Table 4.14. Means for CGR and total aboveground dry matter (DM) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa in two years.

Year	CGR			DM		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(g m^{-2} d^{-1})			(kg ha^{-1})	
1995	14.19	13.69	10.49	6565	6057	5446
1996	23.14	25.70	22.59	11415	12927	11255
LSD(0.05)[1]		1.17			683	

[1]LSD for comparing cultivar x year interaction for each trait.

The LAIave and LAD in 1996 were higher than in 1995 with different seeding rates (Table 4.15). A tendency for larger increases in LAIave and LAD from 1995 to 1996 with increasing seeding rates, however, led to a significant year x seeding rate interaction.

Table 4.15. Means for LAIave and LAD at four seeding rates in two years averaged over three cultivars.

Seeding rate	LAIave		LAD	
(seeds/m^2)	95	96	95	96
			(wk m^2 m^{-2})	
150	0.88	2.03	8.02	23.88
250	0.93	2.04	8.19	23.84
350	0.93	2.13	8.09	24.76
450	0.89	2.21	7.49	25.63
LSD (0.05)[1]	0.10		1.04	

[1]LSD for comparing seeding rate x year interaction for each trait.
[ns] H_0 was not rejected for the trait.

4.2 Seeding Date Experiment

4.2.1 Floral Initiation of Spring Spelt Relative to Common Wheat

With both seeding dates, Katepwa common wheat produced approximately 0.5 main stem leaves more than CDC Bavaria spelt wheat (Table 4.16). Both Katepwa and CDC Bavaria reached the double-ridge stage at 3.7 to 4.1 on the Haun scale. This stage occurred 20-22 and 23-25 d after planting for Katepwa and CDC Bavaria, respectively. When the apical spikelet shows well-defined ridges, it is indicative of the final step of spikelet differentiation and floral initiation. Complete floral initiation was reached by Haun stage 5.5 to 5.8 for Katepwa. This stage was reached at 6.0 to 6.2 for CDC Bavaria. Complete floral initiation took place 31-33 and 36-38 d after planting for Katepwa and CDC Bavaria, respectively.

Table 4.16 Main stem development (Haun scale) during floral initiation of CDC Bavaria and Katepwa seeded on May 23* and 29* in 1996.

Sampling date	May 23 seeding		May 29 seeding	
	Katepwa	CDC Bavaria	Katepwa	CDC Bavaria
June 11	3.5	2.8	2.3	2.3
June 13	3.9 (dr)[1]	3.5	2.7	2.7
June 16	4.3	3.8 (dr)[1]	3.2	3.1
June 20	4.7	4.3	4.2 (dr)[1]	3.6
June 23	5.1	4.7	4.5	4.0 (dr)[1]
June 26	5.5 complete[2]	5.0	4.9	4.7
July 1	6.7	6.1	5.8 complete[2]	5.1

* Fourth and fifth seeding dates, respectively.

[1], [2] Double ridge and complete floral initiation, respectively.

4.2.2 Analysis of Agronomic Traits

Year effects were significant for all traits, except for kernel weight and days to maturity (Table 4.17 and 4.18). Seeding date effects were significant for all traits, with the exception of plants/m^2, tillers/m^2, kernels/spike, kernel weight and grain yield. Orthogonal contrasts indicated that the relationship between the above traits and seeding date varied. For plants/m^2 and grain yield, a linear response to seeding date was detected. Also, a significant lack of fit to the quadratic polynomial was detected for spikes/m^2, GDD to heading and days to maturity. However, with the exception of spikes/m^2, a major portion of the variation in the latter traits, due to seeding date, was described by the linear function. Year by seeding date interaction effects were significant for all traits, with the exception of kernel weight and days to maturity. The two cultivars differed in tillers/m^2 and spikes/m^2, kernels/spike, kernel weight, GDD to heading,

Table 4.17 Analysis of variance (Mean Squares) for plants/m^2, tillers/m^2, spikes/m^2 (Spk/m^2) and kernels/spike (Krnl/spk) of Katepwa and CDC Bavaria sown at six dates in two years.

Source	DF	Plant/m^2	Tiller/m^2	Spk/m^2	Krnl/spk
Year (Y)	1	10600*	744000**	361000**	60.64**
Replication (Y)	6	1260	26800**	4210*	1.76
Date (D)	5	1450	11000	7250**	3.52
Linear (L)	1	5410*	9700	2830	0.85
Quadratic (Q)	1	9	334	16	1.06
Cubic (C)	1	727	9380	2500	3.24
Remainder	2	560	17650*	15450**	6.23**
Y*D	5	4000**	28700**	8580**	5.16*
Replication*D (Y)	30	902	5060	1380	1.84
Cultivar (C)	1	1040	164000**	503000**	79.75**
Y*C	1	1390	3080	50400**	138.96**
C*D	5	554	4590	1110	3.01
C*Polynomial[1]	1				
Y*D*C	5	547	12700	4320	11.56*
Error	36	1180	5960	4130	3.45
CV (%)		20.2	11.2	14.4	7.1

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.
[1] L and C stand for linear and cubic components, respectively. No other function was significant.

days to maturity and grain yield. Year by cultivar interaction effects were statistically significant for spikes/m^2, kernels/spike, GDD to heading and grain yield. Cultivar by seeding date interaction effects were statistically significant for days to maturity and grain yield. Year x cultivar x seeding date interaction effects were significant only for kernels/spike, GDD to heading and days to maturity.

Tables of analyses of variance and means for seedling emergence velocity, spikelets/spike, kernels/spikelet and days to heading are presented in Appendices D1 and D2.

Table 4.18 Analysis of variance (Mean Squares) for 1000-kernel weight (Kw), GDD to heading (GDD-head), days to maturity (D-maturity) and hulled grain yield (Yield) of Katepwa and CDC Bavaria sown at six dates in two years.

Source	DF	Kw	GDD-head	D-maturity	Yield ($MS \times 10^{-3}$)
Year (Y)	1	63.29	213759.4**	0.67	38900**
Replication(Y)	6	12.27*	113.7	7.47	243**
Date (D)	5	2.72	42713.6**	384.80**	153
Linear (L)	1	5.48	209118.2**	1735.03**	562**
Quadratic (Q)	1	0.56	7.3	138.86**	63.6
Cubic (C)	1	4.31	946.5*	20.67	59.5
Remainder(R)	2	1.64	1748.0**	14.72*	40.5
Y*D	5	7.11	1246.2**	6.14	3480**
Replication*D (Y)	30	3.59	135.2	6.88	64.2
Cultivar (C)	1	1329.45**	282534.0**	4320.17**	17100**
Y*C	1	0.16	1600.7**	0.04	1670**
C*D	5	5.19	146.8	20.14**	635**
C*Polynomial[1]	1	C**	Q**	Q**C**R*	Q* C* R**
Y*D*C	5	6.97	550.4**	30.37**	107
Error	36	3.93	80.1	2.90	108
CV (%)		4.9	1.5	1.7	7.6

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.
[1] Q, C, R stand for quadratic, cubic, and remainder of polynomials, respectively. No other function was significant

Plants/m^2 and kernels/spike were higher in 1995 than in 1996, when averaged over seeding dates and cultivars (Table 4.19). For the rest of the traits, with the exception of 1000-kernel weight and days to maturity, the means were higher in 1996 compared to 1995 (Table 4.19 and 4.20). Tillers/m^2 and spikes/m^2 for Katepwa were higher than for CDC Bavaria, when averaged over seeding dates and years. For the rest of the traits, with the exception of plants/m^2, the means were higher for CDC Bavaria relative to Katepwa. Orthogonal polynomial

Table 4.19 Means for plants/m^2, tillers/m^2, spikes/m^2 (Spk/m^2) and kernels/spike (Krnl/spk) of Katepwa and CDC Bavaria at six seeding dates and two years.

Source	Plant/m^2 (no)	Tiller/m^2 (no)	Spk/m^2 (no)	Krnl/spk (no)
Year				
1995	181	599	386	26.80
1996	160	775	509	25.21
Cultivar				
Katepwa	174	728	520	25.10
CDC Bavaria	167	654	375	26.92
Seeding date				
Date 1	185	679	436	25.92
Date 2	172	660	440	26.19
Date 3	175	701	475	26.13
Date 4	164	665	416	26.59
Date 5	171	731	464	25.17
Date 6	157	684	456	26.06
LSD(0.05)	22^{ns}	51^{ns}	27	0.98^{ns}

^{ns} H_0 was not rejected for the trait.

contrasts indicated that plants/m^2 and grain yield dropped off linearly with delayed seeding, averaged over years and cultivars.

Where seeding date x cultivar interaction or none of the cultivar x year and year x seeding date interactions were not statistically significant, tables of means for the interactions of the agronomic traits are presented in Appendices D3-D8. When averaged over years, plants/m^2 for both cultivars tended to decrease with a delayed seeding, though the decrease was not statistically significant (Appendix D3). Analyses of variance and mean comparisons indicated that Katepwa and CDC Bavaria responded to seeding date similarly for all traits (Appendices D1-D8), with the exception of days to maturity and grain yield (Table 4.21).

Table 4.20 Means for 1000-kernel weight (Kw), GDD to heading (GDD-head), days to maturity (D-mature) and hulled grain yield (Yield) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates and two years.

Source	Kw (g/1000)	GDD-head (gdd)	D-mature (day)	Yield (kg ha^{-1})
Year				
1995	41.56	533.1	98.52	3690
1996	39.93	627.5	98.35	4970
Cultivar				
Katepwa	37.02	526.1	91.73	3910
Bavaria	44.47	634.6	105.15	4750
Seeding date				
Date 1	40.17	516.6	106.44	4400
Date 2	40.57	530.0	102.13	4390
Date 3	41.24	565.4	97.13	4440
Date 4	40.59	605.8	96.38	4320
Date 5	40.69	615.8	95.31	4210
Date 6	41.21	648.3	93.25	4220
LSD(0.05)	1.37^{ns}	8.4	1.88	180^{ns}

^{ns} H_0 was not rejected for the trait.

Orthogonal polynomial contrasts for days to maturity (all orders with the exception of linear) and grain yield (all orders with the exception of linear) showed that some components for cultivar x seeding date interactions are significant. A greater number of days to maturity were required for CDC Bavaria than for Katepwa, irrespective of seeding date. A significant cultivar by seeding date interaction and significant polynomials arose from no decrease in days to maturity for CDC Bavaria at the three latest seeding dates while for Katepwa days to maturity at the third and fourth seeding dates did not differ. The significant cubic and higher order polynomials of the interaction for grain yield indicated fluctuations

Table 4.21 Means for days to maturity (D-maturity) and hulled grain yield (Yield) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates.

Seeding date	D-maturity		Yield	
	Katepwa	Bavaria	Katepwa	Bavaria
	(day)		($kg\ ha^{-1}$)	
Date 1	99.5	113.4	3950	4850
Date 2	95.3	109.0	3910	4870
Date 3	90.4	103.9	4150	4740
Date 4	91.6	101.1	3560	5080
Date 5	88.6	102.0	3820	4600
Date6	85.0	101.5	4050	4380
LSD(0.05)[1]	1.7		330	
LSD(0.05)[2]	2.2		310	

[1] Least significant difference for comparing cultivars at the same seeding date.
[2] Least significant difference for comparing cultivars at different seeding dates.
[ns] H_0 was not rejected for the trait.

in the grain yield with almost every increment of seeding date. More detailed analysis showed that when hulled grain yield of CDC Bavaria was compared with the grain yield of Katepwa, the latter was outyielded at every seeding date (Table 4.21). While grain yield of Katepwa did not follow an obvious trend, CDC Bavaria appeared to produce lower grain yields at the two last seeding dates, leading at least partially to a significant cultivar x seeding date interaction. The lowest grain yield for Katepwa was at the 4th seeding date.

An interaction of seeding date with year for plants/m^2 (Table 4.17) arose from a low seedling establishment at the fifth seeding date in 1995, which contrasted with a high seedling establishment at the same seeding date in 1996 (Table 4.22). In 1995, there was a tendency toward a poor establishment at the late seeding dates. In 1996, no such tendency was evident. All seeding dates in

1995, with the exception of the fifth seeding date, were done into relatively wet soil or were followed by rainfall, leading to good crop establishment. The fifth seeding date was done into a dry soil and followed by a 10-day dry period, leading

Table 4.22 Means for plants/m^2, tillers/m^2, and spikes/m^2 of Katepwa and CDC Bavaria (Bavaria) at six seeding dates in two years.

Source	Plants/m^2		Tillers/m^2		Spikes/m^2	
	95	96	95	96	95	96
	(no)		(no)		(no)	
Seeding date						
Date 1	196	173	580	777	348	523
Date 2	183	162	522	798	353	528
Date 3	203	147	598	805	429	520
Date 4	184	145	567	763	385	446
Date 5	153	190	652	810	399	529
Date 6	169	144	673	695	404	507
LSD(0.05)[1]	31		73		38	
Cultivar						
Katepwa	181	167	634	822	436	604
Bavaria	182	153	563	728	337	414
LSD(0.05)[2]	20^{ns}		45^{ns}		38	

[1] LSD for seeding date x year interaction for each trait.
[2] LSD for cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

to poor crop establishment. The first and second seeding dates in 1996 were done into wet-cool soil, leading to a relatively good crop establishment. The third and fourth seedings were followed by several days of rain, leading to soil crusting and poor emergence. The fifth seeding date in 1996 was followed by 21 mm of rainfall during 48h, leading to a high level of seedling emergence. The sixth seeding was done into a dry soil followed by hot weather, leading to poor seedling establishment. Furthermore, precipitation in winter 1995 was higher than the long-term average (36%), leading to high soil moisture storage at the time of seeding while in the winter 1996 precipitation was not much different (6 pre cent) from the average. The above difference in soil moisture storage, probably, played a role in lower seedling emergence in 1996 relative to 1995. A significant interaction of seeding date with year for tillers/m^2 arose from a high tiller production at the two late seeding dates in 1995 and a low tiller production at the last seeding date in 1996. A significant interaction of seeding date with year for spikes/m^2 arose from limited spike production at the two early seeding dates in 1995 and a low spike production at the fourth seeding date in 1996. Spikees/m^2 in 1996 was significantly higher than in 1995, irrespective of seeding date. A significant interaction of seeding date with year for kernels/spike was a result of no significant change in kernel number with seeding date in 1995 while the highest and lowest kernels/spike in 1996 were achieved at the fourth and fifth seeding dates, respectively. Kernels/spike in 1995 was higher than in 1996 for most seeding dates.

There is a contrasting trend for the two years in terms of grain yield at different seeding dates, leading to year x seeding date interaction (Table 4.23). An increase in grain yield with delayed seeding in 1995 contrasted with a decrease in grain yield with delayed seeding in 1996. In 1996 a greater GDD was needed for heading, irrespective of seeding date than in 1995. It appears that a significant interaction for GDD to heading arose from smaller differences between years for the two late seeding dates.

While plants/m^2 in 1995 was higher than in 1996, a higher tiller production in 1996 led to a higher spikes/m^2 for both cultivars (Table 4.22). A greater inter-year difference for Katepwa led to a significant interaction of year and cultivar. The

Table 4.23 Means for kernels/spike (Krnl/spk), GDD to heading (GDD-head) and hulled grain yield (Yield) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates in two years.

