THE CONTRIBUTION OF ATTRIBUTES IN THE SEED, SEEDLING, AND MATURE PLANT PHASES TO BARLEY (*HORDEUM VULGARE*) CULTIVAR COMPETITIVENESS AGAINST WEEDS

BY

PAUL WATSON

A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfillment of the Requirements

for the Degree of

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Department of Plant Science
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

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DEDICATION

Dedicated to

my mother, Carol Elizabeth Watson,
and the memory of my father, Robert Ronaldson Watson
(January 27th 1920 – October 26th 2001)
who have given me support and encouragement all my life

No man is an island, entire of itself;
every man is a piece of the continent, a part of the main;
if a clod be washed away by the sea, Europe is the less,
as well as if a promontory were, …
… and therefore never send to know for whom the bell tolls;
it tolls for thee.

John Donne.

ABSTRACT

Barley is an economically important crop in western Canada and is considered competitive, although cultivar competitiveness varies. Utilization of crop and cultivar competitive ability is an integrated weed management strategy that has no cost for producers. Adoption of cultivar competitive ability by producers requires a ranking system for cultivar competitive ability, that is not currently in place.

Cultivar competitive ability can be improved by identifying attributes strongly related to competitive ability. Attributes, such as early height growth, percent leaf area, and percent light extinction are widely held to contribute to barley cultivar competitive ability. However, measurement of attributes has occurred at different developmental stages without considering the relationship among stages.

A Seed-Leaf-Height (SLH) framework was adapted from ecology to examine the relationship of attributes in the seed (S), seedling, (L), and mature plant (H) phases to barley cultivar competitive ability. Major phases and sub-phases are defined by morphological or physiological characteristics relevant to barley. Attributes were examined within this framework to determine their relationship to barley cultivar competitive ability.

Field and greenhouse trials were conducted in 2001 and 2002. In general, the primary comparison was weedy (weeds seeded) and weed-free (weeds not seeded) plots. Barley cultivars grown on more than 5% of the acreage in their class, based on combinations of number of rows (2 and 6), height (full and semi-dwarf), caryopsis covering (hulled versus hull-less), and end use (feed and malt) were selected for this trial. Twenty-nine barley cultivars were employed, representing most of the acreage on the Canadian prairies in 1999. Tame oat was generally used as a surrogate for wild oat since rapid and uniform germination was desirable. Competitive ability was considered as both the ability of the crop to suppress weeds, and the ability of the weed to compete with the crop. These measures were termed ability to compete (AC) and ability to withstand competition (AWC), respectively.

Substantial differences in competitive ability exist among cultivars commonly used in western Canada. Differences in barley cultivar competitive ability occurred by the various phenotypic (2-row vs. 6-row, full height vs. semi-dwarf, hulled vs. hull-less,) and end-use (feed vs. malt) classes. As a class, semi-dwarf and hull-less cultivars were less competitive than full height and hulled cultivars, respectively. These differences are partially related to genetic and phenological differences, but were not absolute. Differences in competitive ability may also be related to other factors such as producer requirements within a class of cultivars (e.g. malt cultivars), or the maturity of breeding efforts within a class (e.g. hull-less cultivars).

The two aspects of competitive ability, ability to withstand competition (AWC) and ability to compete (AC), had a sufficiently strong relationship that breeding for one should increase the other for some cultivars. Highly- and poorly-competitive cultivars had consistent competitive rankings among site-years, while intermediately-competitive cultivars were less consistent. Consistency of competitive rank simplifies producer selection of competitive cultivars and breeding efforts to improve barley cultivar competitive ability.

Attributes in the seed, seedling, and mature plant phases widely held to contribute to barley cultivar competitive ability generally had correlation coefficients less than 0.5 with AWC and AC . While statistically significant correlation coefficients were common for the various height- and growth-related attributes collected, only yield in weedy plots had a sufficiently strong relationship with either aspect of competitive ability (AWC or AC) to be

useful in a breeding program. The contribution of attributes to cultivar competitive ability was variable by year and location. Removal of classes of cultivars (e.g. semi-dwarf), reduced the strength of relationship between attributes and competitive ability.

To elucidate the importance of the H phase in cultivar competitive ability, foliar fungicides were applied to increase the duration of green leaf area. There was no effect of foliar fungicide application on either AWC or AC. However, impacts of foliar fungicide application were not restricted to the crop since grain and weed seed yield were increased proportionally. Potential impacts on weeds include: 1) increased seed weight, potentially leading to increased vigour and, ultimately, competitive ability, and, 2) altered dormancy characteristics. The decision to apply foliar fungicides is based on economic return resulting from either increased yield or quality. Future research should investigate impacts on weed seed characteristics to determine their long-term economic impact on crop production.

The SLH framework allowed us to see connections between measurements taken at different stages. Seed, seedling, and mature plant vigour are all thought to contribute to barley cultivar competitive ability. However, seed vigour is not well-defined from a competitive ability perspective, and thus, its contribution to increased competitive ability in later stages is unclear. Some attribute measurements (e.g. height) may be taken from the early L phase (after emergence) well into the H phase (at harvest). This research indicated the importance of measuring attributes earlier, rather than later, and suggested a dependence of later measurements on earlier ones. Competition research incorporating attribute measurements from later developmental stages has not considered the dependence of these later measurements on measurements from earlier stages and could profitably do so (Jordan 1993).

Using information from this thesis, breeders can breed for increased cultivar competitive ability and rank the cultivars. Weed research can integrate relative differences in cultivar competitive ability into crop-weed competition models (e.g. herbicide rate) and agronomic research (e.g. seeding rate) into improving cultivar, and hence, crop competitive ability. Extension personnel can use this information in decision support systems (e.g. herbicide rate) to provide information to producers. Producers can then use this information select more competitive cultivars for their cropping systems. This value-added information chain can reduce increase the effectiveness of cultivar competitive ability as an integrated weed management tool and enhance the economic and environmental sustainability of agriculture.

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CHAPTER 1: INTRODUCTION

1.1 ECONOMIC CONTEXT

Barley (*Hordeum vulgare* L.) is a C_3, short-season, early-maturing crop with high yield potential that is tolerant of high temperatures at low humidity and is more salt-tolerant than other cereals (Harlan 1976). Barley is primarily used for animal feed and malt, but a small amount is used for human consumption (Harlan 1976). Human consumption is primarily from pearled barley, but efforts are being made to expand the range of food products containing barley (Briggs 1978 pp. 481-491; Tremere 1989) due to its superior nutritional qualities (Newman and Newman 1989).

Globally, barley is a major crop, with worldwide production being approximately 25% of total wheat production between 1991 and 2000 (Canada Grains Council 2001). On the Canadian prairies, barley production increased in the early 1990's concurrently with livestock production. In 1996 barley production peaked and, of grain crops sown, was second in acreage in each of the prairie provinces. Between 1991 and 2000, barley acreage ranked third in western Canada behind wheat and canola (Canada Grains Council 2001). Although barley is the most competitive annual crop grown on the Canadian prairies (Todd 1989), yield loss due to weed competition was estimated in excess of $61 million (Swanton et al. 1993).

Wild oat (*Avena fatua* L.) is a ubiquitous weed on the Canadian prairies that occurs at the second highest density of all weeds (Thomas et al. 1996, 1998a, 1998b) after green foxtail (*Setaria viridis* (L.) Beauv.), but is more competitive (Wall 1993). Wild oat is particularly problematic in spring cereals where it can be costly to control. It is one of the most economically harmful annual grassy weeds in North America (O'Donovan and Sharma

1983). Dew (1978) estimated the economic cost of wild oat in western Canada due to crop losses and herbicide costs at $280 million.

1.2 AGRONOMIC CONTEXT

1.2.1 Integrated Weed Management

The development of integrated weed management (IWM) systems are the result of increased herbicide costs, herbicide resistance, the social, health and environmental impacts of agriculture (Swanton and Murphy 1996). Additionally, in low-external-input (LEI) farming systems (Forcella et al. 1993; Kristensen and Rasmussen 2002; Liebman and Davis 2000), such as organic and pesticide-free production systems, the use of herbicides is prohibited for the duration of a specified time period. Consequently, a need for alternative and complementary weed control measures is essential.

IWM was developed from integrated pest management (IPM) and shares many of the same goals (Thill et al. 1991). IPM operates by applying multiple tactics to control pests and aspires to maintain pest populations below economic thresholds while conserving environmental quality. IWM has been linked to sustainable agriculture systems (Elmore 1996; Swanton and Weise 1991) and has been defined and discussed complementarily by various authors. Thill et al. (1991) defined IWM as: "The integration of effective, environmentally safe, and socially acceptable control tactics that reduce weed interference below the economic injury level.". Swanton and Weise (1991) suggested implementation of IWM requires a paradigm shift from short-term productivity as the dominant goal of agriculture to one where environmental, social and human health concerns become paramount.

IWM has three strategies (Derksen 2002): 1) decrease weed density at crop emergence, 2) keep weeds off balance by altering management strategies such as tillage, seeding date, herbicide rotation, and crop rotation, and, 3) increase the competitive ability of crops either i) agronomically, by altering seeding rate, crop spatial arrangement, and fertilizer placement and timing, or ii) through the use of competitive cultivars. Barley is considered a competitive crop (Lemerle et al. 2001b; López-Castañeda 1995; Tremere 1989) although cultivar competitiveness varies (e.g. Baghestani et al. 1999; Christensen 1994, 1995; Didon 2002; O'Donovan et al. 1999, 2000). Consequently, the use of barley cultivars to suppress weeds is feasible as an IWM strategy.

1.2.2 Competition

Competition occurs when water, nutrient or light resources are limited and two or more plants seek the same limiting resources (Lindquist 2001). The term 'interference' encompasses competition but also includes induced effects caused by changes in the environment brought on by the proximity of neighbours, such as allelopathy (Harper 1977). Lindquist (2001) uses the term interference when describing relationships between crop yield and weed density where the cause of the observed yield reduction is not evaluated. In practice, the terms competition and interference have often been used interchangeably (Lemerle et al. 2001b) and this review will use the term competition unless it is certain that interference is operative (e.g. allelopathy).

There are two aspects of competitive ability (Goldberg and Landa 1991; Jordan 1993) that describe: 1) a species ability to withstand competition (AWC) and, 2) a species ability to compete (AC) with another species. Goldberg and Landa (1991) used the terms competitive response (AWC) and competitive effect (AC), while Jordan (1993) used the terms crop tolerance (AWC) and weed suppression (AC), respectively. In varietal studies of competitive ability, both aspects need to be considered (Jordan 1993; Lemerle et al. 2001b), since differential varietal response to weed competition might arise if cultivars have peak resource demands at times when weed resource use is low. This may be true irrespective of actual weed density (Lemerle et al. 2001b). However, both aspects may not be present in the same cultivar and most studies only measure one aspect (Lemerle et al. 2001b).

In ecology, competition is evaluated by persistence over time in systems that are often predominantly perennial, and may be at varying post-disturbance stages (van der Werf et al. 1998; Weiher et al. 1999). A similar situation does not exist in annual cropping systems as weeds are often predominantly annual (Thomas et al. 1996, 1998a, 1998b) and disturbance can be considerable, even in reduced-tillage systems (Lafond and Derksen 1996a). Consequently, in annual cropping systems, measurement of competitive outcomes has not relied on persistence over time.

Instead, competitive outcomes have been measured using leaf area (e.g. Zand and Beckie 2002; O'Donovan et al 1999), biomass (e.g. Ni et al. 2000; Zand and Beckie 2002) and seed yield (e.g. Ogg and Seefeldt 1999). However, annual plants reproduce solely by seed. Consequently, the conclusive measure of interplant competition between an annual crop and annual weed is seed production (e.g. Lemerle et al. 2001b) in the form of seed yield from the crop and weed, respectively.

Cultivar competitive ability may be considered hierarchically (Figure 1.1) and is accomplished through the differential acquisition of limiting light, moisture and nutrient resources (Table 1.1). The effect of these strategies may be determined using integrated measurements, or by measuring their components (Table 1.1). The components of the strategies are morphological and physiological attributes and need not be exclusive to a strategy. Differences in barley cultivar competitive ability exist (e.g. Baghestani et al. 1999; Blijenburg and Sneep 1975; Christensen 1994, 1995; Didon 2002; Fadeeva and Kirillova 1986; Froud-Williams 1997; Hucl 1996; Konesky et al. 1989; Lemerle et al. 1995; O'Donovan et al. 2000; Suneson 1949) but may not be due to the same specific strategies, or combinations of strategies at all times (Lemerle et al. 2001b). Different strategies may be more useful for different varieties, and at different developmental stages, than at other stages. Consequently, determining the importance of specific attributes, such as specific leaf area and leaf angle, contributing to cultivar competitive ability may be difficult since they are hierarchically further removed from competitive ability than are strategies (Figure 1.1).

Table 1.1. Examples of strategies, integrated measurements, and attributes associated with cultivar competitive ability.

Strategy	Integrated Measurement	Attributes
Light acquisition	Light extinction	Specific leaf area (SLA), leaf angle, tillering capacity (TC)
	Rate of canopy closure	SLA, leaf angle, TC
	Rapid height growth	rate of stem elongation, internode length
	Relative growth rate (RGR)	SLA
Moisture acquisition	Rate of evapotranspiration	Root size, biomass, and pattern,
	Relative growth rate	Root surface area
Nutrient acquisition	Leaf nutrient analysis	Mycorrhizal associations, surface area of fine root hairs
	Relative growth rate	Root surface area

Evaluation of the importance of attributes to cultivar competitive ability should facilitate breeding efforts to improve cultivar competitive ability (Lemerle et al. 2001a). This effort has become more urgent with the increased development of herbicide-tolerant weeds (Lemerle et al. 2001b) as alternative control measures are limited. However, the search for attributes consistently contributing to cultivar competitive ability needs to cover wide genotypic variability. If it does not, the apparent contribution of attributes to cultivar competitive ability may reflect either chance associations (Lemerle et al. 2001b) or preconceptions based on other research or observations of relatively few cultivars.

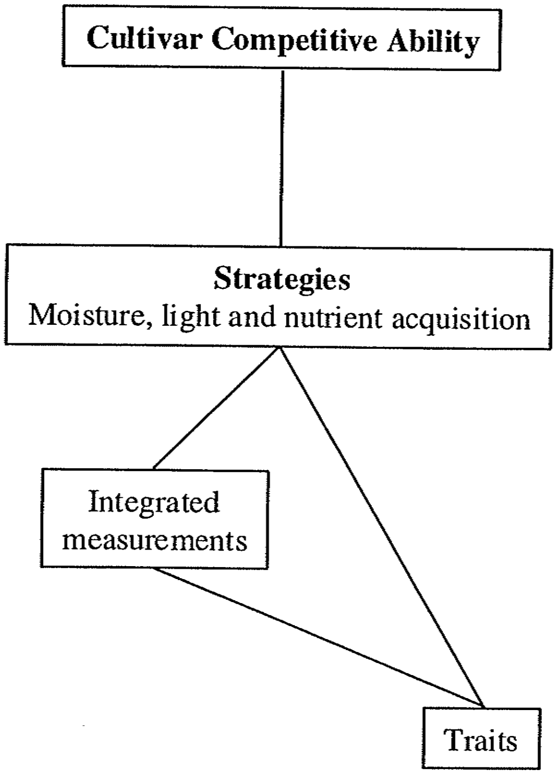

Figure 1.1. Hierarchical representation of cultivar competitive ability, strategies, integrated measurements and attributes.

Attributes that have been considered important to cultivar competitive ability include, crop density (Barton et al. 1992; Doll et al. 1995; Evans et al. 1991; Lafond 1994; Lafond and Derksen 1996b; O'Donovan et al. 1999, 2001; Van Acker et al. 1997b), plant height (Blackshaw et al. 1981; Challaiah et al. 1986; Christensen 1995), rate of canopy closure (Mian et al. 1998), canopy architecture (Légère and Schreiber 1989), early height growth

(Mian et al. 1998), and comparative rates of emergence and leaf appearance (Cousens et al. 1992). Some research has found that attributes contributing to cultivar competitive ability are different under weed pressure (Dhaliwal 1998; Didon 2002). Breeding programs have generally not adopted attributes thought to contribute to cultivar competitive ability since breeders need attributes that are both deterministic and offer simplicity of measurement.

1.3 SCIENTIFIC CONTEXT

1.3.1 Ecological Framework

Plant ecology strategy schemes (PESSs) arrange species in categories, or along axes representing a continuum, using their ecological attributes (Westoby 1998). The PESS concept has arisen largely from the ecological succession literature and thus needs to be considered over a series of generations, operating in the presence of competing species, under different edaphic conditions and disturbance regimes (Westoby 1998). The objectives of a PESS are: 1) to express an understanding of important opportunities and selection pressures on plant persistence in an ecosystem, 2) to describe the persistent flora using a limited number of ecological components or variables, and, 3) to describe plant resource capture and reproductive survival.

Westoby (1998) recognized three major classifications of PESSs. One classification is based on population distribution (i.e. realized niche). An example of this is "vital attributes" (Noble and Slatyer 1980) in which species' vital attributes are determined by: 1) the method of arrival or persistence at a site during and following disturbance, 2) the ability to establish and grow to maturity in the developing community, and, 3) the time taken to reach critical life-history stages such as reproduction. Attributes favoured when disturbances are rare will be maladapted when disturbances are comparatively frequent.

A second classification is based on phenological or physiognomic characters. For example, Raunkiaer (1934) based his classification on the location of the buds where the regrowth arises after an unfavourable season (e.g. winter). This classification, while simple, has been widely adopted in Europe (Westoby 1998).

The third classification distinguishes categories based on ecological opportunities exploited within a landscape. One example is the r-K continuum (MacArthur and Wilson 1967) where species have characteristics (Bazzaz 1979) that enable them to persist longer in the succession (K-selection) or have characteristics enabling them to escape succession, and find and colonize early stages of succession elsewhere (r-selection). Another example is Grime's CSR triangle (Grime 1974, 1977; Grime et al. 1997), where habitats vary in disturbance regime and resource availability. When disturbance is rare and resources are abundant, a competitive (C) strategy enables species' persistence. A stress-tolerant (S) strategy is appropriate when resources are scarce and disturbance is uncommon. A ruderal (R) strategy is apt under high-disturbance regimes where resources are abundant, but conditions are benign.

Westoby (1998) proposed a leaf-height-seed (LHS) plant ecology strategy scheme to be universally adopted for functional ecology (Weiher et al. 1999) thereby providing a common language for comparing species and vegetation types worldwide. In the LHS framework there would be three axes, and approximate comparisons to Grime's CSR triangle would be possible. The measurements suggested for the LHS axes are 1) specific leaf area, 2) plant canopy height at maturity, and, 3) seed mass. These, and similar, measurements are used to investigate cultivar competitive ability in annual cropping systems. Therefore, this plant ecology strategy scheme is more easily adaptable to annual agriculture than others outlined above.

1.3.2 Agro-Ecological Framework

The primary goal of IWM is to provide the crop a competitive advantage over weeds within a sustainable agriculture system (Derksen 2002; Swanton and Weise 1991). Crop competition with weeds is a fundamental method of non-chemical weed control (Jordan 1993) and considerable research has been conducted on crop and cultivar competitiveness (e.g. Lemerle et al. 2001a and references within). As with the leaf-height-seed plant ecology strategy scheme (Westoby 1998), attributes thought to contribute to plant resource capture and reproductive survival (i.e. cultivar competitive ability) have been measured at the seed (S), seedling(L) and mature plant (H) phases (Lemerle et al. 2001a). However, linkages between stages and their relative importance are rarely considered. Consequently, a framework that integrates relationships between growth stages would be useful.

In annual cropping systems, the life cycle of the crop begins at seeding and can be described in a seed-leaf-height (SLH) framework (Figure 1.2). Each phase is separated by morphological or physiological characteristics (Zadoks et al. 1974) relevant to annual agriculture and can similarly be further be divided into sub-phases. The seed (S) phase begins with dry seed (Zadoks 00) and continues through germination and emergence until immediately prior to the onset of photosynthesis (Zadoks 09). The seed phase can be logically subdivided into two sub-phases. The first sub-phase (S_1) is the dry seed phase (Zadoks 00), while the second sub-phase (S_2) comprises the post-seeding germination phase (Zadoks 01 – 09), where the seed is still reliant upon stored resources. The seed phase ends when photosynthesis begins (Zadoks 10).

The start of photosynthesis (Zadoks 10) signals the beginning of the leaf (L), or seedling, phase (Figure 1.2). This phase is subdivided into early (L_1) and late (L_2) sub-phases, separated by the onset of tillering (Zadoks 20). The tillering phase represents a shift from purely vegetative growth to partly sexual development since tillers have the capacity to bear ears (Evers et al. 1999). Additionally, ear primordia develop in this phase and the ear-bearing potential of barley is set by the end of tillering. The seedling (S) stage terminates immediately prior to the onset of stem elongation (Zadoks 30).

The height (H), or mature plant phase begins (Figure 1.2) at the onset of stem elongation (Zadoks 30) and terminates at the end of harvest. This phase can be subdivided into early (H_1) and late (H_2) sub-phases based on ear visibility (i.e. at boot stage). This morphological distinction also has physiological bases. Maximum foliar canopy height occurs shortly after boot stage and barley susceptibility to foliar diseases increases rapidly after the boot stage. Consequently, senescence seldom occurs before boot stage.

The seed-leaf-height framework integrates across all growth and developmental stages of cereals, with meaningful separation of both the main phases and sub-phases. It allows measurements believed to be related to cultivar competitive ability to be taken at either a point in time or over time. Measurements taken after harvest may be considered crop quality measurements, such as percent protein, or seed phase measurements, such as percent germination, for the following crop. Furthermore, it implicitly recognizes prior and later effects of attributes and permits the evaluation of the relative impact of attributes contributing to cultivar competitive ability.

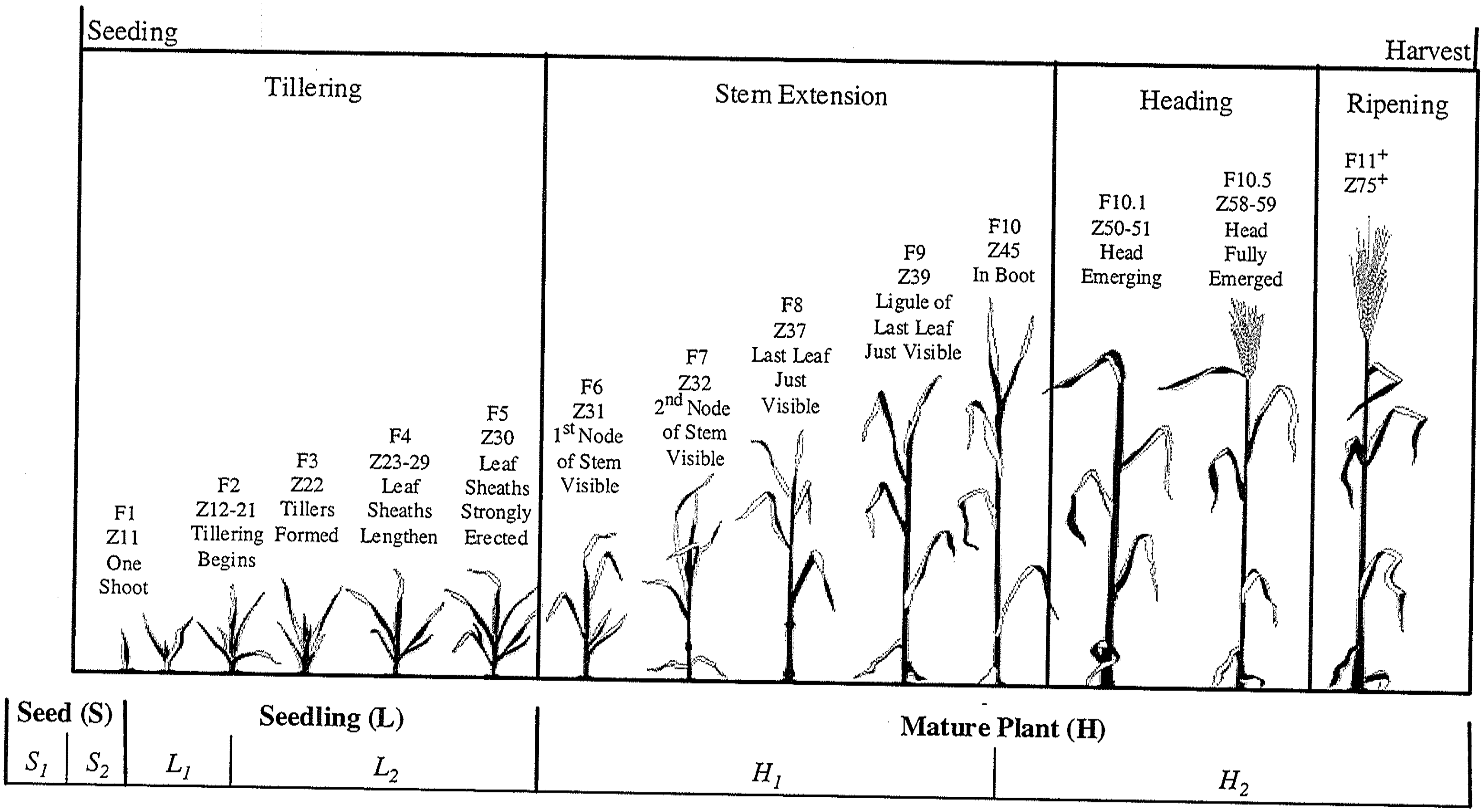

Figure 1.2 The relationship of the SLH framework to the Feekes (F) and Zadoks (Z) cereal development scales.

CHAPTER 2: LITERATURE REVIEW IN THE CONTEXT OF THE SEED-LEAF-HEIGHT (SLH) FRAMEWORK

2.1 SEED (S)

2.1.1 Introduction

The seed (S) phase (Figure 1.2) begins with dry seed (Zadoks 00), continues through emergence, and ends when photosynthesis begins (Zadoks 10). In this phase, all three integrated weed management strategies are employed to reduce the effects of weed competition. Firstly, reducing seedling density at the time of crop emergence results in more competitive crops and higher yields, since crop emergence prior to weed emergence alters the competitive balance in favour of the crop (Blackshaw 1993a, 1993b; O'Donovan 1992, O'Donovan et al. 1985, Peters and Wilson 1983). Secondly, altering management strategies such as tillage (Du Croix Sissons et al. 2000; Hutcheon et al. 1998; Lafond and Derksen 1996a), crop rotation (Dorado et al. 1999), and seeding date (Spandl et al. 1998) modifies seedbank emergence and contributes to a reduction of seedling density. Finally, although competition has been suggested to begin prior to emergence (Bowden and Friesen 1967; Hoffman et al. 1996; Laterra and Bazzalo 1999), the contribution of seed vigour to cultivar competitive ability in the seed phase is paramount (Ayre 1980; Perry 1976b). Competitive cultivars are thought to have superior seed vigour (Entz et al. 1990; Perry 1976a).

In his review of seed vigour (Perry 1976a) concluded that: 1) seed vigour is a widely used term that conveys the concept of variability in the performance of the seed during germination and its subsequent effects on seedling development and plant growth, and therefore, 2) properties which have been reported to be controlled by vigour should generally be regarded as measurable components of vigour. However, seed vigour is a term which has different meaning to seed analysts and agronomists. The seed analyst is interested in the behaviour of seeds in laboratory tests, whereas the agronomist is concerned with field performance aspects of seed (Perry 1976a).

Measurable agronomic components of seed vigour include rapid and uniform germination and emergence (Ching et al 1977; Lafond and Baker 1986b; Naylor 1993; Torres and Paulsen 1982) and seedling vigour (Bulisani and Warner 1980; Evans and Bhatt 1977; Gan and Stobbe 1996; Mian and Nafziger 1994; Lafond and Baker 1986a; Lowe et al. 1972). These components are thought to be measurable by morphological or physiological attributes. Seed size (Aparicio et al. 2002; Bockus and Shroyer 1996; Gan and Stobbe 1996; Lafond and Baker 1986a, 1986b; Stougaard and Xue 2004; Xue and Stougaard 2002), and variations such as seed mass (Berdahl and Frank 1998) or specific gravity (Odiemah 1991; Prasad et al. 1994), as well as embryo size (Lopez-Castaneda et al. 1996) are morphological seed attributes indicative of seed vigour.

Measurable physiological attributes indicative of seed vigour include percent protein (Guy and Black 1998; Siebert and Pearce 1993), protein type (Ayers et al. 1976) adenosine triphosphate content (Briggs and Horak 1980; Ching et al. 1977), nutrient content (Naylor 1993; Szirtes et al. 1978; Yusuf et al. 2000) respiration rate (Hall and Weisner 1990) nitrogen content (Bulisani and Warner 1980), and mitochondrial quality and quantity (McDaniel 1969). In most cases, a increased levels of morphological or physiological attributes are associated with an increase in the vigour components, a subsequent increase in later vigour components (Lafond and Baker 1986a, 1986b), superior vegetative growth and stand establishment (Bockus and Shroyer 1996; Lafond and Baker 1986a; Sonntag et al 1993), and final yield (Ayre 1980; Dasgupta and Austenson 1973; Gan and Stobbe 1996; Hall and Weisner 1990; Kim et al. 1994; Perry 1976b). Since vigour components and increased vegetative growth, and superior stand establishment are important to competitive ability, increased seed vigour should lead to increased competitive ability (Lemerle et al. 1996; Ni et al. 2000; Seavers and Wright 1999; Xue and Stougaard 2002).

There are numerous seed vigour tests available (Association of Official Seed Analysts 1983; International Seed Testing Association 1995) and evaluation of the relationship between field performance and the analytical measurement of seed vigour has been conducted for single cultivars of winter wheat (Mian and Nafziger 1994), and meadow bromegrass (Hall and Weisner 1990), as well as multiple cultivars of canola (Elias and Copeland 1997) and barley (Kim et al. 1994). Mian and Nafziger (1994) found that seed size was related to seedling vigour, but was unrelated to percent germination as measured by the standard germination test.

More complex approaches (Elias and Copeland 1997; Hall and Weisner 1990; Kim et al. 1994) have used the standard germination test in conjunction with other tests such as cold germination, electroconductivity, accelerated aging, and respiration rate. These studies all found that predicting field performance of crops and cultivars from laboratory tests required the use of multiple tests. Kim et al. (1994) examined the greatest genotypic diversity, using malt, food, and feed barley cultivars from both Korea and the USA. Their objective was to use multiple seed vigour indices to predict field emergence and performance of each barley type. They were successful, except for an inability to develop a composite index predicting field emergence of food varieties. The composition of the indices varied somewhat by type (malt, food, field) and by performance attributes such as emergence and performance.

In summary, seed vigour is a term that conveys the concept of variable performance in germination, emergence and subsequent growth. Its field measurement has been related to a variety of morphological, physiological and biochemical (Black et al. 1969) seed characteristics. Increased seed vigour has been presumed key to increased cultivar competitive ability as a result of advantages arising from greater early growth and development. However, yield and competitive ability may not always be closely related to seed vigour (Lemerle et al. 2001a) and this relationship has not been investigated.

2.1.2 Review of Seed (S) Attributes and Cultivar Competitive Ability

Considerable variation in seed vigour exists among spring barley cultivars (Briggs and Dunn 1999, 2000), and spring wheat cultivars (Lafond and Baker 1986a, 1986b) in North America although less has been found for Australian wheats (Lemerle et al. 2001a.). However, little research has been undertaken to quantify the contribution of seed vigour to cultivar competitive ability. Kaufman and McFadden (1960), used one cultivar of barley and measured the outcome of intra-specific competition between plants from large versus small seeds. They found that plants from large seeds had superior yield to plants from small seeds. In spring wheat, Xue and Stougaard found that larger seed prevented yield loss (Xue and Stougaard 2002) and reduced wild oat over time (Stougaard and Xue 2004).

Lopez-Castaneda et al. (1995) sowed two cultivars each of wheat and barley and found that differences between wheat and barley early vigour could not be attributed solely to seed size as barley was more competitive despite using the same seed size between crops. Their study suggested the interval between germination and the 2-leaf stage as being responsible for the greater vigour of barley, compared to wheat. In a later paper, they (Lopez-Castaneda et al. 1996), compared the early vigour of barley, triticale, bread wheat, durum wheat, and tame oat. They again used seed of the same size and found that embryo size was, by far, the most important factor accounting for differences among the crop species. This result supports previous research relating seed vigour to percent protein since most of the protein is stored in the embryo.

Ching et al. (1977) examined two 2-row and four 6-row cultivars and related laboratory and field measurements to emergence on these cultivars. They found that a stepwise multiple regression consisting of seed weight, 7-day seedling dry weight, and two measures of seed phosphate content adequately described field emergence.

2.1.3 Conclusions

Seed vigour has been attributed to seed size, protein content and type, ATP production and mitochondrial quality and quantity. Some, or all, of these factors could contribute to differences in competitive ability among cultivars or among species. Within and between cultivars, larger seeds have larger embryos and the embryo contains the "machinery" while the endosperm contains the "fuel" (Lopez-Castaneda et al. 1996). Since embryo size accounts for most of the variation in vigour among crops (Lopez-Castaneda et al. 1996), seed size, protein content and type, ATP production and mitochondrial quality and quantity may also contribute to differential cultivar competitive ability. However, little research has been conducted to connect seed vigour to cultivar competitive ability. Consequently, the widely-held notion that seed vigour contributes to cultivar competitive ability is generally assumed and often unsubstantiated. This may be a result of applying research whose applicability to competitive ability is uncertain.

Extensive research could be conducted to determine the feasibility of integrating analytical measurement of seed vigour to field trials on competitive ability. The integration of analytical and field evaluation of seed vigour has focused largely on emergence, subsequent growth, and yield. Since yielding ability does not directly translate into competitive ability (Lemerle et al. 2001a, 2001b), this effort may be needed, but may produce a positive result.

2.2 LEAF (L) PHASE

2.2.1 Introduction

The seedling (L) phase (Figure 1.2) begins after the plant emerges from the ground and begins to photosynthesize (Zadoks 10) and terminates at the start of stem elongation (Zadoks 30). However, attributes measured in this phase have correlative and stochastic relationships to attributes and measurements in the seed (S) phase. For example, Lemerle et al. (2001b) suggested “early vigour” as being comprised of a high rate of emergence, high relative growth rate, or large initial size. The rate of emergence is controlled by seed attributes such as seed size, seed protein content and germination resistance (Lafond and Baker 1986a). A high relative growth rate for a newly emerged plant is attributable to the quality of the “machinery” and the quantity of “fuel” remaining (Lopez-Castaneda et al. 1996). Large initial size has been often correlated with seed size (Lemerle et al. 2001b), but may also be somewhat attributable to the “machinery” and the quantity of “fuel” remaining. As growth proceeds over time, measurements may become less correlated with those taken at much earlier times due to non-linear growth patterns and random environmental events. For example, if one cultivar had begun stem elongation while another remained prostrate, advantages due to larger seed or embryo size and an initial high relative growth rate could be lost in a hail storm. Hence future growth would become less correlated with past growth. Since a clear division between autocorrelated measurements in the S and L phases does not exist, this section includes research commencing in the seed phase.

In contrast with the seed phase, competition in the leaf (seedling) phase has received considerable attention for two reasons. First, the critical weed-free period often exists only during the seedling phase (e.g. Bosnic and Swanton 1997; Knezevic et al. 2002; Martin et al. 2001; Ni et al. 2000; Van Acker et al. 1993), and so both the onset and termination of competition occur in this phase (e.g. Chancellor and Peters 1974). Second, with the exception of allelopathic interference, (Baghestani et al. 1996; Nelson 1996; Weidenhamer 1996; Weston 1996; Wu et al. 1999) competition is either for resources directly or in preparation for imminent competition. Consequently, agronomic and modelling efforts have been directed primarily at this phase.

Research on crop and cultivar competitive ability in this phase can be placed into three categories. In the first category, agronomic research aims to improve seedling vigour at the expense of weeds. In the second, confirmatory research is intended to substantiate preconceived hypotheses. Thirdly, exploratory research is intended to investigate attributes not widely accepted as contributing to competitive ability.

Agronomic research is often published under the "umbrella" of integrated weed managment (e.g. Barton et al. 1992; Bostrom and Fogelfors 2002a; Vizantopoulos and Katranis 1994). It includes nominal seed research, such as the seeding date, rate, and geometry, as well as the effect of the type and timing of nutrient and herbicide application (Blackshaw et al 2001a). The objective of these strategies is to minimize crop yield loss by providing an advantage over weeds.

Seeding date research aims to minimize weed competition by decreasing weed density at crop emergence. Altering seeding dates keeps weeds "off balance" (Derksen 2002) and late-emerging weeds have little influence on yield while their own reproductive capacity is diminished by a vigorous crop stand (Murphy et al. 1996; O'Donovan 1992, O'Donovan et al. 1985, Peters and Wilson 1983). This is accomplished either by weed removal after late seeding, or early seeding to avoid weed pressure (Elberse and de Kruyf 1979; McFadden 1970; Spandl et al. 1998; Vezina 1992). This approach has had limited success in much of western Canada as the opportunity to alter seeding date without incurring yield loss is limited (Martin et al. 2001). This is aggravated by the limited number of actual days usually available for seeding within this period due to inclement weather.

Crop seeding rate (crop density) has been widely used as a weed management tool (Cudney et al. 1989; Doll 1997; Doll et al. 1995; Evans et al. 1991; Johnston and Stevenson 2001). The optimal crop seeding rate to maximize competitive ability against weeds is contingent upon both crop and weed density (Dielman et al. 1999; O'Donovan et al. 1999; Torner et al. 1991; Wilson et al. 1990). Crop yield loss can be minimal at low weed density (Ervio 1983) and increasing crop density above an optimal rate does not increase crop competitiveness against weeds (Blackshaw et al. 2000b; Ervio 1983; Xue and Stougaard 2002). By contrast, lowering crop density below optimum can result in increased weed biomass (Doll 1997; Ervio 1983; O'Donovan et al. 1999; Wilson et al.

1995) and seed production (Doll 1997; O'Donovan et al. 1999; Wilson et al. 1990, 1995). Crop seeding rate has been used in conjunction with other strategies such as herbicide rate reduction (Barton et al. 1992; Kirkland et al. 2000; O'Donovan et al. 2001), nutrient management (Lafond 1994) and, seeding geometry (Barton et al. 1992; Lafond 1994; Lafond and Derksen 1996b; Malik et al. 1993). Optimizing crop seeding rate and geometry results in rapid canopy closure (Legere and Schreiber 1989; Murphy et al. 1996;) and decreases growth (Lanning et al. 1997; Wilson et al. 1995) and seed production (Murphy et al. 1996; Wilson et al. 1995) from late-emerging weeds.

The objective of nutrient research is to provide needed nutrients to the crop while simultaneously rendering limiting resources unavailable to weeds as quickly as possible (Di Tomaso 1995). By altering the type (Chang and Robertson 1968; Legere et al. 1994; Suzuki and MacLeod 1970), timing (Angonin et al. 1996; Ball et al. 1996), and quantity of nutrients (Andersson and Milberg 1998b; Angonin et al. 1996; Chang and Robertson 1968; Dhima and Eleftherohorinos 2001; Exley and Snaydon 1992; Grundy et al. 1993; Legere et al. 1994; O'Donovan et al. 1997; Siddiqi et al. 1985, 1987; Thurston 1959), yield loss due to weeds can be reduced.

There are four research objectives in the interaction of competitive ability with herbicide application, that often overlap. These are: 1) the prevention of herbicide resistance (e.g. Vizantopoulos and Katranis 1994; Jaseniuk et al. 1996), 2) herbicide efficacy in unregistered and newly registered products (e.g. Vizantopoulos and Katranis 1994), 3) net producer returns (e.g. Böstrom and Fogelfors 2002b; O'Donovan et al. 2001), through the reduction of herbicide rates (e.g. Christensen 1994; Kirkland et al. 2000; Richards and Davies 1991) and, 4) long-term effect on weed communities (e.g.

Böstrom and Fogelfors 2002a; Schreiber 1992). In general, the objective of these research areas is to give an advantage to the crop seedlings while minimizing producer costs.

Confirmatory research is initiated based on theoretical grounds as well as previous research on particular strategies and attributes. Verification of factors such as rate of canopy closure (Mian et al. 1998), canopy architecture (Legere and Schreiber 1989), early height growth (Mian et al. 1998), and comparative rates of emergence and leaf appearance (Cousens et al. 1992) has been conducted. Models have attributed crop yield loss due to weeds using weed density (Cousens 1985a, 1985b; Cousens et al. 1987; Dew 1972, Kropff and Spitters 1991; Kropff et al. 1995; Lutman et al. 2000; Ngouajio et al. 1999), weed and crop densities (Cousens 1985b; O'Donovan et al. 1999; Van Acker et al. 1997a), weed density and relative time of weed emergence (Cousens et al. 1987), and relative leaf area of weeds (Kropff and Spitters 1991; Lotz et al. 1996; Ngouajio et al. 1999; Van Acker et al. 1997b). Recently, weed seed reproduction has been modelled as a function of crop yield loss (Canner et al. 2002). In general, research has been conducted on weed-crop competition rather than crop-weed competition (but see e.g. Canner et al. 2002; Cousens 1985b). Consequently, the focus of competition research has been the ability to withstand competition rather than the ability to compete.

Exploratory research is currently quite rare. Factors discussed above are widely held to contribute to competitive ability and hence, cultivar competitive ability. There appears to be a complete lack of research that does not presuppose factors such as light extinction, ground cover, crop density are important in cultivar competitive ability.