Source	Krnl/spk		GDD-head		Yield	
	95	96	95	96	95	96
	(no)		(gdd)		(kg ha^{-1})	
Seeding date						
Date 1	26.6	25.2	470.6	562.5	3350	5450
Date 2	27.7	24.7	479.4	580.6	3270	5510
Date 3	26.5	25.8	508.6	622.3	3600	5280
Date 4	26.6	26.6	553.8	657.8	3670	4970
Date 5	26.4	23.9	569.1	662.5	4050	4380
Date 6	27.0	25.2	617.3	679.4	4220	4210
LSD(0.05)[1]	1.4		11.9		260	
Cultivar						
Katepwa	27.1	23.1	483.0	569.2	3400	4410
Bavaria	26.5	27.3	583.3	685.8	3980	5520
LSD(0.05)[2]	1.1		5.3		190	

[1] LSD for seeding date x year interaction for each trait.
[2] LSD for cultivar x year interaction for each trait.
[ns] H_0 was not rejected for the trait.

kernels/spike decreased for Katepwa in 1996 compared to 1995 but did not change with year for CDC Bavaria, leading to the interaction. Grain yield for both cultivars was higher in 1996 than in 1995 (Table 4.23). A larger difference between years for grain yield in CDC Bavaria than Katepwa, led to a significant year x cultivar interaction. Growing degree-days to heading in CDC Bavaria were higher than for

Katepwa, irrespective of year. Both cultivars needed more GDD to heading in 1996, compared to 1995. This is probably a reflection of the five- to seven-d delay in seeding in 1996. It appears that a significant year x cultivar interaction arose from a greater delay in heading in 1996 for CDC Bavaria than for Katepwa.

Kernels/spike in CDC Bavaria was greater than in Katepwa for all seeding dates. The difference in kernels/spike between CDC Bavaria and Katepwa varied with seeding date, with the maximum differences at the fourth and fifth seeding dates. The kernels/spike of Katepwa was subject to a greater reduction than that of CDC Bavaria from 1995 to 1996. Also, the difference in kernels/spike across years varied with seeding date, with no difference at the fourth seeding date. The above interactions led to a three-way interaction for kernels/spike.

CDC Bavaria required a greater number of GDD for heading relative to Katepwa at all seeding dates. The inter-cultivar difference, however, varied with seeding date. In 1996 a greater number of GDD was needed than in 1995 for heading at all seeding dates. The inter-year difference varied with seeding date, with the smallest difference at the sixth seeding date. The greater GDD for heading in 1996 was at least partially related to the one-week delay in all seedings in 1996 compared to 1995. Both cultivators needed greater GDD for heading in 1996 relative to 1995, but the inter-year difference for CDC Bavaria was greater than Katepwa. The above interactions led to a year x seeding date x cultivar interaction.

CDC Bavaria required a greater number of days to maturity relative to Katepwa at all seeding dates. The inter-cultivar difference was at a minimum at the fourth seeding date. In 1996 a greater number of days was needed than in 1995 (due, probably, to the delayed seeding) for maturity at all seeding dates, with the exception of the fourth seeding date where the reverse was true. A three-way interaction for days to maturity might be related to the above changes in the rank of seeding dates depending on year and cultivar.

4.3 Seed Form Effects on Crop Establishment and Yield Traits

Year effects were statistically significant for all traits except for kernels/spike and 1000-kernel weight (Tables 4.24 and 4.25). The two seeding dates differed in plants/m^2, velocity of seedling emergence, kernels/spike, and 1000-kernel weight. Year by seeding date interactions were significant for all traits with the exception of spikes/m^2 and kernels/spike (Table 4.24). Seed form effects were statistically significant for all traits, with the exception of plants/m^2. Contrast comparisons indicated that removal of the hull from spelt seeds led to changes in plants/m^2 and velocity of seedling emergence. The two spelt cultivars differed in kernels/spike when the two seed forms of CDC Bavaria were compared with the two seed forms of PGR8801. The two spelt cultivars differed from the common wheat cultivar, Katepwa, for all traits with the exception of plants/m^2 and kernels/spike. Year by seed form interaction effects were statistically significant for plants/m^2, spike/m^2 and kernels/spike. Seeding date by seed form interaction effects were statistically significant for velocity of seedling emergence. The three-way interaction effect was significant for 1000-kernel weight.

Tables of interactions of seed form x seeding for those traits that F-test for the interactions was not significant is presented in appendix (Appendices E1 and

Table 4.24 Analysis of variance (Mean Squares) for plants/m^2, velocity of emergence (Cfv) and spikes/m^2 (Spk/m^2) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa sown at early and late dates in two years.

Source	DF	Plants/m^2	Cfv	Spk/m^2
Year (Y)	1	15800**	128.22**	400000**
Date (D)	1	15500**	1651.47**	245
Y*D	1	5500*	89.72**	13780
Replication (Y*D)	12	881	0.83	3750**
Seed form (S)	4	1970	29.07**	62000**
Hulled vs. Naked[1]	1	6790**	104.14**	2050
Bavaria vs. PGR	1	722	0.20	3840
Bavaria & PGR vs. Katepwa	1	247	7.10*	240000**
Y*S	4	2560*	0.16	14000**
D*S	4	1550	24.56**	1490
Y*D*S	4	1730	0.05	1060
Error	48	813	1.47	1150
CV (%)		16.1	11.9	8.7

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.
[1] Only naked seeds of spelt were included in the comparison.

E2). While plants/m^2 in 1995 was higher than in 1996, velocity of emergence, spikes/m^2 and grain yield was higher in 1996 than in 1995 (Table 4.26). While plants/m^2 and 1000-kernel weight at the early seeding date were, on average, higher than at the late seeding, velocity of seedling emergence and kernels/spike with late seeding were higher than with the early seeding. Contrasts indicated that seedling emergence of the spelt cultivars decreased with the removal of the hull, however, velocity of seedling emergence of the spelt cultivars improved with the removal of the hull (Tables 4.24 and 4.26). Spelt cultivar CDC Bavaria produced a greater kernels/spike than PGR8801. While the common wheat cultivar

Table 4.25 Analysis of variance (Mean Squares) for kernels/spike (Krnl/spk), 1000-kernel weight (Kw) and hulled grain yield (Yield) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa sown at early and late dates in two years.

Source	DF	Krnl/spk	Kw	Yield (MS x 10^{-2})
Year (Y)	1	5.95	4.63	746000**
Date (D)	1	40.04**	149.47**	8440
Y*D	1	7.32	143.78**	173000**
Replication (Y*D)	12	1.61	7.33	2180
Seed form (S)	4	35.95**	190.41**	14600**
Hulled vs. Naked[1]	1	10.40	1.49	5270
Bavaria vs. PGR	1	124.32**	6.41	546
Bavaria & PGR vs. Katepwa	1	6.27	705.52**	51300**
Y*S	4	36.71**	2.39	4300
D*S	4	5.48	2.18	2530
Y*D*S	4	2.70	17.79**	1050
Error	48	4.54	4.12	1780
CV (%)		8.4	4.7	9.5

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.
[1] Only naked seeds of spelt were included in the comparison.

produced more spikes/m^2, the spelt cultivars had heavier kernels and a higher hulled grain yield than Katepwa.

Detailed analysis of interaction effects revealed that a significant interaction of year and seeding date for plants/m^2 arose from a large decline in seedling numbers with late seeding in 1996 compared to no changes with seeding date in 1995 (Table 4.27). Late seeding in 1996 was done into a dry soil and was followed by a hot dry weather, leading to a poor seedling emergence in 1996, in general, and at the late seeding, in particular. A significant interaction of year and

Table 4.26 Means for plants/m^2, coefficient of velocity of seedling emergence (Cfv), spikes/m^2, kernels/spike (Krnl/spike), 1000-kernel weight (Kw) and hulled grain yield (Yield) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa (Katep) at two seeding dates and two years.

Source	Plant/m^2 (no)	Cfv (%/day)	Spk/m^2 (no)	Krnl/ Spk (no)	Kw (g/1000)	Yield (kg ha^{-1})
Year						
1995	191	8.88	318	25.5	43.8	3500
1996	163	11.41	460	25.5	43.3	5430
Seeding date						
Early	191	5.60	387	24.8	44.9	4570
Late	163	14.69	391	26.2	42.2	4360
Seed form						
Bavaria-naked	168	11.06	343	27.6	46.1	4670
Bavaria-hulled	191	9.05	366	26.4	44.6	4430
PGR-naked	164	11.49	370	24.4	43.7	4660
PGR-hulled	182	8.39	369	24.0	45.7	4580
Katep-naked	181	10.74	499	24.9	37.6	3960
LSD (0.05)	20^{ns}	0.86	24	1.5	1.4	300

^{ns} H_0 was not rejected for the trait.

seeding date for velocity of emergence arose from a larger increase in velocity with delayed seeding in 1996, compared to the response observed in 1995. Hot weather following the late seeding in 1996 led to a higher velocity of emergence of the emerged seeds.

A sharp decline in kernel weight with delayed seeding in 1996, was contrasted by no change with seeding date in 1995, leading to the interaction of year and seeding date for 1000-kernel weight (Table 4.28). Increasing grain yield with delayed seeding in 1995, in contrast to a decrease in yield with delayed seeding in 1996 led to the interaction of year and seeding date for the grain yield.

Table 4.27 Means for plants/m^2, coefficient of velocity of emergence (Cfv) and spikes/m^2 of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa at two seeding dates in two years.

Source	Plants/m^2		Cfv		Spikes/m^2	
	95	96	95	96	95	96
	(no)		(%/day)		(no)	
Seeding date						
Early	197	185	5.4	5.8	304	471
Late	186	141	12.4	17.0	333	448
LSD(0.05)[1]	21		0.6		42^{ns}	
Seed form						
Bavaria-naked	173	163	9.8	12.3	289	395
Bavaria-hulled	222	161	7.8	10.3	335	396
PGR-naked	164	164	10.1	12.9	280	459
PGR-hulled	193	171	7.3	9.5	293	445
Katepwa-naked	204	156	9.5	12.0	394	604
LSD (0.05)[2]	29		1.2^{ns}		34	

[1] LSD for seeding date x year interaction for each trait.
[2] LSD for seed form x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

An interaction of year and seed form for plants/m^2 arose from no change in seedling establishment of spelt with hull removal in 1996, opposed to a decline with the hull removal in 1995. Generally, plants/m^2 of hulled spelt and naked Katepwa seeds decreased in 1996, leading to no difference between the seed forms in 1996. A significant interaction of year and seed form for spikes/m^2 is due, at least partially, to a decrease in spike number with hull removal for CDC Bavaria seeds in 1995, while spike number in PGR8801 did not change with seed form and no significant changes in spike number were detected in 1996. PGR8801 had lower spikes/m^2 than CDC Bavaria in 1995, but higher spikes/m^2 in 1996. A significant interaction of year and seed form for kernels/spike could have arisen from a decrease in kernel number for Katepwa in 1996 compared to 1995, in contrast to a relatively stable kernels/spike for the different seed forms of the spelt cultivars over the two years.

Table 4.28 Means for kernels/spike (Krnl/spk), 1000-kernel weight (Kw) and hulled grain yield (Yield) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa at two seeding dates in two years.

Source	Krnl/spk		Kw		Yield	
	95	96	95	96	95	96
	(no)		(g/1000)		(kg ha^{-1})	
Seeding date						
Early	25.1	24.5	43.8	46.0	3140	6000
Late	25.9	26.5	43.8	40.6	3860	4860
LSD(0.05)[1]	0.8 [ns]		1.9		320	
Seed form						
Bavaria-naked	27.2	28.0	45.8	46.3	3790	5610
Bavaria-hulled	26.5	26.3	44.7	44.5	3670	5180
PGR-naked	23.1	25.7	44.1	43.3	3490	5840
PGR-hulled	23.0	25.0	45.9	45.5	3500	5650
Katepwa-naked	27.4	22.4	38.4	36.8	3060	4860
LSD (0.05)[2]	2.1		2.0[ns]		420[ns]	

[1] LSD for seeding date x year interaction for each trait.
[2] LSD for seed form x year interaction for each trait.
[ns] H_0 was not rejected for the trait.

Since seeding date x seed form interaction was not significant for any of the traits, with the exception of emergence velocity, Tables of means for the interaction are presented in Appendices C4 and C5. Detailed analysis of interaction of seed form and seeding date indicated that a significant interaction for velocity of seedling emergence arose from a differential rate of increase in velocity with delayed seeding between naked seed of the spelt cultivars and Katepwa, on one hand, and the hulled seed forms of the spelt cultivars, on the other (Appendix E1). Late seeding increased the velocity of the naked seeds more than hulled seeds.

A significant year x seeding date x seed form interaction for 1000-kernel weight may have arisen due to the following. Heavier kernels were produced with early seeding in 1996, while heavier kernels were produced with late seeding in 1995 (Table 4.28). In addition, heavier kernels were produced with early seeding for all seed forms (Appendix E2).

4.4 Controlled Environment Experiments

4.4.1 Preliminary Seed Germination Experiment

Seed form effects for velocity of germination and germination percentage were significant (Table 4.29). Contrast comparisons indicated significant differences for both velocity of germination and percentage of germination between seed forms of the spelt cultivars, with velocity of germination being higher and germination lower for naked seed forms compared to hulled seed forms (Table 4.30). Velocity of germination for Katepwa was lower than that for the two seed forms of the two spelt cultivars. Neither mean comparisons nor contrasts detected significant differences between hand-dehulled and machine-dehulled seed forms of the spelt cultivars. This suggested that removing the hull by rubber belt de-awner machines and by hand will

Table 4.29. Analyses of variance (Mean Squares) for coefficient of velocity of germination (Cfv) and per cent germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa.

Source	DF	Cfv	Germination
Experiment (E)	1	1684.1**	8.0
Replication (E)	6	16.5	39.7
Seed form	6	434.4**	172.9**
Naked vs. hulled	1	282.6**	172.0**
Naked-machine vs. naked-hand	1	46.8	12.9
CDC Bavaria vs. PGR8801	1	1639.2**	789.8**
CDC Bavaria & PGR8801 vs. Katepwa	1	18.7	43.4
Error	42	34.2	33.3
CV (%)		11.9	6.3

* F test significant at the 0.05 level of probability.
** F test significant at the 0.01 level of probability.

not affect germination per cent and germination velocity differently. Germination percentage for naked seed forms of CDC Bavaria was lower than that of naked PGR8801 and Katepwa. Contrast comparisons indicated that CDC Bavaria had a lower velocity of germination as well as a lower germination percentage than PGR8801, when averaged over naked and hulled seed forms.

Table 4.30 Means for velocity of germination (%/day) and per cent germination of hand dehulled (Hand), machine dehulled (Machine) and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa.

	CDC Bavaria			PGR8801			Katepwa
	Hand	Machine	Hulled	Hand	Machine	Hulled	
Velocity[1]	45.3	47.6	41.2	56.8	59.3	53.0	40.9
Germination	86.3	86.0	90.0	92.8	95.6	98.3	94.0

[1] LSD (0.05) = 5.9 and 5.8 for velocity and germination, respectively.

4.4.2 Seed Germination of Spring Spelt Relative to Common Wheat

Analyses of variance indicated that temperature had no significant effect on either per cent of germination or velocity of germination (Table 4.31). Seed form effects were statistically significant for per cent germination and germination velocity. Contrast comparisons detected significant differences for germination percentage and germination velocity of hulled vs. naked seed forms of the spelt cultivars. CDC Bavaria, when averaged over naked and hulled seed forms, differed from PGR8801 for germination percentage. The spelt cultivars differed from the common wheat in germination percentage. Water potential effects were statistically significant for per cent germination and germination velocity. Significant linear and quadratic responses to water potential for germination percentage and a significant linear response for germination velocity were detected. Temperature by seed form and temperature by water potential

Table 4.31 Analysis of variance (Mean Squares) for per cent germination (Germination) and velocity of germination (Velocity) of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under four water potentials.