2.2.2 Review of Seedling (L) Attributes and Cultivar Competitive Ability

Substantial research has been conducted on weed-crop competition and crop losses due to weeds (Chandler et al. 1986). However, there has been little exploration of the attributes contributing to cultivar competitive ability. Research has indicated the importance of seedling attributes such as tiller number (Challaiah et al. 1986) early crop growth rate (Ni et al. 2000), early height development (Ogg and Seefeldt 1999), and early stem extension (Didon 2002) and early-season advantages are carried throughout the season (Lopez-Castaneda et al 1995, 1996). However, these studies have employed relatively few cultivars. Challaiah et al. (1986) seeded 10 cultivars of winter wheat, Ogg and Seefeldt (1999) planted 7 cultivars of winter wheat while Ni et al. (2000) and Didon (2002) used four rice cultivars and two barley cultivars, respectively. As the number of cultivars declines, it becomes more likely that attributes observed to contribute to cultivar competitive ability may actually be chance associations (Lemerle et al. 2001b).

2.2.3 Conclusions

The limited research specifically exploring the attributes contributing to cultivar competitive ability (Challaiah et al. 1986; Didon 2002; Ogg and Seefeldt 1999; Ni et al. 2000) in the seedling (L) phase indicates a need for considerably more research. Lemerle et al. (2001b) suggested that if the number of cultivars considered within a study is small, attributes apparently contributing to cultivar competitive ability may actually be chance associations. Furthermore, attributes contributing to competition in moisture-limiting conditions need not be the same attributes contributing to light or nutrient-limiting conditions. Finally, some attribute expression is variable in weed-infested versus weed-free conditions (Dhaliwal 1998; Didon 2002). Consequently, the expectation that one attribute, or a small set of attributes, will provide complete insight into competitive ability may be unrealistic. This strongly suggests a need for a wide range of cultivars to be grown over multiple seasons at multiple locations.

2.3 HEIGHT (H)

2.3.1 Introduction

The mature plant (H) phase begins at stem elongation (Zadoks 31) and terminates at the end of harvest (Figure 1.2). As with the relationship between the seed (S) and seedling (L) phases, auto-correlated measurements between the L and H phases do not have clear divisions. For example, crop height can be measured over a continuum starting at emergence and terminating shortly before harvest. Consequently, attributes researched in this phase may not be phase-specific, but may represent a continuance from previous phases.

In the H phase, measurement of ability to compete rather than ability to withstand competition may be of paramount importance. Crop yield loss due to weeds is generally considered inconsequential as most yield loss occurs in the L phase. However, prior to boot stage, rate of stem elongation has been considered important (Didon 2002).

After boot stage, suppression of later-emerging weeds through light competition naturally terminates due to crop senescence. As competition ends, weeds that have survived below the canopy may be released from light competition and may resume growth and development, and may potentially increase their yield. This gradual termination of light competition can be accelerated through increases in lodging, disease development, or insect pressure. If lodging occurs early enough, weeds that mature more quickly than the crop can benefit from late tillering (Byron Irvine pers. comm.), thereby increasing weed seed yield. Application of foliar fungicides (Dimmock and Gooding

2002a) and insecticides has the potential to delay the onset of canopy opening, thus preventing late-season release of weeds. The release of weeds and subsequent increased seed return can have negative economic effects through grade reductions due to contamination and increased herbicide costs and yield loss in subsequent years.

In addition to the ability to compete, optimal pre-harvest and harvest conditions have implications for crop seed as well (e.g. Entz and Fowler 1988, 1990). This is particularly important to seed growers or farmers wishing growing seed to be sown the following year. Reduced disease incidence decreases lodging (Scott 1996) which increases yield (Jedel and Helm 1991b). Under substantive insect or disease pressure, application of insecticides or foliar fungicides reduces the destruction of photosynthetically active plant matter. This allows the crop to reallocate more photosynthate from leaves to seed, thus increasing test weight and grain yield (e.g. Entz et al. 1990; Kelley 2001; Moes et al. 1992).

2.3.2 Review of Mature Plant (H) Attributes and Cultivar Competitive Ability

In the height (H) phase, final height has been considered to be an important attribute (Blackshaw et al. 1981; Challaiah et al. 1986 Christensen 1995). However, research arriving at this conclusion has often been based on comparisons between full height and semi-dwarf varieties (Blackshaw et al. 1981; Juskiw et al. 2000; Gonzalez-Ponce and Sattin 2001; Grundy et al. 1993; Seefeldt et al. 1999). In exploratory research, Ni et al (1999) and Ogg and Seefeldt (2000) have suggested that final height is less important than the rate of height growth, particularly in the early stages of growth and development (e.g. Lopez-Castaneda et al. 1995, 1996). In water-seeded rice, Caton et al. (1997) reported that competitive effects with *Ammania* spp. were not detectable until the stem elongation phase had begun. This was attributed to the lack of resource limitation until light competition began after *Ammania* spp. height surpassed that of rice. Consequently, the proposition that competition predominantly occurs during the seedling (L) phase may be contingent upon the nature, and extent, of resource limitations in this phase.

Research on the effect of cultivar competitive ability with weeds due to lodging, foliar disease and insect pressure has not been conducted. However, Caton et al. (1997) suggested that increased lodging in rice due to increased density of *Ammania* spp. caused a decrease in rice yield through reduced tiller production. Consequently, these areas of research specific to H phase cultivar competitive ability remain under-exploited.

2.3.3 Conclusions

Research conducted into the effect of the H phase on cultivar competitive ability has been minimal. Competitive differences due to height have generally involved comparisons of full-height versus semi-dwarf varieties. Determining the impact of lodging, or the application of foliar fungicides and insecticides to crop and weed seed quantity (yield) and quality could prove profitable. Negative economic impacts due to increased quality and quantity of weed seed return include grade reductions due to contamination, as well as increased herbicide costs and yield loss in subsequent years. For the seed grower or the producer wishing to use home-grown seed, this research offers potential to improve seed vigour in the seed (S) phase of the subsequent crop.

Competition research in the H phase should be directed at the quantity and quality of weed and crop seed production. Weed and crop seed quality and quantity can be addressed in the context of lodging, insect pressure, disease development, and prevailing environmental and agronomic conditions. The ability of the crop to withstand competition (AWC) needs to address yield loss specifically due to weed competition in the H phase. In addition to this, research could be undertaken to relate seed vigour loss to competitive ability. For example, loss of measurable components of seed vigour has been attributed to factors such as threshing cylinder speed (Bourgeois et al. 1996; Entz et al. 1991), disease incidence (Entz et al. 1990; Fernandez et al. 1996), heat stress (Grass and Burris 1995a, 1995b), or other stresses during critical periods (Entz and Fowler 1988). Similarly, the ability of crops to compete with weeds needs to address the potential for increased seed return specifically due to reduction of competitive ability in the H phase.

2.4 OVERALL CONCLUSIONS

Exploratory research into attributes contributing to cultivar competitive ability has been lacking. There has been a considerable amount of research conducted in the seed phase relating seed vigour to yield has been assumed. Comparable research relating seed vigour to competitive ability has not been undertaken. Furthermore, seed vigour is not the only area within the seed phase available for research. Several researchers have suggested allelopathic interference can occur before the crop emerges (Bowden and Friesen 1967; Hoffman et al. 1996; Laterra and Bazzalo 1999). In the L phase, abundant research has been undertaken on competitive ability, but the vast majority have been agronomic or confirmatory studies. Few studies have searched for attributes contributing to cultivar competitive ability. In the H phase, virtually no research has been initiated on the late impact of competition. Integration of research across the seed (S), seedling (L), and mature plant phases has not occurred. Consequently, the relative importance of, and linkages between the S. L. and H phases has not been undertaken.

Lemerle et al. (2001b) have suggested that if the range of genotypic variability is insufficient, the apparent contribution of attributes to cultivar competitive ability may actually be chance associations. In addition to this, preconception of the importance of attributes to cultivar competitive ability may also play a role since most research uses relatively few cultivars. Considerable effort has been expended into confirmatory research where attributes widely held to contribute to cultivar competitive ability may be modeled. Confirmatory studies having the minimum of nine cultivars required for three replications of poor, moderate and high competitive ability are few (Challaiah et al. 1986; Fofana and Rauber 2000). Furthermore, few studies of any other type exceed nine cultivars (Cousens and Mokhtari 1998; Doll 1997; Konesky et al. 1989; Richards and Davies 1991) and of these, two are surveys of cultivar competitive ability (Cousens and Mokhtari 1998; Doll 1997). Relatively few cultivars have been used in confirmatory analysis and, consequently, the risk of attributes observed being chance associations is considerable.

Cultivar competitive ability has two aspects: 1) the ability to withstand competition, and, 2) ability to compete. These two aspects may not only respond to different conditions, but may also be operative at different times in the SLH framework. For example, in the L phase, ability to withstand competition may be more important in conventional farming systems, while ability to compete may be equally important in low-external-input systems. In the H phase, ability to compete may be paramount regardless of farming systems since yield loss occurs primarily in the L phase. Consequently, attributes contributing to ability to compete and ability to withstand competition may need to be considered separately.

2.5 OBJECTIVES

Barley is an economically important and competitive crop, both globally and in western Canada. Furthermore, barley cultivars are morphologically, physiologically and competitively diverse. Consequently, the research objectives are to use a wide range of barley cultivars: 1) to determine the range of competitive ability available in cultivars commonly grown in western Canada, 2) to determine if attributes commonly associated with cultivar competitive ability are effective over wide genotypic variability, 3) to determine if, and how, competitive ability is expressed in each of the seed (S), seedling (L) and mature plant (H) phases on barley cultivar competitive ability and 4) to develop and test a method of ranking barley cultivar competitiveness, that employs both ability to withstand competition and the ability to compete, for use by producers, extension professionals and breeders.

CHAPTER 3: THE COMPETITIVE ABILITY OF 29 BARLEY CULTIVARS

3.1 INTRODUCTION

Competition occurs when water, nutrient or light resources are limited and two or more plants seek the same limiting resources (Lindquist 2001). The term 'interference' encompasses competition but also includes induced effects caused by changes in the environment brought on by the proximity of neighbours, such as allelopathy (Harper 1977). Lindquist (2001) uses the term interference when describing relationships between crop yield and weed density where the cause of the observed yield reduction is not evaluated. In practice, the terms competition and interference have often been used interchangeably (Lemerle et al. 2001b) and the term competition will be used hereafter.

There are two aspects of competitive ability (Goldberg and Landa 1991; Jordan 1993) that describe: 1) a species ability to withstand competition (AWC) and, 2) a species ability to compete (AC) with another species. In crop-centric research, AWC has previously been considered as the ability of the crop to withstand yield loss due to weed competition. Ability to compete (AC) has been considered as the ability of the crop to suppress weeds. Goldberg and Landa (1991) used the terms competitive response (i.e. AWC) and competitive effect (i.e. AC), while Jordan (1993) used the terms crop tolerance (i.e. AWC) and weed suppression (i.e. AC), respectively. In varietal studies of competitive ability, both aspects need to be considered (Jordan 1993; Lemerle et al. 2001b), since differential cultivar response to weed competition might arise if cultivars have peak resource demands at times when weed resource use is low. This may be true irrespective of actual weed density (Lemerle et al. 2001b). However, both aspects may not be equally present in all cultivars and most studies only measure one aspect (Lemerle et al. 2001b).

The development of integrated weed management (IWM) systems are the result of increased herbicide costs, herbicide resistance, and the social, health and environmental impacts of agriculture (Swanton and Murphy 1996). Additionally, low-external-input (LEI) farming systems (Forcella et al. 1993; Kristensen and Rasmussen 2002; Liebman and Davis 2000; Nazarko et al. 2003), such as organic and pesticide-free production systems, prohibit the use of herbicides for a specified time period. Using competitive cultivars is one IWM strategy (Derksen 2002) that can be useful in both conventional and LEI farming systems.

Barley is not only the most competitive annual crop grown on the Canadian prairies (Todd 1989), it is considered globally to be competitive (Lemerle et al. 2001a; López-Castañeda 1995; Tremere 1989). However, yield loss due to weed competition in barley on the Canadian prairies has been estimated to be in excess of $61 million (Swanton et al. 1993). Although barley cultivar competitiveness varies (Baghestani et al. 1999; Christensen 1994, 1995; Didon 2002; O'Donovan et al. 1999, 2000), insufficient knowledge of the range of competitive ability exists to use cultivar competitive ability as an IWM tool. Ranking cultivar competitive ability has potential for use by producers, extension personnel and breeders. For producers and extension personnel, knowledge of competitive ability is useful in cultivar selection and recommendation, respectively. For breeders, knowledge of cultivar competitive ability offers a preliminary step to understanding attributes contributing to competitive ability.

Screening efforts have been directed at large (>20) numbers of cultivars with the goal of selecting a subset of cultivars to examine attributes contributing to cultivar competitive ability in wheat (Lanning et al. 1997; Lemerle et al. 1996;) and barley (Doll 1997; Lanning et al 1997). In wheat, moderate numbers of cultivars (10-20) of available genotypes have been selected as "representative" of the range of a particular attribute believed to contribute to cultivar competitive ability and variance in cultivar competitive ability has been reported (Challaiah et al. 1986; Cousens and Mokhtari 1998; Lemerle et al. 2001b; Wicks et al 1994). In barley, most studies examining cultivar competitiveness employed few cultivars (<10) where values for competitive ability have been reported (Baghestani et al. 1999; Christensen 1994, 1995; Didon 2002; O'Donovan et al. 1999, 2000). Consequently, the objectives of this research were to: 1) determine the competitive ability (both AWC and AC), against oats, of barley cultivars commonly grown on the Canadian prairies, 2) determine the relationship between AWC and AC, and, 3) examine the feasibility of ranking barley cultivar competitive ability using either or both of AWC and AC.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Design

A screening trial was conducted in 2001 and 2002 to determine the range in competitive ability of barley cultivars commonly grown in Western Canada. A split-plot design, with 4 replicates, was employed using barley cultivars (Table 3.1) as the main plot, and the presence or absence of a weed as the subplot. Experimental plots (sub-plots) were 2m wide by 6m long.

Table 3.1. Barley cultivars selected for the screening trial.

Cultivar	Rows	Height	Hull	Use
B1602	6	Full	Yes	Malt
AC Bacon	6	Full	No	Feed
Bedford	6	Full	Yes	Feed
CDC Candle	2	Full	No	Feed
Condor	2	Full	No	Feed
CDC Dawn	2	Full	No	Feed
CDC Dolly	2	Full	Yes	Feed
CDC Earl	6	Semi-dwarf	Yes	Feed
Excel	6	Full	Yes	Malt
Falcon	6	Semi-dwarf	No	Feed
CDC Gainer	2	Full	No	Feed
Harrington	2	Full	Yes	Malt
AC Hawkeye	6	Full	No	Feed
Kasota	6	Semi-dwarf	Yes	Feed
CDC Kendall	2	Full	Yes	Malt
AC Lacombe	6	Full	Yes	Feed
Manley	2	Full	Yes	Malt
CDC McGwire	2	Full	No	Feed
AC Metcalfe	2	Full	Yes	Malt
AC Oxbow	2	Full	Yes	Malt
Peregrine	6	Semi-dwarf	No	Feed
Phoenix	2	Full	No	Feed
AC Ranger	6	Full	Yes	Feed
Robust	6	Full	Yes	Malt
Stander	6	Full	Yes	Malt
Stein	2	Full	Yes	Malt
CDC Stratus	2	Full	Yes	Malt
CDC Thompson	2	Semi-dwarf	Yes	Feed
Virden	6	Full	Yes	Feed

Twenty-nine barley cultivars (Table 3.1) were selected based on 3 criteria. Firstly, to represent four major classes based on seed rows (2- and 6-row) and seed covering (hulled and hull-less). Secondly, each cultivar selected was grown on at least 5% of the acreage in its class in one or more of the prairie provinces (Manitoba, Alberta or Saskatchewan) in 1999. Thirdly, to represent the range in competitive ability of barley cultivars. Prior to the 2001 field season, certified, registered or breeder seed was obtained from breeders and certified seed growers for all but two cultivars (CDC Buck and CDC Silky), which were unavailable

The subplots either had tame oat (*Avena sativa* L. cv. AC Assiniboia) seeded (weedy plots) or not (weed-free plots). Since early weed emergence maximizes yield loss (Cousens et al. 1987; Lotz et al. 1996; O'Donovan 1992; O'Donovan et al. 1985.), tame oat was used as a surrogate for wild oat (*Avena fatua* L.). Wild oat is a ubiquitous weed on the Canadian prairies that occurs at the second highest density of all weeds (Thomas et al. 1996, 1998a, 1998b) after green foxtail (*Setaria viridis* (L.) Beauv.), but is the more competitive weed (Wall 1993). Wild oat is particularly problematic in spring cereals where it can be costly to control and difficult to separate from barley seed. It is one of the most economically harmful annual grassy weeds in North America (O'Donovan and Sharma 1983). Dew (1978), estimated the economic cost of wild oat in western Canada due to crop losses and herbicide costs at $280 million.

3.2.2 Site Descriptions

Field experiments to determine barley cultivar competitiveness were conducted in 2001 and 2002. In 2001, two site-years of data were collected with one site-year of data from each of a Prodan clay loam soil and a Newdale clay loam soil (Table 3.2). In 2002, four site-years of data were collected with two site-years of data from each of a Ramada clay loam soil and a Newdale clay loam soil (Table 3.2). All experiments were direct-seeded into fields previously under zero-till management.

The Prodan soil series is a carbonated, calcareous to strongly calcareous, Gleyed Rego Black soil developed on imperfectly drained lacustrine sediments. The Ramada soil series is an Orthic Black soil developed on well- to moderately well-drained, strongly calcareous lacustrine sediments. The Newdale soil series is a well-drained, slightly to moderately stony, strongly calcareous Orthic Black soil developed on glacial till that occurs on rolling topography. While the Newdale series is quite typical of the Parkland Region, the Prodan and Ramada series are generally higher-yielding.

Table 3.2. Summary of the number of cultivars in each permutation of phenotype and end-use.

# Cultivars	Rows	Height	Hull	Use
6	2	Full	No	Feed
1	2	Full	Yes	Feed
7	2	Full	Yes	Malt
1	2	Semi-dwarf	Yes	Feed
2	6	Full	No	Feed
4	6	Full	Yes	Feed
4	6	Full	Yes	Malt
2	6	Semi-dwarf	No	Feed
2	6	Semi-dwarf	Yes	Feed

The Prodan and Ramada sites were located in the Assiniboine River valley on the Brandon Research Centre (BRC) in Brandon, MB. The two Ramada sites were conducted adjacently, in the same field, and were situated approximately 100m south of the trials seeded on a Prodan clay loam in 2001. The Newdale site in 2001 and the first Newdale site (Newdale 1) seeded in 2002, were located approximately 20 km NNE of

Brandon at the Phillips Farm subsidiary location of the BRC. The second Newdale site (Newdale 2), seeded later than the first site, was located 4.8 km south of the first Newdale site.

At the first Ramada site seeded (Ramada 1) in 2002, 2 replicates were accidentally cross-seeded with oats. These two replicates were replanted immediately north of replicate 1, but on barley rather than oat stubble. At the Newdale 1 site, the seeder was thought not to be dispensing seed properly. At the Newdale 1 site, it was considered possible that seed was being deposited in clumps and that emergence would reflect a clumped distribution. Consequently, after these two sites were seeded, the decision was made to seed two more sites (Ramada 2 and Newdale 2) as a precaution. Based on even emergence and appropriate crop densities, all site-years were kept.

3.2.3 Field Operations

Screening Trial

In 2001 when seed came from multiple sources, all barley and weed (tame oat) seed was treated with triticonazole (Charter, BASF Canada, Toronto, ON) at 0.25g a.i. per 100 kg of seed. After seed treatment, germination tests were performed. Barley cultivars and tame oats were sown simultaneously in seed rows to achieve a target density of 250 and 70 plants m^{-2}, respectively according to equation 1. A target density of 70 plants m^{-2} for tame oat was selected to achieve a 25% yield reduction (Guide to Crop Protection 2001). In 2002 when all barley seed came from a common source, seed treatment was not applied to either the crop or weed. Seeding for target densities was identical to 2001.

$$\text{Seeding rate (plants m}^{-2}\text{)} = \text{(1000-kernel weight/4)/(\% Germination)} \qquad (3.1)$$

In all years, nitrogen fertilizer was applied at a rate of 78.4 kg ha^{-1} actual N as 46-0-0 in a mid-row band. Phosphorus was seed-placed as 0-45-0 to prevent nitrogen toxicity at a rate of 22.4 kg actual P_20_5 ha^{-1}. Soil tests were conducted for both sites in 2001 and the Ramada 1 and Newdale 1 locations in 2002. Soil tests were not performed for the Ramada 2 and Newdale 2 locations in 2002. Where tested, fertilizer applied was sufficient to serve a yield potential of 3430 kg ha^{-1} (approximately 80 bu ac^{-1}).

Where necessary, pre-seeding herbicide application occurred not more than two days prior to seeding and consisted of glyphosate at a rate of either 450 g a.e. ha^{-1} or 900 g a.e. ha^{-1} (Table 3.3) depending on the weed spectrum. All plots received an in-crop application of a mixture of 100 g a.e. ha^{-1} clopyralid and 550 g a.e. ha^{-1} MCPA ester formulated as an emulsifiable concentrate (Curtail M, Dow AgroSciences, Indianapolis, Indiana) for broadleaf weed control. Plots not seeded with tame oat were considered "weed-free" and also received an in-crop application of 80% tralkoxydim formulated as a dispersable granule (Achieve 80 DG, Syngenta, Basel, Switzerland) at a rate of 200 g a.i. ha^{-1} to control late-emerging wild oats. All herbicides were applied with a tractor-mounted boom sprayer using 110 L ha^{-1} (10 gal ac^{-1}) at 275kPa (40 PSI) through 8001 nozzles. In-crop herbicide application occurred per label recommendation; when barley cultivars were between the 2- and 4-leaf stage.

Harvest in experimental plots was performed with a Hege 125C combine (Hege Maschinen GmbH, Waldenburg, Germany) with a 1 m table. Six crop rows were harvested per plot with the two outside rows on either edge of the plot left standing. Prior to assessing yield, harvested seed was put through a de-awner, and then sieved to remove trash and unwanted seed. Yield in weed-free plots was determined by weighing the sample from each plot after cleaning. In weedy plots, the percentage of weed seed yield by weight (i.e. the dockage) was determined by manually separating oat from barley seed and weighing the oat seed from a sample weighing approximately 25g. Yield was then calculated by subtracting dockage from the gross yield.

Table 3.3. Field operations for the screening trial at each site-year.

Cultivar	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Pre-seed glyphosate application	900 g a.e.	900 g a.e.	450 g a.e.	450 g a.e.	450 g a.e	n/a
Previous Crop	Oat	Oat	Oat[1]	Barley	Oat	Lentil
Seeding Date	May 11	May 17	April 30	May 13	May 7	May 14
In-crop herbicide application	June 2	June 7	May 31	June 4	June 3	June 4
Harvest Date[2]	August 9	August 20	August 20	August 23	August 27	August 30

1. Replicates 5 and 6 were re-seeded on barley stubble.
2. Date harvest commenced

Seed Increase

Crop seed vigour is affected by the growing conditions under which the mother plant matures (Anderson and Milberg 1998a) and differences in harvest practices (Bourgeois et al. 1996). Consequently, a seed increase was undertaken in 2001 at the Newdale site to provide common seed for future trials. Plot size for the seed increase was either 0.05 ha or 0.08 ha, depending on projected cultivar seed requirements. All seed was treated with triticonazole at 0.25g a.i. per 100 kg of seed prior to seeding. Cultivars were direct-seeded on May 24th with a ConservaPak hoe-drill (ConservaPak, Indian Head, Canada) on a 23.0 cm row spacing. Pre-seeding herbicide treatment consisted of an application of glyphosate at 900 g a.e.ha^{-1}. In-crop herbicide application occurred at the 3-leaf stage. Herbicides applied were a tank-mix of 100 g a.e. ha^{-1} clopyralid and 550 g a.e. ha^{-1} MCPA ester formulated as an emulsifiable concentrate (Curtail M) and 80% tralkoxydim formulated as a dispersable granule (Achieve 80DG) at a rate of 200 g a.i. ha^{-1} at the 3-leaf stage. Plots were fertilized at seeding with 78.4 kg ha^{-1} actual N, mid-row banded as 46-0-0 and 22.4 kg ha^{-1} actual $P_2 0_5$ seed-placed as 0-45-0. In addition to herbicide application, plots were hand-weeded within 2 days of harvest and also as required at earlier dates.

Foliar fungicide application consisted of two applications of propiconazole (Tilt 250E, Syngenta, Basel, Switzerland) at 120 g a.i. ha^{-1}. Application times were as close as possible to label recommendation: 1) at stem elongation, and, 2) before the barley heads were half emerged as was possible given the genotypic and phenotypic variability of the cultivars. Tilt 250E was applied using a tractor-mounted boom sprayer at 275kPa (40 PSI) through 8001 nozzles. The seed increase was harvested with a Hege 140 combine and the outside rows in each plot were harvested and bagged separately as they were less mature than the inside rows. Harvest occurred from August 28 to September 4th, 2001.

3.2.4 Data Analysis

Cultivar ability to withstand competition (i.e. the ability of a cultivar to maintain yield) was calculated from the following equation:

$$\mathrm{AWC} = 100 * \mathrm{Yield}_{\mathrm{WP}} / \mathrm{Yield}_{\mathrm{WFP}} \qquad (3.2)$$

but can also be calculated as:

$$\mathrm{AWC} = 100 - \%\ \mathrm{Yield\ Loss} \qquad (3.3)$$

where Yield_{WP} is the yield from the weedy plot and Yield_{WFP} is the yield from the weed-free plot. Cultivar ability to compete was calculated from the following equation:

$$AC = 100\text{-}\%\ \text{dockage} \qquad (3.4)$$

Transformation of data to improve normality was required only if the data was not normal and a transformation improved normality. All data were tested for normality using PROC UNIVARIATE (SAS 1990). SAS produces four statistics assessing normality but the Cramer-von Mises statistic (W^2) was selected (Steel et al. 1997 pp. 45-48). While this analysis indicated the data were not statistically normal, Velleman (1997), has suggested that if a normal probability plot is linear or nearly linear, then the distribution of the variable is nearly normal. Inspection of the normal probability plots for AWC and AC indicated that they were approximately normal. A suitable transformation for proportional data is the arcsin square root transformation (Finney 1989). Data were approximately normal and many of the values for AWC and AC were between 30 and 70 where the arcsin square root transformation is approximately linear (Steel et al. 1997, p. 246). On these bases, data were not transformed.

Data were tested for homogeneity of variance using Levene's test (SAS 1990). Data from 2001 and 2002 were considered separately, *a priori*, since there were biological differences due in field trials. In 2001 seed for field trials came from multiple sources whereas in 2002, seed was from a common source. In 2001, AWC and AC were homogeneous between sites, but significant ($P \leq 0.05$) location by cultivar interactions occurred. In 2002, AWC and AC were not homogeneous between sites. Consequently, a separate ANOVA using PROC GLM (SAS 1990) was conducted for each site-year and mean AWC or AC for cultivars were separated using a Fisher's protected LSD at $\alpha=0.05$.

Since barley is commonly classified and discussed by breeders and producers in terms of phenotypic attributes (2- vs. 6-row, hulled vs. hull-less, full height vs. semi-dwarf) and end-use (malt vs. feed), linear contrasts were performed on these phenotypic and end-use classes to determine if these classes varied in competitive ability.

The relationships of AWC and AC with themselves and each other were examined using correlation coefficients. When examining the relationship between AWC and AC within a site-year, partial correlation coefficients removing replicate effects were calculated using PROC GLM (SAS 1990). When examining the relationships of AWC and AC with themselves across site-years, simple correlation coefficients were calculated using PROC CORR (SAS 1990).

Statistical significance for simple correlation, partial correlation, and regression is a function of the number of observations (Steel et al. 1997) and if sufficient observations are present, then statistical significance is easily achieved (Table 3.4). Achen (1982) states that a coefficient large enough to be of some practical scientific value or useful in practical application be termed "*substantive*, to distinguish it from the less important statistical significance".

While defining "substantive" is subjective, one breeder suggested a minimum correlation coefficient of 0.75 is useful (Mario Therrien pers. comm.). Fox et al. (1997), suggest that for most quantitative attributes, within a 90% confidence interval, an R^2 of 0.7 is the minimum coefficient of determination (corresponding to a correlation coefficient $\geq |0.8367|$) useful for trait selection in a breeding program. A correlation coefficient of 0.75 yields an R^2 of 0.5625, which is considerable lower than the 0.7 suggested (Fox et al. 1997). While breeding is not a primary objective in this research, it does provide a benchmark for utility. Consequently a correlation coefficient of 0.8 will be considered substantive in this research.

Table 3.4. Number of cultivars (n), degrees of freedom (df) and the minimum correlation coefficient significant ($p \leq 0.05$) at the specified degrees of freedom (critical r).

Class		All cultivars			Semi-dwarf cultivars excluded			Semi-dwarf and hull-less cultivars excluded		
	*	n	df	Critical r	n	df	Critical r	n	df	Critical r
ALL		29	114	0.1824	24	94	0.2006	16	62	0.2460
ROWS	2	15	58	0.2542	14	54	0.2632	8	30	0.3493
	6	14	54	0.2632	10	38	0.3120	8	30	0.3493
HEIGHT	F	24	94	0.2006	-	-	-	-	-	-
	SD	5	18	0.4682	-	-	-	-	-	-
HULL	N	10	38	0.3120	16	62	0.2460	-	-	-
	Y	19	74	0.2256	8	30	0.3493	-	-	-
USE	F	18	70	0.2318	13	50	0.2732	5	18	0.4437
	M	11	42	0.2973	11	42	0.2973	11	42	0.2973

* Codes for classes are: ROWS; 2 = 2-row, 6 = 6-row: HEIGHT; F = full, SD = semi-dwarf: HULL; N = No, Y = yes: USE; F = feed, M = Malt.

3.3 RESULTS

3.3.1 The Competitive Ability of 29 Barley Cultivars

Ability to withstand competition (AWC) and ability to compete (AC) both have a theoretical minimum and maximum of zero and 100, respectively. The minimum for AWC occurs when competition in weedy plots causes total yield loss. Conversely, the maximum is achieved when weedy plot yield is unaffected by weed competition. The minimum for AC occurs when 100% of the weedy plot yield is weed seed, whereas the maximum occurs when there is no weed seed return in the weedy plot. Values for AWC and AC ranged from minimums of 21 and 17, respectively, to maximums of 94 and 90, respectively (Table 3.5). Significant ($p \leq 0.0001$) differences were found in cultivar competitive ability in all site-years for both AWC (Table 3.6) and AC (Table 3.7).

Cultivars with high overall competitive ability (highly competitive) will have high scores for both AWC and AC. Since the target yield loss for the tame oat seeding rate was 25% (Guide to Crop Protection 2001), cultivars having less than 25% yield loss and less than 25% of yield in weedy plots as weed seed (dockage) may be considered to be highly competitive (Figure 3.1, Table 3.5). In addition to the cultivars Virden, Lacombe, Ranger, Robust, B1602 and Excel meeting these criteria, Metcalfe and Dolly were both ranked in the top 10 for both AWC and AC (Table 3.8) and could, therefore, also be considered highly competitive (Appendix A).

Cultivars with low overall competitive ability (poorly competitive) will have low scores for both AWC and AC. A clearly identifiable group of poorly competitive cultivars (Figure 3.1) included Peregrine, Falcon, Thompson, Dawn and Kasota. Although Gainer was ranked in the bottom 10 for both AWC and AC, Condor was 11th and 7th for AWC and AC, respectively. There is minimal difference in competitive ability between Gainer and Condor. Furthermore, Gainer and Condor are not substantively different from cultivars of intermediate competitive ability (Figure 3.1). Consequently, Gainer and Condor were not classed as poorly competitive. The remainder of cultivars not classed as poorly or highly competitive may be considered as being intermediately competitive.

When all cultivars were considered, contrasts indicated that phenotypic and end-use classes of cultivars generally differed for both AWC (Table 3.6) and AC (Table 3.7). The exception was for the 2- versus 6-row comparison for AWC. When row phenology is considered alone (Figure 3.2A), 6-row cultivars were both the most and least competitive cultivars, whereas 2-row cultivars tended to be intermediately competitive. The 5 semi-dwarf cultivars were observed to be poorly competitive relative to full height cultivars (Figure 3.2B). Hull-less cultivars were observed to be less competitive than hulled cultivars (Figures 3.1, 3.2C). As with row phenology, feed cultivars were observed to be both the most and least competitive cultivars (Figures 3.1, 3.2D).

Table 3.5. Values for ability to withstand competition (AWC) and ability to compete (AC) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Data are means with LSD given.

Cultivar	2001				2002								Mean	
	Prodan		Newdale		Ramada 1		Ramada 2		Newdale 1		Newdale 2			
	AWC	AC	AWC	AC	AWC	AC	AWC	AC	AWC	AC	AWC	AC	AWC	AC
	%													
B1602	88	83	76	72	78	82	71	70	73	71	77	77	77	76
Bacon	82	78	71	59	83	81	70	60	72	61	74	70	75	68
Bedford	83	78	65	61	78	79	76	69	68	64	78	72	75	71
Candle	80	71	65	52	88	79	82	64	79	65	79	70	79	67
Condor	66	64	53	46	83	78	74	58	73	63	83	68	72	63
Dawn	57	52	45	34	78	72	64	45	73	57	76	65	66	54
Dolly	84	80	72	69	79	83	78	69	74	65	74	72	77	73
Earl	73	73	58	55	80	79	61	58	68	64	61	64	67	66
Excel	79	77	59	63	89	88	78	78	81	75	76	74	77	76
Falcon	41	30	29	17	78	70	51	41	64	53	65	56	55	45
Gainer	66	67	68	57	78	74	63	52	64	55	84	75	71	63
Harrington	86	79	76	61	81	77	72	54	72	63	75	69	77	67
Hawkeye	73	69	66	58	81	79	71	68	69	62	77	73	73	68
Kasota	78	73	72	58	76	60	45	30	72	54	68	63	69	56
Kendall	69	71	66	58	80	76	65	59	70	63	75	69	71	66
Lacombe	87	88	72	72	84	82	78	73	81	73	88	80	82	78
Manley	76	72	73	61	90	81	78	59	77	64	82	68	79	68
McGwire	68	67	65	55	78	73	65	60	74	65	78	73	71	66
Metcalfe	81	78	65	55	86	85	76	73	83	74	84	79	79	74
Oxbow	81	75	61	56	86	83	75	68	76	67	73	70	75	70
Peregrine	50	44	21	18	56	48	40	30	54	43	50	48	45	39
Phoenix	84	75	64	53	87	81	77	69	72	66	80	76	77	70
Ranger	77	79	61	65	91	90	77	73	80	77	85	82	79	78
Robust	79	81	65	70	86	83	75	75	88	74	77	78	78	77
Stander	76	76	53	60	85	82	61	61	68	63	74	70	70	69
Stein	75	74	63	59	77	74	73	51	82	63	80	67	75	65
Stratus	78	80	67	66	77	83	81	73	71	61	72	67	74	72
Thompson	69	66	39	37	81	67	63	48	57	48	63	56	62	54
Virden	94	89	80	82	91	88	93	83	88	82	90	84	89	85
Mean	75	72	62	56	82	78	70	61	73	64	76	70	73	67
LSD (0.05)	9	4	13	8	10	7	11	7	13	9	11	8		

Table 3.6. Analysis of variance and contrasts (p-values) for values of ability to withstand competition (AWC) using all barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts						
Rows: 2 vs. 6	ns	ns	ns	0.0015	ns	0.0443
Height: Full vs. semi-dwarf	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Hull: Yes vs. No	<0.0001	<0.0001	0.0068	<0.0001	0.0013	ns
Use: Feed vs. Malt	<0.0001	<0.0001	0.0580	0.0012	0.0027	ns

Table 3.7. Analysis of variance and contrasts (p-values) for values of ability to compete (AC) using all barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) t-tests are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts						
Rows: 2 vs. 6	0.0134	0.0041	ns	0.0569	0.0142	ns
Height: Full vs. semi-dwarf	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Hull: Yes vs. No	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004
Use: Feed vs. Malt	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0439

Poorly competitive 6-row cultivars were semi-dwarf, hull-less, or both (Figure 3.2). In the absence of semi-dwarf, and subsequently, hull-less cultivars, the competitive ability of 6-row cultivars may have increased, relative to 2-row cultivars. In the absence of hull-less cultivars, feed cultivar competitive ability may have increased relative to malt cultivars. Semi-dwarf and hull-less cultivars are generally less competitive, and are genetically and morphologically different from full height and hulled cultivars. Therefore analysis of phenotypic and end-use classes was undertaken by sequentially removing semi-dwarf, then hull-less cultivars.

Table 3.8. Rank, and variance of rank (Var), for ability to withstand competition (AWC) and ability to compete (AC) for barley cultivars grown over two years on Prodan, Newdale, and Ramada soil series. Data are ordered by overall rank of AC, then by rank of AWC.

Cultivar	AWC								AC							
	2001		2002						2001		2002					
	P*	N	R1	R2	N1	N2	Rank	Var	P	N	R1	R2	N1	N2	Rank	Var
Virden	1	1	1	1	1	1	1	0.0	1	1	2	1	1	1	1	0.2
Lacombe	3	5	11	4	5	2	2	10.0	2	2	9	4	6	3	2	7.5
Ranger	16	20	1	8	7	3	3	55.0	7	7	1	4	2	2	2	7.0
Robust	12	13	7	12	1	13	7	23.1	4	4	5	3	4	5	4	0.6
B1602	2	2	20	17	13	13	8	57.4	3	2	9	8	7	6	5	7.8
Excel	12	22	4	4	5	16	8	55.9	12	8	2	2	3	9	5	18.0
Metcalfe	9	13	7	10	3	4	3	14.3	9	20	4	4	4	4	7	41.5
Dolly	5	5	19	4	11	20	8	53.1	5	5	5	9	10	12	8	9.5
Stratus	14	10	26	3	20	24	17	77.8	5	6	5	4	22	22	9	77.5
Bedford	7	13	20	10	23	11	13	38.4	9	9	15	9	13	12	10	6.6
Phoenix	5	18	6	8	16	8	8	29.8	14	23	12	9	9	7	11	33.5
Oxbow	9	20	7	12	10	23	13	41.9	14	19	5	12	8	14	11	24.4
Stander	17	24	10	25	23	20	23	31.8	13	12	9	15	16	14	13	6.2
Manley	17	4	3	4	9	7	3	27.5	19	9	12	18	13	20	14	19.8
Bacon	8	8	12	19	16	20	13	28.2	9	13	12	16	22	14	14	19.5
Hawkeye	20	11	14	17	22	13	18	18.2	22	15	15	12	21	10	14	23.0
Candle	11	13	5	2	8	10	3	16.6	20	24	15	14	10	14	17	25.0
Harrington	4	2	14	16	16	18	8	47.1	7	9	20	22	16	18	17	36.7
Kendall	22	11	17	20	21	18	20	15.8	20	15	21	18	16	18	19	5.2
McGwire	24	13	20	20	11	11	20	30.7	23	20	24	16	10	10	19	38.6
Earl	20	23	17	25	23	28	25	14.7	17	20	15	20	13	25	19	18.3
Stein	19	19	26	15	4	8	13	64.6	16	13	22	24	16	22	22	19.4
Condor	25	24	12	14	13	6	19	54.7	26	25	19	20	16	20	23	14.4
Gainer	25	9	20	23	26	4	20	83.8	23	18	22	23	25	8	23	39.0
Kasota	14	5	28	28	16	25	24	85.5	17	15	28	28	26	26	25	33.5
Dawn	27	26	20	22	13	16	26	30.3	27	27	25	26	24	24	26	1.9
Thompson	22	27	14	23	28	27	27	27.5	25	26	27	25	28	27	26	1.5
Falcon	29	28	20	27	26	26	28	10.0	29	29	26	27	27	27	28	1.5
Peregrine	28	29	29	29	29	29	29	0.2	28	28	29	28	29	29	29	0.3

*symbols for sites are given as : P=Prodan, N=Newdale, R=Ramada.

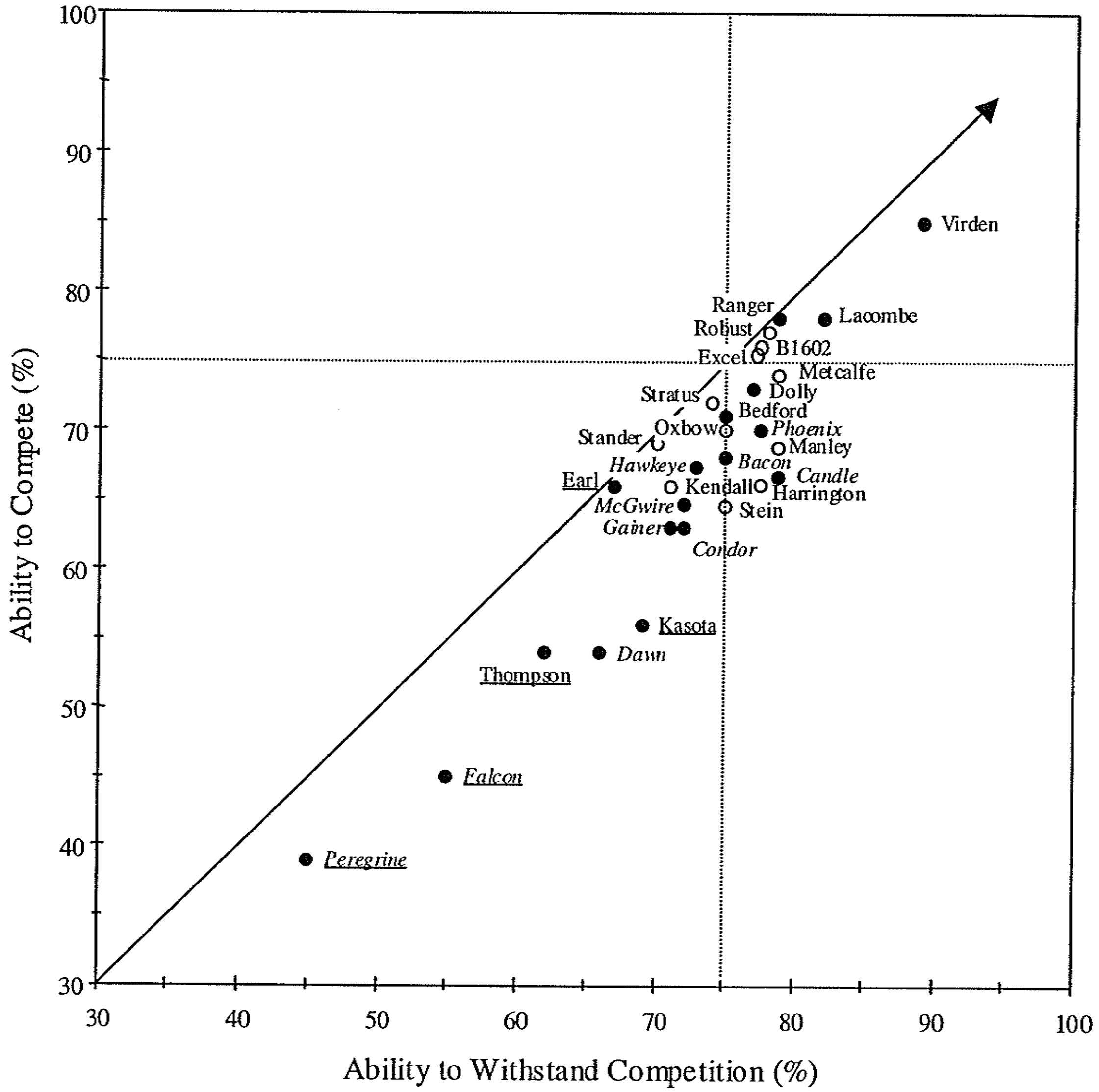

Figure 3.1. Scatterplot of ability to compete versus ability to withstand competition. Data are averaged across all site-years. The arrow points in the direction of increasing competitive ability. Dashed lines represent: 1) on the abscissa (AWC), the target of 25% yield loss, based on the tame oat seeding rate, and, 2) on the ordinate, 25% weed seed by weight in the weedy sample (i.e. dockage). Malt cultivars are denoted by open circles, semi-dwarf cultivars are underlined, and hull-less cultivars are in *italics*.

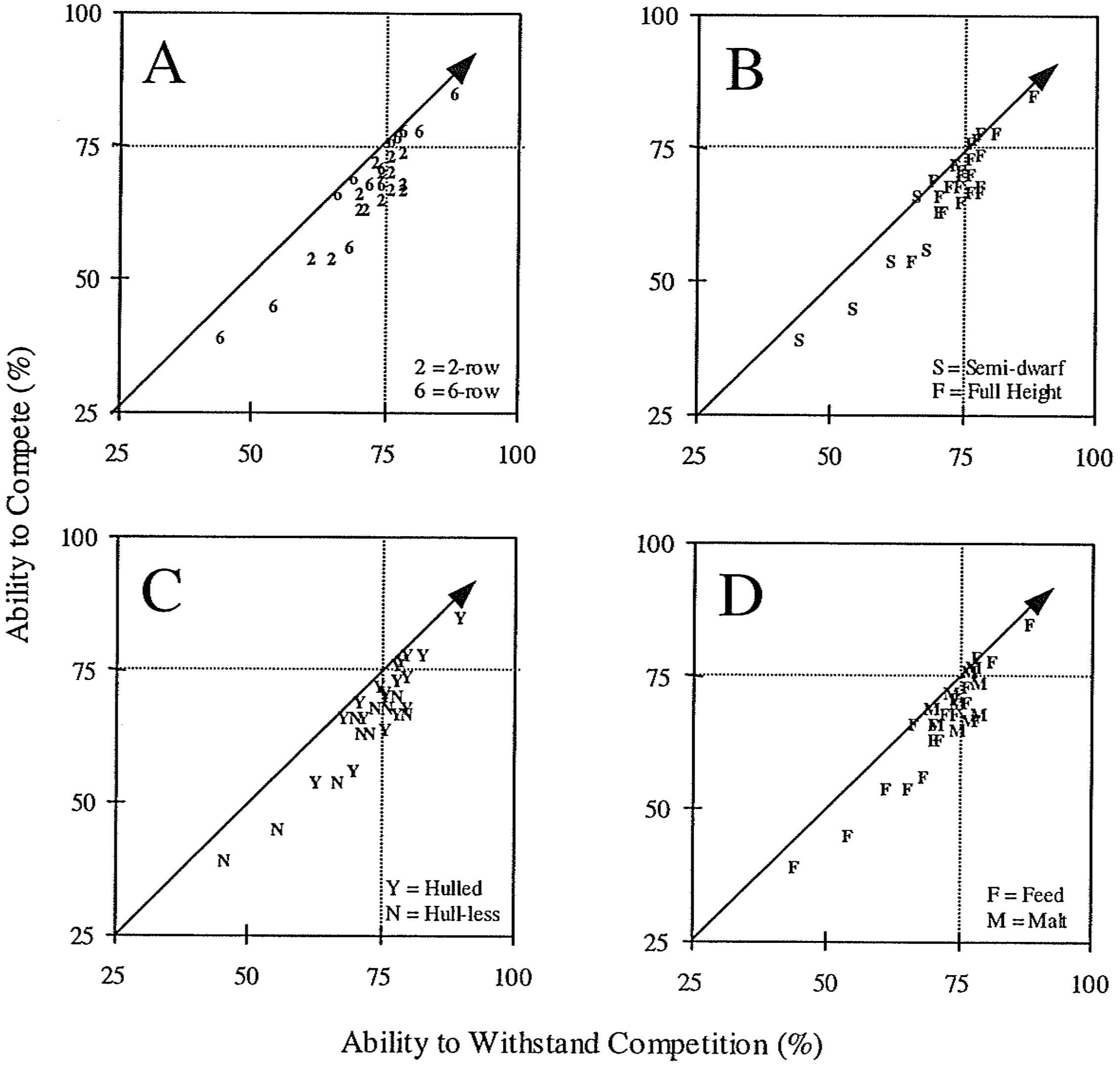

Figure 3.2. Scatterplot of ability to compete versus ability to withstand competition indicating labeled by the cultivar classes: A) 2-vs. 6-row, B) semi-dwarf vs. full height, C) hulled vs. hull-less, and, D) feed vs. malt cultivars. Data are averaged across all site-years. The arrow points in the direction of increasing competitive ability. Dashed lines represent: 1) on the abscissa (AWC), the target of 25% yield loss, based on the tame oat seeding rate, and, 2) on the ordinate, 25% weed seed by weight in the weedy sample (i.e. dockage).

3.3.2 Differences in Competitive Ability of Barley Cultivars Related to Phenotypic and End-Use Classes

Values for AWC (Table 3.9) and AC (Table 3.10) differed for some cultivars after removal of semi-dwarf cultivars prior to ANOVA and contrasts. For AWC, differences were generally present for the hulled versus hull-less comparison, but not for the 2- versus 6-row and feed versus malt comparisons (Table 3.9). For AC, differences were found for all 2- versus 6-row comparisons and hulled versus hull-less comparisons, but for only half of the feed versus malt comparisons (Table 3.10).

Values for AWC (Table 3.11) and AC (Table 3.12) differed for some cultivars despite removal of semi-dwarf cultivars prior to ANOVA and contrasts. For AWC, differences were commonly found for the 2-versus 6-row comparison, but infrequently for feed versus malt comparison (Table 3.11). For AC, differences occurred in 4 of 6 site-years for the 2-versus 6-row comparison and 5 of 6 years for the feed versus malt comparison (Table 3.12).

Differences in AWC that did not appear to be present (Table 3.6) for 2- versus 6-row cultivars, appeared when class confounding was reduced (Table 3.11). By contrast, apparent differences between feed versus malt classes (Table 3.6) were less common when confounding was reduced (Table 3.11). Few changes for significant differences in AC were observed among cultivars, whether or not semi-dwarf and hull-less classes were removed.

Individual cultivars did not necessarily reflect the classes they occurred in. For example, Earl was the most competitive semi-dwarf (Figure 3.1), and in some site-years was intermediately competitive (Tables 3.5 and 3.8). Phoenix was the most competitive hull-less cultivar (Figure 3.1) and only just missed being ranked as highly competitive since its overall rank was 8th in AWC and 11th in AC (Table 3.8).

Table 3.9. Analysis of variance and contrasts (p-values) for values of ability to withstand competition (AWC) with semi-dwarf cultivars removed, grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	<0.0001	0.0009	0.0094	<0.0001	0.0208	0.0186
Cultivar	<0.0001	0.0004	0.0109	<0.0001	0.0167	0.0806
Contrasts						
Rows: 2 vs. 6	<0.0001	ns	0.0426	ns	ns	ns
Hull: Yes vs. No	<0.0001	0.0131	ns	0.0063	0.0121	ns
Use: Feed vs. Malt	ns	ns	ns	ns	ns	0.0225

Table 3.10. Analysis of variance and contrasts for values (p-values) of ability to compete (AC) with semi-dwarf cultivars removed, grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts						
Rows: 2 vs. 6	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Hull: Yes vs. No	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0639
Use: Feed vs. Malt	<0.0001	0.0046	ns	ns	ns	0.0424

3.3.3. The Relationship Between AWC and AC

Within site-years, examination of cultivar scores indicates cultivar performance. Hence, averaging cultivars over plots and presenting average cultivar performance across replicates is useful. However, the relationship between AWC and AC is best examined using partial correlation and regression analysis on the plot data without averaging plots by cultivars. This approach best illustrates the relationship between AWC and AC because: 1) replication can be accounted for, and, 2) the relationship between AWC and AC is not filtered by cultivar performance.

Table 3.11. Analysis of variance and contrasts (p-values) for values of ability to withstand competition (AWC) with semi-dwarf and hull-less cultivars removed, grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	0.0005	0.0004	0.0017	<0.0001	0.0023	<0.0001
Cultivar	0.0002	0.0003	0.0051	<0.0001	0.0015	<0.0001
Contrasts						
Rows: 2 vs. 6	0.0006	0.0350	0.0881	0.0429	ns	ns
Use: Feed vs. Malt	0.0154	ns	0.0043	ns	ns	ns

Table 3.12. Analysis of variance and contrasts for (p-values) values of ability to compete (AC) with semi-dwarf and hull-less cultivars removed, grown over two years on Prodan, Newdale and Ramada soil series. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts						
Rows: 2 vs. 6	<0.0001	<0.0001	0.0333	<0.0001	ns	ns
Use: Feed vs. Malt	<0.0001	<0.0001	<0.0001	<0.0001	0.0045	ns

Partial correlation coefficients ranged from a minimum of 0.4050, at the Newdale 2001 site-year, to a maximum of 0.9640 at the Prodan 2001 site-year (Appendix A). In general, a statistically significant ($p \leq 0.05$) relationship existed between AWC and AC, irrespective of exclusion of cultivars belonging to less-competitive classes (Appendix A). When data were averaged over site-years, the relationship between AWC and AC was stronger for semi-dwarf than full height, hull-less than hulled, 6-row than 2-row, and feed than malt (Table 3.13). In general, the strength of the relationship between AWC and AC either declined or remained constant with successive removal of less-competitive classes (Table 3.13).

The slope of the regression line indicates the number of units of AC required to achieve a unit increase in AWC. A regression analysis, treating AWC as the independent variable and AC as the dependent variable, was undertaken. Most slope coefficients were statistically significant (Appendix A). Exclusion of semi-dwarf cultivars slightly decreased the slope for both hulled and hull-less cultivars (Table 3.13). Exclusion of both semi-dwarf and hull-less cultivars decreased the slope for 2-row cultivars but increased the slope for both 6-row and feed cultivars as a class. Since malting varieties are not found in either semi-dwarf or hull-less classes, malt relationships are always unchanged.

Table 3.13. Average partial correlation (*r*) and regression slope (*m*) coefficients for AC on AWC for all cultivars across site-years. Replicate was partialled out and successive removal of semi-dwarf and hull-less classes was undertaken due to lower competitive ability. See table 3.4.

Cultivar class	All cultivars		Semi-dwarf cultivars excluded		Semi-dwarf and hull-less cultivars excluded	
	r	*m*	*r*	*m*	*r*	*m*
All cultivars	0.8236	0.8492	0.7017	0.7949	0.6457	0.7997
2-row	0.7450	0.8860	0.7120	0.8563	0.5991	0.8138
6-row	0.8838	0.8493	0.7305	0.9402	0.7603	1.0874
Full height	0.7017	0.7949	-	-	-	-
Semi-dwarf	0.8689	0.9141	-	-	-	-
Hull-less	0.8957	0.9710	0.7551	0.9512	-	-
Hulled	0.7249	0.8102	0.6457	0.7996	-	-
Feed	0.8712	0.8822	0.7760	0.8405	0.7624	1.0339
Malt	0.5564	0.7173	0.5564	0.7173	0.5564	0.7173

3.3.4. The Effect of Genotype and Environment on Cultivar Competitive Ability

Six site-years of data contains insufficient environments for a proper analysis of genotype-by-environment (GxE) interactions. However, some understanding of the effects of genotype and environment on cultivar competitive ability may be achieved by: 1) examining the correlation coefficients of AWC and AC with themselves (AWC:AWC and AC:AC) over time, and 2) stability of ranking of cultivar competitive ability across site-years. The former differs from the latter in that the former indicates the relationships of AWC and AC with themselves over time, while the latter is filtered by the cultivar response since rankings are based on mean cultivar response.

Although all site-years had 4 replicates, blocking within years differs from blocking across years. Therefore, pair-wise simple correlation coefficients of AWC and AC with themselves between different site-years were used. Since statistical significance for correlation is a function of the number of observations (Steel et al. 1997), the correlation coefficient needs to be substantive (i.e. biologically meaningful), or statistical significance does not contribute to our understanding (Achen 1982).

The average correlation coefficient (Table 3.14) was derived by averaging pair-wise combinations for each of AWC and AC (Appendix A) for 6 site-years. At the minimum level of confounding, when either or both of semi-dwarf and hull-less cultivars were absent, no mean correlation coefficient exceeded 0.5. As classes of barley cultivars were excluded from the analysis, correlation coefficients generally declined or remained approximately constant (Table 3.14). Ability to compete (AC) had higher coefficients than AWC and more pair-wise correlation coefficients were statistically and substantively significant (Table 3.14, Appendix A).

Comparisons of the statistical significance of correlation coefficients between classes are confounded by the number of observations in each class (Table 3.4), but some general trends have emerged. The correlation coefficients are higher for 6-row vs. 2-row, hulled vs. hull-less and feed vs. malt classes (Table 3.14). The correlation of AWC with itself over time was higher for semi-dwarf cultivars than full height ones.

Genotype and environmental effects on cultivar competitive ability over time can also be addressed by observing the consistency of rankings for AWC and AC. If the rank of the cultivars remains unchanged from site-year to site-year, then genotype has greater effect than environment. Using rankings has the advantage of rendering all site-years homogeneous by placing all data on the same scale, but has the disadvantage that small changes (≈ 5%) in AWC or AC can result in large changes in ranking (cf Tables 3.5 and 3.8) in a particular site-year. For example, Ranger at the Newdale 2001 site-year was ranked 20th for AWC (Table 3.8) and the score associated with that ranking was 61 (Table 3.5). A change from 61 to 66 would have tied Ranger with Hawkeye, which was ranked 11th. Consequently, a minimum difference of approximately 8 places would be required in order for a difference in rank to be considered substantive.

The rank of AC was generally less variable than AWC (Figure 3.1, Table 3.8, Appendix A). In the group of highly competitive cultivars, Excel, Metcalfe and Dolly each had one ranking not in the top 10 (Table 3.8) for AC. Except for Virden and Lacombe, each cultivar had more than one ranking not in the top 10 for AWC. When considering poorly competitive cultivars, only Kasota escaped a bottom 10 ranking in both AWC and AC. While highly and poorly competitive cultivars tended to have fewer substantive differences in ranking, intermediately competitive cultivars tended to have many substantive differences in competitive ranking. Manley, Candle, Harrington and Stein all had substantively better ranking for AWC than AC. By contrast, Stratus and Stander had substantively better ranking for AC than AWC.

Table 3.14. Average of simple correlation coefficients of AWC with AWC and AC with AC using 6 site-years of data. The number of significant occurrences is given (in parentheses) out of 15 possible pair-wise correlation coefficients. See also Appendix A.

Cultivar class	All cultivars		Semi-dwarf cultivars excluded		Semi-dwarf and hull-less cultivars excluded	
	AWC	AC	AWC	AC	AWC	AC
All cultivars	0.4326 (15)	0.6329 (15)	0.2016 (7)	0.4603 (15)	0.2002 (6)	0.4301 (13)
2-row	0.2103 (5)	0.3679 (12)	0.1388 (3)	0.2734 (6)	0.0900 (0)	0.1517 (2)
6-row	0.5626 (15)	0.7424 (15)	0.2450 (5)	0.4568 (13)	0.2696 (6)	0.4247 (11)
Full height	0.2016 (7)	0.4603 (15)	n/a	n/a	n/a	n/a
Semi-dwarf	0.3735 (4)	0.4650 (7)	n/a	n/a	n/a	n/a
Hull-less	0.5111 (14)	0.6303 (15)	0.1180 (2)	0.2629 (8)	n/a	n/a
Hulled	0.2994 (11)	0.5706 (15)	0.2002 (6)	0.4301 (13)	n/a	n/a
Feed	0.5010 (15)	0.6790 (15)	0.2695 (6)	0.5581 (15)	0.2852 (2)	0.4962 (10)
Malt	0.0875 (2)	0.2803 (6)	0.0875 (2)	0.2803 (6)	0.0875 (2)	0.2803 (6)

Some cultivars differed in competitive ranking between years. Cultivars such as Kasota, Ranger, Excel and Metcalfe had consistently higher competitive rankings for AWC and AC in 2001 compared to 2002 (Table 3.8). Other cultivars, such as B1602 and Harrington, and to a lesser extent, Bacon and Condor, had consistently higher competitive rankings for AWC and AC in 2002 compared to 2001 (Table 3.8). Overall, cultivars frequently varied substantively in AWC, AC, or both. The difference between the minimum and maximum rank for AWC was substantive (>8) for all but 2 cultivars (Peregrine and Virden), and for AC for 16 of 29 cultivars (Table 3.8).

Within a growing season, variability of ranking for cultivar competitive ability also occurred between sites and between soil series. The cultivar Stratus provides examples of both situations in 2002. Stratus ranked 26th and 3rd for AWC on sites within the Ramada soil series. Stratus also ranked 5th and 4th on the Ramada series sites for AC, as compared to 22nd on both Newdale soil series sites (Table 3.8). Ranking variability occurs in either or both of AWC and AC for other cultivars (Table 3.8).

3.4 DISCUSSION

3.4.1 The Competitive Ability of 29 Barley Cultivars

Three studies have had sufficient genotypic variability to be considered an effort to screen large numbers of cultivars and all have used wheat (Cousens and Mokhtari 1998; Lemerle et al. 1996, 2001b). All studies reported wheat yield loss, but conversion to AWC is easily accomplished by subtracting percent yield loss from 100 (Equation 3.3). Substantial wheat yield losses of 0-60% (Lemerle et al. 1996) and 19-67% (Cousens and Mokhtari 1998) were reported, Lemerle et al. (2001b) did not report yield loss, but instead use "competitive advantage", which incorporated environmental effects due to climate and location. For weed suppression, Lemerle et al. (1996) have shown a factor of 2.5x for actual weed biomass from least to most competitive.

In the present study, the lowest barley AWC was 21 for Peregrine and the maximum barley AWC was 94 for Virden. The lowest AC was 17 for Falcon and the maximum was 90 for Virden. Consequently, a factor of approximately 5.3x separated the most from least suppressive cultivars. This result suggests that 1) barley may have greater genotypic variability with respect to competitive ability than wheat, and, 2) selection of cultivars for comparison of crop competitive ability can influence the outcome if insufficient genotypic variability is utilized.

Barley cultivar competitive ability has been reported by several authors (Bell and Nalewaja 1968; Christensen 1995; Didon 2000; Konesky et al. 1989; O'Donovan et al. 2000; Satorre and Snaydon; Siddiqi et al. 1985), generally as yield or biomass loss, but sometimes also as weed biomass (Konesky et al. 1989; Siddiqi et al. 1985) or seeds m^{-2} (O'Donovan et al. 2000). When converting yield loss or biomass loss to AWC (Equation 3), these studies generally have had moderate to high AWC. The exceptions occurred in fertility studies where low P (Konesky et al. 1989) and high K rates caused some cultivars to have AWC scores below 50. In general, a factor of approximately 2.5x is reported for dry matter (Christensen 1995; O'Donovan et al. 2000) from most to least competitive in terms of weed suppression ability. However, this can be variable when nutrients are plentiful or withheld (Konesky et al. 1989; Siddiqi et al. 1985). Excluding the least competitive cultivars, values for AWC and AC reported in this study appear to be similar to those of other researchers. However, direct comparisons are difficult, especially for AC since the effect on weed biomass has seldom been reported as a percentage.

This research indicates large differences in cultivar competitive ability exist and that highly- and poorly-competitive cultivars have stable competitive (AWC and AC) rankings. However, other considerations often supercede competitive ability when producers are selecting cultivars. For example, cultivar selection to meet malting standards or for local fertility and moisture regimes are often higher priority than selection for competitive ability. Consequently, producer usage of competitive cultivars as an IWM tool remains under-exploited.

To increase producer usage of cultivar competitive ability requires a suitable ranking system for cultivar competitive ability and publishing these ranking in seed guides distributed on the Canadian prairies. Producers currently rely on information derived informally, from extension personnel and other area producers. While attributes such as yield and resistance to important diseases is reported from variety trials, a similar competitive ranking is not available. Consequently, providing producers with competitive rankings requires barley breeders to rate barley cultivar competitive ability in a consistent manner akin to the ratings that are currently done for important diseases.

For Canadian barley breeders, increasing cultivar competitive ability is a low priority, well behind other issues such as feed quality and disease resistance (Barley Development Council 2000). By contrast, in Australia there has been considerable research intended to determine attributes conferring competitive ability to cultivars (Cousens and Mokhtari 1998; Lemerle et al. 1996, 2001a, 2001b). Most studies tend to measure yield loss (Lemerle et al. 2001b) and breeding efforts in Australia are directed towards obtaining attributes preventing yield loss. Our research indicates that environment influences crop yield loss more than weed seed yield. On the Canadian prairies, a breeding program targeted at reducing yield loss (i.e. AWC) may be suboptimal since measurement of seed yield was more consistent (i.e. AC).

Should cultivar competitive ability be adopted as a breeding objective, percent dockage (i.e. AC) may not be utilized as the basis for selection despite its lower variability compared to yield loss. Time and labour requirements are higher to collect weed seed as opposed to crop seed, since it is a simple matter to use a small-seeded weed (e.g. canola) and remove seed at harvest than to separate seed after harvest. Consequently, AC may not be adopted as the measure of cultivar competitive ability despite its superiority for this purpose.

3.4.2. Differences in Competitive Ability of Barley Cultivars Related to Phenotypic and End-Use Classes

Differences in barley cultivar competitive ability occurred for the various phenotypic and end-use classes (2-row vs. 6-row, full height vs. semi-dwarf, hulled vs. hull-less, and feed vs. malt). In this research, clear differences in both AWC and AC were observed for semi-dwarf versus full height cultivars. This result was not entirely consistent as Earl, a semi-dwarf, was an intermediately-competitive cultivar overall, and Kasota, a semi-dwarf, ranked highly for AWC in 2001, particularly at the Newdale site. Furthermore, height alone did not necessarily confer a competitive advantage. For example, Ranger, a full-height shorter-stature cultivar, was highly competitive in 2002. Hawkeye was the tallest cultivar, but was among the least competitive of the full height cultivars, although this may confounded by its hull-less attribute (Figure 3.1).

Other authors have noted that semi-dwarf (Blackshaw et al. 1981; O'Donovan et al. 2000) and smaller-stature cultivars (Wicks et al. 1994) are less competitive than taller cultivars. Lanning et al. (1997) found that wild oat suppression (i.e. AC) was superior in barley compared to wheat and noted that barley had better light extinction than wheat, but that a negative correlation between height and light extinction occurred in four of seven nurseries. Consequently, the relationship between height and competitive ability is not deterministic.

Differences in competitive ability between semi-dwarf and full height cultivars may be confounded by pleiotropic effects of the presence or absence of the *sdw* (semi-dwarf) gene. Furthermore, semi-dwarf cultivars have traditionally been developed for, and used under, high-fertility, irrigated conditions. Under these conditions, semi-dwarf cultivars lodge less than full-height cultivars and may be more competitive than under dryland agriculture. Consequently, utilization of a semi-dwarf cultivar as a short-stature ideotype to demonstrate a relationship between height and competitive ability (O'Donovan et al. 2000) may be inappropriate.

In this research, hull-less cultivars were less competitive as a class than were hulled cultivars. However, as with semi-dwarf cultivars, this was not absolute. Although Phoenix was intermediately competitive, it just missed being classed as highly competitive. O'Donovan et al. (2000) examined the competitive ability of six cultivars: three hull-less, two full height and one semi-dwarf. They found that two of three hull-less cultivars were poorly competitive although the third, Phoenix, was relatively competitive. The poor competitive ability of hull-less cultivars was attributed to poor emergence. Poor emergence may result from hull-less cultivars' greater susceptibility to loss of seed vigour due to vulnerability to mechanical damage and subsequent invasion by fungi than hulled cultivars (O'Donovan et al. 2000; White et al. 1999).

As with semi-dwarf cultivars, hull-less cultivar competitive ability may be confounded by pleiotropic effects of the *n* (naked caryopsis) gene. In general, hull-less cultivars were less competitive than hulled ones. However, Phoenix was relatively competitive, the deleterious effect of the *n* gene attribute may not be unconditional. An alternative possibility is that the poor competitive ability of hull-less cultivars may be related to the relative immaturity of hull-less barley breeding programs (Byron Irvine, Mario Therrien pers. comm.).

Differences in competitive ability between feed and malt cultivars could not easily be unconfounded from row phenology. Once semi-dwarf and hull-less cultivars were removed, there remained: seven 2-row malt cultivars, four each of 6-row malt and 6-row feed cultivars, and one 2-row feed cultivar. However, feed cultivars are often thought to be more competitive overall than malt cultivars.

The assumed superior competitive ability of feed over malt may be real and have both a genetic and passive selection basis. Genetically, most feed cultivars have 6 rows. In general, when comparing 6- and 2-row cultivars, 6-row cultivars are leafier, have more biomass, and tend to close canopy more quickly as a result of their genetic background (Appendix A). By contrast, malt cultivars are bred for attributes contributing to malt quality such as rapid germination and enzyme activity and other attributes whose contribution to competitive ability is uncertain.

In practice, passive selection may occur as a result of low economic returns available to feed cultivars. When returns are low, inputs need to be low, and high competitive ability and increased tolerance for weeds may be an outcome. By contrast, malt cultivars offer a premium for achieving malt quality. As a result, producers may be more likely increase herbicide inputs to reduce weed seed return and achieve malt quality. Consequently, producers may be influencing competitive ability of feed and malt cultivars as a class through cultivar selection.

Differences in barley cultivar competitive ability occurred by the various phenotypic and end-use classes (2-row vs. 6-row, full height vs. semi-dwarf, hulled vs. hull-less, and feed vs. malt). Differences in competitive ability may be based on genetics, adaptation and end-use requirements. This research strongly suggests that when considering barley cultivar competitive ability, selection based on barley ideotypes may be of dubious value. This is particularly relevant for semi-dwarf and hull-less cultivars, but may also apply for 2- versus 6-row comparisons and feed versus malt comparisons.

Research investigating attributes contributing to cultivar competitive ability seldom use more than 10 cultivars. More commonly, research has used ideotypes, and use of semi-dwarf cultivars to represent "short" cultivars is not uncommon. This research showed that the genetically different semi-dwarf and hull-less cultivars are less competitive than full height and hulled cultivars, respectively. Sources for differences in competitive ability of these classes may be attributable to genetics (*sdw* and *n* genes), the maturity of the breeding program, and possibly even from "passive selection pressure" where high competitive ability is not a requirement. This suggests caution should be exercised when representing cultivars through ideotypes in competition research. Therefore, future research investigating attributes contributing to barley cultivar competitive ability needs to be exhaustive within the class or classes investigated.

3.4.3. The Relationship Between AWC and AC

In varietal studies of competitive ability, both AWC and AC need to be considered (Jordan 1993; Lemerle et al. 2001b). Lemerle et al. (2001b) suggested that differential varietal response to one aspect of weed competition (either AWC or AC) might arise if cultivars have peak resource demands at times when weed resource use is low. This may be true irrespective of actual weed density. Both aspects may not be equally present in the same cultivar and many studies measure only one aspect (Lemerle et al. 2001b), frequently crop yield loss (AWC). However, the relationship between AWC and AC has been considered from a theoretical standpoint (Goldberg and Landa 1991; Jordan 1993; Lemerle et al. 2001a), but has not been addressed from a practical perspective.

The two components of competitive ability have been described under different names. Competitive response (Goldberg and Landa 1991), crop tolerance (Jordan 1993), and competitive advantage (Lemerle et al. 2001b) describe ability to withstand competition (AWC). Competitive effect (Goldberg and Landa 1991) and weed suppression (Jordan 1993) have been used to describe ability to compete (AC). Terminologically, AWC and AC are descriptive of competitive ability. If a species (not necessarily a crop) is able to withstand competition, its yield (or biomass) is not reduced by the presence of competitors. Similarly, if a species has the ability to compete, it will reduce the yield of its competitors.

Some authors have measured only crop and weed seed yield (Challaiah et al. 1986; Ogg and Seefeldt 1999) as the outcome of competition. Using crop yield restricts studies of competitive ability to similar-yielding cultivars, although comparisons of weed seed yield are valid irrespective of the cultivar yield potential. Consequently, AWC and AC are useful measurements of competitive ability and their development and naming was a worthwhile effort.

In our research, a statistically significant relationship between AWC and AC was common. However, statistical significance for correlation and regression is a function of the number of observations (Steel et al. 1997) and if sufficient observations are present, then statistical significance is easily achieved. Achen (1982) states that a coefficient large enough to be of some practical scientific or practical consequence ought to be termed "*substantive*, to distinguish it from the less important statistical significance".

Consequently, a relationship between AWC and AC needs to have sufficient correlation to be practically useful or statistical significance is not useful.

If a sufficiently strong relationship between AWC and AC exists, breeding for cultivar competitive ability could be targeted at increased AWC under the assumption that AC will arise as a result. For breeding purposes, a minimum correlation coefficient of 0.75 has been suggested (Mario Therrien pers. comm.). Fox et al. (1997), suggest that for most quantitative attributes, within a 90% confidence interval, an R^2 of 0.7 is the minimum coefficient of determination (which corresponds to a correlation coefficient $\geq |0.8367|$) useful in a breeding program. While defining "substantive" is subjective, a correlation coefficient of 0.75 yields an R^2 of 0.5625, which is considerable lower than the 0.7 suggested (Fox et al. 1997). Consequently, in this research, a correlation coefficient of 0.8 was considered substantive.

In this research, AC was less variable than AWC and may be more consistent for ranking and therefore more useful as a breeding tool. However, adoption of AC for ranking cultivars may prove more problematic for two reasons. Firstly, yield loss (AWC) has often been of more interest than weed seed return (AC) in agricultural research (Peterson and Higley 2001). Secondly, AC can be more difficult to collect than AWC. In barley, retaining seed from small-seeded weeds can be difficult, whereas for large-seeded weeds the difficulty arises in separation. In this research, each sample (approximately 25g) took an average of about 15 minutes to separate weed from crop seed. Consequently, AWC may continue to be collected unless the research objective is to reduce weed seed return (Ogg and Seefeldt 1999; Seavers and Wright 1999).

In our research, substantive correlation coefficients between AWC and AC only occurred before exclusion of the less-competitive semi-dwarf and hull-less cultivars. Once less competitive cultivars were excluded, the more-competitive 6-row and feed classes were closest to having substantive correlation coefficients between AWC and AC. Consequently, breeding for increased AWC to get increased AC will be most effective in the least competitive classes of cultivars, somewhat effective in the highly competitive classes of cultivars, and least effective in intermediately competitive classes of cultivars.

Since breeding for increased AWC may be effective in only some classes of cultivars, determining if regression coefficients are substantive may be profitable. Substantive has a different meaning for regression, as opposed to correlation coefficients. A substantive regression coefficient is one for which biologically attainable changes in one variable occur for changes in the other variable. Regression coefficients generally were between 0.8 and 1.0 and a change in AWC was reflected by an approximately equal change in AC. Excepting the malt cultivars, all barley classes had statistically significant and substantive regression coefficients.

Lemerle et al. (2001b) suggested that differential cultivar response to weed competition might arise if cultivars have peak resource demands at times when weed resource use is low. This hypothesis does not appear relevant in this research as tame oat and barley have similar resource demands and phenology (Ball et al. 1995). AWC and AC are strongly related for the least and most competitive classes, but less so for intermediately-competitive classes. This suggests that AWC and AC can arise from separate mechanisms, which are not well understood. Overall, breeding for increased AWC to get higher AC may not be an effective strategy.

3.4.4. The Effect of Genotype and Environment on Cultivar Competitive Ability

The effect of genotype and environment on cultivar competitive ability has not been addressed in barley. In wheat, it has been addressed in two multi-year, multi-location trials (Cousens and Mokhtari 1998; Lemerle et al. 2001a). These researchers have found that few wheat cultivars were consistently more competitive than others, and the competitive ability of cultivars varied considerably by years. As a result, Lemerle et al. (2001a) suggested that making reliable recommendations to producers was difficult given the considerable environmental component.

Our research has demonstrated that poorly- and highly-competitive cultivars tended to be less affected by environmental variability, whereas intermediately-competitive cultivars were more affected. Competitive cultivars were generally in the top 10 for both AWC and AC. Non-competitive cultivars were generally in the bottom 10 for AWC and AC. The intermediately-competitive cultivars made occasional appearances in the top or bottom ten. Our results agree that environment plays a larger role than genotype (Cousens and Mokhtari 1998; Lemerle et al. 2001b), however, their conclusion that reliable recommendation for producers are difficult to obtain are only true for intermediately-competitive barley cultivars However, highly- or poorly-competitive barley cultivars may be reliably recommended.

Genotype and environmental effects are confounded between growing seasons. In 2001, seed was obtained from a variety of sources across the Canadian prairies, whereas in 2002 seed from a common seed increase was used. Differences in seedlots can result in differences in vigour (Morrison et al. 1991; Sonntag et al. 1993; White 1990). While this is an environmental effect, it does not occur within the growing season and cannot easily be parsed out from genotypic effects unless that is the stated objective of the trial.

Ranger had a low ranking for AWC in 2001, but had consistently high AWC in 2002. In 2000, harvest conditions were wet and Ranger was germinating in the ear (Mario Therrien pers. comm.). Seed for 2001 had a moldy smell (personal observation). Interestingly, poor quality seed seems to have affected AWC more than AC for Ranger as its AC rank was consistently in the top 10 (Table 3.8). Consequently, this apparent environmental difference in cultivar competitive ability may be attributable to seed source.

Genotype and environmental effects may also be confounded by cultivar adaptation. For example, Kasota had fair to good competitive ability in 2001, but was a poor competitor in 2002 (Table 3.8). In 2001, the Brandon area experienced a warm, moist spring, whereas in 2002, the spring was cold and dry (Appendix B). Consequently, 2001 was arguably a more productive growing season with higher potential yield (Appendix B). Kasota was developed in Central Alberta (Helm et al. 1996) and, at the most recent census, was grown on considerably more acres in the more productive Black soil zone compared to the less productive thin Black soil zone (Alberta Agriculture, Food and Rural Development 2004a, 2004b). Since 2001 was more productive than 2002, an apparent environmental effect may partially have a genetic basis in environmental adaptation.

Separating genotypic from environmental effects when there are insufficient environments can be difficult. Highly competitive cultivars need to be competitive at multiple locations in multiple years. However, this can be confounded by the use of seed from a variety of sources since differences in seed vigour between seedlots (Morrison et al. 1991) may impact competitive ability. Consequently, research into cultivar competitive ability should be undertaken with seed grown at a common location to prevent confounding of cultivar competitive ability due to genotypic and environmental variability.

Poorly- and highly-competitive cultivars were relatively consistent among environments compared to intermediately-competitive cultivars. Poorly competitive cultivars would benefit most from increased competitive ability, but this may not be easily accomplished as most poor competitors were semi-dwarf, hull-less, or both and were less competitive as a class. Intermediately-competitive cultivars could also benefit substantially from increased competitive ability, but accomplishing this may be may difficult due to the larger effect of environment than genotype on their competitive ability. Highly competitive cultivars were stable, showed minimal yield loss, and allowed little weed seed return under weedy conditions. Consequently, increasing the competitive ability of these cultivars may not be a priority.

Most previous research has not considered differences in phenotypic and genotypic classes of barley cultivars. Lanning et al. (1997), explored the relationship of height to competitive ability using ideotypes, which were not exclusively semi-dwarf cultivars. O'Donovan et al. (2000), examined competitive ability of barley cultivars containing full height, semi-dwarf, hulled, and hull-less but had insufficient replication of classes to eliminate confounding. Differences in competitive ability of semi-dwarf and hull-less cultivars that have been attributed to height and mechanical damage to seed, respectively, represent only part of the story. Since these attributes were not deterministic in their contribution to competitive ability (Lanning et al. 1997; O'Donovan et al. 2000), other factors must be considered. We (Dr. Byron Irvine and Paul Watson) observed that cultivars bred under moisture-limiting conditions tended to be less competitive. Cultivars bred under more optimal conditions need not be more competitive, but all competitive cultivars were from parentage bred under optimal conditions. Consequently, cultivar competitive ability cannot be fully described on the basis of phenotypic, genetic, or end-use classes.

3.5 CONCLUSIONS

While barley is considered a competitive crop (Todd 1989), barley cultivar competitive ability differs substantially, with scores for AWC (100-% yield loss) and AC (100-% dockage) ranging from less than 20 to greater than 80. Research examining the relative competitiveness of crops (Cousens et al. 1992; Lanning et al. 1997; Lemerle et al. 2001b; O'Donovan et al. 1985) has generally used one, or a few, cultivars. Results from these trials should be considered with caution. Our research indicates that "barley" is not a homogeneous entity and should not be considered such.

Differential cultivar response to AWC and AC has been postulated (Jordan 1993; Lemerle et al. 2001b). Our results indicate a strong relationship between AWC and AC, with AC being the more stable competitive measure. This suggests some dependence of the ability to maintain yield on the ability to suppress weeds, which in turn suggests a pre-emptive strategy where the first to interfere with the other gains an advantage. This is supported by López-Castañeda et al. (1995) who suggested the interval between germination and the 2-leaf stage as being responsible for the greater vigour of barley, compared to wheat. Given the lack of limiting resources in this interval, competition is not operative and allelopathic research may prove fruitful (Baghestani et al. 1999).

Different ratings for cultivar competitive ability may be important in different production systems. AWC may be more suitable for conventional production systems where herbicides are used compared to organic systems. While yield loss is incurred as a result of low AWC, high seed return (low AC) need not occur since herbicide application can reduce weed numbers, and therefore, weed seed yield. In organic (and other low-external-input) systems, some yield loss may be acceptable, but minimizing seed return is an important objective. Consequently both ratings have useful attributes.

Research has been undertaken to model crop competitive ability of cultivars based on factors such as light competition and crop height. In general, these studies have used few cultivars. Given the wide range of competitive ability observed within barley cultivars, it seems improbable that a single cultivar can be used to represent "barley". Furthermore, properly representing the range of competitive ability available requires numerous cultivars, and should preferably contain replication within classes of cultivars. For decision-support systems this has profound implications. Scores for AWC and AC ranged from less than 20 to greater than 80. If herbicide application decisions are determined with a competitive cultivar, then the decision to spray might not occur when needed. Alternatively, if yield loss equations are determined with a poor competitor, the decision to apply herbicides might be undertaken when not needed. Future research into yield loss due to weeds (Cousens et al. 1987) could profitably employ cultivars known to vary in competitive ability. This requires that cultivar competitive ability be known. Therefore, a ranking system, using both AWC and AC, is vital in crop-weed competition research.

CHAPTER 4: THE RELATIONSHIP OF BARLEY ATTRIBUTES IN SEED, SEEDLING, AND MATURE PLANT PHASES TO CULTIVAR COMPETITIVE ABILITY

4.1 INTRODUCTION

Research into competitive ability of crops and cultivars has a long history (Pavylchenko and Harrington 1934), but has recently acquired a new urgency. Herbicide resistance, socioeconomic pressures requiring reduced herbicide input, and increasing market share for low-external-input agricultural products (e.g. pesticide-free and organic), is changing high cultivar competitive ability from being a desirable property to an increasingly-necessary one (Lemerle et al. 2001a). Despite the need for competitive cultivars, examining and increasing cultivar competitive ability requires that four issues be addressed.