Source	DF	Germination	Velocity
Temperature (T)	2	763.0	585.8
Linear	1	512.5	1132.2
Quadratic	1	1013.4	39.5
Replication (in T)	6	397.5**	2624.6**
Seed form (S)	4	4822.2**	6173.0**
Naked vs. hulled	1	17030.3**	24260.7**
CDC Bavaria vs. PGR8801	1	992.3**	7.4
CDC Bavaria & PGR8801 vs. Katepwa	1	1264.1**	354.1
Water Potential (P)	3	43504.7**	17020.9**
Linear	1	101463.5**	50742.1**
Quadratic	1	28880.0**	298.0
Cubic	1	170.7	22.6
T*S	8	380.2**	25.6
T*P	6	479.8**	22.6
S*P	12	997.3**	517.8**
T*S*P	24	116.8	29.5
Error	114	99.8	96.7
CV (%)		14.6	33.9

*, ** F test significant at the 0.05 and 0.01 levels of probability, respectively.

interactions were significant only for germination percentage. Seed form by water potential interactions were statistically significant for per cent of germination and velocity of germination. On average, the dehulling process enhanced the germination percentage and germination velocity of both spelt cultivars (Table 4.32). Germination percentage for Katepwa was higher than for the hulled seed forms of the spelt wheats but lower than for the naked seed form of PGR8801 and CDC Bavaria, though not significant. However, Katepwa had a higher per cent germination than spelt wheat, when averaged over naked and hulled spelt seed

Table 4.32 Means for per cent germination and velocity of germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under four water potentials.

	Germination (%)	Velocity (%/day)
Temperature (°C)		
9	69.0	25.6
16	72.0	29.7
23	64.9	31.8
LSD(0.05)	8.9^{ns}	22.9^{ns}
Seed form		
CDC Bavaria-hulled	53.9	15.8
CDC Bavaria-naked	75.4	40.4
PGR8801-hulled	58.9	14.9
PGR8801-naked	80.9	42.2
Katepwa-naked	73.9	31.8
LSD(0.05)	4.7	4.6
Water potential (MPa)		
0.0	88.3	53.0
-0.6	90.6	34.8
-1.2	72.0	20.7
-1.8	23.7	7.6
LSD(0.05)	4.2	4.1

^{ns} H_0 was not rejected for the trait.

forms. Germination velocity of naked seeds of spelt wheat was higher than Katepwa. PGR8801 spelt wheat had a higher germination percentage than CDC Bavaria spelt wheat, when averaged over naked and hulled spelt seed forms. Averaged over temperature and seed form, germination percentage decreased parabolically with decreasing water potential. Germination velocity decreased linearly with water potential.

Per cent germination for the naked seeds tended to be higher than for the hulled seeds, irrespective of temperature (Table 4.33). The difference between naked and hulled seeds increased with temperature, leading to a significant temperature x seed form interaction. The interaction of seed form and water potential for germination percentage probably arose from a lower germination of the hulled seed form of PGR8801 spelt wheat at 0.0 than -0.6 MPa water potential, while for CDC Bavaria level of germination at these two water potentials was not different. Also, a greater decrease in germination of the hulled seed form of spelt than naked seed form with more negative water potentials could have played a role in the interaction. A significant interaction of seed form with water potential for velocity of germination probably arose from the differential rate of decrease in velocity of hulled seed forms of the spelt cultivars vs. naked spelt seeds and Katepwa. The velocity of germination of the naked spelt seed at 0 and -0.6 MPa was higher than that of Katepwa.

At all three temperatures, germination percentage decreased with a decrease in water potential below -0.6 MPa (Table 4.34). A significant interaction arose, at

Table 4.33 Means for per cent germination and velocity of germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under four water potentials.

Source	CDC Bavaria		PGR8801		Katepwa
	Hulled	Naked	Hulled	Naked	Naked
Temperature (°C)			Germination (%)		
9	55.8	74.2	65.5	77.5	72.2
16	61.0	74.5	62.7	81.8	80.0
23	45.0	77.7	48.7	83.5	69.7
LSD (0.05)[1]	8.1				
LSD (0.05)[2]	10.3				
			Velocity of germination (%/day)		
9	12.5	36.3	12.9	38.5	28.0
16	14.8	40.7	14.7	43.8	34.4
23	20.1	44.2	17.0	44.5	33.1
LSD (0.05)[1]	8.0[ns]				
LSD (0.05)[2]	21.1[ns]				
Water potenti (MPa)			Germination (%)		
0.0	83.1	89.1	77.8	96.0	95.3
-0.6	82.0	86.4	95.3	93.1	96.2
-1.2	49.6	82.0	62.0	85.6	80.9
-1.8	1.1	44.2	0.7	49.1	23.3
LSD(0.05)	9.2				
			Velocity of germination (%/day)		
0.0	29.4	69.6	28.1	77.0	60.9
-0.6	21.3	49.1	19.7	50.3	33.5
-1.2	11.6	29.9	11.0	29.1	22.0
-1.8	0.9	13.0	0.8	12.5	11.0
LSD(0.05)	9.1				

[1] Least significant difference for comparing seed form means at the same temperature.

[2] Least significant difference for comparisons among seed forms at different temperatures.

[ns] H_0 was not rejected for the trait.

Table 4.34 Means for per cent germination and velocity of germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under four water potentials.

Temperature (°C)	Water potential (MPa) 0.0	-0.6	-1.2	-1.8
		Germination (%)		
9	93.1	92.1	75.3	15.6
16	90.7	92.5	76.7	28.1
23	81.1	87.2	64.0	27.3
LSD (0.05)[1]	7.2			
LSD (0.05)[2]	9.6			
		Velocity of germination (%/day)		
9	48.9	30.9	16.9	5.9
16	53.6	34.8	21.9	8.5
23	56.5	38.6	23.4	8.6
LSD (0.05)[1]	7.1[ns]			
LSD (0.05)[2]	20.8[ns]			

[1] Least significant difference for comparing water potential means at the same temperature.
[2] Least significant difference for comparing water potential means at different temperatures.
[ns] H_0 was not rejected for the trait.

least partially, from a higher rate of decrease of germination percentage at the 9 °C temperature than at the other two temperatures.

4.4.3 Water Uptake by the Seed

The effects of temperature (except for seed water content at the start of germination), seed form and water potential were significant (Table 4.35). A majority of the two-factor-interaction effects was statistically significant. Detailed analysis of the main effects indicated significant linear responses of water uptake rate and time to the start of germination to temperature. In addition, the hulled seed of the spelt wheats differed from the naked seed in water uptake rate and time to start of germination. Contrasts showed that the two spelt wheats differed in water uptake rate and seed moisture content at the start of germination (Table 4.36). Contrasts indicated that Katepwa differed from the average of the two spelt wheats in water uptake rate, time to the start of germination and water content at the start of germination. Significant linear responses to water potential were detected for water

Table 4.35 Analysis of variance (Mean Squares) for water uptake rate, time to start of germination and seed water content at the start of germination of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa at three temperatures under four water potentials.

Source	DF	Water uptake rate	Time to germination	Water content at germination
Temperature (T)	2	626.923**	47700**	55.3
Linear	1	1241.247**	92100**	83.7
Quadratic	1	12.611	3360	27.0
Replication (in T)	6	27.134**	1330**	93.2**
Seed form (S)	4	105.881**	6290**	453.0**
Hulled vs. naked	1	338.529**	23000**	0.0
Bavaria vs. PGR	1	8.658**	9	104.6**
Bavaria & PGR vs. Katepwa	1	75.719**	2090**	1642.0**
Water potential (P)	3	858.776**	63400**	238.7**
Linear	1	2174.885**	188000**	708.3**
Quadratic	1	358.676**	598*	3.3
Cubic	1	42.767**	1040**	4.7
T*S	8	0.207	384**	22.4**
T*P	6	24.717**	2250**	18.5
S*P	12	3.141**	424**	38.5**
T*S*P	24	1.040	242**	9.3
Error	114	0.834	112	10.9
CV (%)		6.3	16.4	6.5

*, ** F test significant at the 0.05 and 0.01 levels of probability, respectively.

uptake rate, time to start of germination and seed water content at the start of germination. Significant deviations from linear and quadratic functions were observed for water uptake rate and time to start of germination. However, a major portion of the variation due to water potential was described by a linear function (Table 4.35). A three-way interaction was detected for time to start of germination.

Seed water uptake rate increased linearly while time to start of germination decreased with increasing temperature (Table 4.36). Water uptake rate spelt wheat increased with dehulling while time to germination decreased. Water uptake rate in CDC Bavaria was higher than in PGR8801, when averaged over naked and hulled seed forms (using contrasts), while seed water content at the start of germination for CDC Bavaria was higher than for PGR8801 (Table 4.36). Water uptake rate, time to the start of germination and seed water content at the start of germination in Katepwa common wheat were higher than for the spelt wheats, when averaged over their two seed forms. While water uptake rate decreased and time to start of germination increased, seed water content at the start of germination decreased linearly with decreasing water potential.

Time to start of germination decreased with increasing temperature for all seed forms (Table 4.37). The difference in time to the start of germination between 9 and 16 °C temperatures was greater than the difference between the intermediate (16 °C) and high (23 °C) temperatures, leading to a significant interaction.

Dehulling CDC Bavaria seeds tended to increase seed moisture content at the start of germination at 9 and 16 °C. Dehulling PGR8801 seeds tended to

Table 4.36 Means for water uptake rate, time to start of germination and seed water content at the start of germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures and four water potentials.

Source	Water uptake rate ($g\ kg^{-1}\ h^{-1}$)	Time to germination (h)	Moisture at germination (%)
Temperature (°C)			
9	11.46	98.9	52.9
16	14.12	62.1	51.3
23	17.90	43.5	51.2
LSD(0.05)	2.32	16.3	4.3^{ns}
Seed form			
CDC Bavaria-hulled	12.82	78.8	50.5
CDC Bavaria-naked	16.01	54.7	51.8
PGR8801-hulled	12.46	79.4	50.1
PGR8801-naked	15.39	53.0	48.8
Katepwa-naked	15.79	75.0	57.8
LSD(0.05)	0.43	4.9	1.5
Water potential (MPa)			
0.0	20.79	25.5	54.5
-0.6	13.98	55.1	52.8
-1.2	12.18	77.6	50.6
-1.8	11.02	114.5	49.3
LSD(0.05)	0.38	4.4	1.4

^{ns} H_0 was not rejected for the trait.

decrease seed water content at the start of germination at 23 °C compared to no changes in the water content of the remainder of seed forms, contributing to a significant temperature x seed form interaction. Seed water content of Katepwa at the start of germination was lower at 16 and 23 °C, which may have played a role in the temperature x seed form interaction. Water uptake rate of the naked seeds was higher than that of hulled seeds, irrespective of water potential. The difference between naked and seeds at the 0 MPa was smaller than at the other water

Table 4.37 Means for water uptake rate, time to start of germination and seed water content at the start of germination of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures.

Temperature (°C)	CDC Bavaria Hulled	CDC Bavaria Naked	PGR8801 Hulled	PGR8801 Naked	Katepwa Naked
		Water uptake rate ($g\ kg^{-1}\ h^{-1}$)			
9	9.68	12.98	9.63	12.31	12.72
16	12.44	15.73	11.98	15.11	15.34
23	16.32	19.33	15.76	18.76	19.32
LSD (0.05)[1]	0.74[ns]				
LSD (0.05)[2]	2.15[ns]				
		Time to germination (h)			
9	110.3	76.0	113.3	83.0	112.0
16	74.0	54.3	73.0	43.0	66.0
23	52.0	33.7	52.0	33.0	47.0
LSD (0.05)[1]	8.6				
LSD (0.05)[2]	15.6				
		Moisture content at germination (%)			
9	50.7	52.8	50.4	49.8	60.9
16	49.2	52.5	49.2	48.6	56.7
23	51.5	50.1	50.7	47.9	56.0
LSD (0.05)[1]	2.7				
LSD (0.05)[2]	4.3				

[1] Least significant difference for comparing seed form means at the same temperature.
[2] Least significant difference for comparing seed form means at different temperatures.
[ns] H_0 was not significant for the trait.

potentials, leading to a significant seed form x water potential interaction (Table 4.38). Time to start of germination increased with decreasing water potential in all seed forms. A slightly greater delay in PGR8801, than in CDC Bavaria, might have led to a significant interaction between seed form and water potential. Seed

Table 4.38 Means for water uptake rate, time to start of germination and seed water content at the start of germination of naked and hulled seed forms of CDC Bavaria and PGR880 and naked seeds of Katepwa at four water potentials.

Water potential (MPa)	CDC Bavaria Hulled	CDC Bavaria Naked	PGR8801 Hulled	PGR8801 Naked	Katepwa Naked
		Water uptake rate ($g\ kg^{-1}\ h^{-1}$)			
0.0	19.96	22.11	19.61	21.12	21.13
-0.6	11.83	15.81	11.76	15.12	15.40
-1.2	9.96	13.77	9.95	13.32	13.91
-1.8	9.52	12.36	8.51	12.01	12.72
LSD(0.05)	0.85				
		Time to germination (h)			
0.0	29.3	20.9	26.7	17.3	33.3
-0.6	72.4	38.7	72.4	36.0	56.0
-1.2	90.7	61.3	93.3	54.7	88.0
-1.8	122.7	97.8	125.3	104.0	122.7
LSD(0.05)	9.9				
		Moisture content at germination (%)			
0.0	52.2	54.5	51.7	49.0	65.2
-0.6	52.5	52.4	53.0	48.8	57.2
-1.2	49.1	50.9	48.3	48.7	55.8
-1.8	48.1	49.4	47.5	48.6	53.2
LSD(0.05)	3.1				

water content at the start of germination decreased with more negative water potential in all seed forms, with the exception of the naked seed form of PGR8801, leading to a significant interaction.

Seed water uptake rate decreased with more negative water potentials, irrespective of temperature (Table 4.39). A major drop in the water uptake rate

Table 4.39 Means for water uptake rate, time to start of germination and seed water content at the start of germination at three temperatures under four water potentials averaged over five seed forms.

Temperature	Water potential (MPa)			
(°C)	0.0	-0.6	-1.2	-1.8
	Water uptake rate ($g\ kg^{-1}\ h^{-1}$)			
9	16.12	10.97	9.62	9.15
16	20.12	13.79	11.85	10.71
23	26.12	17.18	15.07	13.21
LSD (0.05)[1]	0.66			
LSD (0.05)[2]	2.12			
	Time to germination (h)			
9	40.0	85.3	112.0	158.4
16	20.8	48.0	69.6	109.9
23	15.7	32.0	51.2	75.2
LSD (0.05)[1]	7.6			
LSD (0.05)[2]	15.1			
	Water content at germination (%)			
9	57.2	54.0	50.8	49.6
16	52.8	52.8	50.6	48.9
23	53.6	51.5	50.3	49.5
LSD (0.05)[1]	2.4[ns]			
LSD (0.05)[2]	4.1[ns]			

[1] Least significant difference for comparing water potential means at the same temperature.

[2] Least significant difference for comparing water potential means at different temperatures.

[ns] H_0 was not significant for the trait.

occurred with lowering water potential from 0.0 to –0.6 MPa, with the largest drop at 23 °C, contributing to a significant temperature x water potential interaction. Furthermore, the magnitude of the water uptake rate increase with increasing temperature decreased with more negative water potentials and may have played a role in the temperature x water potential interaction. Time to start of germination increased with more negative water potentials at all temperatures. A more pronounced increase in time to start of germination with 9 °C than with 16 °C or 23 °C led to a significant temperature x water potential interaction.

4.4.4 Seedling Establishment of Spring Spelt Relative to Common Wheat

The amount of water that had to be added to the test soil to achieve -0.01, -0.03, -0.5, -1.0 and -1.5 MPa was 28, 20, 12.6, 12 and 11.3 per cent (w/w), respectively. When target water potentials were selected, the above water potentials were chosen as representative for a wet soil, a soil at field capacity, and soils with light, moderate and relatively serious moisture shortage, respectively.

Temperature effects were statistically significant for seedling establishment and seedling emergence velocity (Table 4.40). Orthogonal polynomial contrasts indicated a significant quadratic response of emergence percentage and a linear response of emergence velocity to temperature. Seed form effects and water potential effects were statistically significant for both per cent of seedling emergence and velocity of emergence. Contrasts comparing the naked vs. hulled seed forms of the two spelt cultivars, CDC Bavaria vs. PGR8801 and spelt wheat vs. common wheat indicated significant differences for both per cent of emergence and velocity of emergence. Orthogonal polynomial contrasts for water potential indicated a significant lack of fit to a quadratic function for per cent of seedling emergence and significant lack of fit to a cubic function for velocity of seedling emergence. Seed form by temperature interaction effects were statistically significant for both per cent of seedling emergence and velocity of emergence. The

Table 4.40 Analysis of variance (Mean Squares) for seedling emergence, and velocity of emergence of hulled and naked seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under five water potentials.