One issue is the strength of association between attributes and competitive ability. Lemerle et al. (2001b) have suggested that a strong association between attributes and competitive ability is required for breeding to be feasible. There must also be a useful increase in competitive ability with an achievable increase in the desired attribute. Statistical significance for correlation and regression is a function of the number of observations and if sufficient observations are present (Table 3.4), statistical significance is easily achieved (Steel et al. 1997). Achen (1982) stated that a coefficient large enough to be of some practical or scientific value be termed "substantive, to distinguish it from the less important statistical significance". For breeding purposes, a correlation coefficient of approximately 0.8 could be considered substantive.

A second issue is the measurement of competitive ability. There are two aspects of competitive ability (Goldberg and Landa 1991; Jordan 1993) that describe: 1) a species ability to maintain seed production despite competition, and, 2) a species ability to interfere with the seed production of another species. These two aspects have been termed ability to withstand competition (AWC) and ability to compete (AC), respectively (Chapter 3). Goldberg and Landa (1991) used the terms competitive response (i.e. AWC) and competitive effect (i.e. AC), while Jordan (1993) used the terms crop tolerance (i.e. AWC) and weed suppression (i.e. AC), respectively. Cultivars may vary with respect to these measures of competitive ability relative to the life cycle of weeds in specific environments (Lemerle et al. 2001b), and may differ in importance under different production systems (see Chapter 3). Although both aspects of cultivar competitive ability need to be considered in varietal studies of competitive ability, (Jordan 1993; Lemerle et al. 2001b), both aspects may not be present in the same cultivar and most studies only measure one aspect (Lemerle et al. 2001b). Cousens and Mokhtari (1998) suggested that AC may be more consistent for cultivars than AWC. However, this has not been further examined. Consequently, the relationship between AWC and AC has not been established, and both aspects should be measured and related to attributes contributing to cultivar competitive ability.

A third issue relates to the number of cultivars examined. Lemerle et al. (2001b) have suggested that, as the number of cultivars declines, it becomes more likely that attributes observed to contribute to cultivar competitive ability may actually be chance associations. Screening efforts have been directed at large numbers (>20) of cultivars with the goal of selecting a subset cultivars to examine attributes contributing to cultivar competitive ability in wheat (Lanning et al. 1997; Lemerle et al. 1996) and barley (Doll

1997; Lanning et al 1997). In wheat, moderate numbers (10-20) of cultivars of available genotypes have been selected as "representative" of the range of a particular attribute believed to contribute to cultivar competitive ability and cultivar competitive ability has been reported (Challaiah et al. 1986; Cousens and Mokhtari 1998; Lemerle et al. 2001b; Wicks et al 1994). In barley, few (<10) cultivars have been used to examine the link between attributes and competitive ability (Baghestani et al. 1999; Christensen 1994, 1995; Didon 2002; O'Donovan et al. 1999, 2000). Consequently, research using large numbers of barley cultivars to examine the relationship between attributes and competitive ability would be beneficial.

The final issue relates to time of measurement of attributes. Westoby (1998) proposed a leaf-height-seed (LHS) plant ecology strategy scheme, using attributes useful for describing species persistence and reproductive success, to be universally adopted for functional ecology (Weiher et al. 1999). In the LHS framework there would be three axes, and the measurements suggested (Westoby 1998) for these LHS axes are: 1) specific leaf area, 2) plant canopy height at maturity, and, 3) seed mass. These, and similar, measurements are used to investigate cultivar competitive ability in annual cropping systems. This plant ecology strategy scheme would be useful in research pertaining to cultivar competitive ability.

In annual cropping systems, the life cycle of the crop begins at seeding and can be described in a seed-leaf-height (SLH) framework (Figure 4.1). Each phase is separated by morphological or physiological attributes (Zadoks et al. 1974) relevant to annual agriculture and can similarly be further divided into sub-phases. The seed (S) phase begins with dry seed (Zadoks 00) and continues through germination and emergence until immediately prior to the onset of photosynthesis (Zadoks 09). The seed phase can be logically subdivided into two sub-phases. The first sub-phase (S_1) is the dry seed phase (Zadoks 00), while the second sub-phase (S_2) comprises the remainder of the germination phase (Zadoks 01 – 09), where the seed is still reliant upon stored resources. The seed phase ends when photosynthesis begins (Zadoks 10).

Attributes contributing to competition in the seed (S) phase (Figure 4.1), considered potentially important include seed vigour (Perry 1976a) and it components and outcomes such as: 1) rapid and uniform germination and emergence (Ching et al 1977; Lafond and Baker 1986b; Naylor 1993; Torres and Paulsen 1982), 2) seedling vigour (Bulisani and Warner 1980; Evans and Bhatt 1977; Gan and Stobbe 1996; Mian and Nafziger 1994; Lafond and Baker 1986a; Lowe et al. 1972), 3) seed size (e.g. Aparicio et al. 2002; Bockus and Shroyer 1996; Gan and Stobbe 1996; Lafond and Baker 1986a, 1986b; Stougaard and Xue 2004; Xue and Stougaard 2002). Crop emergence, commonly measured as early crop density (Doll 1997), is highly dependent on both seed and seedling vigour. A number of researchers have found crop density to be important in determining competitive ability in barley (Barton et al. 1992; Doll et al. 1995; Evans et al. 1991; Lafond 1994; Lafond and Derksen 1996b; O'Donovan et al. 1998, 2001; Van Acker et al. 1997b) but few have researched the effect on more than one barley cultivar (Doll 1997, McFadden 1970). Reduced response to increasing crop density could occur for competitive compared to non-competitive cultivars.

The seedling, or leaf (L), phase (Figure 4.1) commences when photosynthesis begins. This phase is subdivided into early (L_1) and late (L_2) sub-phases, separated by the onset of tillering (Zadoks 20). The tillering phase represents a shift from purely vegetative growth to partly sexual development since tillers have the capacity to bear ears (Evers et al. 1999). Additionally, ear primordia develop in this phase and the ear-bearing potential of barley is set by the end of tillering. The seedling (L) stage terminates immediately prior to the onset of stem elongation (Zadoks 30).

In the L stage, attributes such as rate of canopy closure (Mian et al. 1998), canopy architecture (Légère and Schreiber 1989), early height growth (Mian et al. 1998), and comparative rates of emergence and leaf appearance (Cousens et al. 1992) have been condsidered. Models have attributed crop yield loss due to weeds using weed density (Cousens 1985a, 1985b; Cousens et al. 1987; Dew 1972, Kropff and Spitters 1991; Kropff et al. 1995; Lutman et al. 2000; Ngouajio et al. 1999), weed and crop densities (Cousens 1985b; O'Donovan et al. 1999; Van Acker et al. 1997a;), weed density and relative time of weed emergence (Cousens et al. 1987), and relative leaf area of weeds (Kropff and Spitters 1991; Lotz et al. 1996; Ngouajio et al. 1999; Van Acker et al. 1997b). Recently, weed seed reproduction has been modelled as a function of crop yield loss (Canner et al. 2002). In general, research has been conducted on crop yield maintenance rather than weed suppression (but see Canner et al. 2002; Cousens 1985b). Consequently, the focus of competition has been the ability to withstand competition rather than the ability to compete.

The height (H), or mature plant phase begins (Figure 4.1) at the onset of stem elongation (Zadoks 30) and terminates at the end of harvest. This phase can be subdivided into early (H_1) and late (H_2) sub-phases based on ear visibility (i.e. at boot stage). This morphological distinction also has a physiological basis. Maximum foliar canopy height occurs shortly after boot stage and barley susceptibility to foliar diseases increases rapidly after the boot stage. Consequently, senescence seldom occurs before boot stage.

In the height (H) phase, final height has been considered to be an important attribute (Blackshaw et al. 1981; Challaiah et al. 1986 Christensen 1995). However, research leading to this conclusion has often been based on comparisons between full height and semi-dwarf varieties (Blackshaw et al. 1981; Juskiw et al. 2000; Gonzalez-Ponce and Sattin 2001; Grundy et al. 1993; Seefeldt et al. 1999). Ni et al (1999) and Ogg and Seefeldt (2000) have suggested that final height is less important than the rate of height growth, particularly in the early stages of growth and development (López-Castañeda et al. 1995, 1996). Consequently, height may be best considered as an L phase attribute that continues into the H phase.

In water-seeded rice, Caton et al. (1997) reported that competitive effects with *Ammania* spp. were not detectable until the stem elongation phase had begun. This was attributed to the lack of resource limitation until light competition began after *Ammania* spp. height surpassed that of rice. Consequently, the proposition that competition predominantly occurs during the seedling (L) phase may be contingent upon the nature, and extent, of resource limitations in the L phase.

As with the leaf-height-seed plant ecology strategy scheme (Westoby 1998), attributes thought to contribute to plant resource capture and reproductive survival (i.e. cultivar competitive ability) have been measured at the seed (S), seedling(L) and mature plant (H) phases. However, linkages between stages and their relative importance are rarely considered. Consequently, the objectives of this research were to : 1) determine the relationship between attributes commonly thought to contribute to barley cultivar competitive ability (AWC and AC) in each of the S, L and H phases for a wide genetic and phenotypic range of cultivars, and, 2) investigate the relative importance of each stage to barley cultivar competitive ability (AWC and AC).

4.2 MATERIALS AND METHODS

4.2.1. Field Trial

A screening trial was conducted in 2001 and 2002 to determine the range of competitive ability available in barley cultivars commonly grown in Western Canada. A split-plot design, with 4 replicates, was employed using barley cultivars as the main plot, and the presence or absence of a weed as the subplot. Experimental plots (sub-plots) were 2m wide by 6m long.

Twenty-nine barley cultivars (Table 3.1) were selected if they met one of three criteria. Firstly, to represent four major classes based on seed rows (2- and 6-row) and seed covering (hulled and hull-less). Secondly, cultivars were grown on at least 5% of the acreage in its class in one or more of the prairie provinces (Manitoba, Alberta or Saskatchewan) in 1999. Thirdly, to represent the range in competitive abilities of barley cultivars. Prior to the 2001 field season, certified, registered or breeder seed was obtained from breeders and certified seed growers for all but two cultivars meeting these criteria. CDC Buck and CDC Silky met these criteria, but these were not included since pedigreed seed was unavailable.

The subplots either had tame oat (*Avena sativa* L. cv. AC Assiniboia) seeded (weedy plots) or not (weed-free plots). Since early weed emergence maximizes yield loss (Cousens et al. 1987; Lotz et al. 1996; O'Donovan 1992; O'Donovan et al. 1985.), tame oat was used as a surrogate for wild oats. Wild oat (*Avena fatua* L.) is a ubiquitous weed on the Canadian prairies that occurs at the second highest density of all weeds (Thomas et al. 1996, 1998a, 1998b) after green foxtail (*Setaria viridis* (L.) Beauv.), but is more competitive (Wall 1993). Wild oat is particularly problematic in spring cereals where it can be costly to control and difficult to separate from barley seed. It is one of the most economically harmful annual grassy weeds in North America (O'Donovan and Sharma 1983). Dew (1978), estimated the economic cost of wild oat in western Canada due to crop losses and herbicide costs at $280 million.

Site Descriptions

Field experiments to determine barley cultivar competitiveness were conducted in 2001 and 2002. In 2001, two site-years of data were collected with one site-year of data from each of a Prodan clay loam soil and a Newdale clay loam soil. In 2002, four site-years of data were collected with two site-years of data from each of a Ramada clay loam soil and a Newdale clay loam soil. All experiments were direct-seeded into fields previously under zero-till management.

The Prodan soil series is a carbonated, calcareous to strongly calcareous, Gleyed Rego Black soil developed on imperfectly drained lacustrine sediments. The Ramada soil series is an Orthic Black soil developed on well- to moderately well-drained, strongly calcareous lacustrine sediments. The Newdale soil series is a well-drained, slightly to moderately stony, strongly calcareous Orthic Black soil developed on glacial till that occurs on rolling topography. While the Newdale series is quite typical of the Parkland Region of western Canada, the Prodan and Ramada series are generally higher-yielding.

The Prodan and Ramada sites were located in the Assiniboine River valley on the Brandon Research Centre (BRC) in Brandon, MB. The two Ramada sites were conducted adjacently, in the same field, and were situated approximately 100m south of the trials seeded on a Prodan clay loam in 2001. The Newdale site in 2001 and the first Newdale site (Newdale 1) seeded in 2002, were located approximately 20 km NNE of Brandon at the Phillips Farm subsidiary location of the BRC. The second Newdale site (Newdale 2) seeded was located 4.8 km south of the first Newdale site.

At the first Ramada site seeded (Ramada 1) in 2002, 2 replicates were accidentally cross-seeded with oats. These two replicates were replanted immediately north of replicate 1, but on barley rather than oat stubble. At the Newdale 1 site, the seeder was thought not to be dispensing seed properly. At the Newdale 1 site, it was considered possible that seed was being deposited in clumps and that emergence would reflect a clumped distribution. Consequently, after these two sites were seeded, the decision was made to seed two more sites (Ramada 2 and Newdale 2) as a precaution. Emergence was evaluated at the Newdale 1 site and was not noticeably clumped.

Field Operations

Screening Trial

In 2001 when seed came from multiple sources, all barley and weed (tame oat) seed was treated with triticonazole (Charter, BASF Canada, Toronto, ON) at 0.25g a.i. per 100 kg of seed. After seed treatment, germination tests were performed. Barley cultivars and tame oats were sown simultaneously in seed rows to achieve a target density of 250 and 70 plants m^{-2}, respectively according to equation 4.1. A target density of 70 plants m^{-2} for tame oat was selected to achieve a 25% yield reduction (Guide to Crop Protection 2001). In 2002 when all barley seed came from a common source, seed treatment was not applied to either the crop or weed. Seeding for target densities was identical to 2001.

$$\text{Seeding rate (plants m}^{-2}\text{)} = \text{(1000-kernel weight/4)/(\% Germination)} \qquad (4.1)$$

In all years, nitrogen fertilizer was applied at a rate of 78.4 kg ha^{-1} actual N as 46-0-0 in a mid-row band. Phosphorus was seed-placed as 0-45-0 to prevent nitrogen toxicity at a rate of 22.4 kg actual $P_2 0_5$ ha^{-1}. Soil tests were conducted for both sites in 2001 and the Ramada 1 and Newdale 1 locations in 2002. Due to circumstances, soil tests were not performed for the Ramada 2 and Newdale 2 locations in 2002. Where tested, fertilizer applied was sufficient for a yield of 3430 kg ha^{-1} (approximately 80 bu ac^{-1}).

Where necessary, pre-seeding herbicide application occurred not more than two days prior to seeding and consisted of glyphosate at a rate of either 450 g a.e. ha^{-1} or 900 g a.e. ha^{-1} depending on the weed spectrum. All plots received an in-crop application of a mixture of 100 g a.e. ha^{-1} clopyralid and 550 g a.e. ha^{-1} MCPA ester formulated as an emulsifiable concentrate (Curtail M, Dow AgroSciences, Indianapolis, Indiana) for broadleaf weed control. Plots not seeded with tame oat were considered "weed-free" and also received an in-crop application of 80% tralkoxydim formulated as a dispersable granule (Achieve 80 DG, Syngenta, Basel, Switzerland) at a rate of 200 g a.i. ha^{-1} to control late-emerging wild oats. All herbicides were applied with a tractor-mounted boom sprayer applying 110 L ha^{-1} (10 gal ac^{-1}) at 275kPa (40 PSI) through 8001 nozzles. In-crop herbicide application occurred per label recommendation; when cultivars were between the 2- and 4-leaf stage.

Harvest in experimental plots was performed with a Hege 125C combine (Hege Maschinen GmbH, Waldenburg, Germany) with a 1 m table. Six crop rows were harvested per plot with the two outside rows on either edge of the plot left standing. Prior to assessing yield, harvested seed was put through a de-awner, and then sieved to remove trash and unwanted seed. Yield in weed-free plots was determined by weighing the sample from each plot after cleaning. In weedy plots, the percentage of weed seed yield by weight (i.e. the dockage) was determined by manually separating oat from barley seed and weighing the oat seed from a sample weighing approximately 25g. Yield was then calculated by subtracting dockage from the gross yield.

Seed Increase

Crop seed vigour is affected by the growing conditions under which the mother plant matures (Anderson and Milberg 1998a) and differences in harvest practices (Bourgeois et al. 1996). Consequently, a seed increase was undertaken in 2001 at the Newdale site to provide common seed for future trials. Plot size for the seed increase was either 0.05 ha or 0.08 ha, depending on projected cultivar seed requirements. All seed was treated with triticonazole at 0.25g a.i. per 100 kg of seed prior to seeding. Cultivars were direct-seeded on May 24th with a ConservaPac hoe-drill on a 23.0 cm row spacing. Pre-seeding herbicide treatment consisted of an application of glyphosate at 900 g a.e.ha^{-1}. In-crop herbicide application occurred at the 3-leaf stage. Herbicides applied were a tank-mix of 100 g a.e. ha^{-1} clopyralid and 550 g a.e. ha^{-1} MCPA ester formulated as an emulsifiable concentrate (Curtail M) and 80% tralkoxydim formulated as a dispersable granule (Achieve 80DG) at a rate of 200 g a.i. ha^{-1} applied at the 3-leaf stage of barley. Plots were fertilized at seeding with 78.4 kg ha^{-1} actual N, mid-row banded as 46-0-0 and 22.4 kg ha^{-1} actual P_20_5 seed-placed as 0-45-0. In addition to herbicide application, plots had weeds manually removed within 2 days of harvest and as required earlier in the growing season.

Foliar fungicide application consisted of two applications of propiconazole (Tilt 250E, Syngenta, Basel, Switzerland) at 120 g a.i. ha^{-1}. Application times were as close as possible to label recommendation: 1) at stem elongation, and, 2) before the head was half emerged as was possible given the genotypic variability of the cultivars. Tilt 250E was applied using a tractor-mounted boom sprayer, applying 110 L ha^{-1} at 275kPa (40 PSI) through 8001 nozzles. The seed increase was harvested with a Hege 140 combine and the outside rows in each plot were harvested and bagged separately as they were less mature than the inside rows. Harvest occurred from August 28 to September 4th, 2001.

Data Collection and Collation

Data were collected on integrated measures and attributes believed to contribute to cultivar competitive ability in each of the S, L, and H phases (Figure 4.1, Table 4.1). In the seed phase, data collected on the seed to be sown included seed mass, germination rate, and percent germination. Seed mass was calculated based on 1000-kernel counts enumerated as 4 replicates of 250 seeds each. Germination rate and percent was evaluated by placing a petrie dish with 100 seeds in a Conviron Model I18L growth chamber (Conviron, Winnipeg, Manitoba) at 5° C and documenting germination on a daily basis for 7 days.

In the seedling (L) stage, crop and weed counts were performed to determine if emergence was similar in all plots. At the Prodan site, the number of barley plants in weed-free plots was counted in 2 x 1 meter rows and converted to density m^{-2} assuming the meter row accounted for 1m length x 0.2032m wide. Consequently, crop density was calculated according as:

$$\text{Crop density } m^{-2} = ((\text{Crop count } 1 + \text{Crop Count } 2)/2)/0.2032 \qquad (4.2)$$

In weedy plots at the Prodan site, crop and weed density were assessed in a similar manner. Crop and weed counts at the Newdale site were performed using a 0.25 m^2 quadrat (0.5m x 0.5 m) (due to the presence of barnyard grass (*Echinocloa crus-galli* (L.)) Beauv.) and were converted to a density m^{-2} by multiplying by four.

Rate of leaf area expansion (i.e. canopy closure) was enumerated (Table 4.1) by taking digital pictures in weed-free plots with an Olympus digital camera (Olympus Canada Inc., Toronto, ON) until all cultivars had closed their canopy. A single picture, covering an area of approximately 1 m^2 was taken weekly. Percent cover was then calculated using digital image analysis (Ngouajio et al. 1998), performed with Assess version 1.0 (American Phytopathological Society 2002).

Cory Feschuk (pers. comm.) found that early development (Haun stage) might be indicative of competitive ability. To determine Haun stage (Haun 1973), a minimum of 5 plants per plot were collected in the outside two rows of weed-free plots at the 3- to 4-leaf stage and their Haun stage evaluated. Haun stage was then calculated as the average of these five observations.

Cultivar height was to be enumerated in weed-free plots at weekly intervals from approximately the 5-leaf stage to heading, when maximum height occurs. Not all of these measurements were taken in 2001, but all were taken in 2002 (Table 4.1). Canopy height in each plot was enumerated by measuring the tallest plants in a random sample of plants (a handful of approximately 10-15 plants) in four random locations in the plot and averaging these values.

Light extinction measurements (Table 4.1), using a model # LI-1915A line quantum sensor and model # LI-185B quantum radiometer (LI-COR Inc, Lincoln, Nebraska) commenced in weed-free plots at the 3- to 4-leaf stage and continued weekly until approximately the 6-leaf stage had been reached by all cultivars. Measurements were taken within two hours of solar noon under clear skies. In 2001, measurements began at about the 5-leaf stage.

In the mature plant (H) phase, oat panicles were counted in two 1-meter row lengths in each weedy plot and converted to density m^{-2} in the same manner as for crop density (equation 4.2). Barley growth and development were quantified on the Feekes (Large 1954) scale on 2 occasions, corresponding approximately to Feekes 9 (just prior to boot stage) and 11 (beginning of the ripening stage). Lodging and disease load ratings were visually estimated in weed-free plots on a scale from 0 to 100, with zero representing an absence of lodging or disease and 100 representing complete lodging or disease. Lodging ratings were performed within a few days of harvest. Disease load was evaluated at the soft-dough stage.

Grain quality measurements from the field experiments included protein, percent dockage and yield. Protein was determined using Foss Grainspec (Foss North America, Eden Prairie, IL) near-infrared whole-grain analyzer. Yield in weed-free plots was determined by weighing the sample from each plot after cleaning. In weedy plots, yield was determined by subtracting dockage from the gross yield. Dockage was evaluated by manually separating oat from barley seed in a subsample weighing approximately 25 g. Oat seed was then weighed and the proportion of oat seed in the subsample was calculated as:

$$\% \text{ Dockage} = 100 * \text{Subsample}_{\text{Oat}} / \text{Subsample}_{\text{Total}} \tag{4.3}$$

where $\text{Subsample}_{\text{Oat}}$ is the weight of the oats in the (approximately) 25g subsample and $\text{Subsample}_{\text{Total}}$ is the actual weight of the subsample. Statistically, % dockage is identical to AC for cultivar significance and partial correlation since AC = 100 - % Dockage. All samples were oven-dried to a moisture content of less than 10% (approximately 8-10 %).

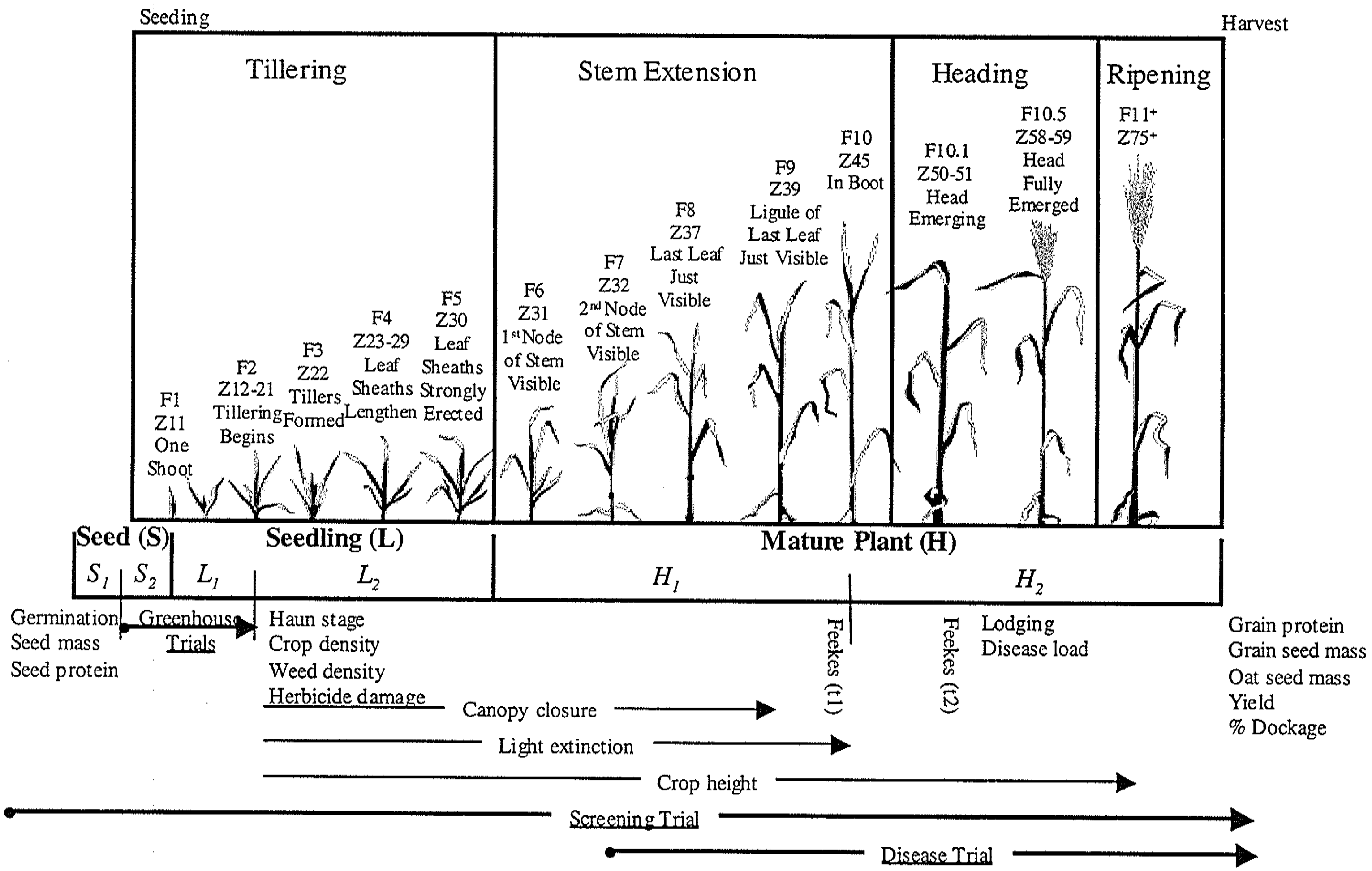

Figure 4.1. A graphical representation of the Seed-Leaf-Height framework and its correspondence to the Feekes (F1 – F11$^+$) and Zadoks (Z11-Z75$^+$) developmental stages. Developmental phases are indicated in bold, sub-phases in italics. Trials are underlined and their duration indicated by arrows. Point measurements are indicated in regular text and were taken at (approximately) the leftmost character.

Table 4.1. Julian date and growing-degree-days (GDDs in parentheses) after seeding for measurements in each site-year of the screening trial on Prodan, Newdale and Ramada soil series. GDDs are based on 5 °C.

Attribute	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Crop Density	May 29 (159)	Jun 01 (122)	May 27 (70)	May 30 (96)	May 27 (63)	May 30 (84)
Herbicide damage	Jun 07 (239)	Jun 14 (260)	-	-	Jun 13 (232)	Jun 14 (224)
Haun stage	Jun 04 (210)	Jun 05 (155)	Jun 03 (155)	Jun 05 (157)	Jun 06 (180)	Jun 06 (160)
% Lt. Ext. (t_1)	Jun 29 (479)	Jul 03 (457)	Jun 14 (259)	Jun 21 (328)	Jun 17 (280)	Jun 17 (260)
% Lt Ext. (t_2)	Jul 06 (551)	Jul 09 (541)	Jun 18 (310)	Jun 26 (409)	Jun 20 (317)	Jun 20 (297)
% Lt Ext. (t_3)	-[a]	-	Jul 02 (531)	Jul 10 (616)	Jun 26 (408)	Jun 26 (388)
% Lt Ext. (t_4)	-	-	-	-	Jul 10 (614)	Jul 10 (594)
% Cover (t_1)	May 25 (117)	Jun 04 (146)	Jun 12 (237)	Jun 14 (241)	Jun 13 (232)	Jun 14 (224)
% Cover (t_2)	May 29 (159)	Jun 08 (189)	Jun 17 (294)	Jun 21 (328)	Jun 20 (317)	Jun 20 (297)
% Cover (t_3)	Jun 01 (188)	Jun 12 (244)	-	Jun 26 (409)	Jun 26 (408)	Jun 25 (370)
% Cover (t_4)	Jun 05 (219)	Jun 21 (315)	-	Jul 05 (548)	Jul 02 (509)	Jul 02 (489)
% Cover (t_5)	Jun 10 (281)	Jul 04 (467)	-	-	-	-
% Cover (t_6)	Jun 20 (362)	-	-	-	-	-
Height (t_1)	Jul 06 (551)	Jul 05 (479)	Jun 12 (237)	Jun 21 (328)	Jun 13 (232)	Jun 14 (224)
Height (t_2)	Jul 20 (776)	Jul 09 (541)	Jun 27 (445)	Jun 27 (427)	Jun 27 (426)	Jun 27 (406)
Height (t_3)	-	Jul 24 (761)	Jul 12 (663)	July 12 (644)	Jul 12 (642)	Jul 12 (622)
Height (t_4)	-	Aug 13 (1052)	Jul 23 (851)	Jul 29 (928)	Jul 23 (825)	Jul 24 (818)
Height (t_5)	-	-	-	Aug 16 (1146)	-	Aug 6 (987)
Feekes stage (t_1)	-	-	Jun 28 (466)	Jul 03 (523)	Jul 02 (509)	Jul 03 (501)
Feekes Stage (t_2)	-	-	Jul 18 (773)	Jul 22 (822)	Jul 22 (816)	Jul 22 (796)
Lodging[b]	Aug 07 (1064)	Aug 13 (1052)	-	-	-	-
Disease load	-	-	Jul 19 (794)	Jul 22 (822)	Jul 22 (816)	Jul 22 (796)

a: - = data not collected.

b: No lodging occurred in 2002

4.2.2. Greenhouse trials

In the field, biomass has been measured early in the field season to determine competitive ability (O'Donovan et al. 2000). However, biomass may fluctuate considerably due to variability of factors such as seed depth and microsite conditions (Boyd and Van Acker 2003). While this variability becomes less heterogeneous over the course of the growing season, measurements early in the field season often have enough variability that statistical differences between treatments are undetectable (D. Derksen pers. comm.). Consequently, greenhouse trials are one approach used to reduce sources of variability such as seed depth and moisture (Boyd and Van Acker 2003).

Two greenhouse trials were undertaken to provide detailed measurements in the seed (S) and early seedling (L) phases. In the S phase, a seed vigour trial was used to determine the relationship of seed vigour to competitive ability. In the early L phase, A competition trial was undertaken to quantify early competitive ability based on equal crop density for all cultivars. These two trials were intended to account for the period where field measurements were not sufficiently sensitive.

Seed Vigour Trial

Seed vigour has been assessed in a number of ways. The proportion of normal seedlings in a cold germination test (Bourgeois et al. 1996), seedling emergence (Ching et al. 1977; Wilson 1985), germination and seedling vigour (Grass and Burris 1995a), and crop emergence (Saayman 1996). Perry (1976a, 1976b) has suggested seed vigour is best measurable based on field performance (e.g. germination, emergence and seedling growth) and physiological variation (e.g. enzyme activity or oxygen uptake). Consequently, seed vigour has been measured on an as needed basis to meet research objectives.

The experimental design was split-plot, with cultivar as the main plot and seed burial depth as the sub-plot. All 29 cultivars used in the screening trial (Table 3.1) were used in this greenhouse trial. Twenty-five seeds per pot were sown at a depth of either 2 cm (shallow-seeded) or 8 cm (deep-seeded). Four replicates were seeded for two runs into pots containing ProMix, a peat-based growing medium (Premier Horticulture Ltd., Steinbach, Manitoba). Pots were filled with a consistent volume of ProMix in the following manner. Each pot was filled with one scoop of ProMix in a 4" tall x 3' diameter pot, which was then tamped down with a wooden paddle to prevent water and soil leakage from the bottom of the pot. To achieve a seeding depth of 8 cm, one more scoop of ProMix was added and hand-pressed to a measured depth of 10 cm from the top of the pot. To achieve a seeding depth of 2 cm, 3 scoops of ProMix were added and hand-pressed to a depth of 4 cm from the top of the pot. After seeding, all pots were then topped off to a uniform depth of 2 cm below the pot lip.

Measurements in this trial included emergence quantity, fresh biomass, and dry biomass. Emergence was enumerated on a daily basis from the time the first plant emerged from the 2 cm depth until the end of the trial, 7 days after final plant emergence. Fresh biomass was enumerated at the end of each trial by trimming plants at ground level and weighing samples. To obtain dry biomass, harvested plants were dried at 70° C for 72 hours and weighed. Vigour was calculated from both wet and dry biomass as:

$$\text{Vigour} = 100^{*}\ \text{Biomass}_{\text{Deep}}/\text{Biomass}_{\text{Shallow}} \qquad (4.4)$$

Competition Trial

A split-plot experimental design identical to the screening trial was used. The twenty-nine cultivars used in the screening trial were the main plot. Weed treatment (weedy versus weed-free) was the sub-plot. In 2001, crop density made an important contribution to competitive ability and this trial was designed to equalize crop density. To accomplish this, weed seed (tame oat was used as the weed species) and seed from each barley cultivar was pre-germinated in a petrie dish prior to seeding. All seed came from the seed increase undertaken in 2001.

This trial was run four times and some portions were implemented differently in runs one and three. In runs 1, 2, and 4, each petrie dish filter (Whatman PLC, Kent, UK) was first saturated with deionized water. After the first run, 5 ml of NoDamp fungicide (Plant Products Co. Ltd., Brampton) at a 10% solution was added after filter saturation with deionized water to prevent disease. In the third run, an error was made and fungicide was applied to saturate the filter paper. This had a negative effect on germination, especially for Virden. However, these data were still used in the analysis.

Except for Virden, which germinated on days two and three in the petrie dish, barley cultivars and tame oats, germinated on day one, or day two, or approximately equally on both days (Appendix B). Due these differences in germination rate, germination was staggered to have sufficient germinated seed of each barley cultivar and tame oat ready for seeding at approximately the same stage on seeding day.

In the first run of this experiment, four replicates were seeded and many cultivars were under-represented due to poor emergence of pre-germinated seed. Many plants suffered from foliar diseases, and fungi were observed on the seed as well. Consequently, in the three later runs, 5 replicates were seeded and extra pots of cultivars with poor emergence (Bacon, Dawn, Harrington, McGwire, Peregrine) were placed with each replicate to be used as replacements if required.

In all runs, weed and crop seeds were placed at a depth of 2 cm in pots filled with ProMix. In the weedy treatment, germinated weed seed was placed in the center of the pot. All seeds were placed in pots through a template to ensure spatially uniform seed placement and depth in each pot. In all pots, four seeds were planted with the weakest plant removed if all four seedlings emerged. An exception occurred in the third run where the "most different" plant was removed.

Harvest occurred approximately 14-17 days after seeding, when crop plants were approaching the 4-leaf stage. Since yield loss due to weed competition is thought to be complete by approximately the 4-leaf stage, harvest occurred approximately 14-17 days after seeding. At this time most cultivars were approaching, and none were substantially exceeding, the 4-leaf stage.

Measurements taken on each plant from this trial included: emergence date for each plant, final height, height to base of first leaf, Haun stage, fresh and dry barley leaf and stem biomass, fresh and dry oat biomass, and barley leaf area. Barley leaf area was mesured with an LI-3000 leaf area meter (LI-COR Inc, Lincoln, Nebraska). Competitive ability (AWC only) in this trial was calculated for both fresh and dry biomass as:

$$\mathrm{AWC} = 100^{*}\mathrm{Biomass}_{\mathrm{WP}}/\mathrm{Biomass}_{\mathrm{WFP}} \qquad (4.5)$$

where $\mathrm{Biomass}_{\mathrm{WP}}$ is the crop biomass in weedy pots and $\mathrm{Biomass}_{\mathrm{WFP}}$ is the biomass in weed-free pots.

4.2.3. Data Analysis

Transformation of data to improve normality is required only if the data is not normal and a transformation will improve data normality. All attributes were tested for normality using PROC UNIVARIATE (SAS 1990). SAS produces four statistics assessing normality but the Cramer-von Mises statistic (W^2) was selected (Steel et al. 1997 pp. 45-48). While this analysis indicated attributes were not statistically normal, Velleman (1997) has suggested that if a normal probability plot is linear or nearly linear, then the distribution of the variable is nearly normal. Inspection of the normal probability plots for the attributes collected indicated that most were approximately normal. Since data were approximately normal, and different transformations would be required to normalize different data types, it was considered useful to treat data homogeneously. Therefore, data were not transformed.

Data were tested for homogeneity of variance using Levene's test (SAS 1990). Data from 2001 and 2002 were considered separately, *a priori*, since there was a biological difference due to seed sources for field trials. In 2001 crop seed for field trials came from multiple sources whereas in 2002, crop seed was from a common source. In 2001, significant ($P \leq 0.05$) location by cultivar interactions occurred for most attributes. In 2002, attributes were frequently not homogeneous between sites. Consequently, a separate ANOVA using PROC GLM (SAS 1990) was conducted for each site-year and mean values for cultivar attributes were separated using a protected LSD at α=0.05. Since barley is commonly classified and discussed by breeders and producers in terms of phenotypic attributes (2- vs. 6-row, hulled vs. hull-less, full height vs. semi-dwarf) and end-use (malt vs. feed), linear contrasts were performed on these phenotypic and end-use classes to determine if attributes differed by these classes.

Since measurements of field-sown seed attributes were not replicated, ANOVA was not possible. However, differences in competitive ability between semi-dwarf and full-height, and between hulled and hull-less cultivar classes were established in Chapter 3. Consequently, the impact of these attributes on cultivar competitive ability may be examined by determining if attributes differed by pair-wise class comparisons, or by using simple correlation coefficients between these attributes and competitive ability

(AWC and AC). T-tests were performed to determine if differences existed between classes using PROC TTEST (SAS 1990).

Relationships between competitive ability (AWC and AC) and attributes were examined using simple correlation, partial correlation and regression analysis. Simple correlation was implemented using PROC CORR (SAS 1990), whereas partial correlation and regression analysis were implemented using PROC GLM (SAS 1990). The partial correlation coefficient measures the net correlation between two variables after excluding the common influence of another independent variable in the model. In replicated experiments, replicate was partialled out and, therefore, partial correlation coefficients accounted for experimental design. Linear regression analysis accounted for replicate as part of the model statement.

For breeding purposes, a correlation coefficient of 0.75 and repeatability of attribute relationships with competitive ability of greater than 2 in 3 (66.7%) has been suggested (Mario Therrien pers. comm.). Fox et al. (1997), suggest that for most quantitative attributes, within a 90% confidence interval, an R^2 of 0.7 is the minimum coefficient of determination useful in a breeding program. This corresponds to a correlation coefficient $\geq |0.8367|$. While defining "substantive" is subjective, a correlation coefficient of 0.75 yields an R^2 of 0.5625, which is considerable lower than the 0.7 suggested by Fox et al. (1997). Consequently, in this research, a correlation coefficient of 0.8 will be considered substantive.

Canonical correlation analysis (CANCORR) determines the linear relationship between two sets of variables (Kenkel et al. 2002). CANCORR summarizes the correlation between two variable sets by maximizing the correlation between a pair of derived linear composites, or canonical variates, for each data set. Conceptually, CANCORR is somewhat like performing PCA on two data sets such that the correlation between the i^{th} axis of each data set is maximally correlated. In this research, CANCORR was used to relate the two vigour calculations (based on wet and dry biomass) to the two components of competitive ability (AWC and AC). CANCORR was implemented in SAS (SAS 1990) using PROC CANCORR.

4.3 RESULTS

4.3.1 Seed (S) Phase

Attributes measured directly on the seed to be sown in the field included seed mass, daily germination for 7 days, and total percent germination. Since measurements of these attributes was not replicated, ANOVA was not possible. However, differences in competitive ability between semi-dwarf and full-height, and between hulled and hull-less cultivar classes were established in Chapter 3. Consequently, the impact of these attributes on cultivar competitive ability can be examined by determining if attributes differed by pair-wise class comparisons, or by using simple correlation coefficients between these attributes and competitive ability (AWC and AC).

Seed phase attributes have been summarized by cultivar (Appendix B). In general, t-tests indicated that these attributes did not differ by cultivar grouping excepting the hull versus hull-less comparison (Table 4.2). Seed mass, percent germination in each of the first 3 days, and total percent germination differed between hull-less and hulled classes of barley cultivars. As a class, hulled cultivars were heavier, germinated at a slower rate, and had lower total germination than hull-less cultivars (Table 4.3). Further results on "seed attributes" pertain only to seed mass, germination on Days 1, 2, and 3, and total percent germination.

A statistically significant correlation coefficient of seed attributes with either AWC (Table 4.4) or AC (Table 4.5) was generally present only when all cultivars were considered, but not when hulled and hull-less cultivars were considered separately. However, percent germination on Day 3 in 2002 was significantly correlated with AWC and AC when all, or only hulled cultivars were considered, but not when only hull-less cultivars were considered. Furthermore, total percent germination was significantly correlated only with the hull-less class of cultivars.