Source	DF	Emergence	Velocity
Replication (R)	2	1230**	23.15
Temperature (T)	2	1420**	2387.43**
Linear	1	423*	4774.82**
Quadratic	1	2410**	0.03
R*T	4	30	23.40**
Seed form (S)	4	1970**	285.40**
Hulled vs. naked	1	2470**	1034.88**
CDC Bavaria vs. PGR8801	1	1950**	31.58**
CDC Bavaria & PGR8801 vs. Katepwa	1	2930**	67.68**
Water potential (P)	4	8190**	754.70**
Linear	1	21900**	2837.05**
Quadratic	1	9530**	3.92
Cubic	1	394	47.89**
Remainder	1	889*	129.95**
T*S	8	506**	26.63**
T*P	8	352	106.18**
S*P	16	991**	4.94*
T*S*P	32	115	2.14
Error	144	186	2.34
CV (%)		16.9	11.3

* F test significant at the 0.05 level of probability.

** F test significant at the 0.01 level of probability.

temperature by water potential interaction was statistically significant for velocity of emergence. The seed form by water potential interaction was statistically significant for both per cent of seedling emergence and velocity of seedling emergence.

The intermediate temperature (16 °C) appeared to be better suited for achieving maximum seedling emergence compared to the low (9 °C) and high (23 °C) temperatures while velocity of emergence increased linearly with temperature (Table 4.41). Dehulling of the spelt seed led to increases in both seedling emergence and velocity, when averaged over the temperatures and water potentials. CDC Bavaria had a lower emergence percentage than PGR8801, while Katepwa had a higher emergence percentage and emergence velocity than the spelt wheats, when averaged over the naked and hulled spelt seeds. Both per cent of seedling emergence and velocity of emergence decreased with water potentials more negative than field capacity (-0.03 MPa). However, for seedling emergence percentage all orders of polynomials with the exception of the cubic component, and for velocity of seedling emergence all orders of polynomials with the exception of the quadratic component were significant, indicating that the magnitude of reduction in these traits varied across water potentials.

Dehulling led to increased seedling emergence of the spelt cultivars at 9 °C, while it did not affect emergence at 23 °C, contributing, in part, to a significant interaction of seed form with temperature (Table 4.42). Another source of interaction may be a decrease in per cent of seedling emergence of naked and hulled seeds of CDC Bavaria when the temperature was increased from 16 to 23 °C compared to no consistent change in the two seed forms of PGR8801 and naked seeds of Katepwa. The highest emergence percentage was achieved by Katepwa and

Table 4.41 Means for per cent seedling emergence and velocity of emergence of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures and five water potentials.

Source	Emergence (%)	Velocity (%/day)
Temperature (°C)		
9	79.8	7.9
16	85.1	13.6
23	76.5	19.2
LSD (0.05)	2.5	2.2
Seed form		
CDC Bavaria-hulled	73.4	10.7
CDC Bavaria-naked	77.4	15.1
PGR8801-hulled	76.6	11.1
PGR8801-naked	87.4	16.3
Katepwa-naked	87.7	14.7
LSD(0.05)	5.6	0.6
Water potential (MPa)		
-0.01	87.1	17.9
-0.03	91.6	17.6
-0.5	85.1	12.5
-1.0	81.4	11.3
-1.5	57.3	8.5
LSD (0.05)	5.7	0.6

Table 4.42 Means for per cent seedling emergence and velocity of emergence of naked and hulled seed forms of CDC Bavaria and PGR8801 and naked seeds of Katepwa at three temperatures under five water potentials.

Source	CDC Bavaria Hulled	CDC Bavaria Naked	PGR8801 Hulled	PGR8801 Naked	Katepwa Naked
Temperature (°C)			Emergence (%)		
9	74.8	81.7	69.5	86.4	86.8
16	82.4	82.0	77.7	91.6	91.9
23	62.9	68.4	82.5	84.1	84.4
LSD (0.05)[1]	6.9				
LSD (0.05)[2]	8.9				
			Velocity of emergence (%/day)		
9	6.7	8.7	6.8	9.4	8.1
16	11.0	15.3	10.6	16.4	14.8
23	14.5	21.2	16.0	23.2	21.2
LSD (0.05)[1]	0.8				
LSD (0.05)[2]	1.9				
Water potential (MPa)			Emergence (%)		
-0.01	85.6	73.3	98.4	87.6	90.4
-0.03	89.3	84.9	98.7	94.4	90.7
-0.5	82.2	81.3	79.6	92.0	90.2
-1.0	74.0	81.8	72.9	90.0	88.2
-1.5	35.8	65.6	33.2	72.9	78.9
LSD(0.05)	12.6				
			Velocity of emergence (%/day)		
-0.01	15.3	19.3	16.3	20.8	18.0
-0.03	13.5	19.8	15.0	21.3	18.6
-0.5	9.5	14.3	9.4	15.4	14.1
-1.0	8.4	12.8	8.6	13.8	12.9
-1.5	6.8	9.3	6.4	10.3	9.8
LSD(0.05)	1.4				

[1] Least significant difference for comparing seed form means at the same temperature.
[2] Least significant difference for comparing seed form means at different temperatures.

naked seeds of PGR8801 at 16 °C. The lowest emergence percentage was obtained for the hulled seed form of CDC Bavaria at 23 °C. Dehulling led to an increase in velocity of emergence at all temperatures. A larger increase in velocity of emergence at 23 °C than at 9 °C, led to an interaction between seed form and temperature. The interaction of seed form with water potential for per cent of emergence arose partially from a higher emergence percentage at -0.01 MPa for hulled than naked seed forms of spelt compared to a higher emergence for the naked seed in the dry soil. No change in per cent emergence of Katepwa with water potential could be another source of the interaction. Lowering the water potential below field capacity (-0.03 MPa) led to a decrease in the velocity of emergence for all seed forms. Lowering the water potential to field capacity (-0.03 MPa) decreased the velocity of seedling emergence for hulled seed forms of the spelt while no such tendency was observed for the naked seed forms, leading to a significant seed form x water potential interaction.

With the three temperatures used in this experiment, lowering the water potential below field capacity reduced the velocity of emergence (Table 4.43). A significant interaction of water potential and temperature for velocity of emergence arose, partially, from an increase in velocity due to lowering water potential to field capacity (-0.03 MPa) at 16 °C, in contrast to a decrease in velocity at 23 °C. Furthermore, velocity of seedling emergence increased with increasing temperature at all water potentials. The magnitude of the increase in the velocity decreased with more negative water potentials that may have played a role in temperature x water potential interaction.

Table 4.43 Means for per cent seedling emergence and velocity of emergence at three temperatures under five water potentials averaged over five seed forms.

Temperature (°C)	Water potential (MPa) -0.01	-0.03	-0.5	-1.0	-1.5
			Emergence (%)		
9	91.2	95.3	82.4	78.8	51.5
16	84.8	94.3	91.1	86.9	68.5
23	85.2	85.2	81.7	78.4	51.9
LSD (0.05)[1]	6.9[ns]				
LSD (0.05)[2]	8.9[ns]				
			Velocity of emergence (%/day)		
9	9.7	9.5	7.1	7.3	6.1
16	17.2	18.0	12.9	11.1	8.9
23	26.9	25.4	17.6	15.6	10.7
LSD (0.05)[1]	0.8				
LSD (0.05)[2]	1.9				

[1] Least significant difference for comparing water potential means at the same temperature.

[2] Least significant difference for comparing water potential means at different temperatures.

[ns] H_0 was not rejected for the trait.

5.0 DISCUSSION

5.1 Seeding Rate

Years were considered fixed in the current studies. Therefore, one must exercise caution in extrapolating results of the current field experiments (seeding rate, seeding date and seed form) to all environmental conditions of central Saskatchewan.

The objective of this study was to determine whether spring spelt and common wheat differ in their response to seeding rate. Seeding rates recommended for common wheat in central Saskatchewan (250 seeds/m^2) are appropriate for achieving maximum grain yield in spring spelt wheat. The above conclusion can be made based on the *lack of significant interaction for cultivar x seeding rate and year x cultivar x seeding rate* for many traits including grain yield (Tables 4.3 and 4.4). This confirms that relative grain yields of the common wheat and spelt cultivars did not change with seeding rate (Table 4.8).

The significant *year x cultivar interaction* for many traits, including grain yield implies that the performance of the cultivars is not consistent from one year to the next. It appears that, despite a large increase in tiller number for PGR8801 in 1996 relative to 1995 (Table 4.10), high tiller mortality led to a relatively low spike number for this cultivar. The largest increase in spike number from 1995 to 1996 was observed in Katepwa. A high spike number in Katepwa was partially offset by a decrease in kernels/spike in 1996 (Table 4.10). No significant change in kernel weight between the two years indicates that grain yield of the cultivars was sink-limited (Johnson and Kanemasu, 1982) because environmental conditions for assimilation in 1996 were more optimal (*i.e.* likely no source limitation) than 1995. Results of the current experiment agree with previous reports that spike number and kernels/spike are the major determinants of wheat grain yield (Middleton, *et al.*, 1963; Lafond, 1994; McMaster, 1994) and yield component compensation changes the relative contribution of these components to final grain yield (Baker, 1966). The change in the rank of cultivars between the two years arose from a smaller increase in grain yield of CDC Bavaria compared to PGR8801 (Table 4.12). Precipitation in 1996 was higher than in 1995 for most of the growing season (Table 4.1). While the higher precipitation led to an increase in grain yield, it led to excessive vegetative growth in the spelt cultivars. Low rainfall is known as a major source of low wheat grain yield in the Canadian prairies (Campbell *et al.*, 1969). Furthermore, the nature of the negative impact of drought on final wheat grain yield depends on the growth stage at which the drought is severe (Fischer and Kohn, 1966; Wardlaw, 1971; Fischer, 1979, Entz and Fowler, 1988). In the current experiment, low precipitation early in the season in 1995 led to low tiller formation and thus low spike numbers compared to 1996. A plow wind occurred at the boot stage of the spelt cultivars. Combined with the excessive vegetative growth this led to severe lodging of CDC Bavaria plots in 1996. It appears that the relatively small inter-year increase in grain yield of CDC Bavaria compared to PGR8801 was due to the lodging. This lodging resulted in the change in cultivar rank between years.

Tiller mortality rate was higher in spelt compared to the common wheat. Therefore, despite a higher number of tillers (especially in PGR8801), the largest numbers of spikes were produced by the common wheat. It has been argued that spelt wheat has the ability to stabilise grain yield under adverse environmental conditions, due to its high tillering capacity (Ruegger *et al.*, 1990a; Schmid *et al.*, 1996). According to Hucl and Baker (1993), in spring wheat cultivars with a restricted tiller number, kernels/spike is the major yield component for responding to changing environmental resources. Thus, limited crop plasticity makes them undesirable for production under stressful conditions. In a relatively dry year, 1995, Katepwa and CDC Bavaria produced a smaller number of tillers than PGR8801. In 1996, which was relatively wet, the highest number of tillers was produced by PGR8801 followed by Katepwa and CDC Bavaria. However, both spelt cultivars produced a smaller number of spikes than Katepwa in both years. The fact that the two spelt cultivars produced a large number of tillers indicates that spelt has a high grain yield potential. Environmental conditions, however, curtailed the development of tillers so that up to 44 per cent of the tillers failed to produce a spike (Table 4.8). These findings indicate that the spelt cultivars did not have an advantage in crop plasticity over Katepwa during the two years of evaluation. The results, however, indicate that there were some differences between spelt and the common wheat in sink versus source limitations. Of the two spelt cultivars, PGR8801 had a greater ability to adjust grain yield, as a result of the plasticity brought about by a higher tiller capacity. In CDC Bavaria, kernels/spike, rather than spike number, was important in adjusting the grain yield.

Results of the present study do not agree with those of Ruegger and Winzeler (1993) who found no difference in grain yield at low and high seeding rates and between hulled grain yield of winter spelt and naked grain yield of common wheat. Ruegger and Winzeler (1993) found that a high spike yield for both winter spelt and common wheat compensated for a low spike number at the low seeding rates.

A number of studies have been conducted on the impact of seeding rate on grain yield of common spring wheat in western Canada. Maximum grain yields with seeding rates of 45 kg ha^{-1} (Pelton, 1969), 68-102 kg ha^{-1} (Larter *et al.*, 1971), greater than 90 kg ha^{-1} (Briggs and Aytenfisu, 1979), 160 kg ha^{-1} (Lafond, 1994, Lafond and Derksen, 1996) and 400 seeds/m^2 (Baker, 1982) have been reported for spring wheat.

The current results to some extent contrast with those of Baker (1982) and Lafond and Derksen (1996) since no increase in grain yield with seeding rate was observed. However, results of the current study are in agreement with those of Lafond and Derksen (1996) in that spikes/m^2 increased and kernels/spike decreased while kernel size did not change significantly with seeding rate. Hucl and Baker (1990a), in a pot experiment, found that interplant competition (due to increased plant density) resulted in decreases in both kernels/spike and kernel weight of spring wheat cultivars. Hucl and Baker (1990b) reported that increasing seeding rates (under field conditions) decreased kernels/spike and kernel weight of three spring wheat cultivars with differing tillering habits. They concluded that kernels/spike played an important role in grain yield variation due to differing environmental conditions.

The dependency of grain yield on numerous physiological events (McMaster *et al.*, 1994) and limitation of grain yield by one or more yield components under stressful conditions (Johnson and Kanemasu, 1982) has been established. In the present study, the number of spike-bearing tillers increased with seeding rate in both years. Thus, with increasing seeding rate combined with a lack of precipitation probably led to a limited number of kernels, due to an increase in competition during post-anthesis developmental stages. In 1995 high seeding rates led to an early moisture depletion of the soil due to below-average precipitation, thus lack of sufficient moisture for kernel formation and filling and a reduction in grain yield with increasing seeding rate in 1995. The increase in spike number with seeding rate in 1995 was smaller than the decrease in kernels/spike. The increase in spike number in 1996 was compensated by a decrease in kernel number, leading to no overall impact of seeding rate on the grain yield.

5.2 Seeding Date

The objective of this study was to contrast the response of spring spelt and common wheat to seeding date. A significant *cultivar x seeding date interaction* indicated that grain yield of spelt and common wheat was affected differently by changes in seeding date. An early seeding date (not later than mid-May) for spelt wheat is preferable for maximum grain yield while for common wheat seeding date did not affect grain yield (Table 4.21). While the last two seeding dates (late May and early June) produced the lowest grain yields for CDC Bavaria, the fourth seeding date produced the lowest grain yield for Katepwa. Considering its long maturity requirement, spelt wheat should not be seeded late since the late seeding may expose it to the risk of damage from early fall frosts.

The presence of the *year x cultivar interaction* for some traits, including grain yield, implies that the performance of the spelt and common wheat cultivars cannot be compared without taking into account the environmental conditions encountered in 1995 and 1996. The low tiller mortality in Katepwa led to substantially higher spike/m^2 in Katepwa in 1996 compared to CDC Bavaria (Table 4.22). Due to the high spike population of Katepwa in 1996, a competition for assimilates between spikes led to a decrease in kernels/spike. It appears that the major source of differential yield response of the two cultivars to the years was lodging in the CDC Bavaria plots. The lodging, probably, limited the dry matter production and grain filling of CDC Bavaria, therefore, resulting in a smaller increase in grain yield of CDC Bavaria compared to Katepwa between 1995 and 1996 (Table 4.23).

While there are no reports in the literature on the impact of seeding date on spring spelt, studies on seeding date of spring wheat in Western Canada have shown that the optimum seeding date for grain yield is dependent on environmental conditions in each year. An early seeding (prior to mid-May) has been reported as optimal by Larter *et al.* (1971), Briggs and Aytenfisu (1979) and Baker and Gebeyehou (1982), while a late seeding (after mid-May) has been reported by Hucl and Baker (1989b) and Baker (1990). Hucl and Baker (1989b) found that seeding 10 spring wheat cultivars in early May resulted in greater spike production than seeding in late May. The late seeding, however, led to more spikelets and kernels per spike, higher spike yield and grain yield than early seeding, due, in part, to high precipitation during the tillering stage. They concluded that the greater yield obtained with late seeding was associated with a higher number of spikelets/spike and kernels/spike compared to an early seeding. Earlier, Jessop and Ivins (1970) had found that kernels/spike is the most variable yield component, as affected by seeding date. Cutforth *et al.* (1990) concluded that seeding earlier or later than May at Saskatoon decreases grain yield of spring wheat. Hucl (1995) found no uniform response from four spring wheat cultivars, including Katepwa, to seeding date in different years at Saskatoon. While seeding in late May in one year led to a 10% increase in grain yield relative to seeding in early May, seeding in late May led to 17 and 27% reductions in the remaining two years of the study. These contradicting reports serve to emphasize that there is no clear-cut answer to the question of optimum seeding date for spring wheat in western Canada, mainly because of the unpredictability of the growing conditions. In 1995, precipitation in May and June were each 30 mm below the long-term average (Table 4.1). Precipitation in July and August were 23 and 48 mm above the long-term average, respectively. In 1996, precipitation in May, June and July were 15, 37 and 56 mm above long-term average, respectively. Precipitation in August was 18 mm below the long-term average. In the current study, contrasting yield responses to seeding date were observed in the two years. In 1995, changes in grain yield were closely associated with changes in spike number. In 1996, on the other hand, changes in grain yield and yield components did not follow a particular trend. These contradictions emphasize that, in any year, responses can differ from the norm due mainly to unpredictable weather. Results of the current experiment agree with conclusions made by Hucl and Baker (1989b) that precipitation played an important role in relative yield of spring wheat with late vs. early seeding dates. Furthermore, the current results agree with those of Hucl (1995) in that variation in grain yield with differing seeding dates was attributed to the coincidence of optimal environmental conditions with the plant growth stages critical to grain yield production. Based on the current results, it seems that any seeding date that is followed by optimal environmental conditions in general, and precipitation patterns in particular, probably results in a higher grain yield under the moisture-limited conditions typical of the Canadian Prairies.

Double ridge is considered the stage when floral initiation commences in cereals (Klepper *et al.*, 1983). Occurrence of the double ridge stage suggests that leaf initiation has ceased. At this stage, the shoot apex is distinctly elongated and a few ridges are visible and the first sign of the spikelet initiation, which is the doubling of the ridges, can be observed (George, 1982; Klepper *et al.*, 1983). Wong and Baker (1986) found that floral initiation began at earlier Haun stages in genotypes with fewer leaves than those with higher numbers of leaves. In the current study, floral initiation (double ridge stage) of Katepwa and CDC Bavaria, which are 7- and 8-leaved types, respectively, did not occur at different Haun stages (Table 4.16). But CDC Bavaria required a longer time (3 days) for spike differentiation than Katepwa.

Days to heading and thus maturity for Both CDC Bavaria and Katepwa decreased when seeding was delayed (Table 4.21). This is a reflection of a more rapid accumulation of heat units with delayed seeding. There was no strong evidence to suggest that the relative maturity of the two cultivars changed from early to late seeding dates. Late planting conditions that lead to seedling emergence and development under relatively high temperature conditions do not induce vernalization (Jedel *et al.*, 1986; Jedel, 1994). If spring spelt had required vernalization, delayed seeding should have led to a delay in spelt's heading relative to common wheat (Levy and Peterson, 1972). The lateness of spelt compared to common wheat was, mainly, a result of an additional phyllochron interval (Bauer *et al.*, 1984) and to some extent an inherent lower development rate rather than a significantly different vernalization requirement. A greater GDD accumulation to heading (Table 4.24) in 1996 than in 1995 could have been due to delayed plant development in a wet year (1996) (Cutforth *et al.*, 1988 and 1990).

5.3 Seed Form, Crop Establishment and Grain Yield

The objective of the seed form study was to investigate the impact of hulls of spring spelt on seedling establishment under field conditions. The results obtained under two years of study were inconclusive. In 1995, hulled spelt seeds and naked Katepwa seed had a higher per cent seedling emergence than naked spelt while in 1996 no differences were discovered (Table 4.27). The results of the seeding method experiment suggest that using either naked or hulled seed forms of spelt will result in similar grain yields. Calculating coefficient of velocity and per cent of seedling emergence provided an insight into the speed of emergence and stand establishment of different seed forms (Scott *et al.*, 1984). *Lack of significant seeding date x seed form interaction* (Tables 4.4.24 and 4.25) serves to emphasise that relative plant establishment, spike production and grain yield of different seed forms did not change with seeding date. Velocity of emergence of the naked spelt seeds was higher than that of the hulled seeds (Table 4.26). The naked seeds of PGR8801 tended to have a higher emergence velocity than the naked seeds Katepwa. Data presented later indicates that the difference in the emergence velocity of the two types of wheat probably is related to water content threshold necessary for germination, rather than to seed water uptake rate.

The plant establishment of the naked seeds relative to the hulled seeds of the spelt cultivars was not consistent over the two years (Table 4.27). While dehulling reduced seedling establishment in 1995 it did not affect establishment in 1996. Seedling establishment in 1996 tended to be lower than in 1995. The reasons of the inconsistent response (establishment percentage) of naked vs. hulled seed forms over years and a generally lower plant establishment in 1996 relative to 1995 are not known.

5.4 Grain Yield of Spelt vs. Common Wheat

Based on the grain yields from the three field experiments (seeding rate, seeding date and seed form) conducted in 1995 and 1996, the spring spelt cultivars out-yielded the common wheat cultivar when hulled grain (combine harvested grain yield) was used in the cultivar comparison (Tables 4.8, 4.20 and 4.26). Dehulling seed samples indicated that for CDC Bavaria, PGR8801 and Katepwa combine harvested samples contain approximately 32, 36 and 4 per cent chaff, hulls, *etc.*, respectively. Therefore, spelt could equal the common wheat in naked grain production, when planted early. All grain yield components of the three wheat cultivars varied with treatment and environmental conditions, with the exception of kernel weight. The fact that spikes/m^2 and kernels/spike are the major determinants of grain yield has been emphasized by other scientists (Middleton *et al.*, 1963; McMaster *et al.*, 1994). In the present experiments, of the yield components, spike number and kernels/spike were more closely associated with grain yield and its variation than kernel weight. A close relationship between spike number and final grain yield of cereals has been reported by some researchers (Black and Siddoway, 1977; Garcia Del Moral *et al.*, 1985; Bulman and Hunt, 1988). In the present study, when kernels/m^2 (as a function of spikes/m^2 and kernels/spike) is estimated, it is closely associated with grain yield. The current results agree with previous reports that kernels/m^2 is more closely related to wheat grain yield than is kernel weight (Entz and Fowler, 1990).

The difference between spelt and common wheat yield tended to start with a difference in seedling establishment. Some studies have indicated that plant establishment in winter spelt is higher than in common wheat (Ruegger and Winzeler, 1993). In the present study, however, the reverse was the case. CDC Bavaria and PGR8801 tended to produce lower and higher tiller numbers than common wheat, respectively. The spelt cultivars were characterized by a high tiller mortality, leading to a lower spike number than for the common wheat cultivar. The heavier kernels of the spelt compensated for its low spike number relative to common wheat. Hucl and Baker (1988) found no association between tillering capacity and tiller mortality with grain yield in a wide array of spring wheat germplasm. They found, however, that high-tillering genotypes tended to produce high spike numbers and light kernels, in contrast to low spike numbers and heavy kernels of the low tillering genotypes. In spring barley, no association of tiller number and grain yield has been reported (Simmons *et al.*, 1982). Results of the present study agree with the above studies in that high tiller production by the spelt did not guarantee high spike number and grain yield. The current results agree with those of Ruegger *et al.* (1990a and b) in that tiller mortality is high in the spelt cultivars and with those of Evans and Dunstone (1970), Waines *et al.* (1986) and Ruegger *et al.* (1990a) in that spelt produces heavier kernels than common wheat. Ruegger *et al* (1990b) found that with a similar number of spikes per plant for winter spelt and common wheat, the heavy kernels of spelt could not compensate for reduced numbers of kernels per spike, leading to a lower spike yield and grain yield than common wheat. Results of the current studies disagree with those of Ruegger *et al.* (1990b) in that heavy kernels of spelt led to a higher spike yield compared to common wheat and in that spelt had a lower number of spikes per plant compared to common wheat. Rimle (1995) found that despite differences between the grain yield components of winter spelt and common wheat, the grain yield of the two wheats did not differ. In the current studies, differences in yield components of spelt vs. common wheat led to differing grain yields.

Nesbitt and Sammuel (1995) pointed out (based on contradictions among reports on relative performance of spelt) that if differences in yield between spelt and common wheat exist, they are not necessarily a reflection of consistent differences between spelt and common wheat. Current results, however, indicate that there were differences between spring spelt and Katepwa. While the current experiments did not detect a differential response (grain yield) of spring spelt and common wheat to seeding rate (plant population), they detected a tendency for differential response to date of seeding.

The performance of spring spelt wheat in Saskatchewan, based on the current findings within a limited range of environmental conditions, is somewhat more promising than that of winter spelt in Western Europe. An approximate 800-1000 kg ha^{-1} (*i.e.* up to 20-25%) advantage of hulled spelt grain yield over common wheat with early seeding indicates that spelt wheat may have a place in cropping systems of central Saskatchewan.

The two spelt cultivars differed in grain yield, with PGR8801 producing a higher grain yield than CDC Bavaria (Table 4.8). A cultivar by year interaction for grain yield was, at least in part, due to a change in the productivity of the two spelt cultivars relative to one another over the two years. The cultivar x year interaction was, at least partially, due to the severe lodging of CDC Bavaria in 1996. The lodging probably led to a reduction in the dry matter accumulation of CDC Bavaria.

The low harvest index of spelt relative to common wheat (Table 4.8) coincided with a higher total aboveground biomass production (Table 4.9) by the spelt cultivars. Furthermore, differences in harvest index may be related to differences in pattern of allocation of photosynthates (Gent *et al.*, 1989). Since naked grain yield of spelt was lower than that of Katepwa, it seems that spelt is less efficient in converting dry matter to grain yield than common wheat. A lower efficiency of conversion of dry matter to grain yield of tall wheat cultivars relative to semi-dwarf cultivars has been postulated (Entz and Fowler, 1990). It appears that allocation of a large portion of the biological yield to non-reproductive portions of the plant in spelt wheat cultivars led to a relatively smaller increase in grain yield in 1996 compared to 1995 relative to common wheat. A more stable conversion of dry matter to grain yield across environments for semi-dwarf winter wheat compared with tall wheat has been reported (Entz and Fowler, 1990). Rimle (1995) and Schmid *et al.* (1996) reported a low harvest index for spelt wheat. Results of the current studies agree with those of Rimle (1995) and Schmid *et al.* (1996). A greater biomass production by spelt wheats than common wheat, as well as grain yield fluctuations under different environmental conditions encountered in the present study, can be further explained by the results obtained in the growth analysis.

5.5 Growth Analysis Factors Relations, Biomass and Grain Yield

LAI, LAD and CGR in 1995 were severely reduced relative to 1996 (Table 4.9, 4.13 and 4.14). According to Hunt (1982) any departure from an adequate supply of light, water, nutrients, temperature, *etc.* produces an adverse effect on CGR, RGR, LAD and other quantitative measures of plant growth. The LAI, LAD and to some extent CGR of the spelt cultivars were substantially higher than those of Katepwa. Hucl (1995) found that at early anthesis the LAI of spring wheats was approximately 1.7. The above report disagrees with results of the current study (Table 4.9) likely because LAI is maximum at early anthesis. While there is no report on CGR of spelt wheat, in an artificial canopy of wheat maximum CGR reached 30 g m^{-2} d^{-1} (King and Evans, 1967). Hucl (1995) reported a CGR of 17 to 18 g m^{-2} d^{-1} for four spring wheat cultivars, including Katepwa. Results of the present study agree with that of Hucl (1995) because CGR's of 18.7, 19.7 and 16.5 g m^{-2} d^{-1} (Table 4.9) were found for CDC Bavaria, PGR8801 and Katepwa, respectively. In the present study, higher LAD of spelt compared to Katepwa led to higher DM production (Table 4.14). Despite a close correlation between leaf area and plant dry matter (Aase, 1978), LAD is a more efficient expression of the photosynthetic capability of the plant than LAI because it takes into account both the magnitude of leaf area and its persistence over time. Indeed, the final biological yield of a crop is the product of LAD and NAR. According to Watson (1947) and Gifford and Evans (1981), the role of LAI, thus LAD, in determining CGR and final yield is more important than NAR because LAI is more influenced by environment and management practices.

In the current study, the higher LAD of CDC Bavaria compared to that of PGR8801 did not lead to a yield advantage in 1996. This contradicts Watson's (1947) conclusion regarding the relationship between LAD and grain yield. The most likely explanation for this disagreement is the lodging that occurred in 1996. It seems that due to lodging, CDC Bavaria did not use its entire LAD for DM production. This conclusion is supported by the fact that CGR of the three cultivars was closely associated with their DM. There is a close relationship between the green LAI value and the amount of light being intercepted by the plant (Shibles and Weber, 1965; Wilfong *et al.*, 1967). Normally, CGR is at its peak when LAI is maximal. However, there is a point, *i.e.* optimum or critical LAI in the case of wheat (King and Evans, 1967), where an increase in LAI does not lead to a further increase in CGR. Thus, maximum dry matter production is achieved at the optimum LAI. Optimum LAI's of up to nine (Watson *et al.*, 1963) or ten (King and Evans, 1967) have been reported for spring wheat. The lodging of CDC Bavaria plots created a situation similar to having LAI's beyond the optimum LAI. Furthermore, it can be speculated that lodging leads to a decrease in yield by decreasing NAR (Welbank *et al.*, 1966).

When the yield of interest is grain, the process of net translocation (Wiegand *et al.*, 1979) and green area during grain development (Welbank *et al.*, 1966; Khalifa, 1973) cannot be underestimated. In the present study Katepwa, likely, had a more efficient translocation system compared to the spelt cultivars, since it had a higher harvest index. Leaf area measurements do not provide a suitable index of active growing material that can be used for estimating NAR (Williams, 1946). Also, photosynthetic rate and LAD during grain development were not estimated in the present study. Results of studies of the photosynthetic rate per unit leaf area of spelt wheat are not consistent. According to Khan and Tsunoda (1970), a spring spelt had one of the lowest photosynthetic rates per unit leaf area amongst a number of diploid, tetraploid and hexaploid winter and spring wheats. Evans and Dunstone (1970) reported a lower photosynthetic rate for spelt compared to common wheat. Ruegger *et al.* (1993), on the other hand, found no difference between photosynthetic rate of the flag leaf of winter spelt and common wheat. In the present study, higher LAI and LAD of spelt relative to Katepwa did not transfer into a same difference in CGR. Thus, NAR of spelt cultivars probably was lower than that of Katepwa. Since many studies have indicated that there is a negative correlation between leaf size and photosynthetic rate (Bhagsari and Brown, 1986), a lower photosynthetic rate of spelt, which has large leaves relative to common wheat, was not surprising.

There is no detailed information on the quantitative growth aspects and growth analysis of spelt wheat. The only previous reference to growth characteristics of spelt is made by Ruegger *et al.* (1993), where a lower LAI for spelt than common wheat was reported. The current results do not confirm the above report.