The relationship between seed mass and competitive ability (AWC or AC) was consistently positive, excepting hulled cultivars at the Prodan 2001 site (Tables 4.4 and 4.5). The correlation of percent germination on Day 1 was consistently negative with both AWC (Table 4.4) and AC (Table 4.5). Correlation of percent germination on Day 2 with AWC (Table 4.4) or AC (Table 4.5) was consistently positive when all cultivars, or only hull-less cultivars were considered, but it was negative when only the hulled cultivars were considered. Day 3 germination was consistently positive for all classes (Tables 4.4 and 4.5). In 2001, more germination occurred on or after Day 3 than in 2002 (Appendix B). In 2002, more competitive cultivars, such as Virden, Ranger, Robust, Lacombe and Bedford tended to have substantial germination on or after Day 3 (Appendix B). For the producer, increased seed mass is perceived (Entz et al. 1990; Gan and Stobbe 1996; Lafond and Baker 1986a, 1986b) as an option to improve vigour, and hence competitive ability. Our results indicate this is true within, rather than among, cultivars.

Despite being measured in the seedling (L) phase, crop emergence is a seed-dependent attribute that integrates seed germinability, quality and vigour. However, since emergence was measured as crop density at the 3- to 4-leaf stage, it is also influenced by soil and air moisture and temperature. Significant differences in cultivar emergence were detected in 2001, but in only one location in 2002 (Table 4.6). Crop density (Table 4.6) was relatively well-correlated with both AWC and AC in 2001, but not in 2002 when a common seed source was used and drier climatic conditions prevailed (Appendix B).

Despite the comparative homogeneity of climate, moisture, and seed substrate in greenhouse versus field experiments, the two runs of the greenhouse vigour trial were not homogeneous according to Levene's test (SAS 1990). Therefore, each run was considered separately. Significant differences in vigour, based on fresh and dry biomass, were found among cultivars in run 1, but not in run 2 (Table 4.7). The mean vigour for each cultivar is presented in Appendix B. While differences in vigour existed among cultivars, the relationship between seed vigour and competitive ability was variable between greenhouse runs and among site-years (Table 4.8). Run 2 had fewer statistically significant canonical correlation coefficients with competitive ability than run 1 and less frequently accounted for significant variance on the first canonical axis (Table 4.8).

Table 4.2 Phenotypic and end-use class differences (p-values), based on t-tests, for seed attributes measured on seed to be seeded in field trials. Non-significant ($\alpha=0.05$) t-tests are denoted ns.

Attribute	ROWS: 2 vs 6		HEIGHT: Full Vs. Semi-Dwarf		HULL: Yes vs. No		USE: Feed Vs. Malt	
	2001	2002	2001	2002	2001	2002	2001	2002
Seed Mass	ns	ns	0.0448	ns	0.0027	0.0002	0.0179	0.0349
% Germination (Day 1)	ns	0.0150	ns	ns	0.0018	0.0006	ns	ns
% Germination (Day 2)	ns	ns	ns	ns	ns	0.0021	ns	0.0190
% Germination (Day 3)	ns	0.0174	ns	0.0477	0.0356	0.0041	ns	ns
% Germination (Day 4)	ns	ns	ns	ns	ns	ns	ns	ns
% Germination (Day 5)	ns	ns	ns	0.0428	ns	0.0419	ns	ns
% Germination (Day 6)	ns	-	0.0024	-	0.0019	-	ns	-
% Germination (Day7)	ns	ns	ns	ns	ns	ns	ns	ns
% Germination (Total)	ns	0.0392	0.0366	ns	0.0054	0.0172	ns	ns

Table 4.3. Means (± standard errors) for hulled versus hull-less cultivars for seed attributes collected by cultivar.

Attribute	2001		2002	
	Hull-less	Hulled	Hull-less	Hulled
Seed Mass (g 1000-kernel^{-1})	37.2 ± 1.1	42.8 ± 1.0	33.1 ± 0.7	39.4 ± 1.0
% Germination (Day 1)	70.9 ± 6.0	38.7 ± 5.2	56.9 ± 7.2	16.5 ± 3.8
% Germination (Day 2)	21.4 ± 5.5	35.2 ± 2.9	35.2 ± 6.4	65.4 ± 3.6
% Germination (Day 3)	1.6 ± 0.4	4.9 ± 1.4	1.0 ± 0.4	7.3 ± 1.8
% Germination (Day 4)	1.6 ± 0.6	3.2 ± 0.6	0.1 ± 0.1	0.7 ± 0.4
% Germination (Day 5)	0.3 ± 0.2	0.3 ± 0.2	0.0 ± 0.0	0.2 ± 0.1
% Germination (Day 6)	0.0 ± 0.0	0.6 ± 0.2	-[a]	-
% Germination (Day7)	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.3 ± 0.2
% Germination (Total)	95.8 ± 2.1	83.1 ± 3.3	95.8 ± 0.8	90.7 ± 1.7

a: indicates data not collected

4.3.2 Seedling (L) and Seedling-Mature Plant (L-H) Phase

Competition Trial

In general, when ratios of attributes, such as leaf area, biomass, and Haun stage, were calculated for weedy versus weed-free pots, there were no differences between cultivars (Table 4.9) and most ratios were approximately 100. For these same attributes collected in weedy pots, differences between cultivars were found in most cases (Table 4.9, Appendix B). Consequently, measurements on weedy and weed-free attributes did not differ from each other.

In the greenhouse, plant height had the best relationship to competitive ability. Within runs (Appendix B), correlation coefficients were more often significant for AC than for AWC and were generally greater for AC than AWC. While many of these correlation coefficients were statistically significant (Appendix B), none were substantive (i.e. $|r| \geq 0.8$).

Screening Trial

In this field trial, herbicide damage and Haun stage were specific to the seedling stage (Figure 4.1). Cultivars generally differed by Haun stage (Table 4.11). Herbicide damage differed significantly for cultivars in 2001, but generally not in 2002 (Table 4.11) when conditions were drier and colder (Appendix B). Measurement of percent light extinction, % cover and plant height, all commenced in the seedling (L) phase and continued into the mature plant (H) phase (Figure 4.1). Differences occurred among cultivars for most observations in most site-years (Table 4.11, Appendix B).

Table 4.4. Correlation coefficients for seed measurements by cultivar and ability to withstand competition (AWC). The critical minimum value for significance for each class ($p \leq 0.05$) is indicated in parentheses. Non-significant (α=0.05) correlation coefficients are denoted ns.

Attribute	2001		2002				Mean
All (0.3672)	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
SeedMass	0.4298	0.4269	0.4759	0.5752	0.4393	0.3419^{ns}	0.4482
Day1	-0.5936	-0.4509	-0.3629^{ns}	-0.3835	-0.4492	-0.1695^{ns}	-0.4016
Day2	0.4238	0.3401^{ns}	0.1918^{ns}	0.2234^{ns}	0.2321^{ns}	-0.0236^{ns}	0.2313
Day3	0.3770	0.2966^{ns}	0.4831	0.5454	0.5900	0.4944	0.4644
Day4	0.1463^{ns}	0.1365^{ns}	0.3338^{ns}	0.3494^{ns}	0.4084	0.3331^{ns}	0.2846
Day5	-0.0734^{ns}	-0.1480^{ns}	0.1826^{ns}	0.3414^{ns}	0.1821^{ns}	0.1916^{ns}	0.1127
Day6	0.4024	0.2997^{ns}	-[a]	-	-	-	0.3510
Day7	0.3685	0.3297^{ns}	0.3634^{ns}	0.4098	0.4679	0.4094	0.3915
% Germination (total)	-0.4630	-0.3250^{ns}	-0.2377^{ns}	-0.1496^{ns}	-0.3035^{ns}	-0.1205^{ns}	-0.2666
Hull-less (0.6319)							
SeedMass	0.3455^{ns}	0.3957^{ns}	0.4271^{ns}	0.5884^{ns}	0.4440^{ns}	0.3864^{ns}	0.4312
Day1	-0.5598^{ns}	-0.4902^{ns}	-0.2422^{ns}	-0.2118^{ns}	-0.1453^{ns}	0.0264^{ns}	-0.2705
Day2	0.5521^{ns}	0.3981^{ns}	0.3296^{ns}	0.2676^{ns}	0.2126^{ns}	0.0162^{ns}	0.2960
Day3	0.1138^{ns}	0.3274^{ns}	0.3801^{ns}	0.4674^{ns}	0.2597^{ns}	0.1891^{ns}	0.2896
Day4	-0.1402^{ns}	-0.3994^{ns}	0.1615^{ns}	0.0882^{ns}	0.1792^{ns}	0.2912^{ns}	0.0301
Day5	-0.1800^{ns}	-0.3608^{ns}	-	-	-	-	-0.2704
Day6	-	-	-	-	-	-	-
Day7	-	-	0.1615^{ns}	0.0882^{ns}	0.1792^{ns}	0.2912^{ns}	0.1800
% Germination (total)	-0.1796^{ns}	-0.4338^{ns}	0.8026	0.7626	0.8014	0.7853	0.4231
Hulled (0.4555)							
SeedMass	0.0374^{ns}	0.2091^{ns}	0.4745	0.4803	0.2671^{ns}	0.3896^{ns}	0.3097
Day1	-0.3412^{ns}	-0.1907^{ns}	-0.2336^{ns}	-0.1970^{ns}	-0.4039^{ns}	-0.2878^{ns}	-0.2757
Day2	-0.1995^{ns}	-0.0227^{ns}	-0.3520^{ns}	-0.1844^{ns}	-0.1235^{ns}	-0.2417^{ns}	-0.1873
Day3	0.4650	0.2657^{ns}	0.6101	0.5383	0.6019	0.6713	0.5254
Day4	0.0477^{ns}	0.3077^{ns}	0.4348^{ns}	0.3584^{ns}	0.4176^{ns}	0.4066^{ns}	0.3288
Day5	-0.0569^{ns}	-0.0670^{ns}	0.1723^{ns}	0.3275^{ns}	0.1051^{ns}	0.2332^{ns}	0.1190
Day6	0.3907^{ns}	0.2481^{ns}	-	-	-	-	0.3194
Day7	0.5578	0.4362^{ns}	0.5000	0.4719	0.5207	0.4962	0.4971
% Germination (total)	-0.4715	-0.1295^{ns}	-0.4742	-0.1568^{ns}	-0.3642^{ns}	-0.3007^{ns}	-0.3162

a: indicates data not collected

Table 4.5. Correlation coefficients for seed measurements by cultivar and ability to compete (AC). The critical minimum value for significance for each class ($p \leq 0.05$) is indicated in parentheses. Non-significant ($\alpha=0.05$) correlation coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
All (0.3672)							
SeedMass	0.4857	0.4977	0.6201	0.4987	0.4040	0.4928	0.4998
Day1	-0.6374	-0.5792	-0.2700^{ns}	-0.5096	-0.3161^{ns}	-0.3627^{ns}	-0.4458
Day2	0.4618	0.3674	0.1015^{ns}	0.2578^{ns}	0.0915^{ns}	0.1740^{ns}	0.2423
Day3	0.3641^{ns}	0.3853	0.5082	0.6890	0.6013	0.5518	0.5166
Day4	0.1803^{ns}	0.1699^{ns}	0.4255	0.4877	0.3912	0.3809	0.3393
Day5	-0.0269^{ns}	-0.0575^{ns}	0.2787^{ns}	0.3359^{ns}	0.2357^{ns}	0.2481^{ns}	0.1690
Day6	0.3156^{ns}	0.2864^{ns}	-[a]	-	-	-	0.3010
Day7	0.3286^{ns}	0.3899	0.4250	0.5119	0.3983	0.4150	0.4115
% Germination (total)	-0.5062	-0.4967	-0.1304^{ns}	-0.3537^{ns}	-0.1826^{ns}	-0.1989^{ns}	-0.3114
Hull-less (0.6319)							
SeedMass	0.4670^{ns}	0.4603^{ns}	0.4943^{ns}	0.4511^{ns}	0.5006^{ns}	0.4767^{ns}	0.4750
Day1	-0.6043^{ns}	-0.5511^{ns}	-0.0528^{ns}	-0.2390^{ns}	-0.0227^{ns}	-0.1513^{ns}	-0.2702
Day2	0.5438^{ns}	0.4535^{ns}	0.1330^{ns}	0.3021^{ns}	0.0376^{ns}	0.2107^{ns}	0.2801
Day3	0.2990^{ns}	0.4178^{ns}	0.3832^{ns}	0.3489^{ns}	0.3446^{ns}	0.3604^{ns}	0.3590
Day4	-0.1111^{ns}	-0.2914^{ns}	0.2251^{ns}	0.1962^{ns}	0.0236^{ns}	0.1643^{ns}	0.0345
Day5	-0.1664^{ns}	-0.3328^{ns}	-	-	-	-	-0.2496
Day6	-	-	-	-	-	-	-
Day7	-	-	0.2251^{ns}	0.1962^{ns}	0.0236^{ns}	0.1643^{ns}	0.1523
% Germination (total)	-0.2831^{ns}	-0.4103^{ns}	0.8514	0.8092	0.8139	0.8015	0.4304
Hulled (0.4555)							
SeedMass	-0.0275^{ns}	0.1197^{ns}	0.6726	0.2993^{ns}	0.2896^{ns}	0.4256^{ns}	0.2966
Day1	-0.3840^{ns}	-0.2615^{ns}	-0.1206^{ns}	-0.3776^{ns}	-0.3409^{ns}	-0.2721^{ns}	-0.2928
Day2	-0.1768^{ns}	-0.1846^{ns}	-0.3234^{ns}	-0.2250^{ns}	-0.2224^{ns}	-0.2258^{ns}	-0.2263
Day3	0.4112^{ns}	0.3468^{ns}	0.5536	0.7094	0.7209	0.6147	0.5594
Day4	0.0636^{ns}	0.1670^{ns}	0.4904	0.5122	0.4751	0.4295^{ns}	0.3563
Day5	0.0547^{ns}	0.0684^{ns}	0.2812^{ns}	0.2877^{ns}	0.2324^{ns}	0.2299^{ns}	0.1924
Day6	0.1132^{ns}	0.0590^{ns}	-	-	-	-	0.0861
Day7	0.5225	0.5148	0.4996	0.5777	0.5158	0.4968	0.5212
% Germination (total)	-0.5490	-0.3738^{ns}	-0.2104^{ns}	-0.4000^{ns}	-0.3042^{ns}	-0.2933^{ns}	-0.3551

a: indicates data not collected

Table 4.6. Cultivar differences (p-values), based on ANOVA, in crop density, and correlation coefficients with AWC and AC. Non-significant (α=0.05) p-values and correlation coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Cultivar	<0.0001	<0.0001	ns	<0.0001	ns	ns	-
AWC Correlation Coefficient	0.5257	0.4255	0.2238	0.3564	0.1199^{ns}	0.0422^{ns}	0.2823
AC Correlation Coefficient	0.6064	0.6640	0.3219	0.4903	0.2771	0.1341^{ns}	0.4156

Table 4.7. Cultivar differences (p-values), based on ANOVA, for vigour, based on fresh and dry biomass, for the greenhouse vigour trial. Seed vigour is calculated as the ratio of biomass between deep- versus shallow-seeded plants. Non-significant (α=0.05) p-values are denoted ns.

	Run 1		Run 2	
	Fresh	Dry	Fresh	Dry
Cultivar	0.0001	0.0009	ns	ns

Table 4.8. Canonical correlation of seed vigour, as measured in greenhouse vigour trials, to competitive ability of barley at Ramada and Newdale locations in 2002. Non-significant (α=0.05) correlation coefficients are denoted ^{ns}. Seed vigour is calculated as the ratio of biomass between deep- versus shallow-seeded plants.

Site-year	Canonical Correlation		Proportion^{a}	
	Run 1	Run 2	Run 1	Run 2
Ramada 1	0.3458	0.1111^{ns}	0.9980	0.7373^{ns}
Ramada 2	0.5371	0.2845	0.9650	0.8584
Newdale 1	0.3567	0.2403^{ns}	0.9673	0.9221
Newdale 2	0.3546	0.1053^{ns}	0.8108	0.6183^{ns}
Mean	0.3985	0.1853	0.9353	0.7840

a: Represents the proportion of total generalized variance accounted for on axis 1 of the canonical correlation analysis. Axes were statistically different from zero unless indicated (^{ns}).

Table 4.9. Cultivar differences (p-values), based on ANOVA, for attributes measured in the greenhouse competition trial. All ratios were calculated as: $100*(\text{Attribute}_{\text{weedy}}/\text{Attribute}_{\text{weed-free}})$. Non-significant ($\alpha=0.05$) p-values are denoted ns.

	Ratios			Weedy plots		
Attribute	Run 2	Run 3	Run 4	Run 2	Run 3	Run 4
Leaf area	ns	ns	ns	<0.0001	<0.0001	<0.0001
Leaf biomass (fresh)	ns	ns	ns	<0.0001	0.0005	<0.0001
Stem biomass (fresh)	ns	ns	ns	<0.0001	0.0040	0.0012
Total biomass (fresh)	ns	ns	ns	<0.0001	0.0018	<0.0001
Leaf biomass (dry)	ns	ns	ns	<0.0001	0.0002	0.0037
Stem biomass (dry)	ns	ns	ns	ns	0.0035	0.0023
Total biomass (dry)	ns	ns	ns	0.0003	0.0006	0.0017
Plant height	ns	ns	ns	0.0035	0.0001	0.0052
1st leaf height[a]	ns	ns	ns	0.0394	<0.0001	<0.0001
Haun stage	ns	ns	ns	<0.0001	<0.0001	<0.0001
Leaf area ratio (LAR)	ns	0.0350	ns	<0.0001	<0.0001	0.0275
Specific leaf area (SLA)	ns	0.0445	ns	<0.0001	<0.0001	ns
Oat fresh biomass	-[b]	-	-	ns	0.0054	0.0163
Oat dry biomass	-	-	-	ns	0.0025	ns

a: height to leaf base

b: data not collected in weed-free plots. Therefore, no ratios can be calculated.

Table 4.10. Mean correlation coefficient for each attribute collected in the greenhouse trial with the mean of ability to withstand competition (AWC) and ability to compete (AC) for 2002. Measurements are on barley unless oat is specified. See Table 3.4.

Attribute	AWC	AC
Leaf area	0.3150	0.4853
Fresh leaf biomass	0.2864	0.4415
Fresh stem biomass	0.3160	0.4431
Fresh total biomass	0.3194	0.4505
Dry leaf biomass	0.3172	0.4453
Dry stem biomass	0.1987	0.3068
Dry total biomass	0.2940	0.4207
Plant height	0.4989	0.5364
1st leaf height[a]	0.3353	0.4713
Haun stage	0.0785	-0.1035
Leaf area ratio (LAR)	0.0122	0.0687
Specific leaf area (SLA)	0.1542	0.2295
Oat fresh biomass	-0.0810	-0.0830
Oat dry biomass	-0.0899	-0.0930

a: Height to leaf sheath of 1st leaf.

On average, correlation coefficients were highest for percent light extinction and crop height with AWC (Table 4.12) and AC (Table 4.13) for the first measurement taken, irrespective of when that occurred (Table 4.1). By contrast, percent cover was best correlated with AWC (Table 4.12) and AC (Table 4.13) for later measurements. The relationship of these attributes with AWC (Table 4.12) and AC (Table 4.13) was variable between years and among assessment dates. While the statistical significance of regression coefficients of these attributes with AWC (Table 4.14) and AC (Table 4.15) was identical to that of the correlation coefficients, regression coefficients varied considerably by year and assessment within year.

Table 4.11. Cultivar differences (p-values), based on ANOVA, for attributes measured on barley cultivars grown in the field over two seasons on Prodan, Newdale and Ramada soil series. Analysis included all cultivars. Non-significant (α=0.05) p-values are denoted ns.

Attribute	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Herbicide damage[a]	<0.0001	<0.0001	ns	ns	0.0221	ns
Haun stage	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001
% Light extinction (t_1)[b]	<0.0001	0.0020	ns	<0.0001	0.0235	ns
% Light extinction (t_2)	<0.0001	ns	0.0179	<0.0001	ns	<0.0001
% Light extinction (t_3)	-	-	-	<0.0001	ns	ns
% Light extinction (t_4)	-	-	-	-	0.0477	0.0019
% Cover (t_1)[c]	<0.0001	<0.0001	0.0066	0.0076	0.0058	0.0074
% Cover (t_2)	<0.0001	-	0.0255	<0.0001	ns	0.0139
% Cover (t_3)	<0.0001	<0.0001	-	<0.0001	0.0403	ns
% Cover (t_4)	<0.0001	<0.0001	-	<0.0001	0.0062	0.0182
% Cover (t_5)	<0.0001	-	-	-	-	-
Height (t_1)[d]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Height (t_2)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Height (t_3)	-	-	<0.0001	<0.0001	<0.0001	<0.0001
Height (t_4)	-	-	<0.0001	<0.0001	<0.0001	<0.0001
Height (t_5)	-	-	-	<0.0001	<0.0001	<0.0001
Height (max)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

a: Rating: 0 = no damage, 100 = dead due to herbicide damage
b: For time of measurement see table 4.1
c: Measured as % green by digital analysis.
d: cm

4.3.3 Mature Plant (H) Phase and Post-Harvest Measurements

Feekes stage (t_1) differed among cultivars for all site-years whereas Feekes stage (t_2) differed only for the later-seeded Ramada 2 and Newdale 2 site-years (Table 4.16, Appendix B). Lodging ratings differed in only one of six site-years and no differences among cultivars were found in oat 1000-kernel weight collected from plots containing the various barley cultivars. For all other attributes collected there were consistent differences among cultivars (Table 4.16).

Table 4.12. Partial correlation coefficients for AWC with attributes collected in the screening trial. Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Herbicide damage^a	-0.3722	0.0803^{ns}			-0.0467^{ns}	-0.1011^{ns}	-0.1099
Haun stage	-0.1430^{ns}	-0.1684^{ns}	0.1414^{ns}	0.0076^{ns}	-0.1281^{ns}	0.0627^{ns}	-0.0380
% Light extinction (t_1)^b	0.3835	0.2615	0.4040	0.4322	0.1931^{ns}	0.2671	0.3236
% Light extinction (t_2)	0.1429^{ns}	0.0688^{ns}	0.1338^{ns}	0.3783	0.1963	0.2003	0.1867
% Light extinction (t_3)				0.3374	0.2688	0.2081	0.2714
% Light extinction (t_4)					0.2471	0.1833^{ns}	0.2152
% Cover (t_1)c	0.5015	0.3396	0.2876	0.3772	0.1949	0.1111^{ns}	0.3020
% Cover (t_2)			0.2883	0.4996	0.2134	0.0990^{ns}	0.2751
% Cover (t_3)	0.6620	0.38856		0.5191	0.2762	0.0426^{ns}	0.3777
% Cover (t_4)	0.6383	0.4819		0.4481	0.2540	0.1169^{ns}	0.3878
% Cover (t_5)	0.6203						0.6203
Height (t_1)^d	0.5581	0.4501	0.3451	0.5733	0.3286	0.4694	0.4541
Height (t_2)	0.5275	0.4884	0.2983	0.5086	0.2325	0.4410	0.4161
Height (t_3)		0.4926	0.2775	0.5589	0.2985	0.4354	0.4126
Height (t_4)		0.5615	0.2992	0.5534	0.2062	0.3943	0.4029
Height (t_5)				0.5433	0.2556	0.4238	0.4076
Height (max)	0.5275	0.5120	0.3049	0.5509	0.2269	0.4211	0.4239

a: Rating: 0 = no damage, 100 = dead due to herbicide damage
b: For time of measurement see table 4.1
c: Measured as % green by digital analysis.
d: cm

Table 4.13. Partial correlation coefficients for AC with attributes collected in the screening trial. Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Herbicide damage^{a}	-0.3536	0.2498			-0.2237	-0.2137	-0.1353
Haun stage	-0.1632^{ns}	-0.2349	0.0572^{ns}	-0.1931	-0.2301	-0.1200^{ns}	-0.1474
% Light extinction (t_1)^{b}	0.4004	0.3072	0.4717	0.5674	0.3010	0.4206	0.4114
% Light extinction (t_2)	0.1654^{ns}	0.1998	0.3376	0.5264	0.3846	0.3431	0.3262
% Light extinction (t_3)				0.4778	0.4678	0.3292	0.4249
% Light extinction (t_4)					0.4321	0.2509	0.3415
% Cover (t_1)^{c}	0.5755	0.5720	0.3536	0.4452	0.4587	0.2427	0.4413
% Cover (t_2)			0.3727	0.6606	0.4442	0.2115	0.4223
% Cover (t_3)	0.7460	0.5991		0.6403	0.4137	0.0990	0.4996
% Cover (t_4)	0.7548	0.6368		0.6209	0.4184	0.1838^{ns}	0.5229
% Cover (t_5)	0.6762						0.6762
Height (t_1)^{d}	0.5880	0.6631	0.4474	0.6905	0.5371	0.6418	0.5947
Height (t_2)	0.5522	0.6694	0.4647	0.6639	0.4780	0.6177	0.5743
Height (t_3)		0.5358	0.4360	0.7289	0.5192	0.6332	0.5706
Height (t_4)		0.6930	0.4498	0.6693	0.3555	0.5407	0.5417
Height (t_5)				0.7227	0.3907	0.5733	0.5622
Height (max)	0.5522	0.5596	0.4528	0.7033	0.3761	0.5652	0.5349

a: Rating: 0 = no damage, 100 = dead due to herbicide damage
b: For time of measurement see table 4.1
c: Measured as % green by digital analysis.
d: cm

The relationship between attributes and AC was slightly stronger than the relationship between attributes and AWC. Feekes stage, lodging, disease load, and oat 1000-kernel weights were seldom or never significantly correlated with either AWC (Table 4.17) or AC (Table 4.18). The correlation between yield in weed-free plots was significantly correlated with AWC in only one-half of the site-years, but was significantly correlated with AC in all site-years. Yield in weedy plots and % protein had significant correlation coefficients with both AWC (Table 4.17) and AC (Table 4.18) in all site-years. Barley 1000-kernel weight was significantly correlated with AC (Table 4.17). Correlation of barley 1000-kernel weight with AWC (Table 4.18) was non-significant only in the weed-free plots in the Newdale 2 site-year. Although the rank of each partial correlation coefficient was similar between attributes (Appendix B) and AWC or AC, the magnitude was generally greater for AC (Table 4.18) than AWC (Table 4.17).

Table 4.14. Regression slope coefficients for AWC with attributes collected in the screening trial. Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Herbicide damage[a]	-0.5223	0.1288^{ns}			-0.7010^{ns}	-0.1699^{ns}	-0.3161
Haun stage	-5.4179^{ns}	-9.2771^{ns}	4.5355^{ns}	0.2692^{ns}	-4.0115^{ns}	1.9274^{ns}	-1.9957
% Light extinction (t_1)[b]	0.9761	0.5088	0.2782	0.6163	0.3680^{ns}	0.5043	0.5420
% Light extinction (t_2)	0.3841	0.1790^{ns}	0.1502^{ns}	0.3708	0.2654	0.3460	0.2826
% Light extinction (t_3)				0.4062	0.2127	0.1541	0.2577
% Light extinction (t_4)					0.5314	0.3313^{ns}	0.4314
% Cover (t_1)[c]	4.1099	1.8352	0.4429	1.3763	0.3055	0.2543^{ns}	1.3874
% Cover (t_2)	2.6736		0.2507	0.6656	0.2068	0.0832^{ns}	0.7760
% Cover (t_3)	1.4247	0.6917		0.5028	0.2876	0.0329^{ns}	0.5879
% Cover (t_4)	1.6950	0.8138		0.5470	0.3485	0.1300^{ns}	0.7069
% Cover (t_5)	1.4154						1.4154
Height (t_1)[d]	0.6115	0.7665	1.3048	2.1713	1.3668	2.6458	1.4778
Height (t_2)	0.6309	0.6302	0.4684	1.4993	0.5357	1.0126	0.7962
Height (t_3)		0.6778	0.3093	1.0011	0.4557	0.5838	0.6055
Height (t_4)		1.1003	0.1007	1.0128	0.2610	0.4433	0.5836
Height (t_5)				0.9790	0.3193	0.4957	0.5980
Height (max)	0.6323	0.7225	0.3348	1.0075	0.2861	0.4785	0.5770

a: Rating: 0 = no damage, 100 = dead due to herbicide damage
b: For time of measurement see table 4.1
c: Measured as % green by digital analysis.
d: cm

Table 4.15. Regression slope coefficients for AC with attributes collected in the screening trial. Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Herbicide damage[a]	-0.4976	0.3824			-3.0595	-0.3137	-0.8721
Haun stage	-6.2008^{ns}	-12.3372	1.8820^{ns}	-7.3332	-6.5661	-3.2195^{ns}	-5.6291
% Light extinction (t_1)[b]	0.9572	0.5708	0.3287	0.8690	0.4976	0.6885	0.6520
% Light extinction (t_2)	0.4460	0.4966	0.3905	0.5543	0.4738	0.5177	0.4798
% Light extinction (t_3)				0.6179	0.3374	0.2128	0.3894
% Light extinction (t_4)					0.8470	0.3960	0.6215
% Cover (t_1)[c]	4.7296	2.9508	0.5616	1.7447	0.6552	0.4851	1.8545
% Cover (t_2)	3.1033		0.3330	0.9453	0.3923	0.1552	0.9858
% Cover (t_3)	1.6101	1.0184		0.6661	0.3926	0.0669^{ns}	0.7508
% Cover (t_4)	2.0101	1.0268		0.8142	0.5231	0.1784^{ns}	0.9105
% Cover (t_5)	1.5471						1.5471
Height (t_1)[d]	0.6460	1.0782	1.7444	2.8092	2.0363	3.1591	1.9122
Height (t_2)	0.6624	0.8247	0.7479	2.1020	1.0039	1.2386	1.0966
Height (t_3)		0.7040	0.5003	1.4025	0.7225	0.7415	0.8142
Height (t_4)		1.2965	0.5106	1.3156	0.4100	0.5309	0.8127
Height (t_5)				1.3988	0.4448	0.5857	0.8098
Height (max)	0.6672	0.7539	0.5121	1.3814	0.4321	0.5609	0.7179

a: Rating: 0 = no damage, 100 = dead due to herbicide damage
b: For time of measurement see table 4.1
c: Measured as % green by digital analysis.
d: cm

Few substantive relationships (i.e. $|r| \geq 0.8$) between attributes and AWC or AC were found. The relationship between yield in weedy plots and AC (Table 4.17) was generally substantive, and the relationship between yield in weedy plots and AWC (Table 4.17) was substantive in 2001, and on average, close to substantive. No other attributes were substantively related to competitive ability (AWC or AC).

Regression slopes for barley cultivar attributes with AWC (Table 4.19) and AC (Table 4.20) had a pattern of statistical significance nearly identical to the correlation coefficients. Substantive regression coefficients occur when meaningful increases in either AWC or AC occur for an achievable increase in an attribute. Since only yield in weedy plots was substantively correlated with competitive ability, it is the only attribute that would be useful in a regression analysis. Since the mean LSDs for AWC and AC were approximately 11 and 7, respectively (Table 3.5), an increase of about 10 units of either (or both) AWC or AC may be deemed to represent a significant increase competitive ability. The mean regression coefficients for yield in weedy plots with AWC and AC were 0.0176 and 0.0206, respectively. To achieve a 10-unit increase in AWC and AC, yield in weedy plots would have to increase by 568 kg ha^{-1} and 485 kg ha^{-1}, respectively. Therefore, to achieve a 10-unit increase in both AWC and AC yield in weedy plots would have to increase by 568 kg ha^{-1}. The minimum average yield of 2171 kg ha^{-1} occurred with Falcon, while the maximum average yield of 3535 kg ha^{-1} occurred with Ranger (Appendix B). Therefore, a 10-unit increase in both AWC and AC would require a weedy plot yield increase of 26% and 16% increase for Falcon and Ranger, respectively.

Table 4.16. Cultivar differences (p-values) in mature plant (H) and post-harvest phase attributes. Measurements were on barley unless otherwise indicated (Oat) and in weed-free plots unless otherwise indicated (weedy). Non-significant (α=0.05) p-values are denoted ns.

Attribute	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Feekes stage (t_1)[a]	-[d]	-	<0.0001	<0.0001	<0.0001	<0.0001
Feekes Stage (t_2)	-	-	ns	<0.0001	ns	<0.0001
Lodging[b]	ns	<0.0001	n/a[e]	n/a[e]	n/a[e]	n/a[e]
Disease load[c]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Yield (kg ha^{-1})	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Yield (weedy: kg ha^{-1})	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
% Protein	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
1000-kernel weight	-	-	-	<0.0001	-	<0.0001
1000-kernel weight (weedy)	-	-	-	<0.0001	-	<0.0001
1000-kernel weight (Oat)	-	-	ns	ns	ns	ns

a: For time of measurement see table 4.1
b: Rating: 0 = no lodging, 100 = all plants lodged
c: Rating: 0 = no disease, 100 = dead due to disease
d: Attribute not rated
e: Attribute not rated since none present

Table 4.17. Partial correlation coefficients for AWC with attributes collected in the mature plant (H) and post-harvest phase attributes. Measurements were on barley unless otherwise indicated (Oat) in weed-free plots unless otherwise indicated (weedy). Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Feekes stage (t_1)[a]	-[d]	-	0.0184^{ns}	-0.1563^{ns}	0.0205^{ns}	-0.1359^{ns}	-0.0633
Feekes Stage (t_2)	-	-	0.0448^{ns}	0.0001^{ns}	0.0357^{ns}	-0.1228^{ns}	-0.0141
Lodging[b]	-0.0409^{ns}	0.2750	n/a[e]	n/a[e]	n/a[e]	n/a[e]	0.1171
Disease load[c]	0.0517^{ns}	0.0123^{ns}	-0.0428^{ns}	0.0811^{ns}	-0.0506^{ns}	0.0278^{ns}	0.1325
Yield (kg ha^{-1})	0.3972	0.1822^{ns}	0.2282	0.2460	0.0563^{ns}	0.0439^{ns}	0.1923
Yield (weedy: kg ha^{-1})	0.8233	0.8164	0.6286	0.7196	0.7430	0.6921	0.7372
% Protein	-0.5601	-0.3653	-0.2920	-0.3056	-0.3443	-0.4515	-0.3865
1000-kernel weight	-	-	-	0.4770	-	0.1553^{ns}	0.3162
1000-kernel weight (weedy)	-	-	-	0.5934	-	0.3196	0.4565
1000-kernel weight (Oat)	-	-	-0.0045^{ns}	-0.0588^{ns}	0.2053	-0.2588	-0.0292

a: For time of measurement see table 4.1
b: Rating: 0 = no lodging, 100 = all plants lodged
c: Rating: 0 = no disease, 100 = dead due to disease
d: Attribute not rated
e: Attribute not rated since none present

4.4 DISCUSSION

4.4.1 Seed (S) Phase

This research represents the first investigation of the contribution of seed attributes to barley cultivar competitive ability using a large number of cultivars. Factors widely considered to contribute to seed vigour, and thus competitive ability, include: seed mass (Ching et al. 1977), early and uniform germination and emergence (Perry 1976a), and rapid seedling growth (Perry 1976a). This research approach offers the opportunity to test these hypotheses.

Previous research has related seed mass to competitive ability in barley (Kaufman and McFadden 1960) and wheat (Aparicio et al. 2002; Bockus and Shroyer 1996; Gan and Stobbe 1996; Lafond and Baker 1986a, 1986b; Stougaard and Xue 2004; Xue and Stougaard 2002) has employed seed mass fractions in single cultivars. Consequently, results cannot be generalized among cultivars. In general, improved performance has been reported with larger/heavier seeds compared to smaller/lighter seeds.

Our research indicates that seed mass, *per se*, does not make a significant contribution to barley competitive ability. When considering hulled and hull-less classes separately, seed mass was no longer significantly correlated with either AWC or AC. Excluding hull-less and semi-dwarf classes, 6-row cultivars represented 6 of the 8 most competitive cultivars (Figure 3.1). Six-row cultivars generally have more variable seed size including a larger fraction of smaller seeds, but are, nonetheless, more competitive than 2-row cultivars. Furthermore, Virden was observed in the cleaning process to have a large proportion of small seed (personal observation), but was consistently the most competitive cultivar (Figure 3.1, Appendix A). Consequently, seed size may contribute to competitive ability within cultivars, but does not necessarily contribute to differences in competitive ability among cultivars.

Table 4.18. Partial correlation coefficients for AC with attributes collected in the mature plant (H) and post-harvest phase attributes. All attribute measurements were on barley unless otherwise indicated (Oat) and were measured in weed-free plots unless otherwise indicated (weedy). Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Feekes stage (t_1)[a]	-[d]	-	0.0912^{ns}	0.0458^{ns}	0.1143^{ns}	-0.0504^{ns}	0.0502
Feekes Stage (t_2)	-	-	0.0776^{ns}	0.1947	0.1133^{ns}	0.0612^{ns}	0.1117
Lodging[b]	-0.0719^{ns}	0.1483^{ns}	n/a[e]	n/a[e]	n/a[e]	n/a[e]	0.0382
Disease load[c]	0.0563^{ns}	-0.0415^{ns}	-0.1430^{ns}	-0.2084	-0.1447^{ns}	-0.1655^{ns}	-0.1078
Yield (kg ha^{-1})	0.6767	0.5871	0.5981	0.6600	0.4869	0.4142	0.5705
Yield (weedy: kg ha^{-1})	0.9200	0.9203	0.8061	0.9238	0.8957	0.8281	0.8823
% Protein	-0.7259	-0.5898	-0.4012	-0.3458	-0.5340	-0.5214	-0.5197
1000-kernel weight	-	-	-	0.5949	-	0.2748	0.4349
1000-kernel weight (weedy)	-	-	-	0.7099	-	0.3564	0.5332
1000-kernel weight (Oat)	-	-	-0.0721^{ns}	-0.1150^{ns}	0.1683^{ns}	-0.1921	-0.0527

a: For time of measurement see table 4.1
b: Rating: 0 = no lodging, 100 = all plants lodged
c: Rating: 0 = no disease, 100 = dead due to disease
d: Attribute not rated
e: Attribute not rated since none present

Table 4.19. Regression slope coefficients for AWC with attributes collected in the mature plant (H) and post-harvest phase attributes. All attribute measurements were on barley unless otherwise indicated (Oat) and were measured in weed-free plots unless otherwise indicated (weedy). Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Feekes stage (t_1)[a]	-[d]	-	0.2443^{ns}	-3.1593^{ns}	0.4120^{ns}	-2.6149^{ns}	-1.2795
Feekes Stage (t_2)	-	-	1.6851^{ns}	0.0002^{ns}	2.6972^{ns}	-4.4288^{ns}	-0.0116
Lodging[b]	-0.0178^{ns}	0.1213	n/a[e]	n/a[e]	n/a[e]	n/a[e]	0.0518
Disease load[c]	0.0399^{ns}	0.0118^{ns}	-0.0210^{ns}	0.0951^{ns}	-0.0454^{ns}	0.0138^{ns}	0.0157
Yield (kg ha^{-1})	0.0084	0.0045^{ns}	0.0051	0.0069	0.0018^{ns}	0.0010^{ns}	0.0046
Yield (weedy: kg ha^{-1})	0.0149	0.0189	0.0135	0.0203	0.0227	0.0151	0.0176
% Protein	-8.4175	-4.6316	-2.1220	-2.7780	-4.1220	-4.7209	-4.4653
1000-kernel weight	-	-	-	1.5737	-	0.4202^{ns}	0.9970
1000-kernel weight (weedy)	-	-	-	1.7856	-	0.9193	1.3525
1000-kernel weight (Oat)	-	-	-0.0160^{ns}	-0.4029^{ns}	0.96789	-1.5032	-0.2386

a: For time of measurement see table 4.1
b: Rating: 0 = no lodging, 100 = all plants lodged
c: Rating: 0 = no disease, 100 = dead due to disease
d: Attribute not rated
e: Attribute not rated since none present

Table 4.20. Regression slope coefficients for AC with attributes collected in the mature plant (H) and post-harvest phase attributes. All attribute measurements were on barley unless otherwise indicated (Oat) and were measured in weed-free plots unless otherwise indicated (weedy). Non-significant (α=0.05) coefficients are denoted ns.

Attribute	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Feekes stage (t_1)[a]	-[d]	-	1.2382^{ns}	0.9937^{ns}	2.0930^{ns}	-0.8461^{ns}	0.8697
Feekes Stage (t_2)	-	-	3.0121^{ns}	7.6896	7.7988^{ns}	1.9279^{ns}	5.1071
Lodging[b]	-0.0313^{ns}	0.0625^{ns}	n/a[e]	n/a[e]	n/a[e]	n/a[e]	0.0156
Disease load[c]	0.0436^{ns}	-0.0382^{ns}	-0.0715^{ns}	-0.2625	-0.1183^{ns}	-0.0719^{ns}	-0.0865
Yield (kg ha^{-1})	0.0145	0.0139	0.0137	0.0199	0.0145	0.0085	0.0142
Yield (weedy: kg ha^{-1})	0.0167	0.0204	0.0178	0.0280	0.0250	0.0158	0.0206
% Protein	-10.9395	-7.1406	-3.0032	-3.3761	-5.8259	-4.7613	-5.8411
1000-kernel weight	-		-	2.1084	-	0.6494^{ns}	1.3789
1000-kernel weight (weedy)	-	-	-	2.2944	-	0.8953	1.5949
1000-kernel weight (Oat)	-	-	-0.2632^{ns}	-0.8473^{ns}	0.7231^{ns}	-0.9742	-0.3404

The premise that rapid and uniform germination contributes to competitive ability (Lemerle et al. 2001b) may be based on seed vigour research indicating early emergence will lead to early rapid growth and a subsequent advantage throughout the growing season (Ayre 1980). In our research, percent germination on Day 1 had a statistically insignificant, but consistently negative, relationship with competitive ability. Percent germination on Day 2 was generally negatively related to AC in 2003, when a common seed source was used. The relationship of percent germination on Day 3 to competitive ability was both significant and positive. This positive relationship occurred since some of the most competitive cultivars had substantial Day 3 (or later) germination. These results suggest that either: 1) rapid and uniform germination may not be necessary, 2) slower germination may be advantageous, or, 3) spurious correlation due to effects of some unmeasured factor.