Measurements of *leaf angle* showed that for Katepwa the leaf angle was significantly higher than that of the spelt wheats (Table 4.9). Some reports suggest that the canopy architecture that maximizes CGR is one where the upper leaves are vertical and the tilt angle decreases in basal leaves (Austin *et al.*, 1976). With horizontal leaves, dry matter production per leaf area is greater than with vertical leaves. With vertical leaves, however, a higher proportion of the light penetrates to the lower leaves, giving them a higher efficiency than if they were below a layer of horizontal leaves. Thus, at a given LAI, a high dry matter production per land area is achieved with vertical leaves in the upper portion and horizontal leaves at the lower portion of the canopy.

In the present study, considering the substantially higher LAI and LAD for spelt relative to common wheat, droopy leaves in spelt wheat cultivars did not appear to be a limiting factor as far as dry matter accumulation is concerned. Even if photosynthetic rate in spelt is lower than in Katepwa, higher LAI and LAD led to higher CGR in spelt wheat. Argus *et al.* (1972) reported that with plant densities that led to a LAI of greater than 4-5, erect leaves enhanced the yield of barley. In the current study, average LAI did not exceed 2.5 (Table 4.13). Therefore, with the current LAI values, the more erect leaves of Katepwa could not play a major role in determining final DM and grain yield.

Baker and Gebeyehou (1982) concluded that LAD was closely associated with biological yield of two spring wheats and a barley cultivar. Dunphy *et al.* (1984) found that LAI and LAD of wheat were highly correlated with grain yield. The current results agree with the above reports. Differences in magnitude of DM produced by spelt cultivars vs. Katepwa and in 1995 vs. 1996 were closely associated with LAD. It appears that in the present study spelt wheat cultivars took advantage of their substantially higher LAI and LAD to produce a higher biological yield compared to Katepwa. The differences in DM of the three cultivars over the years can be explained by their LAD. Having a substantially higher photosynthetic capability in 1996 compared to 1995, the three wheat cultivars produced a substantially higher biological yield and, thus, grain yield. An almost two-fold increase in CGR and DM in 1996 compared to 1995 during the linear period of growth correlates with the difference in leaf area between the two years (Table 4.14).

Since photosynthesis in the spike is a major contributor to grain yield (Watson *et al.*, 1958), the longer spike of spelt relative to common wheat, could be a determining factor for grain yield. Indeed, a major portion of the lower spikes/m^2 in spelt compared to Katepwa was compensated by heavier kernels of spelt. The heavier kernels of spelt relative to Katepwa coincide with longer LAD and larger spikes of spelt. Therefore, it can be speculated that longer LAD and large spikes provide a strong source of assimilates for grain filling in spelt (*i.e.* spelt grain yield is sink-limited).

5.6 Controlled Environment Experiments

The objective of the controlled environment experiments was to evaluate the impact of the spelt hull on spelt seed germination and seedling establishment under contrasting moisture and temperature conditions compared to common wheat. The impact of the spelt hull on water uptake by the spelt seed relative to common wheat was also investigated. The controlled-environment experiments revealed that the impact of the hull on germination and seedling establishment is dependent on soil moisture and temperature. While the hull slowed water uptake, the moisture content threshold for germination of spelt seed was lower than for common wheat.

A controlled environment experiment on *seed germination* with different water and temperature combinations revealed that a high temperature was not appropriate for maximum germination of all seed forms. Results such as a higher germination velocity of the naked seeds relative to hulled seeds (Tables 4.32 and 4.33) and an increase in germination velocity with increasing temperature were to be expected. The fact that the rate of seed germination is more sensitive to environmental conditions than final germination has previously been established (Schimpf *et al.*, 1977). Detailed examination of the temperature x seed form interaction revealed that, at 23 °C, the hulled spelt seeds tended to have a lower germination than at 9 °C and 16 °C (Table 4.33). The naked seeds, on the other hand, tended to respond uniformly to the three temperatures. Thus, increasing temperature (to 23 from 9 °C) had a negative impact on the hulled seed forms relative to the naked seeds of spelt and common wheat. Sharma (1976) found that germination rate of three semi-arid plant species increased with increasing temperature, but the highest final germination was achieved at intermediate temperatures (20 to 25 °C). Results of the current study agree with those of Sharma (1976).

A lower per cent germination and germination velocity at more negative water potentials was anticipated. Water potentials more negative than -0.6 MPa appeared to have a significant negative impact on per cent germination for all seed forms (Table 4.33). The negative impact of more negative soil water potential levels on imbibition and germination processes at different species was predictable (Owen, 1952; Ashraf and Abu-Shakra, 1978; Lafond and Baker, 1986b; McDonald *et al.*, 1988; Qi and Redmann, 1993). Ashraf and Abu-Shakra (1978) found that germination speed dropped with increasing drought stress (ranging from 0 to -1.8 MPa). Lafond and Fowler (1989) reported a larger effect of soil temperature than soil water content on winter wheat seed water uptake rate and germination. In the present study the impact of water potential on per cent germination and germination velocity, in general, and on germination of the hulled seeds, in particular, was shown to be more important than temperature, which disagrees with Lafond and Fowler (1989). The negative impact of more negative water potentials on seed germination appeared to be more serious with the hulled seeds of the spelt cultivars than with the naked seeds. The present study did not include the wide range of temperatures, used by Lafond and Fowler (1989). Also, an equal amount of water or solution was used for each petri dish. The hull limited the amount of water accessible to the hulled seed. Together with the relatively wide range of water potentials used in the present study the above factors led, in part, to a more pronounced impact of water potential than temperature on germination. Furthermore, the larger impact of the negative water potentials on the hulled seeds might have been related to their access to a limited volume of solution relative to the naked seeds. Thus, hulled spelt seeds are likely inappropriate for situations with low soil water content in the field.

Similar to the germination experiment, high temperature appeared to be harmful for maximum *seedling emergence* of all seed forms (Table 4.42). Kaufmann and Ross (1970) reported that temperature (ranging from 15 to 35 °C) has little impact on wheat seed germination. Lafond and Baker (1986b) found no impact of contrasting temperatures (5-30 °C) on final germination of nine spring wheat cultivars. The discrepancy between the above results and those of the present study may be a reflection of differences in medium, cultivars, etc. In the present experiment, on average, maximum seedling emergence was achieved at 16 °C while a maximum velocity was achieved at 23 °C. King and Oliver (1994) pointed out that the optimal temperature for germination rate is expected to be higher than that for maximal per cent germination. The main reason is the increased rapidity of physiological processes at higher temperatures. The increase in the emergence velocity with increasing temperature and the difference between the hulled and the naked seeds in this regard agreed with those of the germination experiment. The results of the seedling emergence experiment confirmed those of the field study in that per cent seedling emergence of Katepwa was highest, followed by PGR8801 and CDC Bavaria (Table 4.42).

Contrary to the European reports (Ruegger *et al.*, 1990c), the presence of the hull did not seem to be beneficial under low temperature conditions. Dehulling led to an increase in seedling emergence with low temperature while it did not affect germination under high temperature conditions (Table 4.42). Since the emergence percentage of both seed forms of CDC Bavaria under high temperature was lower than that of the other three seed forms, 23 °C seems to be detrimental for emergence of this cultivar. Since the naked seeds of PGR8801 tended to produce a higher plant population at 9 and 16 °C relative to the 23 °C, it seems that dehulling is beneficial to PGR8801, unless it is germinated at high temperatures.

In the seedling emergence experiment, increasingly negative water potentials tended to affect the emergence of hulled seeds more than the naked seeds.

Despite having no beneficial impact with regard to contrasting temperatures, the presence of the hull was beneficial for seedling emergence under wet soil (-0.01MPa) conditions. While a higher emergence percentage for hulled seeds than for naked seeds was recorded in wet soil (-0.01 MPa), the reverse tended to be the case for soil with water potentials more negative than field capacity (-0.03 MPa) (Table 4.42). Furthermore, the maximum emergence velocity for the hulled seeds was recorded in the wet soil (-0.01 MPa) while for the naked seeds no difference between the velocity at -0.01 MPa (wet soil) and at -0.03 MPa (field capacity) was observed. Upon observing a long spelt coleoptile with a high growth rate and a higher hypoxia tolerance, Beglinger (1995) concluded that hypoxia tolerance along with rapid seedling growth are absolute necessities for germination in an atmosphere created by tight hulls. In the present study, there was a lack of evidence to support the hypothesis of an advantage of spelt over common wheat with regard to tolerating hypoxia. Indeed, per cent seedling emergence of Katepwa at -0.01 MPa was neither significantly different from its emergence at other water potentials nor from emergence of spelt seeds at -0.01 or -0.03 MPa. The effect of water potential tended to be more pronounced below -0.5 MPa for all seed forms. A greater impact of soil water potential than temperature on seedling emergence was apparent only with the hulled seeds while in the seed germination experiment, the impact of water potential was significant for all seed forms. The latter observation serves to support the conclusion that in the seed germination experiment the amount of solution applied to each petri dish might have been a limiting factor. Therefore, one must practice caution in coming to conclusions based, solely, on results of the seed germination experiment.

In the controlled environment experiments, germination and emergence were reduced and delayed by water potentials more negative than -0.5 to -0.6 MPa. However, water potentials as low as -1.8 MPa did not completely halt germination. No information is available, to date, on the threshold water potential for germination of spelt wheat. Reports on the threshold water potential necessary for common wheat seed germination tend to be inconsistent. Kaufmann and Ross (1970) reported no wheat germination at -1.5 MPa. Huang *et al.* (1983) found that germination of wheat seed decreased only when the water potential was more negative than –1.5 MPa. According to Bouaziz and Bruckler (1989), the non-limiting water range, where the impact on seed imbibition and germination is negligible, is 0 to -0.9 MPa and germination occurs in water potentials as low as -3 MPa. According to Naylor and Gurmu (1990) for wheat the minimum water potential at which germination is halted is between -0.7 and -1.2 MPa. According to Hadas and Russo (1974a), however, each species has a critical water potential below which seed germination will be delayed. Results of the present study agree with those of Huang *et al.* (1983) and Bouaziz and Bruckler (1989) in that germination of wheat seeds was not halted by water potentials as low as –1.5 MPa. Furthermore, the current study supports previous reports that water potentials of -0.5 or –0.6 MPa have a negligible negative effect on germination.

Previous reports by European researchers on the impact of the hull on the seedling establishment of winter spelt are not consistent. They, however, tend to emphasize that dehulling spelt seed leads to a decrease in seedling establishment under wet-cool seedbed conditions. Under those conditions, hulled seeds have the capability to produce a higher plant density than common wheat. According to Percival (1921), the process of mechanical hull removal causes a greater than 50 per cent decrease in germination of naked seeds compared to hulled spelt seeds. Ruegger *et al.* (1990a, c) found that dehulling led to a decrease in seedling emergence of spelt under wet-cool soil conditions while under normal conditions emergence of hulled and naked seeds of spelt was similar to that of common wheat. Ruegger and Winzeler (1993) reported that a higher number of plants was established for winter spelt than common wheat over a range of seeding rates. In an earlier study on the seedling emergence of naked and hulled spelt seeds, under wet-cool seedbed conditions, Riesen *et al.* (1986) found that hulled seeds emerged more frequently than naked seeds. The level of seedling emergence for common winter wheat seed was lower than that of naked and hulled seeds of spelt wheat. Furthermore, hulled spelt was less infested by pathogens than naked spelt and common winter wheat seed. Riesen *et al.* (1986) concluded that the hulls protect the spelt seeds from fungal colonization.

Based on the results obtained from the current field and controlled environment studies, naked spelt seeds do not necessarily germinate or produce seedlings less frequently than hulled seeds. The only evidence for a decrease in seedling emergence due to the use of naked seeds came from a non-significant reduction in seedling emergence of naked seeds of CDC Bavaria and PGR8801 in 1995 and from the emergence of naked seeds of the two spelt cultivars under wet seedbed conditions. Hulled spelt seeds tended to produce seedlings more frequently than naked spelt seeds under hot-wet rather than under wet-cool seedbed conditions. As noted earlier, there is evidence that dehulling PGR8801 is beneficial to its emergence, unless it is seeded into warm soil. The hull worsens the moisture shortage to the seed under cool-dry seedbed conditions while its removal may expose the naked seed to infection under hot-wet seedbed conditions. The difference in the velocity of germination between seeds of common wheat and the naked spelt seeds may be a reflection of the difference between water uptake rate or the seed moisture threshold necessary for germination or both.

There were *some discrepancies between the field and controlled environment experiments* with regard to seed germination and seedling establishment. In the controlled environment studies, there was control over only two factors, namely temperature and water potential. Needless to say, a multitude of factors interact together to determine the plant establishment under field conditions. Differences in the depth of seeding, soil water content and timely precipitation, for example, under field condition might impact differently on the emergence of hulled and naked seed forms.

Water uptake rate increased with temperature for all seed forms. Water uptake rate of naked spelt seeds was higher than that of the hulled spelt seeds at all temperatures (Table 4.37). An increase in seed water uptake rate with increasing temperature is well-established (Keller and Bleak, 1970; Lafond and Baker, 1986b; Lafond and Fowler, 1989). Seed water uptake rate for naked common wheat seed was not different from that of the naked spelt seed, ruling out the involvement of water uptake rate in the difference of velocity of germination and emergence observed in the other two indoor experiments. Dehulling PGR8801 tended to have a more pronounced effect on time to the start of germination at 9 and 16 °C than did dehulling CDC Bavaria seed. PGR8801 has a tighter hull than in CDC Bavaria. Thus, the hull probably acts as a more effective barrier to water absorption in PGR8801 than CDC Bavaria. Time to initiation of germination for all seed forms decreased with increasing temperature while naked common wheat seed tended to behave similarly to hulled spelt seeds. A similar water uptake rate for naked spelt and common wheat seeds emphasizes that a lower germination velocity for common wheat is not a result of differences in water uptake rate. The reason for a lower germination velocity of common wheat seed appears to be, at least in part, the higher threshold water content needed for its germination relative to the spelt wheats. Seed moisture content at germination was higher for Katepwa than for the spelt cultivars.

The threshold seed water content necessary to initiate germination of wheat seed is not agreed upon. According to Bouaziz and Bruckler (1989), a 27% seed water content threshold is necessary for the start of germination in wheat. A 68% moisture content of the wheat seed at 20 °C and under a liquid water phase (Collis-George and Melville, 1975) and a 48-50% moisture contentunder a pure vapor phase (Collis-George and Melville, 1978) have been reported as the threshold for the initiation of germination. A vapor phase for water uptake often is the case in agricultural practices. Ashraf and Abu-Shakra (1978) reported that an approximate 50% (wet weight basis) seed moisture content was the threshold for germination of wheat cultivars. They emphasized that at water potentials more negative than -0.6 MPa the water uptake rate decreased, lengthening the time required for initiation of germination. Lafond and Fowler (1989) found that wheat seeds germinated with a 51 per cent (dry weight basis) water content. In the current study, the threshold seed water content for germination appeared to be the same for the two spelt cultivars, *i.e.* approximately 50% (dry weight basis). The threshold for germination of Katepwa appeared to be approximately 6-10% higher than that of the spelt cultivars. In a study of the impact of temperature and moisture regime on germination of large crabgrass (Digitaria sanguinalis), King and Oliver (1994) found that at low temperatures seeds needed a higher water content compared to higher temperatures in order to reach the lag phase and the onset of germination. In the present study, all seed forms tended to germinate at a higher seed moisture content at 9 °C compared to the other temperatures; however, these differences in threshold seed water content were not significant

The water uptake rate decreased with more negative water potentials for all seed forms. However, the water uptake rate for the naked spelt and common wheat seed was higher than for the hulled spelt seeds (Table 4.37). A negative impact of lowering water potential on imbibition rate of wheat has been reported (Owen, 1952; Lafond and Baker, 1986b). Clarke (1980) found that spring wheats differ in water uptake rate at varying water potentials. Likewise under different temperatures, dehulling PGR8801 tended to have a greater impact on the imbibition rate than did dehulling CDC Bavaria. A longer period of time was necessary to the start of germination with more negative water potentials for all seed forms. Again, Katepwa behaved similarly to the hulled spelt seed under different water potentials with the exception of –0.6 MPa.