Observation of preliminary germination tests suggests slower germination is advantageous. In these tests, 8 ml of water was added to a petrie dish, following protocols from the ISTA seed testing manual (International Seed Testing Association 1995). The most competitive cultivars tended to imbibe more moisture before germination After germination they commenced very rapid growth and quickly surpassed cultivars that had germinated early (personal observation). Virden was easily the most competitive cultivar investigated. It had the slowest germination rate and lowest total germination percentage of all cultivars (Appendix B). The rate of growth immediately after germination may be more important than rapidity or uniformity of germination.

The relationship between germination and competitive ability may vary by cultivar class. Unsurprisingly, malt cultivars generally germinated more quickly than feed cultivars since they are required to have a minimum 90% germination in three days to meet malt standards. However, four of the top eight most competitive cultivars were malt types. Consequently, rate of germination is unlikely to be consistent in its effect on competitive ability.

The relationship between crop emergence and competitive ability was variable between years. In 2001, when conditions were optimal for field crop emergence (Appendix B), emergence was an important factor contributing to AWC and AC. In 2002, when conditions were sub-optimal for seedling emergence, it played a minor role. A similar result has been obtained with green foxtail in wheat (Peterson and Nalewaja 1992) but, our results are confounded by the differences in seed source between 2001 and 2002. Since seed source alters seedlot characteristics (White 1990), emergence characteristics could not be strictly attributed to environment despite the apparent connection. The importance of crop emergence to competitive ability is dependent upon growing conditions within the crop year and when seed was grown.

The two seed vigour runs were unexpectedly heterogeneous. Relatively small differences in microclimate between greenhouse runs apparently superceded genetic effects in this greenhouse trial. It is possible that differences between the greenhouse runs are attributable to differences in seed within lots. However, this is unlikely since each trial used 100 seeds (25 seeds x 4 replicates) from a common source, that was well-mixed prior to usage.

The poor relationship between greenhouse seed vigour and field measurements of competitive ability was unexpected. In the field, Virden was visually superior to other cultivars where lush growth, dense stands, and tall plants were typical (personal observation). In greenhouse trials, Virden appeared ordinary, but was also the only cultivar for which total pot germination exceeded total petrie dish germination. Since greenhouse runs, initiated one month apart, were not homogeneous, and differences in growth occurred, the utility of controlled-environment trials when testing for competitive ability is questionable.

In the seed (S) phase, there was evidence that seed and seedling vigour contributed to competitive ability (AWC and AC), but that contribution was not quantifiable. For example, Ranger was substantially less competitive in 2001 (disparate seed sources) than 2002 (common seed source) and this difference was attributed to the observed condition of the seed. Measurement of seed vigour has been on an as needed basis depending upon research objectives and is, perhaps, not clearly enough defined for cultivar competitive ability research.

Crop density contributed to increased AWC and AC in the field, but was variable by year and location. Increased density contributed more to cultivar competitive ability in a wet spring than a dry one. Increased crop density results in decreased light interception, which reduces the growth of late-emerging weeds (Cousens et al. 1987). However, increased crop density may also exacerbate other problems such as disease pressure and lodging. Therefore, research needs to investigate the longer-term risk and benefits of altered crop density.

4.4.2 Seedling (L) and Seedling-Mature Plant (L-H) Phase

Competition Trial

This research represents the first attempt to quantitatively connect seedling and mature plant attributes to cultivar competitive ability using a wide range of barley cultivars. In the greenhouse competition trial, the lack of difference between weedy and weed-free measurements suggests that competition had not yet begun at approximately the 4-leaf stage. On the Canadian prairies, early weed removal is considered beneficial (May et al. 2003) and weed removal as early as four days after crop emergence has been recommended (John O'Donovan, K. Neil Harker pers. comm.). López-Castañeda et al. (1995) suggested the interval between germination and the 2-leaf stage as being responsible for the greater vigour of barley, compared to wheat. Since barley floret initiation occurs by approximately the 4-leaf stage, potential yield has been set by this time. Environmental stress (Entz and Fowler 1988) may further reduce yield, but yield losses already incurred cannot be regained. It seems likely, therefore, that yield loss due to weed competition may be largely complete by the 4-leaf stage.

The inconsistency between the greenhouse competition trial results and the length of competition duration in the field presents a paradox. In the greenhouse, seedling growth prior to the 4-leaf stage did not reduce biomass in weedy pots. In the field, yield loss is largely complete by the 4-leaf stage. Had fewer cultivars been used in these trials, this paradoxical result might have been attributable to cultivar selection criteria. Since we used 29 cultivars, representing a wide range of genotypic and phenotypic variability, this result is not attributable to cultivar selection. However, other possible explanations include: 1) a lack of competition, 2) a poor understanding of when competition commences, 3) a lack of relevancy between greenhouse and field trials, or, 4) a result of the failure of other factors to operate such as signaling mechanisms or allelopathy.

In the greenhouse, there can be little competition for resources since competition is, by definition, for limiting resources (Lindquist 2001). However, altered growth due to light reflectance has been demonstrated (Ballaré and Casal 2000; Rajcan et al. 2002). Furthermore, in a moist spring (as in 2001), with nutrients applied, it may be argued that there are no limiting resources in a field trial. Consequently, the lack of competition observed in the greenhouse could also be observed in the field, but was not.

The critical period for weed removal has been determined to be less than one month, or before the 6-leaf stage, for canola (Martin et al. 2001) and soybean (Hager et al. 2002; Van Acker et al. 1993). In western Canada, the principle of early weed removal is well-established (May et al. 2003). While the critical period of weed control in barley has not been determined, it is unlikely to be longer than for canola (Martin et al. 2001), since barley is the most competitive annual crop grown on the Canadian prairies (Todd 1989). Hence, the time of onset of competition is not at issue.

Greenhouse trials differ from field trials in three important respects. Firstly, in Canada, they are often performed in the winter when days are shorter. Under these conditions, light levels are low and can vary within a greenhouse. Secondly, soil substrate, nutrient status, and climatic conditions are considered both homogeneous and optimal. Thirdly, soil microorganisms may be excluded if a growing medium is used rather than soil. In our research, Virden was the most competitive cultivar, but was only an average performer in the greenhouse, perhaps as a result of the lack of soil microorganisms. Unpublished research with Dr. Susan Boyetchko indicates that Virden has substantial mycorrhizal colonization. As a result of these differences, greenhouse trials may not be relevant to field trials for competition research.

The remaining possibility is the failure of signaling mechanisms or allelopathy to operate. One above-ground signaling mechanism is a plant growth response due to light reflectance (Ballaré and Casal 2000, Ghersa et al. 1994, Rajcan et al. 2002), based on ratios of red to far-red light. However, greenhouse and field trials both have some opportunity for this mechanism to work.

Below-ground interference can be biochemical. Baghestani et al. (1999) found that several root exudates inhibited root and hypocotyl growth of *Brassica kaber* (DC.) L. C. Wheeler. However, allelopathic research has limitations and Weidenhamer (1996) asserted that it is difficult to distinguish allelopathic interference from competition. Einhellig (1996) stated that increased stress increased the production and effectiveness allelopathic substances, which can also be mediated by soil microorganisms. Either or both of these factors may contribute to differences in cultivar competitive ability between greenhouse versus field conditions. Irrespective of reason, it remains likely that seedling competition at the 4-leaf stage had not begun in the greenhouse. From this, one might assume that the constituents of seedling growth do not contribute to competitive ability. It is, therefore, unsurprising that correlation coefficients for the constituents of seedling growth, such as biomass, leaf area and plant height were not substantively correlated with either component of competitive ability (AWC or AC).

The contribution of herbicide damage to competitive ability was minimal. Minor herbicide damage occurred in 2001, but not in 2002. Herbicides in this trial were chosen after consultation with other researchers on the probable injury due to herbicides and the herbicides selected were those affording suitable control with the least impact on the crop. Furthermore, herbicide application prior to flowering may have less effect on flowering and yield than later applications (Wall 1997). It is, therefore, possible that herbicide application could influence cultivar competitive ability under some circumstances.

Previous unpublished work on the barley cultivar competitiveness (Cory Feschuk, pers. comm.) suggested early plant growth and development might play an important role in cultivar competitive ability. Cultivars were observed to grow and develop at different rates, but the lack of statistical significance between developmental stage (i.e. Haun or Feekes stage) and AWC or AC, indicate minimal contribution of developmental stage to competitive ability.

Researchers have frequently linked growth- and development-related attributes to cultivar competitive ability. Plant growth (Mian et al. 1998, Seavers and Wright 1999), percent light extinction (Lanning et al. 1997, Légère and Schreiber 1989; Mian et al. 1998), percent cover or relative leaf area (Cousens et al. 1992, Kropff and Spitters 1991; Lotz et al. 1996; Ngouajio et al. 1999; Seavers and Wright 1999, Van Acker et al. 1997b) and plant height (Blackshaw et al. 1981; Challaiah et al. 1986; Christensen 1995) have all been linked to competitive ability among cultivars. Our results confirm these attributes make a statistically significant, but not substantive (i.e. $|r| \geq 0.8$) contribution to cultivar competitive ability.

Plant height, particularly early in the growing season, made the largest contribution of any growth-related attribute to competitive ability. Watson et al. (2002) demonstrated, with these data, that the relationship between height and competitive ability was reduced when semi-dwarf cultivars were removed. Lanning et al. (1997) showed an inconsistent relationship between cultivar height and competitive ability. Consequently, the contribution of plant height to cultivar competitive ability is not useful to breeders and may be dependent upon specific cultivars examined.

Seedling and seedling-mature plant attributes widely held to contribute to cultivar competitive ability have been shown to be statistically significant, but lacking substantive relationships (i.e. $|r| \geq 0.8$). Furthermore, the importance of attributes has been shown to vary by year and location. For barley cultivars in western Canada, these attributes are not useful as predictors of cultivars competitive ability and are not deterministic enough to be bred for.

4.4.3 Mature Plant (H) Phase and Post-Harvest Measurements

Our research represents the first attempt to quantify the contribution of H-phase attributes to barley cultivar competitive ability (i.e. AWC and AC) using a wide genotypic range. Research has found that increased yield does not preclude increased competitive ability (Cousens and Mokhtari 1998). Quality measurements (i.e. % protein, and seed mass) are not logically related to competitive ability, but may be more influenced by environmental conditions (Entz and Fowler 1988) and are related more to the subsequent seed (S) phase.

Attributes commonly differed among cultivars but the contribution of individual attributes to competitive ability was generally not substantive (i.e. $|r| \geq 0.8$). The sole exception was yield in weedy plots with AC, although the relationship with AWC was close to being substantive. Although using the mean regression coefficient on mean yield across all cultivars makes invalid assumptions about cultivar responses, it is useful illustratively. Assuming 25 kg equals 1 bushel, a yield increase of about 10 bu ac^{-1} is required in weedy plots to obtain a 10-unit increase in competitive ability. This 10-unit increase would be, or would be close to a significant increase in competitive ability. While such an increase in yield is possible, breeding for an attribute in weedy plots would represent a new paradigm for barley breeders.

The strong relationship between weedy plot yield and AWC may be partially due to the fact that weedy plot yield is numerator in the equation that determines AWC (equation 3.2). Since AWC can be expressed as 100-% yield loss (equation 3.3), and % dockage is related to yield loss (equation 3.4), the relationship of AC to weedy plot yield may also be mathematical. However, the relationship between weedy plot yield and AWC is weaker than for weedy plot yield with AC. Since the relationship between weedy plot yield and AWC is mathematically more direct than with AC, but weaker, weedy plot yield may be an effective attribute to breed for.

Increased weedy plot yield should be correlated with cultivar competitive ability for a single cultivar, although not necessarily among cultivars. One possible explanation for this is the "law of final constant yield" (Harper 1977). This hypothesis suggests each plot will support a fixed final *potential* yield. If a highly-competitive barley cultivar is sown, more of the yield will be barley and weedy plot yield will be high. If a poorly-competitive barley is sown, more of the yield will be oats, and weedy plot yield will be low. Consequently, comparing yield in weed-free versus weedy plots is an integrated measure of cultivar competitive ability and increasing cultivar competitive ability may be most easily accomplished using this comparison.

Breeding for yield stability between weedy and weed-free plots is feasible, but there are four impediments to adoption of this paradigm. One is the potentially large number of advanced lines to be screened. A second is the expanded land base, and consequent human resource costs associated with maintenance, measurement, and travel required. A third is related to choice of weed and difficulty in measuring competitive ability, particularly AC. A fourth is the adoption of the new paradigm of breeding cultivars in weedy plots. However, these impediments are relatively easily addressed.

Firstly, breeding for high competitive ability may, at least initially, be restricted to a small subset of cultivars where barley is used as a forage or clean-up crop. Secondly, an additional 20% of land area is required for, perhaps 15%, of advanced lines selected for screening (Mario Therrien pers. comm.). The total increase in land base required, therefore, could be as little as 3%. Thirdly, less labour-intensive weed options exist to reduce to reduce labour compared to tame oats. Measurement of AWC is faciltated through the use of non-flowering winter crops. Measurement of both AC and AWC are facilitated by the use of small-seeded crops (e.g. canola) as surrogate weeds that are easily separable from barley at harvest. Finally, screening cultivar competitive ability in weedy plots has precedents in yield screening. Although not done in weedy plots, if yield is a desirable attribute, advanced lines not sufficiently high-yielding are discarded. It is our hope that innovative breeders will adopt screening for yield in weedy plots where cultivar competitive ability is a desirable attribute and their research can be used to validate or invalidate our results.

4.4.4 General Discussion

Considerable research has been aimed at improving crop and cultivar competitive ability. In general, the objectives of this research have been to: 1) find attributes that can be bred for, and, 2) increase competitive ability agronomically (Lemerle et al. 2001b). Our research represents the first attempt, using a large number of cultivars, to investigate the relationship between attributes and barley cultivar competitive ability in a manner that explicitly recognizes attributes occurring within and among developmental phases. This allowed us to begin to address outstanding issues from previous research.

Cousens and Mokhtari (1998), suggested that weed suppression abilities (i.e. AC) of cultivars may be more consistent than their yield retention abilities (i.e. AWC). Our research supports this since the strength of the relationship of attributes was generally stronger with AC than with AWC. Furthermore, AC was a more consistent measure of competitive ability than was AWC (Chapter 3). However, the relationship between attributes commonly held to contribute to competitive ability (such as light extinction, height, and percent cover) was insufficient for use in breeding programs and varied considerably by year. Similar results have been reported by other researchers (Cousens and Mokhtari 1998; Lemerle et al. 2001a).

Other attributes could be pursued, but this may not prove useful on the Canadian prairies since we chose integrated attributes, such as light extinction, on the basis of their presumed importance. Since these integrated attributes did not substantively contribute to competitive ability, specific attributes, such as leaf angle (Lemerle et al. 2001b), associated with light extinction should not substantively contribute to competitive ability.

These same attributes may contribute to cultivar competitive ability where post-anthesis biotic and abiotic stress occur later in the growing season (Caton 1997; Cousens and Mokhtari 1998). For example, much of Europe and Australia have a longer growing season, and competition may occur over a longer period than on the Canadian prairies. Consequently, it is possible that attributes examined in our research may contribute to cultivar competitive ability elsewhere.

Research has found that attribute contribution to competitive ability has a substantial environmental component (Cousens and Mokhtari 1998, Lemerle et al. 1995, 2001a). In our research, attribute contribution to competitive ability varied by year and sometimes by location within year as well as seeding date. For example, crop density contributed more to competitive ability in 2001 than 2002. However, the direction of the contribution of attributes to cultivar competitive ability should be consistent, although the magnitude may vary (Cousens and Mokhtari 1998).

Lemerle et al. (2001b) suggested that both components of competitive ability (AWC and AC) need to be measured and our research has validated this. Most attributes had a stronger relationship with AC than AWC (Cousens and Mokhtari 1998). This suggests a need to explore the nature of the relationship between AWC and AC further over a larger number of environments and with cultivars of other crops. AWC may arise more as a result of AC than independently and for cultivar competition trials, this may mean that measuring AWC is sub-optimal compared to AC.

Cousens and Mokhatari (1998) suggested that future competition research should focus on agronomic improvement rather than cultivar selection. Their research indicated wheat cultivar competitive ability was highly susceptible to environmental effects. It is our belief that these agronomic improvement should not be separated from cultivar selection. Firstly, substantive differences in competitive ability existed among barley cultivars (Chapter 3). Secondly, underlying causes of barley cultivar competitive ability have not been defined and cannot be assumed to be independent of cultivar selection. For example, increasing crop density will increase competitive ability, providing the density limit has not been reached (Cousens and Mokhtari 1998). In our research, increasing the seeding rate for Falcon would likely have increased its competitive ability due to its poor emergence and poor competitive ability (Figure 3.1). By contrast, Virden was highly-competitive and emerged much closer to its target density. As a semi-dwarf, Falcon would be less likely to have ancillary problems such as increased lodging than Virden. Since agronomic improvement of cultivar competitive ability is desirable, research should examine techniques that give cultivars, rather than crops, an early advantage over weeds such as: 1) increased cultivar density through increased seeding rates and altered spatial pattern, 2) nutrient management to benefit the cultivar over the weed, and, 3) fungicidal seed treatment to reduce seedborne diseases. The magnitude of the contribution of agronomic practices (Cousens and Mokhatari 1998) and cultivar competitive ability (Chapter 3) vary annually. Therefore, future research into agronomy x cultivar competitive ability needs to be sufficiently long-term to address producer risk and economic returns.

Research directed at determining the relative importance of each developmental stage was not well thought out. The initial assumption in this research was that measuring attributes in each developmental stage and inspection of correlation coefficients with barley cultivar competitive ability would indicate which stage was "most important" with respect to competition. While this assumption proved to be false, our research attempted to determine the contribution to competitive ability of attributes at different stages while explicitly recognizing connections between developmental stages. Future research into the relative importance of each developmental stage could not profitably be undertaken without this vital information.

To properly address the relative importance of each developmental stage, an experiment designed specifically to determine the response of competitive ability (both AWC and AC) within each stage is required. Such a trial might be designed as follows. A subset of six to ten cultivars, chosen to represent the range of competitive ability desired could be employed. In this instance, a subset of cultivars is useful since determining specific attributes is not the objective. In the seed (S) phase, seed treatment (fungicide ±) and seed aging (±), using a standard aging protocol (International Seed Testing Association 1995), could be the treatments. In the seedling (L) phase, crop density and spatial arrangement could be the treatments. In the mature plant (H) phase, lodging (enforced by rolling) and foliar fungicide application (±) could be the treatments. A trial employing all factorial combinations of these treatments could offer insight into the importance of different developmental stages to AWC and AC.

Lemerle et al. (2001b) have suggested that, as the number of cultivars declines, it becomes more likely that attributes observed to contribute to cultivar competitive ability may actually be chance associations. Our research has, perhaps, the most cultivars and attributes examined in a single study of barley cultivar competitive ability undertaken to date, and supports this contention. It is possible to choose a subset of barley cultivars from this study to support a positive, negative or null relationship with many, if not all attributes. Using height as an example, a positive relationship could be observed using Falcon (semi-dwarf), Ranger (short) and Virden (tall) (Figure 3.1, Appendix B). A negative relationship could be observed using Virden (tall), B1602 (taller) and Hawkeye (tallest), and a null relationship with Virden, Ranger and Hawkeye. A similar case can be built for other attributes. Furthermore, differences in competitive ability of classes of cultivars were observed in Chapter 3, suggesting the possibility that different attributes may be important in different classes. This research could easily have drawn spurious conclusions had a narrower genetic or phenotypic range of cultivars been used. Consequently, research examining attributes contributing to cultivar competitive ability should utilize many cultivars from different classes, and where feasible, should be exhaustive.

Previous research has indicated the importance of seed (O'Donovan et al. 1998, 2001), seedling (Christensen 1995; O'Donovan et al. 1999, 2000) and mature plant traits (Christensen 1995) to barley cultivar competitive ability. Our research is the first to consider all phases explicitly. While further research is required, AWC apparently derives primarily from the S and L phases. Ability to compete is also strongly influenced by the S and L phases, but has greater potential to be influenced in the H phase than does AWC. Attribute measurements were taken throughout the growing season and a dependency of later measurements on earlier ones was observed. While observation or enumeration of this dependency cannot occur when only point measurements, such as final plant height, are taken, our research generally supports the premise that early advantages are carried through the growing season (López-Castañeda et al. 1996). The SLH framework has provided a useful framework, both practically and theoretically, within which the contribution of attributes to cultivar competitive ability can be considered.

4.5 CONCLUSIONS

Our research, using many cultivars encompassing a wide genetic and phenotypic range, has demonstrated that attributes thought to contribute to cultivar competitive ability are not strongly enough related to be useful in breeding programs. Excepting yield in weed-free plots, most attributes had mean correlation coefficients of 0.5 or less with competitive ability (AWC or AC). Furthermore, attribute contribution to cultivar competitive ability varied by environment as well as genetic, phenotypic, and end-use classes. Since we used integrated attributes, such as percent light extinction and percent cover, specific attributes contributing to these integrated attributes are unlikely to contribute substantively to cultivar competitive ability. If future research into attributes contributing to cultivar competitive ability is undertaken, it should utilize a large number of cultivars among and within classes to avoid arriving at spurious conclusions on the contribution of attributes to cultivar competitive ability.

Future weed research should integrate relative differences in cultivar competitive ability into crop-weed competition models (e.g. light extinction) and agronomic research (e.g. seeding rate) aimed at improving crop competitive ability. Such models often use one cultivar (or a few) and assume it is "representative" of the crop as a whole. For barley, this assumption is false due to its considerable competitive heterogeneity and may also be false for other crops as well.

For barley breeders, perhaps the simplest method of increasing cultivar competitive ability is to breed for it directly using yield stability in weedy versus weed-free plots. Directly breeding for a trait has precedent in variety trials. A similar approach can be used to rank, and select for, barley cultivar competitive ability.

Extension personnel can utilize competitive rankings for cultivars to modify decision-support-systems, thereby providing producers with superior weed management information. Producer selection of competitive cultivars will enhance weed control and make possible reduced herbicide inputs. This will, in turn, lead to more sustainable cropping systems on the Canadian prairies.

The SLH framework was useful since it connected measurements of attributes across developmental phases. For example, final height has been related to cultivar competitive ability for several crops. However, the relationship of final height to early height growth has not always been recognized. Using the SLH framework required us to consider attributes in the context of the entire life cycle of the crop thereby enhancing our understanding of crop-weed competition.

CHAPTER 5: FUNGICIDE APPLICATION HAD NO EFFECT ON THE COMPETITIVE ABILITY OF BARLEY CULTIVARS

5.1 INTRODUCTION

There are two aspects of competitive ability (Goldberg and Landa 1991; Jordan 1993) that describe: 1) a species ability to withstand competition (AWC) and, 2) a species ability to compete (AC) with another species. Goldberg and Landa (1991) used the terms competitive response (i.e. AWC) and competitive effect (i.e. AC), while Jordan (1993) used the terms crop tolerance (i.e. AWC) and weed suppression (i.e. AC), respectively. In crop-weed competition research, AWC is the ability of the crop to maintain yield in the presence of weed competition, while AC is the ability of the crop to suppress weeds. In varietal studies of competitive ability, both aspects need to be considered (Jordan 1993; Lemerle et al. 2001a), since differential cultivar response to weed competition might arise if cultivars have peak resource demands at times when weed resource use is low. However, both aspects may not be present in the same cultivar and in most studies only one aspect is measured (Lemerle et al. 2001a), generally AWC.

Foliar diseases in cereals reduce the duration of leaf green area (Dimmock and Gooding 2002a). This reduction results in reduced light interception (Dimmock and Gooding 2002b) and Lanning et al. (1997) have suggested that differential light penetration of barley (*Hordeum vulgare* L.) cultivars affects wild oat (*Avena fatua* L.) growth. Therefore, foliar diseases may contribute to a reduction in AC.

The reduction in the duration of leaf green area also results in grain yield loss (Dimmock and Gooding 2002a), which is considered the primary measure of competitive ability (Peterson and Higley 2001). Foliar fungicide application protects host plants from foliar pathogens that use carbohydrates that would otherwise be translocated to developing kernels (Entz et al. 1990). The timely application of foliar fungicides reduces disease incidence and thereby maintains leaf green area longer (Dimmock and Gooding 2002a), resulting in improved yield maintenance (Entz et al. 1990; Kelley 2001). Foliar diseases in barley have resulted in substantial grain yield reductions ranging from about 15% (Martin 1985) to about 70% (Marshall and Sutton 1995). In Saskatchewan, yield loss of 23% due to foliar diseases was recorded (Van Den Berg and Rossnagel 1990). Consequently, a decrease in yield due to disease pressure could result in a reduction in AWC.

In general, the objective of foliar fungicide application is to maintain leaf green area for a longer period. As a result, light interception and grain yield are increased, which may increase both aspects (AWC and AC) of cultivar competitive ability. Since foliar fungicide application does not occur before stem elongation, application effects are limited to the mature plant (H) phase of the SLH framework (Chapter 2). Therefore, competitive effects are more likely to related to AC than AWC.

Research into the impact of fungicide application on barley competitive ability has been limited. Boatman (1992) investigated the effects of herbicide and fungicide use on the yield and yield components of barley. In his research, he found that there were no interactions between herbicide and fungicide effects. While competitiveness was not increased by fungicide application, this trial employed only one cultivar in each site-year. Consequently, the contribution of fungicide application to cultivar competitive ability is unknown. Therefore, the objective of this research is to determine the effect of foliar fungicide application, in the H phase, on AWC and AC among barley cultivars, varying in disease resistance and competitive ability.

5.2 MATERIALS AND METHODS

5.2.1 Experimental Design

A fungicide application trial was initiated in 2001 which used a split-split-plot design, with 4 replicates. Fungicide application (±) was the main plot, cultivar was the sub-plot, and seeding of oats as weeds (±) was the sub-sub-plot. A subset of 6 (Table 5.1) of the 29 barley cultivars (Table 3.1) used in the screening trial (Chapter 3) were selected, based on expert recommendation, to represent 3 levels of disease resistance and two levels of competitive ability. In 2001, tame oats (*Avena sativa* L. cv. AC Assiniboia) were seeded as weeds. A change to wild oats was made for 2002, since an increase in tame oat seed yield, proportional to barley yield, with fungicide application was observed in 2001. We wished to determine if a similar increase in weed yield would occur, since wild oat seed has a considerably lower 1000-kernel weight than tame oat.

Table 5.1. Overall disease resistance[a] and competitive attributes of the subset of barley cultivars selected for the screening trial. Cultivar attributes are given in Table 3.1.

	Competitive	Non-competitive
Resistant	Ranger	Metcalfe
Moderately Susceptible	Stander	Gainer
Highly Susceptible	Harrington	Candle

a: Cultivars were assigned an overall disease resistance based on expert opinion (Mario Therrien (pers. comm..)

5.2.2 Site Descriptions

Field experiments were conducted in 2001 and 2002. In 2001, two site-years of data were collected with one site-year of data from each of a Prodan clay loam soil and a Newdale clay loam soil (Table 3.2). In 2002, four site-years of data were collected with two site-years of data from each of a Ramada clay loam soil and a Newdale clay loam soil (Table 3.2). All experiments were direct-seeded into fields previously under zero-till management.

The Prodan soil series is a carbonated, calcareous to strongly calcareous, Gleyed Rego Black soil developed on imperfectly drained lacustrine sediments. The Ramada soil series is an Orthic Black soil developed on well- to moderately well-drained, strongly calcareous lacustrine sediments. The Newdale soil series is a well-drained, slightly to moderately stony, strongly calcareous Orthic Black soil developed on glacial till that occurs on rolling topography. While the Newdale series is quite typical of the Parkland Region, the Prodan and Ramada series are generally higher-yielding.

The Prodan and Ramada sites were located in the Assiniboine River valley on the Brandon Research Centre (BRC) in Brandon, MB. The two Ramada sites (Ramada 1 and Ramada 2) were conducted adjacently, in the same field, and were situated approximately 100m south of the trials seeded on a Prodan clay loam in 2001. The Newdale (Newdale) site in 2001 and the first trial seeded in 2002 on a Newdale clay loam (Newdale 1), were located approximately 20 km NNE of Brandon at the Phillips Farm subsidiary location of the BRC. The second Newdale location (Newdale 2) seeded was located 4.8 km south of the first Newdale site. Precipitation in 2001 was above average until approximately July (Appendix B, Table B3), but was below average in 2002.

5.2.3 Field Operations

In 2001 when seed came from multiple sources, all barley and weed (tame oat) seed was treated with triticonazole (Charter, BASF Canada, Toronto, ON) at 0.25g a.i. per 100 kg of seed. In 2002 when all barley seed came from a common source, seed treatment was not applied to either the crop or weed (wild oat). After seed treatment, germination tests were performed. Barley cultivars and weeds (tame or wild oats) were sown simultaneously in seed rows to achieve a target density of 250 and 70 plants m^{-2}, respectively (Equation 5.1). A target density of 70 plants m^{-2} for weeds was selected to achieve a 25% yield reduction (2001 Guide to Crop Protection). Tame oats were sown according to equation 5.1 while wild oats were sown at double the rate required by equation 5.1 to ensure adequate emergence and account for past observation of low wild oat field emergence (D. Derksen, pers. comm.). In both years, cultivar and weed seed were direct-seeded simultaneously using a Versatile 2200 hoe-drill on a 20.5 cm row spacing.

$$\text{Seeding rate (plants } m^{-2}) = (\text{1000-kernel weight}/4)/(\text{\% Germination}) \qquad (5.1)$$

In all years, nitrogen fertilizer was applied at a rate of 78.4 kg ha^{-1} actual N as 46-0-0 in a mid-row band at time of seeding. Phosphorus was seed-placed as 0-45-0 to prevent nitrogen toxicity at a rate of 22.4 kg actual P_20_5 ha^{-1}. Soil tests were conducted for both sites in 2001 and the Ramada 1 and Newdale 1 locations in 2002. Due to circumstances, soil tests were not performed for the Ramada 2 and Newdale 2 locations in 2002. Where tested, fertilizer applied was sufficient for a yield of 3430 kg ha^{-1} (approximately 80 bu ac^{-1}).

Where necessary, pre-seeding herbicide application occurred not more than two days prior to seeding and consisted of glyphosate at a rate either 450 g a.e. ha^{-1} or 900 g a.e. ha^{-1} depending on the weed spectrum. All plots received an in-crop application of a mixture of 100 g a.i. ha^{-1} clopyralid and 550 g a.i. ha^{-1} MCPA ester formulated as an emulsifiable concentrate (Curtail M, Dow AgroSciences, Indianapolis, Indiana) for broadleaf weed control. Plots not seeded with tame oat were considered "weed-free" and also received an in-crop application of 80% tralkoxydim formulated as a dispersable grain (Achieve 80 DG, Syngenta, Basel, Switzerland) at a rate of 200 g a.i. ha^{-1} to control late-emerging wild oats. All herbicides were applied with a tractor-mounted boom sprayer using 110 L ha^{-1} (10 gal ac^{-1}) at 275kPa (40 PSI) through 8001 nozzles. In-crop herbicide application occurred per label recommendation; when cultivars were between the 2- and 4-leaf stage.

Foliar fungicide application consisted of two applications of propiconazole (Tilt 250E, Syngenta, Basel, Switzerland) at 120 g a.i. ha^{-1}. Application times were as close as possible to label recommendation: 1) at stem elongation, and, 2) before the head was half emerged as was possible given the genotypic variability of the cultivars. Fungicide was applied using 110 L ha-1 (10 gal ac-1) at 275kPa (40 PSI) through 8001 nozzles.

Harvest in experimental plots was performed with a Hege 125C combine with a 1 m table. Six crop rows were harvested per plot with the two outside rows on either edge of the plot left standing. Prior to assessing yield, harvested seed was de-awned, then sieved to remove trash and small weed seeds. Yield in weed-free plots was determined by weighing the sample from each plot after cleaning. In weedy plots, the percentage of weed seed yield by weight (i.e. the dockage) was determined by manually separating oat from barley seed and weighing the oat seed from a sample weighing approximately 25g. Yield was then calculated by subtracting dockage from the gross yield.

5.2.4 Data Collection and Analysis

Data collected in this trial consisted of disease load rating, yield, percent dockage and percent protein. Disease load rating was a visual rating from zero to 100. where 0 = no damage and 100 = complete foliar disease. From the disease load rating, a disease resistance rating was calculated by fungicide application as:

$$\text{Disease Resistance Rank} = \text{Rank}(100\text{-Disease Load Rating}) \tag{5.2}$$

Yield in weed-free plots was determined by weighing the sample from each plot after cleaning. In weedy plots, yield was determined by subtracting dockage from the gross yield. Dockage was evaluated by manually separating oat from barley seed in a subsample weighing approximately 25 g. The oat seed was then weighed and the proportion of oat seed in the subsample was calculated as:

$$\%\ \text{Dockage} = 100 * \text{Subsample}_{\text{Oat}} / \text{Subsample}_{\text{Total}} \tag{5.3}$$

where $\text{Subsample}_{\text{Oat}}$ is the weight of the oats in the (approximately) 25g subsample and $\text{Subsample}_{\text{Total}}$ is the actual weight of the subsample. Statistically, % dockage is identical to AC for cultivar significance and partial correlation since AC = 100 - % Dockage. Protein was determined using a Foss GrainSpec near infrared reflectance spectroscopy (Foss, Warrington, UK). Ability to withstand competition and ability to compete were calculated in the same manner as in Chapter 3. AWC is the ratio of weedy to weed-free yield and AC is 100 - % dockage.

Analysis of variance (ANOVA) was performed using PROC GLM in SAS (SAS 1990), and data were analyzed as a split-plot for AWC and AC by fungicide application (±). While data failed the Levene's test of normality, no transformations were required as the normal probability plots indicated data were either approximately normal or would not be normalized through transformation. Values for AWC and AC in 2002 were quite high and an arcsin square root transformation linearizes the entire curve rather than just the upper portion of it (Steel et al. 1997, p. 246). Data were not homogeneous between years and locations and consequently, all site-years were analyzed separately.

5.3 RESULTS

Ability to withstand competition did not differ by fungicide application or cultivar (Appendix C). Fungicide application had no effect on AC, but cultivars generally differed (Table 5.2). Since AC = 100 - % dockage, these results are identical for percent dockage (Appendix C). Due to the change from tame to wild oat as a weed between 2001 and 2002, there was an increase in both AWC (Appendix C) and AC (Table 5.3) between years. In 2001, AWC (Appendix C) and AC (Table 5.3) were lower than in 2002. Values for AC in 2002 were substantially less in the foliar fungicide application trial (Table 5.3) than in the screening trial (Table 3.5) since wild and tame oat, respectively, were used in these trials.

Table 5.2. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect barley ability to compete for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002. Non-significant (α=0.05) p-values are denoted ns.

	2001		2002			
Factor	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	ns	ns	ns	ns	ns	ns
Cultivar	0.0010	0.0009	0.0208	<0.0001	0.0034	ns
Fungicide x Cultivar	ns	ns	ns	ns	ns	ns

Generally, disease load was significantly (Table5.4) reduced by fungicide application (Table 5.5). Cultivars varied in their susceptibility to disease (Table 5.5), but fungicide x cultivar interaction was uncommon (Table 5.4). In 2001, both sites had similar overall disease pressure (Table 5.5). In 2002, the Ramada locations were similar to each other, although the Newdale 2 location had less disease pressure than Newdale 1. Fungicide application variably affected cultivars by year and location (Table 5.5).

Table 5.3. Ability to compete (AC) for each cultivar by fungicide treatment. Data are presented as means with LSD for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002. Non-significant (α=0.05) LSDs are denoted by ns.

	2001		2002				Mean
Cultivar	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger	82	66	99	99	93	96	89
Metcalfe	80	58	99	99	92	97	88
Stander	76	57	98	97	93	97	86
Gainer	81	61	99	94	95	98	88
Harrington	80	62	98	96	97	98	89
Candle	77	54	99	98	94	96	86
Mean	79	60	99	97	94	97	88
LSD	3	6	1	1	3	1^{ns}	

The cultivar ranking for disease load rating varied considerably by year (Table 5.6) and did not always match expectations (Table 5.1). For example, Ranger and Metcalfe were expected to have superior overall disease resistance (Table 5.1). While Ranger consistently ranked well, Metcalfe ranked poorly in 2001 and was average in 2002 (Table 5.6). Stander and Gainer were expected to have moderate disease resistance (Table 5.1). However, Stander was intermediate in disease resistance in 2001, but ranked highly in 2002 and Gainer generally performed as expected (Table 5.6). Harrington and Candle were expected to have poor disease resistance (Table 5.1). Harrington generally had poor resistance, but Candle ranked well in 2001 and was intermediate in 2002.

In general, fungicide application significantly increased crop yield in weed-free (Tables 5.7 and 5.8) and weedy (Tables 5.9 and 5.10) plots. Cultivar yield differed significantly in all site-years and there were significant fungicide x cultivar interactions in half the site-years (Tables 5.7 and 5.9). In general, fungicide increased cultivar yield (Tables 5.8 and 5.10).

Table 5.4. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect disease load rating in weed-free plots for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002. Non-significant ($\alpha=0.05$) p-values are denoted ns.

	2001		2002			
Factor	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	ns	0.0123	0.0098	0.0033	0.0016	0.0132
Cultivar	0.0135	0.0010	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	ns	0.0220	0.0219	ns	ns	ns

Table 5.5. Disease load rating for each cultivar by fungicide treatment. The rating ranges from zero (no disease) to 100 (completely diseased). Data are presented as means with LSD. Yes and no in parentheses indicate whether fungicides were applied.

	2001		2002				Mean
Cultivar	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	49	51	80	75	63	29	58
Ranger (Yes)	35	35	53	40	23	15	34
Metcalfe (No)	63	55	93	90	79	53	72
Metcalfe (Yes)	48	68	60	53	18	18	44
Stander (No)	61	80	84	65	59	26	63
Stander (Yes)	46	46	38	28	15	15	31
Gainer (No)	58	74	100	100	90	56	80
Gainer (Yes)	28	36	85	61	36	14	43
Harrington (No)	85	89	100	100	90	79	91
Harrington (Yes)	55	59	90	88	53	38	64
Candle (No)	60	51	100	98	90	53	75
Candle (Yes)	36	34	65	58	28	15	39
Mean rating	52	57	79	71	54	34	58
LSD	16	15	11	10	13	14	

Table 5.6. Rank of cultivar disease resistance for each site-year by fungicide application. The rank is derived according to equation 3. The overall ranking is the rank across site-years for the fungicide application. Yes and no in parentheses indicate whether fungicides were applied.

	2001		2002				Overall
Cultivar	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	1	1	1	2	2	2	1
Ranger (Yes)	2	2	2	2	3	2	1
Metcalfe (No)	5	3	3	3	3	3	4
Metcalfe (Yes)	5	6	3	3	2	5	5
Stander (No)	4	5	2	1	1	1	2
Stander (Yes)	4	4	1	1	1	2	2
Gainer (No)	2	4	4	5	4	5	5
Gainer (Yes)	1	3	5	5	5	1	4
Harrington (No)	6	6	4	5	4	6	6
Harrington (Yes)	6	5	6	6	6	6	6
Candle (No)	3	1	4	4	4	3	3
Candle (Yes)	3	1	4	4	4	2	3

Table 5.7. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect yield from weed-free plots.

	2001		2002			
Factor	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	0.0043	0.0206	0.0177	0.0121	ns	ns
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	ns	0.0239	0.0039	ns	0.0473	ns

Fungicide application significantly (Table 5.11) increased barley 1000-kernel weight in weed-free plots only at the Ramada locations (Table 5.12). In weedy plots, barley 1000-kernel weight was significantly (Table 5.13) increased at all locations (Table 5.14).

Seed weight differences among cultivars were found in weed-free (Table 5.11) and weedy (Table 5.12) plots in all site-years. Fungicide x cultivar interactions were more common in weed-free plots (Table 5.11). Although oat 1000-kernel weight generally did not differ by fungicide application or barley cultivar (Appendix C), the general trend was for oat 1000-kernel weight to increase when fungicides were applied (Appendix C). The cultivar x fungicide interactions indicate that fungicide application did not increase barley seed weight for all cultivars at all sites (Tables 5.13 and 5.14).

Table 5.8. Yield from weed-free plots for each cultivar by fungicide treatment. Data are presented as means with LSD.