Unlike temperature, with more negative water potentials, germination started at a lower seed water content with the exception of naked PGR8801 seeds. Beglinger (1995) found that three hours of soaking led to similar water uptakes for spelt and common wheat and that was sufficient for germination. Results of the current study contradict the above report because a similar water content was not found for naked seeds of Katepwa and spelt cultivars at any time interval. Furthermore, three hours of incubation in distilled water did not lead to germination. The water uptake rate of the naked CDC Bavaria seeds was slightly higher than that of the naked PGR8801 seeds. However, a lower water content threshold of PGR8801 than CDC Bavaria led to a slightly higher velocity of germination for that of PGR8801 spelt cultivar.

The above differences between seed forms in terms of imbibition may, probably, be attributed to differences in seed contact area with moisture, hydraulic conductivity characteristics and seed texture. Imbibition is affected mainly by the seed-soil water potential gradient, seed contact area with liquid or vapor phases and the conductive characteristics of the seed to both liquid and vapor water (Bouaziz and Bruckler, 1989). The seed-soil contact is important in determining the imbibition rate. The larger the surface area of the seed in contact with the liquid or vapor phase, the greater the imbibition rate. With a fixed seed-soil contact area, any change in the hydraulic conductivity changes the water uptake rate, thus germination rate (Hadas and Russo, 1974a). Furthermore, even with non-limiting water potentials, the seed-soil water contact and the hydraulic conductivity are major determinants of seed water uptake rate. The slower water uptake observed at the more negative water potentials, in the present study, was probably governed by a reduced seed-medium water potential gradient. Even though the above gradient was not different between the hulled and naked seeds, the presence of the hull could have had a negative impact on the seed contact area with the medium (soil or solution) as well as on conductive characteristics of the seed. When the spelt seed is dehulled, its large seed size could have become a determinant factor, due to a large surface area and thus more contact with the germination medium than the naked seed of Katepwa. But, this was not confirmed in the current studies.

Studying the effect of temperature and water potential on speed of germination of spring wheat, Lafond and Baker (1986b) found that the fastest germinating cultivars were soft red spring while the slowest germinating cultivars were hard red spring wheats. Lafond and Baker observed no effects of temperature, cultivar and seed size on final germination. Although small seeds germinated faster than large seeds, they did not differ in terms of water uptake rate. Huang *et al*, (1983) argued that looser integument structure and a weaker pericarp of white wheats than red wheats gives rise to faster imbibition and deeper penetration of water into kernels of the white wheats. Katepwa is a hard red spring wheat. CDC Bavaria has a soft kernel while PGR8801 has a hard kernel (Abdel-Aal *et al.*, 1996, 1997). Hulled wheats (including spelt) have a thinner pericarp (Percival, 1921; Nesbitt and Sammuel, 1995). However, there was not enough evidence to argue that factors such as seed size or seed texture played a role on speeding up water uptake rate in the present study. In other words, large naked soft or hard seeds of spelt did not have any advantage over small naked hard seeds of Katepwa in terms of water uptake rate. The only evidence for involvement of seed texture in water uptake rate came from the difference between naked seeds of CDC Bavaria and PGR8801. The reason behind a greater decrease in water uptake rate in naked seeds of the spelt cultivars compared to that in the naked seeds of Katepwa, due to more negative water potentials is not known. The difference in the texture of the seeds of the wheats or the difference in the relative size of the embryo could be a factor. The difference between the naked and hulled seeds of PGR8801 wheat in terms of moisture content at germination cannot be explained. The tight hull of PGR8801 could have played a role in delaying rupturing of the seed coat relative to naked seed.

6.0 CONCLUSIONS

One of the objectives of the current research was to evaluate the performance of spring spelt and its growth characteristics relative to common wheat using differing seeding rates. Seeding rates as low as 150 seeds/m^2 had little effect on grain yield of spring spelt. Therefore, like common wheat, 150-250 seeds/m^2 was recommended for seeding spring spelt in central Saskatchewan. The relative performance of spring spelt wheat in Saskatchewan was somewhat more promising than that of winter spelt in Europe. Even when precipitation varied CDC Bavaria and PGR8801 had a high DM and produced a hulled grain yield greater than that of Katepwa. Based on its yield advantage of up to 800-1000 kg ha^{-1} over common wheat under contrasting environmental conditions in 1995 and 1996 it can be concluded that spelt wheat can be successfully grown in Saskatchewan. Considering differences between spelt and common wheat in growth analysis factors, spelt wheat, probably, produced the high DM and grain yield by having higher LAI, LAD and CGR than common wheat.

Another objective of the current research was to study the impact of seeding date on spring spelt relative to common wheat. Spelt wheat is known for its late maturity. It was hypothesized that a superior yield might be achieved from the ability to establish and grow under the cool conditions of early spring. It can be concluded that when precipitation was average, seeding date did not affect common spring wheat to a great extent. However, delayed seeding decreased the grain yield of spring spelt. While there was not enough evidence for an advantage of spring spelt over common wheat with an early seeding date (late April), it appeared that spring spelt did yield less than common wheat with a late seeding date (late May or early June). Thus, optimum seeding date for spring spelt was earlier than for common wheat. Considering the late maturity of spelt wheat along with its lower grain yield with delayed seeding, the optimal seeding date for maximising grain yield under environmental conditions of the present study in central Saskatchewan was likely late April to early May.

The spring spelt cultivar CDC Bavaria was prone to lodging. Lodging had a negative impact on grain yield of CDC Bavaria to an extent that lodging affected its grain yield relative to PGR8801 and Katepwa in a wet year, 1996.

Spring spelt and common wheat differ in grain yield components. Spring spelt tends to produce a relatively low number of spikes/m^2. Spring spelt has the capability to produce a naked grain yield slightly lower than that of common wheat by producing heavy kernels. Common wheat, on the other hand, outyields spring spelt by producing a higher number of spikes/m^2.

It was hypothesized that differences in seedling establishment capability might exist between common wheat and spelt wheat and between the hulled and naked seeds of the latter. Results of field and controlled-environment experiments, led to the conclusion that the plant establishment ability of the spelt cultivars (either seed form) tended to be lower and less stable than that of common wheat. Plant establishment for the spelt cultivars decreased with delayed seeding, while no significant change was detected for common wheat. High temperatures (23 °C) during emergence were more harmful to the spelt than to the common wheat seedlings. At water potentials more negative than -0.5 MPa seed germination and seedling emergence of all seed forms tended to decrease. The negative impact was more pronounced with hulled spelt seeds than with naked seeds. The negative impact of the low water potential on seedling emergence with both high (23 °C) and low (9 °C) temperatures was more pronounced than at the intermediate temperature (16 °C). Therefore, using hulled spelt seeds was recommended only with seeding under hot-moist soil conditions. There was a tendency for a higher velocity of germination for naked spelt seeds compared to common wheat. Also, a higher velocity of naked vs. hulled seeds of the spelt wheat was observed. Water uptake rate seemed to be a major determinant for differences in velocity of the naked vs. hulled seeds of spelt wheat. There was not enough evidence to argue that the water uptake rate of the common wheat seeds differed from that of naked seeds of the spelt wheat. There was evidence, however, that a difference in the threshold level of the seed water content necessary for the initiation of germination created these differences. Nevertheless, the differences in seedling establishment did not translate into a difference in grain yield.

The current studies were conducted in two years, which were considered fixed. Thus, results and conclusions are applicable only to environmental conditions of those years. Conducting these experiments in a wider range of environments, *i.e.* locations and years, would be helpful in confirming optimal seeding rates and dates for spring spelt. Also, the impact of the hull on germination and seedling establishment needs to be scrutinised by conducting further field and indoor studies. The current studies on spring spelt were the first ones conducted in western Canada, to date. Many aspects of spring spelt agronomics, physiology, and genetic potentials are unknown. Assumptions made about spelt's differential response to factors such as soil fertility, drought and water lodging are not postulated. Quantification of differences between spring spelt and common wheat could detect valuable characteristics for modern Agriculture.

Future research on spring spelt wheat should focus on physiological characteristics such as photosynthetic rate, the pattern of allocation of photoassimilates and their translocation during grain development stages. Screening and breeding for genotypes which are resistant to lodging, while having acceptable agronomic and end-use qualities is important. In order to promote the utilisation of spelt wheat for good health or baking purposes an evaluation of the qualitative characteristics is necessary. Breeding spring spelts with free threshing capability is recommended.

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Appendices

Appendix A Synopsis of precipitation data for winter 1995 and 1996 at Saskatoon Airport[1].

Month	Precipitation (mm)		
	1995[2]	1996[2]	30 year average
January	-4.0	-2.3	15.9
February	0.0	-0.5	12.9
March	14.0	-4.2	16.0
April	14.3	10.4	19.7
January-February	24.3	3.9	64.5

[1]Environment Canada data.

[2]Deviations from the 30 year (1961-1990) average were used for the two years.

Appendix B Means for Belgian lodging index of CDC Bavaria, PGR8801 and Katepwa at four seeding rates in 1996.

Seeding rate	CDC Bavaria	PGR8801	Katepwa
150	5.80	0.60	0.20
250	6.00	0.70	0.20
350	6.35	1.00	0.20
450	7.40	1.15	0.20
LSD (0.05)[1]		0.58	

[1]LSD for comparing cultivar x seeding rate interaction.

Appendix C1 Analysis of variance (Mean Squares) for plants/m^2, spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	Plants/m^2	Spklt/spk	Krnl/spklt (MS x 10^2)
Year(Y)	1	1140	72.802**	126.960**
Replication (Y)	6	4650*	0.570	5.710**
Cultivar (C)	2	7500*	106.378**	226.942**
Katepwa vs. Bavaria & PGR	1	14900**	113.087**	435.607**
Bavaria vs. PGR	1	81	99.750**	18.276**
Seeding rate (R)	3	207000**	13.805**	9.251**
Linear	1	620000**	41.184**	25.210**
C*R	6	3360	0.736	2.741**
C*R Linear	1	3940	2.893**	13.067**
Y*C	2	788	9.248**	40.650**
Y*R	3	1900	0.667	0.718
Y*C*R	6	909	0.301	0.532
Error	66	1600	0.387	0.785
CV(%)		17.0	4.9	4.7

* F test significant at the 0.05 level of probability.

** F test significant at the 0.01 level of probability.

Appendix C2 Analysis of variance (Mean Squares) for spikelet (Spklt) yield, spike (Spk) yield and height of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa sown at four seeding rates in two years.

Source	DF	Spklt yield (MS x 10^7)	Spk yield	Height
Year(Y)	1	26000**	0.0193	7794.0**
Replication (Y)	6	1380	0.0273	85.4**
Cultivar (C)	2	4340*	0.3797**	9660.5**
Katepwa vs. Bavaria & PGR	1	422	0.5558**	19240.0**
Bavaria vs. PGR	1	8270**	0.2036**	81.0**
Seeding rate (R)	3	3310*	0.2334**	302.7**
Linear	1	8010**	0.6855**	893.8**
C*R	6	816	0.0194	62.6**
C*R Linear	1	1930	0.6387	214.8**
Y*C	2	3950*	0.1651**	116.9**
Y*R	3	958	0.0387*	5.2
Y*C*R	6	531	0.0043	16.9
Error	66	647	0.0143	11.2
CV(%)		9.9	11.6	3.3

* F test significant at the 0.05 level of probability.

** F test significant at the 0.01 level of probability.

Appendix C3 Means for plants/m^2, spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) of three wheat cultivars at four seeding rates and two years.

Source	Plants/m^2 (no)	Spklt/spk (no)	Krnl/spklt (no)
Year			
1995	239	11.90	2.012
1996	232	13.64	1.782
Cultivar			
CDC Bavaria	228	14.78	1.693
PGR8801	225	12.29	1.800
Katepwa	253	11.23	2.198
			0.044
LSD (0.05)	20	0.31	
Seeding rate (seeds/m^2)			
150	124	13.60	1.983
250	200	13.14	1.895
350	280	12.47	1.871
450	337	11.87	1.838
LSD (0.05)	23	0.36	0.051

Appendix C4 Means for spike (Spk) yield, spikelet (Spklt) yield and height of three wheat cultivars at four seeding rates and two years.

Source	Spk yield (g)	Spklt yield (g)	Height (cm)
Year			
1995	1.02	0.0865	92.4
1996	1.05	0.0760	110.4
Cultivar			
CDC Bavaria	1.15	0.0772	110.3
PGR8801	1.03	0.0844	112.5
Katepwa	0.93	0.0822	81.3
LSD (0.05)	0.06	0.0040	1.7
Seeding rate (seeds/m^2)			
150	1.16	0.0867	105.1
250	1.05	0.0804	103.1
350	0.99	0.0796	100.4
450	0.93	0.0783	96.9
LSD (0.05)	0.07	0.0046	1.9

Appendix C5 Means for tillers/m^2 and spikes/m^2 of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates.

Seedingrate	Tillers/m^2			Spikes/m^2		
(seeds/m^2)	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(no)			(no)	
150	484	651	541	332	379	473
250	575	682	657	372	394	549
350	619	769	742	402	439	557
450	576	879	716	383	459	597
LSD (0.05)[1]		87^{ns}			51^{ns}	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C6 Means for kernels/spike (Krnl/spk) and 1000-kernel weight (Kw) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates.

Seeding rate	Krnl/spk			Kw		
(seeds/m^2)	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(no)			(g)	
150	27.4	24.1	28.0	47.0	46.2	38.5
250	25.6	23.5	24.7	43.9	48.1	37.1
350	23.8	21.2	24.1	45.8	46.1	38.0
450	23.1	19.7	21.9	46.6	46.3	36.8
LSD (0.05)[1]		1.7^{ns}			3.6^{ns}	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C7 Means for spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates in two years.

Source	Spklt/spk			Krnl/spklt		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
Seeding rate						
(seeds/m^2)		(no)			(no)	
150	15.83	13.19	11.78	1.74	1.83	2.38
250	15.09	12.99	11.35	1.70	1.81	2.18
350	14.39	11.81	11.21	1.66	1.80	2.16
450	13.84	11.16	10.60	1.67	1.76	2.08
LSD (0.05)[1]		0.62^{ns}			0.09	
Year						
1995	13.38	11.41	10.91	1.75	1.84	2.44
1996	16.19	13.17	11.56	1.64	1.76	1.95
LSD (0.05)[2]		0.44			0.06	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
[2] LSD for comparing cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C8 Means for spikelet (Spklt) yield and spike (Spk) yield of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates in two years.

Source	Spklt yield			Spk yield		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
Seeding rate						
(seeds/m^2)		(g)			(g)	
150	0.0825	0.0863	0.0913	1.29	1.12	1.08
250	0.0750	0.0863	0.0800	1.12	1.13	0.91
350	0.0738	0.0838	0.0813	1.09	0.97	0.91
450	0.0775	0.0813	0.0763	1.08	0.91	0.80
LSD (0.05)[1]		0.0080[ns]			0.12[ns]	
Year						
1995	0.0794	0.0888	0.0913	1.07	1.01	0.99
1996	0.0750	0.0800	0.0731	1.22	1.06	0.86
LSD (0.05)[2]		0.0057			0.09	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.

[2] LSD for comparing cultivar x year interaction for each trait.

[ns] H_0 was not rejected for the trait.

Appendix C9 Means for plants/m^2 and tiller mortality (Mortality) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates in two years.

Source	Plants/m^2			Mortality		
	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
Seeding rate						
(seeds/m^2)		(no)			(%)	
150	112	141	120	27.5	40.6	12.3
250	191	181	228	34.3	42.3	15.3
350	291	247	300	34.8	43.0	23.1
450	317	332	363	32.0	46.8	17.3
LSD (0.05)[1]		40^{ns}			8.0^{ns}	
Year						
1995	235	231	251	27.3	42.4	14.6
1996	220	220	255	36.9	43.9	19.4
LSD (0.05)[2]		28^{ns}			5.7^{ns}	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
[2] LSD for comparing cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C10 Means for leaf angle of CDC Bavaria, PGR8801 and Katepwa at four seeding rates in two years.