	2001		2002				Mean
Cultivar	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	kg						
Ranger (No)	5172	4360	3376	2570	3126	4130	3789
Ranger (Yes)	5540	4504	3474	3285	3108	4245	4026
Metcalfe (No)	4901	3690	2660	2325	2444	3351	3229
Metcalfe (Yes)	5417	4316	3058	2820	2890	3723	3704
Stander (No)	5148	4184	3052	2349	2923	3614	3545
Stander (Yes)	5226	4464	3359	2699	3034	3636	3736
Gainer (No)	3922	3056	2231	1706	2303	3293	2752
Gainer (Yes)	4411	4019	3077	2290	2958	3453	3368
Harrington (No)	4182	2837	2132	1523	2436	3018	2688
Harrington (Yes)	5174	3802	2926	2026	2989	3723	3440
Candle (No)	4128	2728	2291	1404	2208	3106	2644
Candle (Yes)	4634	3558	2899	2086	2728	3356	3210
Mean	4821	3793	2878	2257	2762	3554	3344
LSD	432	291	200	234	241	275	

Table 5.9. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect yield from weedy plots.

	2001		2002			
Factor	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	0.0487	0.0003	0.0161	0.0007	ns	ns
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	0.0231	ns	0.0125	ns	0.0228	ns

Table 5.10. Yield from weedy plots for each cultivar by fungicide treatment. Data are presented as means with LSD.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
			kg				
Ranger (No)	4488	2921	2898	2348	2882	3809	3224
Ranger (Yes)	4224	3122	3482	3130	3007	4078	3507
Metcalfe (No)	4028	2400	2503	2309	2474	3107	2804
Metcalfe (Yes)	4344	2780	2980	2675	2620	3458	3143
Stander (No)	3904	2459	2971	2216	2772	3141	2911
Stander (Yes)	4181	2955	2961	2322	2730	3417	3094
Gainer (No)	3257	2066	2040	1469	2071	3071	2329
Gainer (Yes)	3928	2792	2834	2050	2656	3087	2891
Harrington (No)	3391	2112	1895	1390	2128	2796	2285
Harrington (Yes)	4120	2796	2456	1949	2719	3523	2927
Candle (No)	3326	2035	2049	1455	2114	2908	2315
Candle (Yes)	3752	2352	2908	1849	2421	3124	2734
Mean	3912	2566	2665	2097	2550	3293	2847
LSD	300	294	237	240	213	288	

Fungicide application had no significant effect on percent protein (Table 5.15). Cultivar differences were found in all site-years (Tables 5.15 and 5.16), but no significant fungicide x cultivar interactions occurred. Percent protein was consistently negatively correlated with yield (data not shown).

Table 5.11. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect barley 1000-kernel weight from weed-free plots.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	n/a	n/a	0.0091	0.0131	ns	ns
Cultivar	n/a	n/a	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	n/a	n/a	0.0002	0.0285	0.0059	0.0491

Table 5.12. Barley 1000-kernel weight for each cultivar by fungicide treatment from weed-free plots. Fungicide application is indicated by Yes/No. Data are presented as means with LSD.

	2001		2002				Mean
Cultivar	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	g 1000						
Ranger (No)	-[a]	-	39	36	39	42	39
Ranger (Yes)	-	-	42	40	42	42	42
Metcalfe (No)	-	-	40	38	42	44	41
Metcalfe (Yes)	-	-	45	44	43	45	44
Stander (No)	-	-	40	38	40	40	40
Stander (Yes)	-	-	41	40	40	40	40
Gainer (No)	-	-	32	30	35	36	33
Gainer (Yes)	-	-	38	35	40	36	37
Harrington (No)	-	-	34	32	37	38	35
Harrington (Yes)	-	-	41	35	43	43	41
Candle (No)	-	-	32	29	34	35	33
Candle (Yes)	-	-	36	34	37	37	36
Mean	-	-	38	36	39	40	38
LSD	-	-	1	1	1	2	

a: Data not collected.

Table 5.13. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect barley 1000-kernel weight from weedy plots.

	2001		2002			
Factor	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	n/a	n/a	0.0079	0.0373	0.0172	0.0227
Cultivar	n/a	n/a	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	n/a	n/a	0.0130	ns	ns	ns

Table 5.14. Barley 1000-kernel weight (g) for each cultivar by fungicide treatment from weedy plots. Fungicide application is indicated by Yes/No. Data are presented as means with LSD.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	g/1000 seeds						
Ranger (No)	-[a]	-	39	37	40	42	40
Ranger (Yes)	-	-	42	41	43	42	42
Metcalfe (No)	-	-	39	39	41	44	41
Metcalfe (Yes)	-	-	44	44	45	45	45
Stander (No)	-	-	38	37	39	39	38
Stander (Yes)	-	-	40	40	39	40	40
Gainer (No)	-	-	32	31	35	37	34
Gainer (Yes)	-	-	38	35	39	39	38
Harrington (No)	-	-	32	31	38	39	35
Harrington (Yes)	-	-	39	36	44	43	41
Candle (No)	-	-	31	29	34	35	32
Candle (Yes)	-	-	37	34	37	37	36
Mean	-	-	38	36	40	40	38
LSD	-	-	2	1	2	1	

a: Data not collected.

Table 5.15. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect percent protein from weed-free plots. Non-significant ($\alpha = 0.05$) p-values are denoted ns.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	ns	ns	ns	ns	ns	ns
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide x Cultivar	ns	ns	ns	ns	ns	ns

5.4 DISCUSSION

Cultivar competitive ability (AWC and AC) was altered by environmental conditions in 2002 compared to 2001. In spring 2002 (Appendix B), conditions were dry and cold resulting in poor and late wild oat emergence. Consequently, true competitive ability in 2002 is best observed in the screening trial (Table 3.5).

Table 5.16. Percent protein for each cultivar. Data are presented as means with LSD. Non-significant LSDs (α = 0.05) are denoted ns.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger	10.4	9.7	11.8	11.8	10.4	10.9	10.8
Metcalfe	11.7	11.3	13.3	13.4	11.4	12.2	12.2
Stander	10.9	9.9	12.4	12.9	11.0	11.6	11.5
Gainer	10.5	10.5	12.4	12.9	10.6	11.3	11.4
Harrington	11.3	11.3	12.5	12.6	11.3	11.9	11.8
Candle	11.9	12.4	13.8	13.8	11.3	12.4	12.6
Mean	11.1	10.9	12.7	12.9	11.0	11.7	11.7
LSD	0.3	0.5	0.5	0.5	0.2	0.2	

In our research, disease pressure and cultivar disease resistance did not contribute to increased cultivar competitive ability. This was true despite variability in cultivar disease resistance, attributable to soil type, growing season conditions, seed source, and rotation. Boatman (1992), using a single cultivar, also found no herbicide x fungicide interaction. While he had initially expected a healthy population might compete better than a diseased one, he suggested two explanations. Firstly, his trial used naturally-occurring weeds. Thus there were multiple weeds and disease levels may have been low in a mixed weed population dominated by broadleaved weeds. Secondly, benefits of fungicide application may not have been restricted to the crop. In our research, we used tame and wild oat as a weed. Disease levels were similar on barley and tame oat populations (personal observation) since barley and tame oats are susceptible to many of the same diseases (Martens et al. 1994). Since low disease due to mixed weed populations was not a factor in our trial, we conclude that the benefits of fungicide application are not restricted to the crop.

The magnitude of competitive outcomes varied depending on weed choice. Crop species have been used as a surrogate for weeds (O'Donovan 1992; Van Acker et al. 1997a), but the relative merits of using crops as surrogate weeds has not been discussed. In 2001, tame oat was used as a weed, whereas in 2002, wild oat was substituted. In 2002, wild oat emergence was poor and late and AWC and AC were consequently increased compared to 2001. Tame oats were useful since uniform emergence occurred within one day of the barley cultivars, and yield loss due to competition was maximized. Wild oats were less useful since poor and late emergence minimized yield loss. For a short-term trial, using crops as surrogate weeds may be more suitable since "weed" failure will not occur without crop failure. For a longer-term trial, wild types may prove superior, especially if they have attributes of interest to be measured which are not found in crop surrogates (e.g. dormancy).

Crop yield has been shown to increase with fungicide application due to larger seed size (Conry and Dunne 2001; Entz et al. 1990; Van Den Berg and Rossnagel 1990.). In our research, crop yield increased due to larger seed resulting from fungicide application. Percent dockage (i.e. weed seed yield as a proportion of the crop yield) remained constant despite fungicide application. Furthermore, since AWC was also unaffected by fungicide application, an increase in crop yield due to fungicide application was logically offset by a proportional increase in weed seed yield. Consequently, fungicide application impacted not only the crop, but the weed as well. This type of result has apparently not been previously published.

In our research, percent protein had a negative relationship with yield. Therefore, the increase in crop and weed seed yield may be primarily attributable to a larger seed size.

This is borne out by the increase in barley 1000-kernel weight in 2002 due to fungicide application.

Previous research has indicated that foliar fungicide application not only protects grain yield (Entz et al. 1990), but it also protects grain quality. Increased grain protein (Dimmock and Gooding 2002a, 2002b); kernel size (Conry and Dunne 2001; Entz et al. 1990; Jedel and Helm 1991a; Martin 1985; Van Den Berg and Rossnagel 1990), 1000-kernel weight (Boatman 1992; Bockus et al. 1997) and a decreased proportion of small kernels (Entz et al. 1990; Puppala et al. 1995) has been documented. As a result, increased test weight (Conry and Dunne 2001; Kelley 2001), which maintains barley malt quality (Conry and Dunne 2001) or increases milling and baking quality of wheat (Everts et al. 2001), may occur. Entz et al. (1990) suggest that since kernel size is a low-cost method for increasing yield potential of cereals, only large kernels should be used for seeding. Consequently, producers have multiple economic reasons to apply foliar fungicides.

Economically, fungicide application in cereals has produced mixed results. Van Den Berg and Rossnagel (1990) concluded it would be difficult for fungicide application to be economically viable unless heavy disease pressure were encountered. Jedel and Helm (1991a) concluded that fungicide application would generally be unprofitable in years when yield was limited by environmental conditions. By contrast, in winter wheat, Bockus et al. (1997) concluded that, fungicide application under moderate disease pressure would result in an economic return in: 1) low-value winter wheat at least 50% of the time for intermediately disease-resistant cultivars and 90% of the time for susceptible cultivars, and, 2) high-value winter wheat at least 50% of the time for resistant cultivars and 90% of the time for susceptible cultivars. However, the impacts of fungicide application are not limited to the crop, and longer-term costs due to altered weed seed have not been considered.

Potential impacts of fungicide application on the non-target weed may include: 1) increased seed weight, leading to increased vigour and, ultimately, competitive ability, 2) altered dormancy characteristics. For the producer, these potential impacts may be important. In barley, separation of wild oat seed from crop is difficult and economic loss may result from a grade reduction. More importantly, wild oat generally matures more rapidly than barley and few seeds may remain in the head at harvest. Larger wild oat seed has been implicated with increased vigour and competitive ability (Peters 1985). Wild oat has a relatively short-lived seedbank (Sharma and Van Den Born 1978). The effect of increased wild oat seed size on dormancy has not, to our knowledge, been documented, but may possibly be increased. A more competitive wild oat population, with increased dormancy, may make an already serious problem (O'Donovan and Sharma 1983) more severe. Future research into fungicide application, therefore, should address long-term weed-related economics of foliar fungicide application.

Our research examined the effect of duration of leaf green area on competitive ability (H phase), but other issues in this phase may also be of interest. Loss of crop seed vigour has been attributed to other factors such as threshing cylinder speed (Bourgeois et al. 1996; Entz et al. 1991), disease incidence (Entz et al. 1990; Fernandez et al. 1996), heat stress (Grass and Burris 1995a, 1995b), or other stresses during critical periods (Entz and Fowler 1988). In general, H phase research should be directed at the quantity and quality of weed and crop seed production in the context of lodging, insect pressure, disease development, and prevailing environmental and agronomic conditions. The ability of the crop to withstand competition (AWC) needs to address yield loss specifically due to weed competition in the H phase. Finally, the relationship between seed vigour loss and competitive ability in subsequent growing seasons needs to be examined.

5.5 CONCLUSIONS

The effect of foliar fungicide application, in the H phase, on competitive ability (AWC and AC) among barley cultivars, varying in disease resistance and competitive ability has not previously been examined. AWC and AC were unaffected by fungicide application since increases in yield were offset by a proportional increase in dockage. This suggests impacts of foliar fungicide application may extend to weeds in addition to crops. In our research, both weed and crop were cereals, and affected by many of the same diseases. Consequently, this result cannot be generalized to other crop-weed combinations.

Foliar fungicide application is an economic decision for the producer. Previous research has not addressed long-term net returns based on altered weed characteristics. This information has, therefore, not been available to extension personnel or producers. For producers, changing weed seed characteristics such as vigour and dormancy can have negative impacts on their long-term economic prospects and sustainability. Integrated research into the effects of fungicide application on crops and weeds needs to be undertaken to address long-term economic and agro-ecological effects of increased weed seed vigour, weed competitive ability and altered dormancy in cropping systems.

CHAPTER 6: SUMMARY AND CONCLUSIONS

Substantial differences in competitive ability exists among cultivars commonly used in western Canada (Figure 3.1). Differences in barley cultivar competitive ability occurred by the various phenotypic (2-row vs. 6-row, full height vs. semi-dwarf, hulled vs. hull-less,) and end-use (feed vs. malt) classes. As a class, semi-dwarf and hull-less cultivars were less competitive than full height and hulled cultivars, respectively. These differences are partially related to genetic and phenological differences, but were not absolute. Differences in competitive ability may also be related to other factors such as producer requirements within a class of cultivars (e.g. malt cultivars), or the maturity of breeding efforts within a class (e.g. hull-less cultivars). The two aspects of competitive ability, AWC and AC, had a sufficiently strong relationship that breeding for one should increase the other. Highly- and poorly-competitive cultivars had consistent competitive rankings among site-years, while intermediately-competitive cultivars were less consistent. Consistency of competitive rank simplifies producer selection of competitive cultivars and breeding efforts to improve barley cultivar competitive ability.

This research used a single weed, tame oat as a surrogate for wild oat. Weeds with a different life cycle might have resulted in a different outcome since timing of resource utilization may differ. However, spring annual weeds or weed communities should only result in a different outcome if they are either too competitive to produce difference in competitive ability or not competitive enough.

Producers' use of competitive barley cultivars as an integrated weed management (IWM) tool has been constrained by the lack of competitive rankings for cultivars in provincial crop protection guides. It would be useful for barley cultivars to have scores for competitive ability in a manner similar to either rankings for prominent diseases or yield, which are expressed as a proportion of a check cultivar. The under-utilization of barley cultivar competitive ability as an IWM tool can be remedied by using our ranking system for competitive ability for all barley cultivars produced hereafter.

Attributes in the seed, seedling, and mature plant phases widely held to contribute to barley cultivar competitive ability generally had correlation coefficients less than 0.5 with AWC (Table 4.12) and AC (Table 4.13). While statistically significant correlation coefficients were common for the various height- and growth-related attributes collected, only yield in weedy plots had a sufficiently strong relationship with either aspect of competitive ability (AWC or AC) to be useful in a breeding program. The contribution of attributes to cultivar competitive ability was variable by year and location. Removal of classes of cultivars (e.g. semi-dwarf), reduced the strength of relationship between attributes and competitive ability.

Using comparisons of yield in weedy and weed-free plots as a breeding tool represents a new paradigm for breeders. However, obstacles to this paradigm are readily surmountable. Since: 1) poorly- and highly-competitive cultivars were consistent in competitive rank, and, 2) the contribution of attributes to cultivar competitive ability was not useful to breeders, the optimal method of improving cultivar competitive ability may be to use yield comparisons in weedy and weed-free plots as the breeding criterion.

Our research examined the effect of integrated attributes (e.g. % light extinction) instead of specific attributes (e.g. leaf angle). Investigating the contribution of integrated attributes to cultivar competitive ability may be superior to examining specific traits thought to contribute to competitive ability. For example, leaf angle has been suggested as an attribute contributing to cultivar competitive ability. However, if leaf angle is predominantly a component of shading ability, then its contribution must be less than shading ability since it is only one component of shading ability.

The contribution of attributes to competitive ability may have different importance in various production systems and may be altered by agronomic practices (e.g. nutrient regime). For example, in organic farming nutrients are often limiting (Entz et al. 2001) compared to conventional farming systems. However, resource limitations vary in both space and time and the contribution of attributes to competition for limiting resources must also vary. Research into cultivar competitive ability could develop a conceptual model that expands on the SLH framework, accounting for resource use changes over time and the interaction of attributes with each other and the environment.

To elucidate the importance of the H phase in cultivar competitive ability, foliar fungicides were applied increase the duration of green leaf area. There was no effect of foliar fungicide application on AWC or AC. However, impacts of foliar fungicide application were not restricted to the crop since grain and weed seed yield were increased proportionally. Other potential impacts on weeds include: 1) increased seed weight, potentially leading to increased vigour and, ultimately, competitive ability, and, 2) altered dormancy characteristics. The decision to apply foliar fungicides is based on economic return resulting from either increased yield or quality. Future research should investigate impacts on weed seed characteristics to determine their long-term economic impact on crop production.

Using the SLH framework allowed us to see connections between measurements taken at different stages. Seed, seedling, and mature plant vigour are all thought to contribute to barley cultivar competitive ability. However, seed vigour is not well-defined from a competitive ability perspective, and thus, its contribution to increased competitive ability in later stages is unclear. Some attribute measurements (e.g. height) may be taken from the early L phase (after emergence) well into the H phase (at harvest). This research indicated the importance of measuring attributes earlier, rather than later, and suggested a dependence of later measurements on earlier ones. Competition research incorporating attribute measurements from later developmental stages has not considered the dependence of these later measurements on measurements from earlier stages and could profitably do so.

Using the SLH framework has also brought into question widely held assumptions on the timing and extent of competition. The proposition that competition predominantly occurs during the seedling phase may be contingent upon the nature and extent of resource limitations during this phase. When resources are not limiting, competition, *per se*, cannot occur. Consequently, other mechanisms may be operative such as allelopathy, above-ground light signals, and below-ground biochemical signals that are, perhaps, mediated by above-ground light signals. Investigation of these possibilities may add to our knowledge of crop-weed interactions.

Agronomic practices influencing competitive outcomes occur at different stages in the SLH framework. For example, seeding rate (S), spatial geometry (L), and foliar fungicide application (H) can all affect cultivar competitive ability. Research into cultivar, rather than crop, responses to agronomic manipulation should elucidate the range of effects possible within a crop to agronomic manipulation.

Using information from this thesis, breeders can breed for increased cultivar competitive ability and rank the cultivars. Weed research can integrate relative differences in cultivar competitive ability into crop-weed competition models (e.g. herbicide rate) and agronomic research (e.g. seeding rate) into improving cultivar, and hence, crop competitive ability. Extension personnel can use this information in decision support systems (e.g. herbicide rate) to provide information to producers. Producers can then use this information select more competitive cultivars for their cropping systems. This value-added information chain can reduce increase the effectiveness of cultivar competitive ability as an integrated weed management tool and enhance the economic and environmental sustainability of agriculture.

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APPENDIX A

Table A1. Rank score for ability to withstand competition (AWC) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Cultivars are ordered by descending rank of ability to withstand competition, then by variance.

Cultivar	2001		2002				Overall	
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Rank	Variance
Virden	1	1	1	1	1	1	1	0.0
Lacombe	3	5	11	4	5	2	2	10.0
Metcalfe	9	13	7	10	3	4	3	14.3
Candle	11	13	5	2	8	10	3	16.6
Manley	17	4	3	4	9	7	3	27.5
Ranger	16	20	1	8	7	3	3	55.0
Robust	12	13	7	12	1	13	7	23.1
Phoenix	5	18	6	8	16	8	8	29.8
Harrington	4	2	14	16	16	18	8	47.1
Dolly	5	5	19	4	11	20	8	53.1
Excel	12	22	4	4	5	16	8	55.9
B1602	2	2	20	17	13	13	8	57.4
Bacon	8	8	12	19	16	20	13	28.2
Bedford	7	13	20	10	23	11	13	38.4
Oxbow	9	20	7	12	10	23	13	41.9
Stein	19	19	26	15	4	8	13	64.6
Stratus	14	10	26	3	20	24	17	77.8
Hawkeye	20	11	14	17	22	13	18	18.2
Condor	25	24	12	14	13	6	19	54.7
Kendall	22	11	17	20	21	18	20	15.8
McGwire	24	13	20	20	11	11	20	30.7
Gainer	25	9	20	23	26	4	20	83.8
Stander	17	24	10	25	23	20	23	31.8
Kasota	14	5	28	28	16	25	24	85.5
Earl	20	23	17	25	23	28	25	14.7
Dawn	27	26	20	22	13	16	26	30.3
Thompson	22	27	14	23	28	27	27	27.5
Falcon	29	28	20	27	26	26	28	10.0
Peregrine	28	29	29	29	29	29	29	0.2

Table A2. Rank score for ability to compete (AC) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Cultivars are ordered by descending rank of ability to compete, then by variance.

Cultivar	2001		2002				Overall	
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Rank	Variance
Virden	1	1	2	1	1	1	1	0.2
Ranger	7	7	1	4	2	2	2	7.0
Lacombe	2	2	9	4	6	3	2	7.5
Robust	4	4	5	3	4	5	4	0.6
B1602	3	2	9	8	7	6	5	7.8
Excel	12	8	2	2	3	9	5	18.0
Metcalfe	9	20	4	4	4	4	7	41.5
Dolly	5	5	5	9	10	12	8	9.5
Stratus	5	6	5	4	22	22	9	77.5
Bedford	9	9	15	9	13	12	10	6.6
Oxbow	14	19	5	12	8	14	11	24.4
Phoenix	14	23	12	9	9	7	11	33.5
Stander	13	12	9	15	16	14	13	6.2
Bacon	9	13	12	16	22	14	14	19.5
Manley	19	9	12	18	13	20	14	19.8
Hawkeye	22	15	15	12	21	10	14	23.0
Candle	20	24	15	14	10	14	17	25.0
Harrington	7	9	20	22	16	18	17	36.7
Kendall	20	15	21	18	16	18	19	5.2
Earl	17	20	15	20	13	25	19	18.3
McGwire	23	20	24	16	10	10	19	38.6
Stein	16	13	22	24	16	22	22	19.4
Condor	26	25	19	20	16	20	23	14.4
Gainer	23	18	22	23	25	8	23	39.0
Kasota	17	15	28	28	26	26	25	33.5
Thompson	25	26	27	25	28	27	26	1.5
Dawn	27	27	25	26	24	24	26	1.9
Falcon	29	29	26	27	27	27	28	1.5
Peregrine	28	28	29	28	29	29	29	0.3

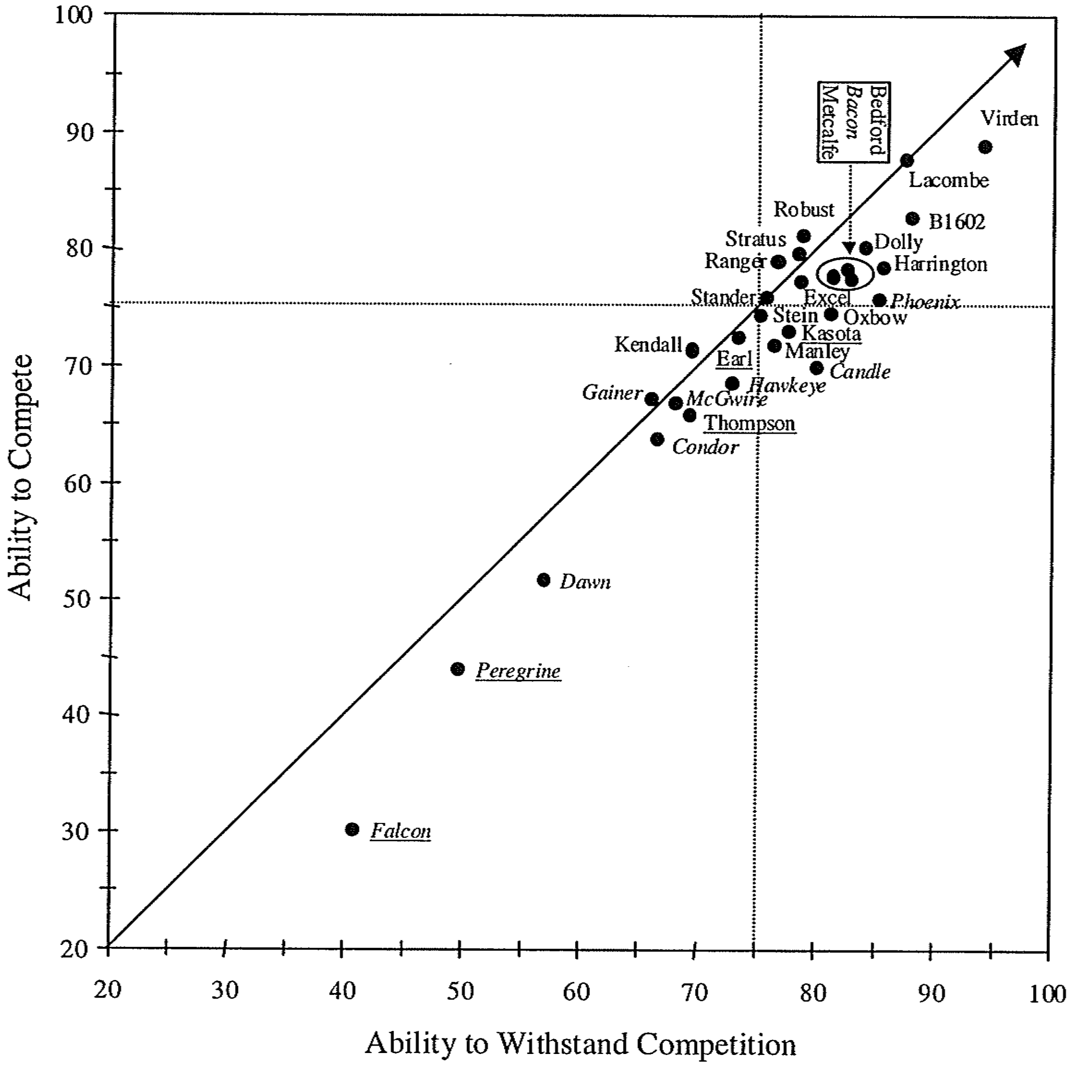

Figure A1. Scatterplot of AC versus AWC for the Prodan 2001 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

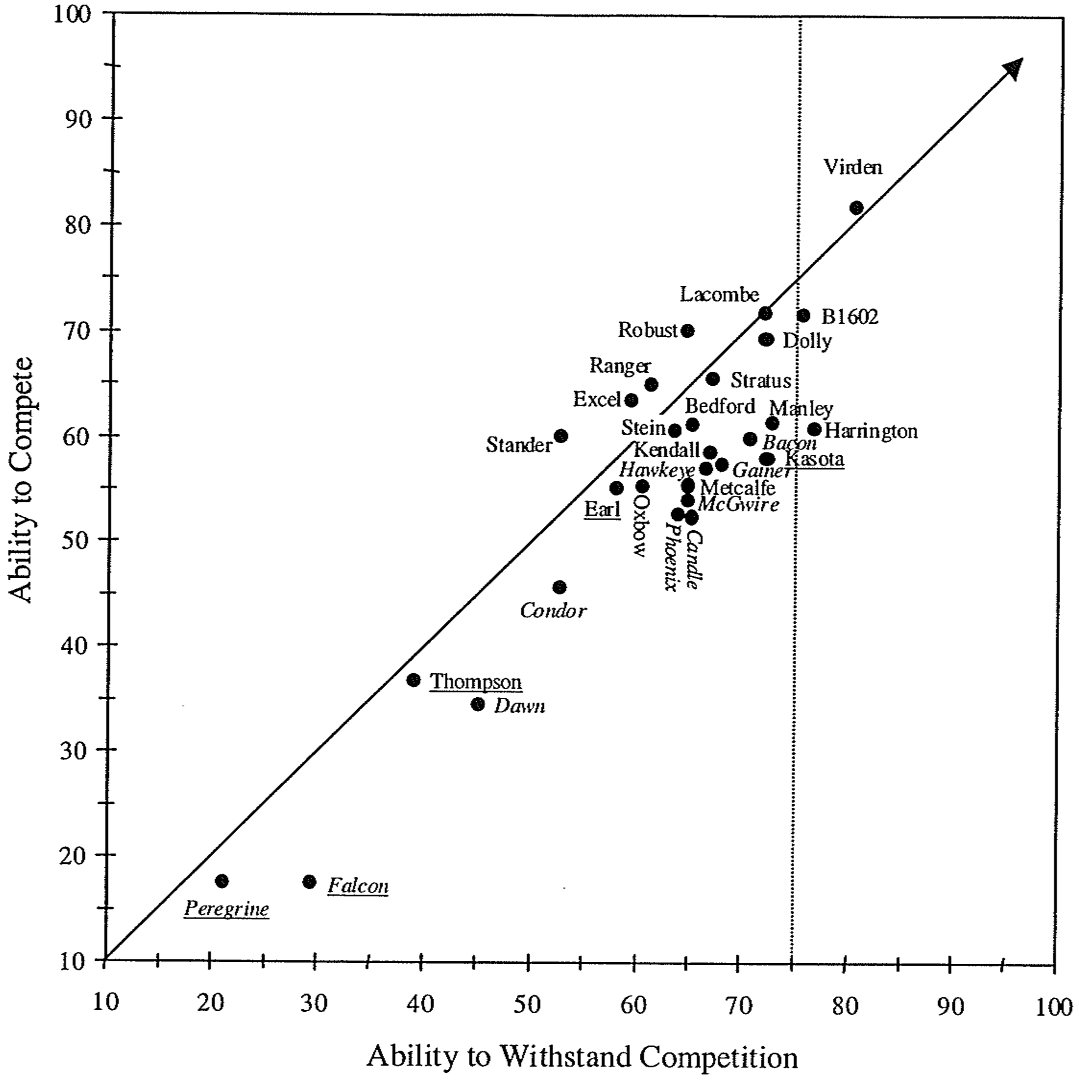

Figure A2. Scatterplot of AC versus AWC for the Newdale 2001 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

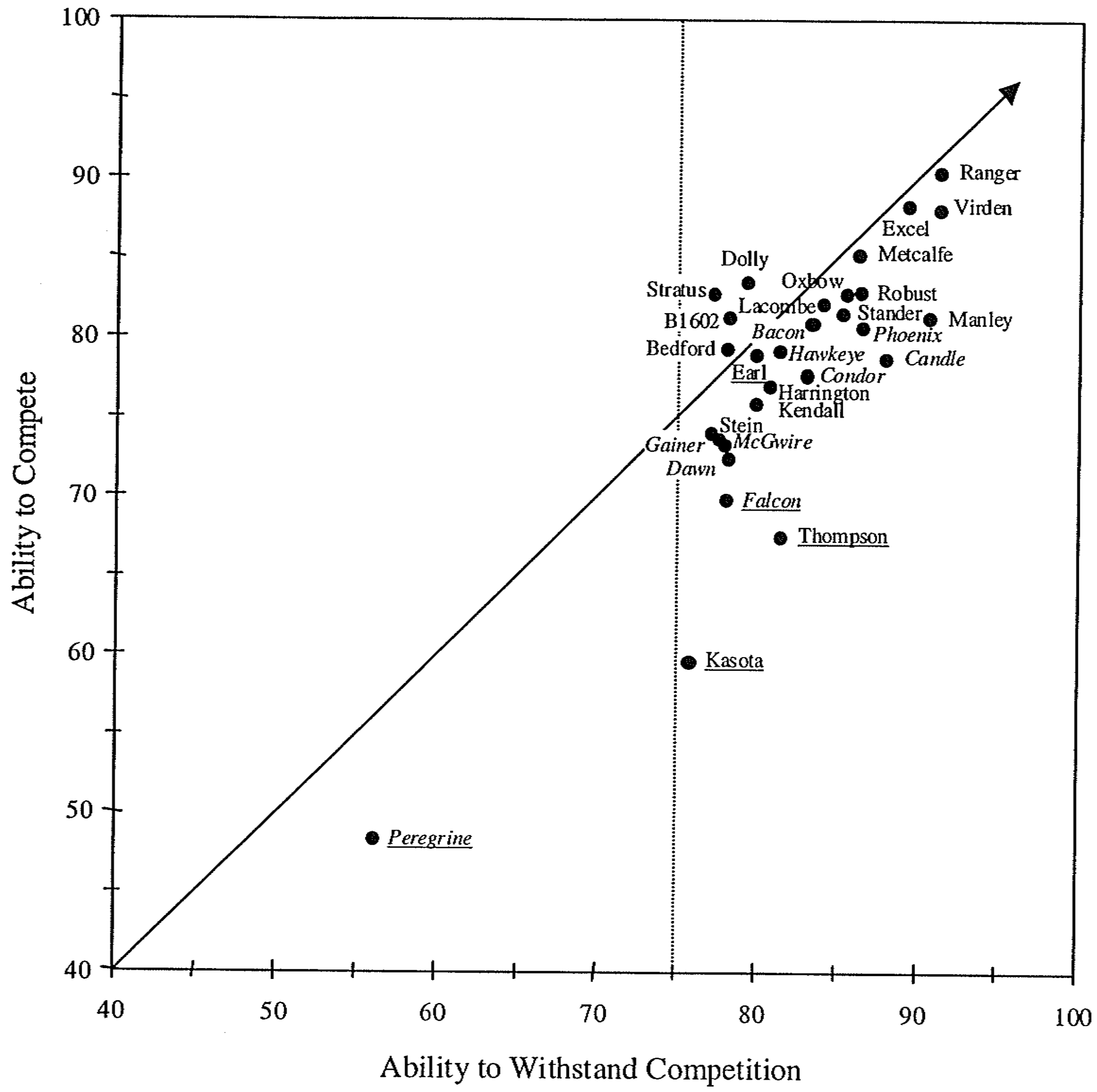

Figure A3. Scatterplot of AC versus AWC for the Ramada 1 2002 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

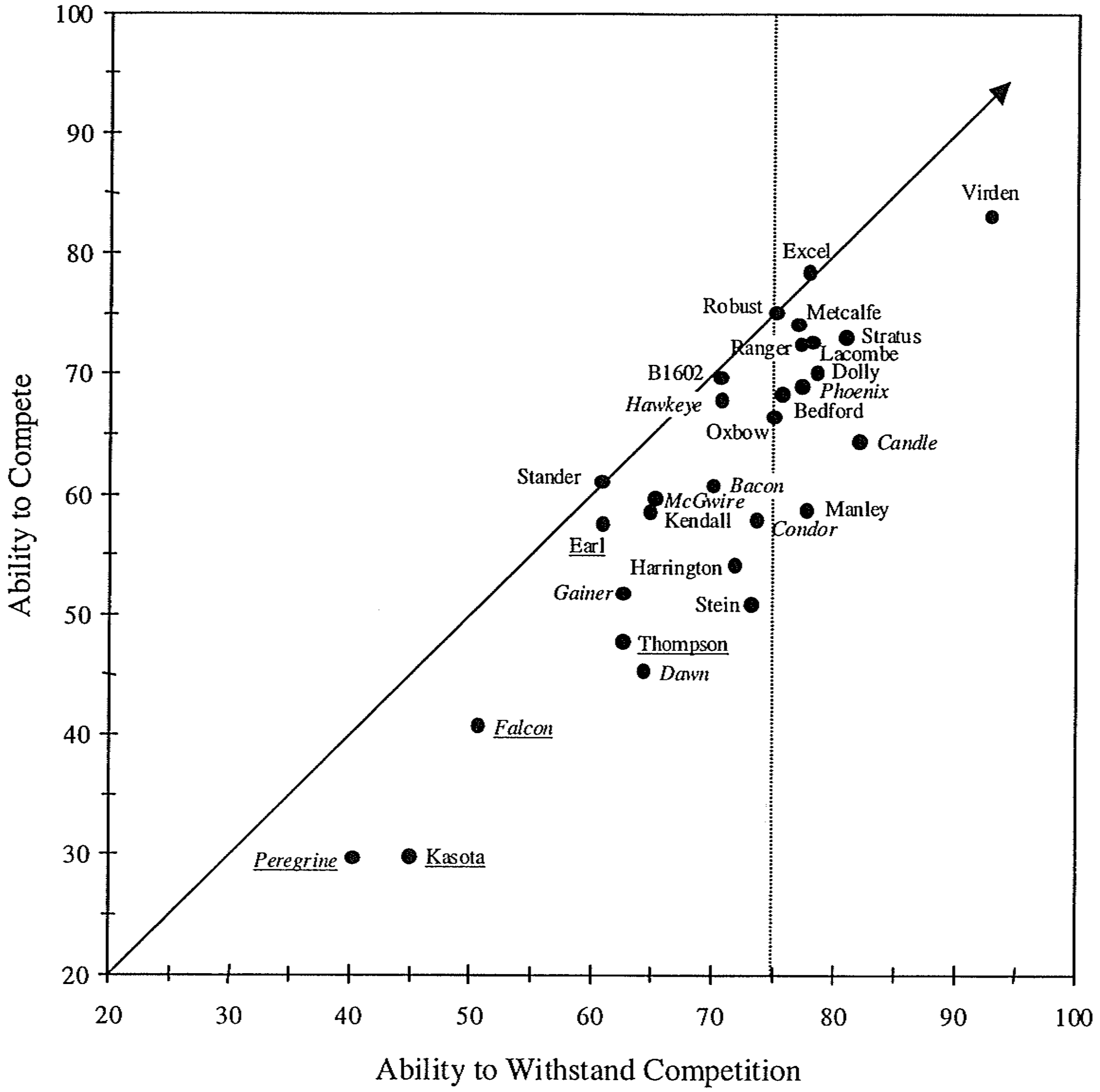

Figure A4. Scatterplot of AC versus AWC for the Ramada 2 2002 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

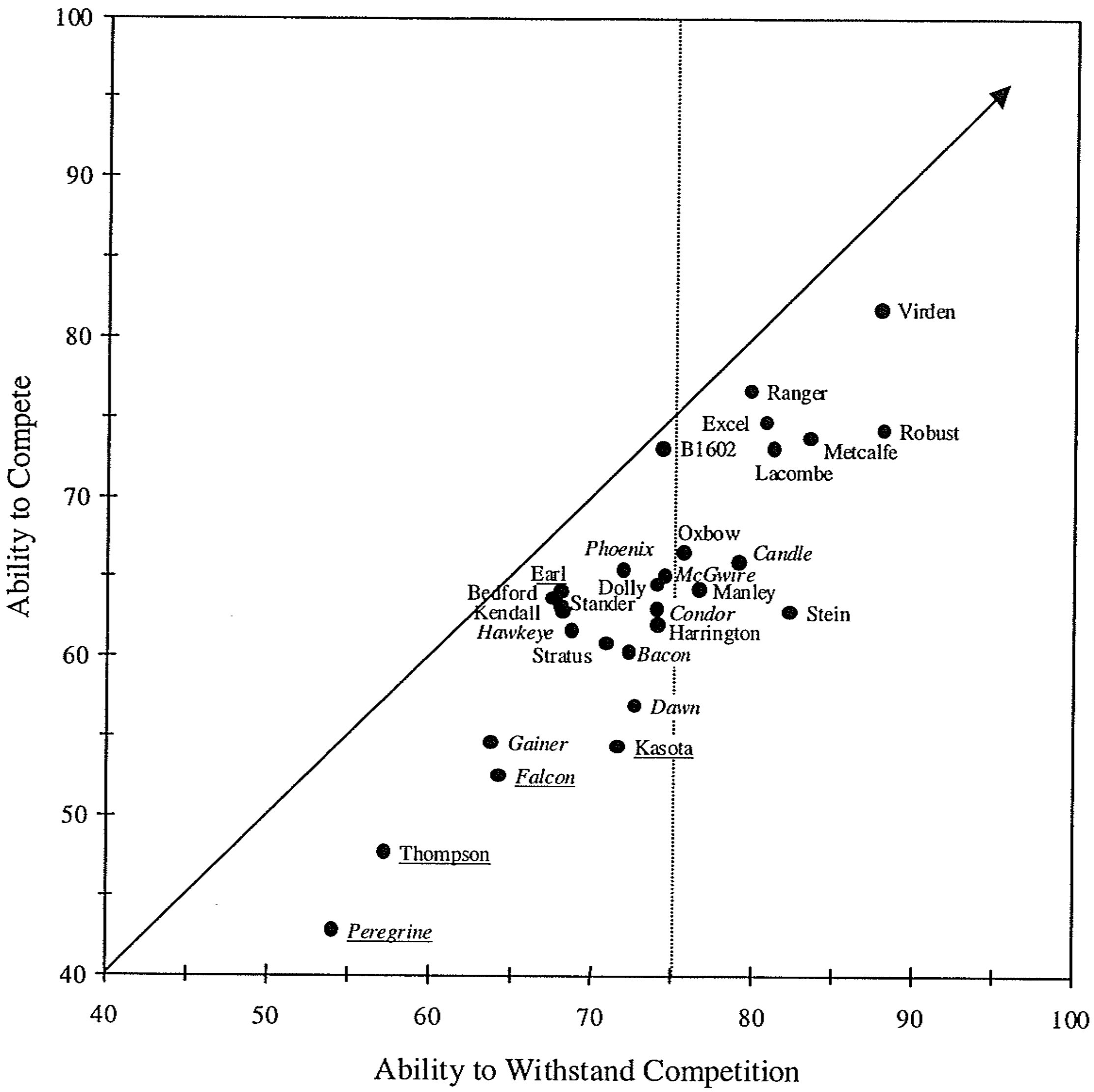

Figure A5. Scatterplot of AC versus AWC for the Newdale 1 2002 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

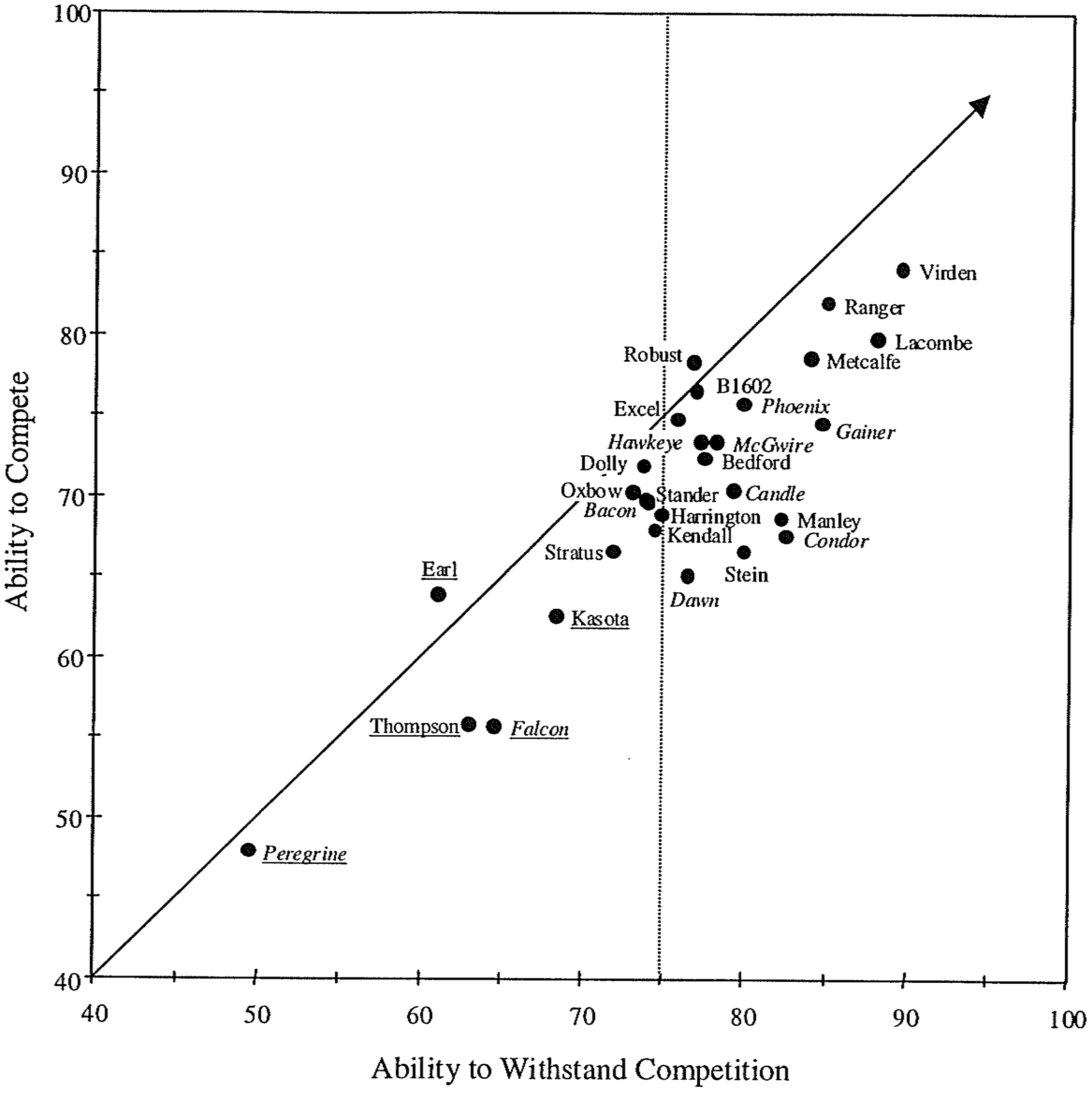

Figure A6. Scatterplot of AC versus AWC for the Newdale 2 2002 site-year. Dashed lines indicate 25% yield loss (AWC) and 25% dockage (AC).