Source	Leaf angle		
	CDC Bavaria	PGR8801	Katepwa
Seeding rate (seeds/m^2)		(°)	
150	62.4	65.9	75.4
250	63.0	64.0	76.0
350	60.8	64.0	74.0
450	65.9	69.1	72.0
LSD (0.05)[1]		6.5^{ns}	
Year			
1995	68.6	73.5	82.8
1996	58.0	58.0	65.9
LSD (0.05)[2]		4.6^{ns}	

[1] LSD for comparing cultivar x seeding rate interaction for each trait.
[2] LSD for comparing cultivar x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C11 Means for plants/m^2, tillers/m^2 and spikes/m^2 at four seeding rates in two years averaged over three wheat cultivars.

Seeding rate	Plants/m^2		Tillers/m^2		Spikes/m^2	
(seeds/m^2)	95	96	95	96	95	96
	(no)		(no)		(no)	
150	120	128	401	716	318	472
250	203	198	500	776	350	526
350	280	280	572	847	367	566
450	353	321	586	861	414	545
LSD(0.05)[1]	33^{ns}		71^{ns}		41^{ns}	

[1] LSD for comparing seeding rate x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C12 Means for 1000-kernel weight (Kw), spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) at four seeding rates in two years averaged over three wheat cultivars.

Seeding rate	Kw		Spklt/spk		Krnl/spklt	
(seeds/m^2)	95	96	95	96	95	96
	(g/1000)		(no)		(no)	
150	44.5	43.3	12.96	14.23	2.12	1.85
250	42.6	43.4	12.23	14.05	2.00	1.79
350	43.7	42.9	11.57	13.38	1.99	1.75
450	42.5	43.9	10.83	12.90	1.94	1.74
LSD(0.05)[1]	2.9^{ns}		0.51^{ns}		0.07^{ns}	

[1]LSD for comparing seeding rate x year interaction for each trait.

^{ns} H_0 was not rejected for the trait.

Appendix C13 Means for kernels/spike (Krnl/spk), spikelet (Spklt) yield and hulled grain yield (Yield) at four seeding rates in two years averaged over three wheat cultivars.

Seeding rate	Krnl/spk		Spklt yield		Yield	
(seeds/m^2)	95	96	95	96	95	96
	(no)		(x 100 g)		(kg ha^{-1})	
150	27.2	25.8	9.42	7.92	3890	5500
250	24.2	25.0	8.42	7.67	3460	5420
350	22.8	23.2	8.58	7.33	3320	5530
450	20.9	22.3	8.17	7.50	3130	5450
LSD(0.05)[1]	1.4^{ns}		0.66^{ns}		260	

[1]LSD for comparing seeding rate x year interaction for each trait.

^{ns} H_0 was not rejected for the trait.

Appendix C14 Means for spike yield (Spk yield), tiller mortality (Mortality) and harvest index (HI) at four seeding rates in two years averaged over three wheat cultivars.

Seeding rate	Spk yield		Mortality		HI	
(seeds/m^2)	95	96	95	96	95	96
	(x 100g)		(%)		(%)	
150	120	112	20.1	33.5	42.4	37.0
250	102	109	29.3	31.8	42.0	36.7
350	099	100	34.6	32.7	40.9	35.8
450	088	098	28.4	35.6	40.7	36.3
LSD(0.05)[1]	10		6.5		1.4^{ns}	

[1]LSD for comparing seeding rate x year interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C15 Means for CGR and total aboveground dry matter (DM) of CDC Bavaria (Bavaria), PGR8801 (PGR) and Katepwa at four seeding rates.

Seeding rate	CGR			DM		
(seeds/m^2)	Bavaria	PGR	Katepwa	Bavaria	PGR	Katepwa
		(g m^{-2} d^{-1})			(kg ha^{-1})	
150	21.13	20.50	17.20	9493	9799	8137
250	19.00	19.79	17.56	8299	10103	8418
350	18.31	20.61	16.63	9280	9146	8495
450	16.21	17.87	14.74	8888	8921	8352
LSD(0.05)[1]		1.64^{ns}			966^{ns}	

[1]LSD for comparing cultivar x seeding rate interaction for each trait.
^{ns} H_0 was not rejected for the trait.

Appendix C16 Means for leaf angle, CGR and total aboveground dry matter (DM) at four seeding rates in two years averaged over three wheat cultivars.

Seeding rate	Leaf angle		CGR		DM	
(seeds/m^2)	95	96	95	96	95	96
	(°)		(g m^2 d^{-1})		(kg ha^{-1})	
150	75.1	60.7	14.23	25.00	6661	11625
250	72.3	63.1	13.60	23.96	6035	11845
350	74.4	58.1	12.70	24.33	5827	12120
450	77.3	60.7	10.60	21.96	5567	11873
LSD (0.05)[1]	5.3^{ns}		1.34^{ns}		789^{ns}	

[1]LSD for comparing seeding rate x year interaction for each trait.

^{ns} H_0 was not rejected for the trait.

Appendix D1 Analysis of variance (Mean Squares) for coefficient of velocity of emergence (Cfv), spikelets/spike (Spklt), kernels/spikelet (Krnl/spklt) and days to heading (D-head) of Katepwa and CDC Bavaria sown at six dates in two years.

Source	DF	Cfv	Spklt	Krnl/spklt	D-head
Year (Y)	1	68.95**	18.410**	1.45288**	661.50**
Replication (Y)	6	4.41*	1.185**	0.01655	1.05
Date (D)	5	177.94**	2.197**	0.09123**	373.32**
Linear (L)	1	870.53**	8.793**	0.27188**	1755.00**
Quadratic (Q)	1	14.62**	1.892**	0.09977**	43.22**
Cubic (C)	1	1.22	0.009	0.01653	63.31**
Remainder	2	1.66	0.148	0.03400**	2.54
Y*D	5	21.82**	1.143**	0.03827**	1.58
Replication*D (Y)	30	1.53	0.186	0.00804	2.06
Cultivar (C)	1	2.53	362.237**	3.79613**	2053.50**
Y*C	1	2.81	6.998**	0.55358**	15.04**
C*D	5	1.76	0.604	0.02176*	2.48
C*Polynomial[1]	1			L*	
Y*D*C	5	1.15	0.797	0.05851**	3.92
Error	36	1.82	0.617	0.00720	1.68
CV (%)		13.1	5.7	4.4	2.3

* F test significant at the 0.05 level of probability.

**Ftest significant at the 0.01 level of probability.

[1]L and C stand for linear and cubic components, respectively. No other function was significant.

Appendix D2 Means for coefficient of velocity of emergence (Cfv), spikelets/spike (Spklt/spk), kernels/spikelet (Krnl/spklt) and days to heading (D-head) of Katepwa and CDC Bavaria at six seeding dates and two years.

Source	Cfv (%/day)	Spklt/spk (no)	Krnl/spklt (no)	D-head (day)
Year				
1995	9.41	13.43	2.031	54.65
1996	11.11	14.31	1.785	59.90
Cultivar				
Katepwa	10.1	11.93	2.107	52.65
CDC Bavaria	10.4	15.81	1.710	61.90
Seeding date				
Date 1	6.34	13.64	1.938	65.25
Date 2	7.45	13.53	1.968	59.50
Date 3	9.13	13.60	1.958	57.63
Date 4	10.89	13.91	1.964	55.69
Date 5	12.37	14.03	1.813	54.38
Date 6	15.38	14.52	1.811	51.19
LSD(0.05)	0.89	0.31	0.065	1.03

^{ns} H_0 was not rejected for the trait.

Appendix D3 Means for plants/m^2, coefficient of velocity of emergence (Cfv) and tillers/m^2 of Katepwa and CDC Bavaria (Bavaria) at six seeding dates.

Seeding date	Plants/m^2		Cfv		Tillers/m^2	
	Katepwa	Bavaria	Katepwa	Bavaria	Katepwa	Bavaria
	(no)		(%/day)		(no)	
Date 1	190	179	5.8	6.9	712	645
Date 2	173	172	7.2	7.7	689	630
Date 3	178	171	9.1	9.2	745	657
Date 4	157	171	10.4	11.4	693	637
Date 5	180	163	12.5	12.3	771	691
Date6	165	148	15.6	15.1	758	611
LSD(0.05)[1]	35^{ns}		1.37^{ns}		78^{ns}	
LSD(0.05)[2]	32^{ns}		1.29^{ns}		74^{ns}	

[1] Least significant difference for comparing cultivars at the same seeding date.
[2] Least significant difference for comparing cultivars at different seeding dates.
^{ns} H_0 was not rejected for the trait

Appendix D4 Means for spikes/m^2, 1000-kernel weight (Kw) and kernels/spike (Krnl/spk) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates.

Seeding date	Spikes/m^2		Kw		Krnl/spk	
	Katepwa	Bavaria	Katepwa	Bavaria	Katepwa	Bavaria
	(no)		(g/1000)		(no)	
Date 1	511	361	36.9	43.4	25.2	26.6
Date 2	514	367	36.7	44.5	25.8	26.6
Date 3	560	389	36.9	45.6	25.3	27.0
Date 4	478	354	37.4	43.8	25.3	27.9
Date 5	529	399	37.5	43.9	23.6	26.7
Date6	529	382	36.8	45.6	25.3	26.8
LSD(0.05)[1]	65^{ns}		2.0^{ns}		1.9^{ns}	
LSD(0.05)[2]	53^{ns}		1.9^{ns}		1.6^{ns}	

[1] Least significant difference for comparing cultivars at the same seeding date.
[2] Least significant difference for comparing cultivars at different seeding dates.
^{ns} H_0 was not rejected for the trait

Appendix D5 Means for spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates.

Seeding date	Spklt/spk (no)		Krnl/spklt (no)	
	Katepwa	Bavaria	Katepwa	Bavaria
Date 1	11.90	15.37	2.134	1.741
Date 2	11.71	15.35	2.203	1.733
Date 3	11.54	15.66	2.189	1.728
Date 4	11.65	16.18	2.183	1.745
Date 5	12.08	15.98	1.954	1.671
Date6	12.70	16.34	1.983	1.640
LSD(0.05)[1]	0.80[ns]		0.086	
LSD(0.05)[2]	0.63[ns]		0.087	

[1] Least significant difference for comparing cultivars at the same seeding date.
[2] Least significant difference for comparing cultivars at different seeding dates.
[ns] H_0 was not rejected for the trait.

Appendix D6 Means for GDD to heading (GDD-head) and days to heading (D-head) of Katepwa and CDC Bavaria (Bavaria) at six seeding dates.

Seeding date	GDD-head (gdd)		D-head (day)	
	Katepwa	Bavaria	Katepwa	Bavaria
Date 1	460.1	573.0	60.3	70.3
Date 2	474.3	585.8	54.4	64.6
Date 3	515.9	615.0	53.0	62.3
Date 4	554.3	657.3	51.6	59.8
Date 5	560.8	670.9	50.0	58.8
Date6	591.1	705.5	46.6	55.8
LSD(0.05)[1]	9.1[ns]		1.3[ns]	
LSD(0.05)[2]	10.4[ns]		1.4[ns]	

[1] Least significant difference for comparing cultivars at the same seeding date.
[2] Least significant difference for comparing cultivars at different seeding dates.
[ns] H_0 was not rejected for the trait.

Appendix D7 Means for 1000-kernel weight (Kw), spikelets/spike (Spklt/spk) and kernels/spikelet (Krnl/spklt) of Katepwa and CDC Bavaria at six seeding dates in two years.

Source	Kw		Spklt/spk		Krnl/spklt	
	95	96	95	96	95	96
	(g/1000)		(no)		(no)	
Seeding date						
Date 1	40.7	39.7	13.13	14.14	2.063	1.813
Date 2	40.5	40.6	13.54	13.53	2.085	1.850
Date 3	41.6	40.9	13.25	13.95	2.029	1.888
Date 4	41.6	39.6	13.19	14.64	2.053	1.875
Date 5	42.5	38.9	13.34	14.71	2.025	1.600
Date 6	42.4	40.1	14.15	14.89	1.935	1.688
LSD(0.05)[1]	1.9^{ns}		0.44		0.091	
Cultivar						
Katepwa	37.9	36.2	11.76	12.10	2.306	1.908
CDC Bavaria	45.2	43.7	15.11	16.52	1.756	1.663
LSD(0.05)[2]	1.2^{ns}		0.46		0.050	

[1] LSD for seeding date x year interaction for each trait.
[2] LSD for cultivar x year interaction for each trait.
[ns] H_0 was not rejected for the trait.

Appendix D8 Means for coefficient of velocity of emergence (Cfv), days to heading (D-head) and days to maturity (D-maturity) of Katepwa and CDC Bavaria at six seeding dates in two years.

Source	Cfv		D-head		D-maturity	
	95	96	95	96	95	96
	(%/day)		(day)		(day)	
Seeding date						
Date 1	5.6	7.1	63.1	67.4	105.9	107.0
Date 2	7.4	7.5	56.8	62.3	102.0	102.3
Date 3	9.7	8.6	54.9	60.4	96.6	97.6
Date 4	8.8	12.9	53.1	58.3	97.5	95.3
Date 5	12.0	12.7	51.9	56.9	95.0	95.6
Date 6	12.9	17.8	48.1	54.3	93.1	93.4
LSD(0.05)[1]	1.3		1.5^{ns}		2.7^{ns}	
Cultivar						
Katepwa	9.4	10.8	50.4	54.9	91.7	91.8
CDC Bavaria	9.4	11.4	58.9	64.9	105.0	105.3
LSD(0.05)[2]	0.8^{ns}		0.8		1.0	

[1] LSD for seeding date x year interaction for each trait.

[2] LSD for cultivar x year interaction for each trait.

^{ns} H_0 was not rejected for the trait.

Appendix E1 Means for plants/m², coefficient of velocity of emergence (Cfv), spikes/m² and kernels/spike (Krnl/spk) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa at two seeding dates.

Source	Plants/m² (no)		Cfv (%/day)		Spikes/m² (no)		Krnl/spk (no)	
	Early	Late	Early	Late	Early	Late	Early	Late
Seed form								
Bavaria-naked	174	162	5.7	16.4	333	352	27.0	28.3
Bavaria-hulled	196	187	5.5	12.6	357	374	26.0	26.8
PGR-naked	181	147	5.8	17.2	382	358	23.0	25.9
PGR-hulled	194	169	5.5	11.3	374	364	22.9	25.1
Katepwa-naked	210	151	5.5	16.0	491	506	24.9	24.9
LSD(0.05)[1]	29[ns]		1.2		34[ns]		2.1[ns]	

[1] LSD for seeding date x seed form interaction for each trait.
[ns] H_0 was not rejected for the trait.

Appendix E2 Means for spikelets/spike (Spklt/spk), 1000-kernel weight (Kw) and hulled grain yield (Yield) of naked and hulled seed forms of CDC Bavaria (Bavaria) and PGR8801 (PGR) and naked seeds of Katepwa at two seeding dates.

Source	Spklt/spk (no)		Kw (g/1000)		Yield (kg ha^{-1})	
	Early	Late	Early	Late	Early	Late
Seed form						
Bavaria-naked	14.9	15.3	47.4	44.7	4710	4690
Bavaria-hulled	15.9	14.9	46.0	43.2	4680	4170
PGR-naked	14.4	13.8	45.6	41.8	4830	4500
PGR-hulled	13.4	14.2	47.1	44.4	4700	4450
Katepwa-naked	13.4	12.8	38.5	36.7	3900	4010
LSD(0.05)[1]	1.5[ns]		2.0[ns]		420[ns]	

[1] LSD for seeding date x seed form interaction for each trait.
[ns] H_0 was not rejected for the trait.