Table A3. Means (± standard error) for ability to withstand competition for classes of barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis includes all cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	75 (1)	63 (2)	82 (1)	72 (1)	73 (1)	77 (1)	74 (3)
6-row	76 (2)	61 (2)	81 (1)	68 (2)	73 (2)	74 (2)	72 (3)
Full height	78 (1)	65 (1)	83 (1)	74 (1)	75 (1)	79 (1)	76 (2)
Semi-dwarf	62 (4)	45 (5)	74 (3)	52 (3)	63 (2)	61 (2)	60 (4)
Hull-less	67 (2)	55 (3)	79 (2)	66 (2)	69 (2)	75 (2)	69 (3)
Hulled	80 (1)	65 (1)	83 (1)	72 (1)	75 (1)	76 (1)	75 (3)
Feed	73 (2)	60 (2)	81 (1)	68 (2)	71 (1)	75 (1)	71 (3)
Malt	79 (1)	66 (1)	83 (1)	73 (1)	76 (2)	77 (1)	76 (2)

Table A4. Means (± standard error) for ability to withstand competition for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	75 (1)	65 (2)	82 (1)	73 (1)	74 (1)	78 (1)	75 (2)
6-row	82 (1)	67 (2)	85 (1)	75 (2)	77 (2)	80 (1)	78 (3)
Hull-less	72 (2)	62 (2)	82 (1)	71 (2)	72 (2)	79 (1)	73 (3)
Hulled	81 (1)	67 (1)	84 (1)	75 (1)	77 (1)	79 (1)	77 (2)
Feed	77 (2)	65 (2)	83 (1)	74 (1)	74 (1)	80 (1)	76 (3)
Malt	79 (1)	66 (1)	83 (1)	73 (1)	76 (2)	77 (1)	76 (2)

Table A5. Means (± standard error) for ability to withstand competition for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf and hull-less cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	79 (1)	68 (1)	82 (1)	75 (2)	76 (2)	77 (2)	76 (2)
6-row	83 (1)	66 (2)	86 (1)	76 (2)	78 (2)	80 (2)	78 (3)
Feed	85 (2)	70 (2)	85 (2)	80 (2)	78 (2)	83 (2)	80 (2)
Malt	79 (1)	66 (1)	83 (1)	73 (1)	76 (2)	77 (1)	76 (2)

Table A6. Means (± standard error) for ability to compete for classes of barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis includes all cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	71 (1)	55 (1)	78 (1)	60 (1)	63 (1)	70 (1)	66 (3)
6-row	73 (2)	59 (2)	78 (2)	62 (2)	65 (2)	71 (2)	68 (3)
Full height	75 (1)	60 (1)	81 (1)	65 (1)	66 (1)	73 (1)	70 (3)
Semi-dwarf	57 (4)	38 (4)	65 (3)	41 (3)	52 (2)	57 (2)	52 (4)
Hull-less	62 (2)	46 (3)	73 (2)	55 (2)	59 (1)	67 (2)	60 (4)
Hulled	77 (1)	62 (1)	80 (1)	64 (1)	67 (1)	72 (1)	70 (3)
Feed	69 (2)	53 (2)	76 (1)	58 (2)	62 (1)	69 (1)	65 (3)
Malt	77 (1)	62 (1)	81 (1)	66 (1)	67 (1)	72 (1)	71 (3)

Table A7. Means (± standard error) for ability to compete for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	72 (1)	56 (1)	78 (1)	61 (1)	64 (1)	71 (1)	67 (3)
6-row	80 (1)	66 (1)	83 (1)	71 (1)	70 (1)	76 (1)	74 (3)
Hull-less	68 (2)	52 (2)	77 (1)	60 (2)	62 (1)	71 (1)	65 (4)
Hulled	79 (1)	64 (1)	82 (1)	68 (1)	69 (1)	74 (1)	73 (3)
Feed	74 (1)	59 (2)	80 (1)	65 (1)	66 (1)	74 (1)	70 (3)
Malt	77 (1)	62 (1)	81 (1)	66 (1)	67 (1)	72 (1)	71 (3)

Table A8. Means (± standard error) for ability to compete for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf and hull-less cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				%			
2-row	76 (1)	61 (1)	80 (1)	63 (2)	65 (1)	70 (1)	69 (3)
6-row	81 (1)	68 (1)	84 (1)	73 (1)	72 (1)	77 (1)	76 (2)
Feed	83 (1)	70 (2)	85 (2)	73 (1)	72 (2)	78 (1)	77 (3)
Malt	77 (1)	62 (1)	81 (1)	66 (1)	67 (1)	72 (1)	71 (3)

Table A9. Overall and class partial correlation of ability to withstand competition with ability to compete for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. All correlation coefficients are significantly different from zero at p≤0.0001 unless otherwise indicated (in brackets). The analysis includes all cultivars.

Cultivar class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				r			
All cultivars	0.8895	0.8240	0.7665	0.8358	0.8104	0.8153	0.8236
2-row	0.8059	0.8131	0.6014	0.6894	0.8229	0.7372	0.7450
6-row	0.9287	0.8647	0.8624	0.9370	0.8288	0.8809	0.8838
Full height	0.7897	0.6461	0.6655	0.6620	0.7571	0.6895	0.7017
Semi-dwarf	0.9640	0.9363	0.8378	0.9035	0.7978	0.7737 (0.0003)	0.8689
Hulless	0.9207	0.9365	0.9134	0.8843	0.8689	0.8505	0.8957
Hulled	0.7211	0.6762	0.6000	0.7907	0.7663	0.7948	0.7249
Feed	0.9114	0.8735	0.8206	0.9148	0.8418	0.8649	0.8712
Malt	0.6031	0.4050	0.5215 (0.0005)	0.4654 (0.0022)	0.7170	0.6264	0.5564

Table A10. Overall and class partial correlation of ability to withstand competition with ability to compete for barley cultivars grown over two growing seasons on Prodan, Newdale and Ramada soil series. All correlation coefficients are significantly different from zero at p≤0.0001 unless otherwise indicated (in brackets). The analysis excludes semi-dwarf cultivars.

Cultivar class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				r			
All cultivars	0.7897	0.6461	0.6655	0.6620	0.7571	0.6895	0.7017
2-row	0.8073	0.7501	0.6132	0.6568	0.7789	0.6657	0.7120
6-row	0.6785	0.6211	0.7361	0.8031	0.7870	0.7571	0.7305
Hulless	0.8188	0.8434	0.8038	0.6601	0.7807	0.6237 (0.0003)	0.7551
Hulled	0.6733	0.5096	0.6258	0.6189	0.7275	0.7193	0.6457
Feed	0.8316	0.7400	0.7581	0.8045	0.7988	0.7229	0.7760
Malt	0.6031	0.4050	0.5215 (0.0005)	0.4654 (0.0022)	0.7171	0.6264	0.5564

Table A11. Overall and class partial correlation of ability to withstand competition with ability to compete for barley cultivars grown over two seasons on Prodan, Newdale and Ramada soil series. All correlation coefficients are significantly different from zero at p≤0.0001 unless otherwise indicated (in brackets). The analysis excludes semi-dwarf and hull-less cultivars.

Cultivar class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				r			
All cultivars	0.6733	0.5096	0.6258	0.6189	0.7275	0.7193	0.6457
2-row	0.6997	0.4931 (0.0066)	0.4678 (0.0105)	0.5252 (0.0034)	0.7338	0.6748	0.5991
6-row	0.6753	0.7175	0.7661	0.8622	0.7964	0.7443	0.7603
Feed	0.6117	0.6155 (0.0085)	0.8121	0.9053	0.8112	0.8185	0.7624
Malt	0.6031	0.4050	0.5215 (0.0005)	0.4654 (0.0022)	0.7171	0.6264	0.5564

Table A12. Overall and class regression slope (*m*) of ability to withstand competition with ability to compete for barley cultivars grown over two growing seasons on Prodan, Newdale and Ramada soil series. All regression slope coefficients are significantly different from zero at p≤0.0001 unless otherwise indicated (in brackets) The analysis includes all cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				m			
All cultivars	0.8870	0.8630	0.7440	0.7781	0.8893	0.9336	0.8492
2-row	1.0006	1.0001	0.7626	0.6894	0.9762	0.8870	0.8860
6-row	0.8613	0.8432	0.7359	0.8307	0.8582	0.9662	0.8493
Full height	0.9321	0.6999	0.8125	0.6275	0.8919	0.8052	0.7949
Semi-dwarf	0.8454	1.0770	0.8871	0.8405	0.9447	0.8896 (0.0003)	0.9141
Hulless	0.9055	1.1011	0.9730	0.9028	0.9581	0.9853	0.9710
Hulled	0.9949	0.7677	0.5601	0.7106	0.8914	0.9362	0.8102
Feed	0.8990	0.9050	0.7812	0.8720	0.8570	0.9789	0.8822
Malt	0.9539	0.5757	0.6478 (0.0005)	0.4126 (0.0022)	0.9549	0.7587	0.7173

Table A13. Overall and class regression slope (*m*) of ability to withstand competition with ability to withstand compete for barley cultivars grown over two growing seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				m			
All cultivars	0.9321	0.6999	0.8125	0.6275	0.8919	0.8052	0.7949
2-row	0.9989	0.9090	0.8054	0.6636	0.9341	0.8269	0.8563
6-row	0.9235	0.7795	0.9566	0.9814	1.0418	0.9581	0.9402
Hulless	1.0373	1.1174	1.1692	0.6489	0.9943	0.7400 (0.0003)	0.9512
Hulled	1.0233	0.6138	0.7914	0.6022	0.9078	0.8593	0.7996
Feed	0.9509	0.7428	0.9158	0.7725	0.8521	0.8087	0.8405
Malt	0.9539	0.5757	0.6478 (0.0005)	0.4126 (0.0022)	0.9549	0.7587	0.7173

Table A14. Overall and class regression slope (*m*) of ability to withstand competition with ability to withstand compete for barley cultivars grown over two growing seasons on Prodan, Newdale and Ramada soil series. The analysis excludes semi-dwarf and hull-less cultivars.

Class	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
				m			
All cultivars	1.0233	0.6138	0.7914	0.6022	0.9079	0.8593	0.7997
2-row	1.2280	0.6704 (0.0066)	0.6030 (0.0105)	0.4911 (0.0034)	0.9444	0.9456	0.8138
6-row	1.1302	0.9971	1.0341	1.1892	1.1815	0.9922	1.0874
Feed	1.0923	0.6739 (0.0085)	1.1462	1.2156	0.9654	1.1100	1.0339
Malt	0.9539	0.5757	0.6478 (0.0005)	0.4126 (0.0022)	0.9549	0.7587	0.7173

Table A15. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis includes all cultivars and has 114 df and the minimum r significant at $p \leq 0.05$ is 0.1824.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.6371	1										
	2002	Ramada 1	0.3912	0.3670	1									
		Ramada 2	0.5606	0.4706	0.4908	1								
		Newdale 1	0.3553	0.3658	0.3701	0.4925	1							
		Newdale 2	0.3591	0.4564	0.3295	0.5408	0.3026	1						
AC	2001	Prodan	0.7659	0.8235	0.3806	0.5946	0.4077	0.5160	1					
		Newdale	0.8866	0.6793	0.3830	0.5674	0.4085	0.3930	0.8654	1				
	2002	Ramada 1	0.4823	0.4156	0.7244	0.6192	0.4198	0.4329	0.5469	0.5181	1			
		Ramada 2	0.5992	0.4746	0.4964	0.8321	0.4550	0.4826	0.6739	0.6550	0.6871	1		
		Newdale 1	0.4986	0.4257	0.4410	0.5911	0.8150	0.3895	0.5763	0.5816	0.6135	0.6919	1	
		Newdale 2	0.5480	0.5458	0.3970	0.5518	0.3221	0.8126	0.6837	0.6140	0.5882	0.6626	0.5346	1

Table A16. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for 2-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis includes all cultivars and has 58 df and the minimum r significant at $p \leq 0.05$ is 0.2542.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4034	1										
	2002	Ramada 1	0.2216^{ns}	0.1669^{ns}	1									
		Ramada 2	0.4274	0.3404	0.2058^{ns}	1								
		Newdale 1	0.1381^{ns}	0.2921	0.0539^{ns}	0.4472	1							
		Newdale 2	0.0248^{ns}	0.1727^{ns}	0.0419^{ns}	0.1184^{ns}	0.0998^{ns}	1						
AC	2001	Prodan	0.5120	0.8002	0.0250^{ns}	0.4126	0.1802^{ns}	0.1237^{ns}	1					
		Newdale	0.7834	0.4622	0.0990^{ns}	0.4239	0.1951^{ns}	-0.0403^{ns}	0.6656	1				
	2002	Ramada 1	0.4016	0.2074^{ns}	0.5556	0.3269	0.1729^{ns}	0.0828^{ns}	0.3274	0.3348	1			
		Ramada 2	0.5342	0.3735	0.1543^{ns}	0.6777	0.2849	0.0487^{ns}	0.4874	0.5864	0.3784	1		
		Newdale 1	0.2604	0.2998	0.0763^{ns}	0.3656	0.8236	0.0927^{ns}	0.2534^{ns}	0.2989	0.3040	0.4425	1	
		Newdale 2	0.2832	0.2674	0.0754^{ns}	0.1177^{ns}	0.0564^{ns}	0.7311	0.3384	0.2444^{ns}	0.3040	0.3113	0.2417^{ns}	1

Table A17. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for 6-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis has includes all cultivars and 54 df and the minimum r significant at $p \leq 0.05$ is 0.2632.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.7796	1										
	2002	Ramada 1	0.4921	0.4980	1									
		Ramada 2	0.6422	0.5366	0.6601	1								
		Newdale 1	0.4854	0.4180	0.6024	0.5397	1							
		Newdale 2	0.5266	0.6067	0.4961	0.7213	0.4341	1						
AC	2001	Prodan	0.8833	0.8651	0.5826	0.7253	0.5424	0.7272	1					
		Newdale	0.9293	0.7966	0.5230	0.6490	0.5218	0.5696	0.9336	1				
	2002	Ramada 1	0.5166	0.5205	0.8254	0.7575	0.5627	0.5918	0.6372	0.5813	1			
		Ramada 2	0.6252	0.5351	0.6818	0.9346	0.5554	0.6867	0.7395	0.6760	0.8049	1		
		Newdale 1	0.6250	0.5246	0.6920	0.7766	0.8248	0.5954	0.7248	0.7076	0.7761	0.8141	1	
		Newdale 2	0.6607	0.6989	0.5751	0.7697	0.4772	0.8762	0.8206	0.7385	0.7040	0.7964	0.6817	1

Table A18. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for full height barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis includes all cultivars and has 94 df and the minimum r significant at $p \leq 0.05$ is 0.2006.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4095	1										
	2002	Ramada 1	0.1959^{ns}	0.1356^{ns}	1									
		Ramada 2	0.4411	0.2327	0.2713	1								
		Newdale 1	0.1665^{ns}	0.0723^{ns}	0.2553	0.3742	1							
		Newdale 2	0.0909^{ns}	0.0631^{ns}	0.0896^{ns}	0.2243	0.0015^{ns}	1						
AC	2001	Prodan	0.6050	0.6474	0.1431^{ns}	0.3836	0.1327^{ns}	0.1634^{ns}	1					
		Newdale	0.7838	0.4318	0.1999^{ns}	0.4048	0.2393	0.0705^{ns}	0.7566	1				
	2002	Ramada 1	0.3476	0.1179^{ns}	0.5991	0.3374	0.2620	0.1020^{ns}	0.3681	0.4094	1			
		Ramada 2	0.5421	0.2504	0.3126	0.6535	0.3123	0.1133^{ns}	0.5680	0.6271	0.4463	1		
		Newdale 1	0.3300	0.1208^{ns}	0.2746	0.3942	0.7637	0.0644^{ns}	0.3521	0.4637	0.4200	0.5534	1	
		Newdale 2	0.3296	0.1900^{ns}	0.1589^{ns}	0.2178	0.0365^{ns}	0.6847	0.4530	0.4131	0.3459	0.4326	0.2947	1

Table A19. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for semi-dwarf barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated ^{ns}. This analysis includes all cultivars and has 18 df and the minimum r significant at $p \leq 0.05$ is 0.4682.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.7804	1										
	2002	Ramada 1	0.3676^{ns}	0.3864^{ns}	1									
		Ramada 2	0.2185^{ns}	0.2186^{ns}	0.5811	1								
		Newdale 1	0.2905^{ns}	0.5648	0.2802^{ns}	0.1198^{ns}	1							
		Newdale 2	0.1213^{ns}	0.6451	0.2903^{ns}	0.3614^{ns}	0.3771^{ns}	1						
AC	2001	Prodan	0.8870	0.9276	0.3794^{ns}	0.3565^{ns}	0.5355	0.5595	1					
		Newdale	0.9598	0.7578	0.2721^{ns}	0.2564^{ns}	0.2837^{ns}	0.1714^{ns}	0.8984	1				
	2002	Ramada 1	0.1864^{ns}	0.2869^{ns}	0.7804	0.5789	0.2385^{ns}	0.2563^{ns}	0.2886^{ns}	0.1661^{ns}	1			
		Ramada 2	0.1578^{ns}	0.1743^{ns}	0.4834	0.9088	0.0800^{ns}	0.2679^{ns}	0.3267^{ns}	0.2270^{ns}	0.6732	1		
		Newdale 1	0.3486^{ns}	0.5087	0.4432^{ns}	0.3710^{ns}	0.8026	0.2859^{ns}	0.5741	0.3795^{ns}	0.5974	0.4939	1	
		Newdale 2	0.4457	0.7252	0.4036^{ns}	0.3488^{ns}	0.2748^{ns}	0.7484	0.6972	0.4728	0.4351^{ns}	0.3946^{ns}	0.3505^{ns}	1

Table A20. Correlation coefficients for ability to withstand competition (AWC) and ability to compete (AC) across site-years for hull-less barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated ^{ns}. This analysis includes all cultivars and has 38 df and the minimum r significant at $p \leq 0.05$ is 0.3120.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.6638	1										
	2002	Ramada 1	0.4862	0.5570	1									
		Ramada 2	0.6110	0.6017	0.6432	1								
		Newdale 1	0.3780	0.3451	0.4112	0.5672	1							
		Newdale 2	0.4466	0.6287	0.4236	0.6291	0.2746^{ns}	1						
AC	2001	Prodan	0.7424	0.9210	0.4765	0.6551	0.3129^{ns}	0.6802	1					
		Newdale	0.9202	0.7273	0.4498	0.5998	0.3425	0.4794	0.8462	1				
	2002	Ramada 1	0.5528	0.6605	0.8619	0.6474	0.4754	0.5899	0.6501	0.5557	1			
		Ramada 2	0.7198	0.6965	0.6268	0.8807	0.5071	0.5930	0.7523	0.6824	0.6617	1		
		Newdale 1	0.5125	0.4905	0.4665	0.6871	0.8642	0.4031	0.4995	0.5144	0.5538	0.6851	1	
		Newdale 2	0.5811	0.6840	0.4262	0.5698	0.1720^{ns}	0.8520	0.7711	0.6525	0.6257	0.6240	0.3795	1

Table A21. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for hulled barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated ^{ns}. This analysis includes all cultivars and has 74 df and the minimum r significant at $p \leq 0.05$ is 0.2256.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4734	1										
	2002	Ramada 1	0.1385 ^{ns}	0.0499 ^{ns}	1									
		Ramada 2	0.4405	0.2635	0.3028	1								
		Newdale 1	0.2168 ^{ns}	0.3112	0.2975	0.4041	1							
		Newdale 2	0.2986	0.2908	0.2241 ^{ns}	0.4712	0.3083	1						
AC	2001	Prodan	0.6106	0.6821	0.1630 ^{ns}	0.4925	0.3755	0.4537	1					
		Newdale	0.7033	0.5174	0.1322 ^{ns}	0.5347	0.4160	0.4310	0.7748	1				
	2002	Ramada 1	0.2299	0.0387 ^{ns}	0.5717	0.5437	0.3149	0.3015	0.3089	0.3118	1			
		Ramada 2	0.3833	0.1876 ^{ns}	0.3418	0.7844	0.3591	0.4162	0.5412	0.6300	0.6459	1		
		Newdale 1	0.3279	0.2685	0.3658	0.4837	0.7753	0.3847	0.5069	0.5847	0.5764	0.6336	1	
		Newdale 2	0.4701	0.3575	0.3099	0.4939	0.3576	0.7893	0.6303	0.6621	0.5044	0.6600	0.5878	1

Table A22. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for feed barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated ^{ns}. This analysis includes all cultivars and has 70 df and the minimum r significant at $p \leq 0.05$ is 0.2318.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.6701	1										
	2002	Ramada 1	0.4803	0.4612	1									
		Ramada 2	0.5981	0.5036	0.5735	1								
		Newdale 1	0.4135	0.4615	0.3993	0.5207	1							
		Newdale 2	0.4404	0.5517	0.3874	0.6410	0.4126	1						
AC	2001	Prodan	0.8053	0.8717	0.4631	0.6433	0.4907	0.6281	1					
		Newdale	0.9103	0.7260	0.4384	0.5941	0.4433	0.4811	0.8842	1				
	2002	Ramada 1	0.5126	0.5185	0.7796	0.6843	0.4806	0.5334	0.5893	0.5369	1			
		Ramada 2	0.6473	0.5576	0.5533	0.9110	0.5088	0.6223	0.7116	0.6643	0.7312	1		
		Newdale 1	0.5425	0.5268	0.4976	0.6784	0.8437	0.5258	0.6492	0.6128	0.6583	0.7428	1	
		Newdale 2	0.5978	0.6537	0.4426	0.6506	0.3997	0.8628	0.7646	0.6685	0.6558	0.7129	0.6028	1

Table A23. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for malt barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated ^{ns}. This analysis includes all cultivars and has 42 df and the minimum r significant at $p \leq 0.05$ is 0.2973.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3041	1										
	2002	Ramada 1	-0.1781^{ns}	-0.1192^{ns}	1									
		Ramada 2	0.1950^{ns}	0.1785^{ns}	0.0948^{ns}	1								
		Newdale 1	-0.0033^{ns}	-0.0454^{ns}	0.2349^{ns}	0.3502	1							
		Newdale 2	-0.0506^{ns}	0.0560^{ns}	0.1252^{ns}	0.1580^{ns}	0.0121^{ns}	1						
AC	2001	Prodan	0.2865^{ns}	0.4267	-0.1919^{ns}	0.1383^{ns}	-0.0875^{ns}	-0.0097^{ns}	1					
		Newdale	0.5647	0.1420^{ns}	-0.1408^{ns}	0.2023^{ns}	0.0955^{ns}	-0.1389^{ns}	0.4590	1				
	2002	Ramada 1	0.0686^{ns}	-0.2891^{ns}	0.4869	0.2078^{ns}	0.1209^{ns}	0.0591^{ns}	0.0150^{ns}	0.0365^{ns}	1			
		Ramada 2	0.1648^{ns}	-0.0796^{ns}	0.2122^{ns}	0.4466	0.1902^{ns}	-0.0136^{ns}	0.2960^{ns}	0.4555	0.3778	1		
		Newdale 1	0.1277^{ns}	-0.1329^{ns}	0.1854^{ns}	0.1722^{ns}	0.7198	-0.0482^{ns}	0.0353^{ns}	0.2537^{ns}	0.3322	0.4168	1	
		Newdale 2	0.2336^{ns}	0.0022^{ns}	0.1905^{ns}	0.0780^{ns}	0.0555^{ns}	0.6416	0.2579^{ns}	0.2945^{ns}	0.2762^{ns}	0.4404	0.2570^{ns}	1

Table A24. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 94 df and the minimum r significant at $p \leq 0.05$ is 0.2006.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4095	1										
	2002	Ramada 1	0.1959^{ns}	0.1356^{ns}	1									
		Ramada 2	0.4411	0.2327	0.2713	1								
		Newdale 1	0.1665^{ns}	0.0723^{ns}	0.2553	0.3742	1							
		Newdale 2	0.0909^{ns}	0.0631^{ns}	0.0896^{ns}	0.2243	0.0015^{ns}	1						
AC	2001	Prodan	0.6050	0.6474	0.1431^{ns}	0.3836	0.1327^{ns}	0.1634^{ns}	1					
		Newdale	0.7838	0.4318	0.1999^{ns}	0.4048	0.2393	0.0705^{ns}	0.7566	1				
	2002	Ramada 1	0.3476	0.1179^{ns}	0.5991	0.3374	0.2620	0.1020^{ns}	0.3681	0.4094	1			
		Ramada 2	0.5421	0.2504	0.3126	0.6535	0.3123	0.1133^{ns}	0.5680	0.6271	0.4463	1		
		Newdale 1	0.3300	0.1208^{ns}	0.2746	0.3942	0.7637	0.0644^{ns}	0.3521	0.4637	0.4200	0.5534	1	
		Newdale 2	0.3296	0.1900^{ns}	0.1589^{ns}	0.2178	0.0365^{ns}	0.6847	0.4530	0.4131	0.3459	0.4326	0.2947	1

Table A25. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for 2-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 54 df and the minimum r significant at $p \leq 0.05$ is 0.2632.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3970	1										
	2002	Ramada 1	0.2149^{ns}	0.1730^{ns}	1									
		Ramada 2	0.4209	0.2245^{ns}	0.2250^{ns}	1								
		Newdale 1	0.1007^{ns}	0.0716^{ns}	0.0777^{ns}	0.3587	1							
		Newdale 2	-0.0329^{ns}	-0.0701^{ns}	0.0585^{ns}	-0.0079^{ns}	-0.1290^{ns}	1						
AC	2001	Prodan	0.5244	0.7335	-0.0265^{ns}	0.3181	-0.0558^{ns}	-0.1111^{ns}	1					
		Newdale	0.7884	0.4356	0.1143^{ns}	0.3952	0.1240^{ns}	-0.1436^{ns}	0.6757	1				
	2002	Ramada 1	0.3607	0.0955^{ns}	0.5699	0.2993	0.1050^{ns}	-0.0020^{ns}	0.2556^{ns}	0.3304	1			
		Ramada 2	0.5316	0.2442^{ns}	0.1783^{ns}	0.6466	0.1518^{ns}	-0.1270^{ns}	0.3954	0.5650	0.3523	1		
		Newdale 1	0.2275^{ns}	0.0734^{ns}	0.0963^{ns}	0.2695	0.7812	-0.1538^{ns}	0.0349^{ns}	0.2407^{ns}	0.2370^{ns}	0.3362	1	
		Newdale 2	0.2449^{ns}	0.0145^{ns}	0.0825^{ns}	-0.0231^{ns}	-0.2155^{ns}	0.6589	0.1380^{ns}	0.1766^{ns}	0.1951^{ns}	0.1703^{ns}	-0.0019^{ns}	1

Table A26. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for 6-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 38 df and the minimum r significant at $p \leq 0.05$ is 0.3120.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4109	1										
	2002	Ramada 1	-0.0156^{ns}	0.0245^{ns}	1									
		Ramada 2	0.4648	0.2270^{ns}	0.3203	1								
		Newdale 1	0.1894^{ns}	0.0497^{ns}	0.4878	0.3801	1							
		Newdale 2	0.2152^{ns}	0.2165^{ns}	0.1003^{ns}	0.4901	0.1138^{ns}	1						
AC	2001	Prodan	0.5620	0.6156	0.2044^{ns}	0.4919	0.2713^{ns}	0.4768	1					
		Newdale	0.6812	0.4548	0.1388^{ns}	0.4472	0.3525	0.3204	0.7059	1				
	2002	Ramada 1	0.0710^{ns}	0.0807^{ns}	0.5906	0.3725	0.4313	0.2000^{ns}	0.2310^{ns}	0.2280^{ns}	1			
		Ramada 2	0.3162	0.2138^{ns}	0.4094	0.7952	0.5124	0.4039	0.5128	0.4009	0.3178	1		
		Newdale 1	0.2419^{ns}	0.1150^{ns}	0.4305	0.5490	0.7897	0.2569^{ns}	0.4583	0.5385	0.4909	0.6604	1	
		Newdale 2	0.2166^{ns}	0.3689	0.1055^{ns}	0.4737	0.2080^{ns}	0.7673	0.5986	0.4689	0.3318	0.5235	0.3854	1

Table A27. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for hull-less barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 30 df and the minimum r significant at $p \leq 0.05$ is 0.3493.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3273 ns	1										
	2002	Ramada 1	0.3211 ns	0.3035 ns	1									
		Ramada 2	0.3607	0.1045 ns	0.3887	1								
		Newdale 1	0.0733 ns	-0.1177 ns	-0.0020 ns	0.3195 ns	1							
		Newdale 2	0.0440 ns	0.0393 ns	-0.1448 ns	0.0387 ns	-0.2864 ns	1						
AC	2001	Prodan	0.4135	0.8141	0.1279 ns	0.1537 ns	-0.2556 ns	0.1442 ns	1					
		Newdale	0.8135	0.3988	0.2896 ns	0.2473 ns	-0.0534 ns	-0.0533 ns	0.5835	1				
	2002	Ramada 1	0.4347	0.3615	0.6218	0.1867 ns	0.0106 ns	0.0221 ns	0.3550	0.4486	1			
		Ramada 2	0.6290	0.3327 ns	0.3432 ns	0.6775	0.1932 ns	-0.0866 ns	0.4191	0.4947	0.2382 ns	1		
		Newdale 1	0.1965 ns	0.0047 ns	-0.0794 ns	0.4153	0.7707	-0.2165 ns	-0.0505 ns	0.1665 ns	-0.0405 ns	0.4118	1	
		Newdale 2	0.2388 ns	0.2392 ns	-0.1514 ns	-0.0670 ns	-0.4005	0.6299	0.4762	0.3186 ns	0.2017 ns	0.0712 ns	-0.1502 ns	1

Table A28. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for hulled barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 62 df and the minimum r significant at $p \leq 0.05$ is 0.2460.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3853	1										
	2002	Ramada 1	0.0621^{ns}	-0.0092^{ns}	1									
		Ramada 2	0.4134	0.2541	0.1843^{ns}	1								
		Newdale 1	0.0758^{ns}	0.1011^{ns}	0.3389	0.3476	1							
		Newdale 2	0.1472^{ns}	0.0868^{ns}	0.1893^{ns}	0.3179	0.1082^{ns}	1						
AC	2001	Prodan	0.5441	0.5227	0.0747^{ns}	0.4164	0.1278^{ns}	0.2463	1					
		Newdale	0.6508	0.3783	0.0741^{ns}	0.4340	0.2462	0.2116^{ns}	0.6797	1				
	2002	Ramada 1	0.1294^{ns}	-0.1351^{ns}	0.5897	0.3273	0.2692	0.1481^{ns}	0.1618^{ns}	0.1624^{ns}	1			
		Ramada 2	0.3436	0.0912^{ns}	0.2679	0.6056	0.2671	0.2172^{ns}	0.4816	0.5864	0.4150	1		
		Newdale 1	0.2055^{ns}	0.0622^{ns}	0.3874	0.3113	0.7427	0.1753^{ns}	0.2925	0.4292	0.4685	0.5005	1	
		Newdale 2	0.3366	0.1202^{ns}	0.2779	0.3091	0.1557^{ns}	0.7210	0.4407	0.5005	0.3622	0.5597	0.4111	1

Table A29. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for feed barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 50 df and the minimum r significant at $p \leq 0.05$ is 0.2732.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.4499	1										
	2002	Ramada 1	0.3608	0.2834	1									
		Ramada 2	0.5582	0.2650 ns	0.3861	1								
		Newdale 1	0.2443 ns	0.1458 ns	0.2737 ns	0.4128	1							
		Newdale 2	0.2087 ns	0.0832 ns	0.0686 ns	0.2639 ns	0.0382 ns	1						
AC	2001	Prodan	0.6767	0.7353	0.2867	0.5059	0.2218 ns	0.3260	1					
		Newdale	0.8307	0.5281	0.3287	0.5163	0.2948	0.2358 ns	0.8080	1				
	2002	Ramada 1	0.4714	0.3507	0.6827	0.4337	0.3628	0.1803 ns	0.5185	0.5510	1			
		Ramada 2	0.7200	0.4398	0.3828	0.7928	0.4062	0.2418 ns	0.7048	0.7373	0.4924	1		
		Newdale 1	0.4122	0.2562 ns	0.3350	0.5408	0.7982	0.1937 ns	0.4754	0.5480	0.4716	0.6430	1	
		Newdale 2	0.4229	0.3180	0.1429 ns	0.2995	0.0560 ns	0.7051	0.6178	0.5620	0.4350	0.4498	0.3564	1

Table A30. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for malt barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf cultivars and has 42 df and the minimum r significant at $p \leq 0.05$ is 0.2973.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3041	1										
	2002	Ramada 1	-0.1781^{ns}	-0.1192^{ns}	1									
		Ramada 2	0.1950^{ns}	0.1785^{ns}	0.0948^{ns}	1								
		Newdale 1	-0.0033^{ns}	-0.0454^{ns}	0.2349^{ns}	0.3502	1							
		Newdale 2	-0.0506^{ns}	0.0560^{ns}	0.1252^{ns}	0.1580^{ns}	0.0121^{ns}	1						
AC	2001	Prodan	0.2865^{ns}	0.4267	-0.1919^{ns}	0.1383^{ns}	-0.0875^{ns}	-0.0097^{ns}	1					
		Newdale	0.5647	0.1420^{ns}	-0.1408^{ns}	0.2023^{ns}	0.0955^{ns}	-0.1389^{ns}	0.4590	1				
	2002	Ramada 1	0.0686^{ns}	-0.2891^{ns}	0.4869	0.2078^{ns}	0.1209^{ns}	0.0591^{ns}	0.0150^{ns}	0.0365^{ns}	1			
		Ramada 2	0.1648^{ns}	-0.0796^{ns}	0.2122^{ns}	0.4466	0.1902^{ns}	-0.0136^{ns}	0.2960^{ns}	0.4555	0.3778	1		
		Newdale 1	0.1277^{ns}	-0.1329^{ns}	0.1854^{ns}	0.1722^{ns}	0.7198	-0.0482^{ns}	0.0353^{ns}	0.2537^{ns}	0.3322	0.4168	1	
		Newdale 2	0.2336^{ns}	0.0022^{ns}	0.1905^{ns}	0.0780^{ns}	0.0555^{ns}	0.6416	0.2579^{ns}	0.2945^{ns}	0.2762^{ns}	0.4404	0.2570^{ns}	1

Table A31. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf and hull-less cultivars and has 62 df and the minimum r significant at $p \leq 0.05$ is 0.2460.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3853	1										
	2002	Ramada 1	0.0621^{ns}	-0.0092^{ns}	1									
		Ramada 2	0.4134	0.2541	0.1843^{ns}	1								
		Newdale 1	0.0758^{ns}	0.1011^{ns}	0.3389	0.3476	1							
		Newdale 2	0.1472^{ns}	0.0868^{ns}	0.1893^{ns}	0.3179	0.1082^{ns}	1						
AC	2001	Prodan	0.5441	0.5227	0.0747^{ns}	0.4164	0.1278^{ns}	0.2463	1					
		Newdale	0.6508	0.3783	0.0741^{ns}	0.4340	0.2462	0.2116^{ns}	0.6797	1				
	2002	Ramada 1	0.1294^{ns}	-0.1351^{ns}	0.5897	0.3273	0.2692	0.1481^{ns}	0.1618^{ns}	0.1624^{ns}	1			
		Ramada 2	0.3436	0.0912^{ns}	0.2679	0.6056	0.2671	0.2172^{ns}	0.4816	0.5864	0.4150	1		
		Newdale 1	0.2055^{ns}	0.0622^{ns}	0.3874	0.3113	0.7427	0.1753^{ns}	0.2925	0.4292	0.4685	0.5005	1	
		Newdale 2	0.3366	0.1202^{ns}	0.2779	0.3091	0.1557^{ns}	0.7210	0.4407	0.5005	0.3622	0.5597	0.4111	1

Table A32. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for 2-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf and hull-less cultivars and has 30 df and the minimum r significant at $p \leq 0.05$ is 0.3493.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.2283 ^{ns}	1										
	2002	Ramada 1	0.0579 ^{ns}	-0.0460 ^{ns}	1									
		Ramada 2	0.3178 ^{ns}	0.0920 ^{ns}	0.0359 ^{ns}	1								
		Newdale 1	0.0020 ^{ns}	0.0659 ^{ns}	0.1501 ^{ns}	0.3019 ^{ns}	1							
		Newdale 2	0.0007 ^{ns}	-0.1231 ^{ns}	0.0872 ^{ns}	0.0908 ^{ns}	0.0880 ^{ns}	1						
AC	2001	Prodan	0.3296 ^{ns}	0.5229	-0.3508	0.2536 ^{ns}	-0.2516 ^{ns}	-0.1658 ^{ns}	1					
		Newdale	0.5641	0.2219 ^{ns}	-0.1784 ^{ns}	0.3819	-0.0203 ^{ns}	-0.1720 ^{ns}	0.4187	1				
	2002	Ramada 1	0.1722 ^{ns}	-0.3370 ^{ns}	0.4683	0.2094 ^{ns}	0.0672 ^{ns}	0.0323 ^{ns}	-0.0446 ^{ns}	0.0301 ^{ns}	1			
		Ramada 2	0.1926 ^{ns}	-0.0922 ^{ns}	0.0252 ^{ns}	0.5047	0.0334 ^{ns}	-0.1213 ^{ns}	0.1102 ^{ns}	0.4173	0.2875 ^{ns}	1		
		Newdale 1	0.0929 ^{ns}	-0.0948 ^{ns}	0.2515 ^{ns}	0.1009 ^{ns}	0.7341	0.0039 ^{ns}	-0.2453 ^{ns}	0.0014 ^{ns}	0.3045 ^{ns}	0.1986 ^{ns}	1	
		Newdale 2	0.3424 ^{ns}	-0.1975 ^{ns}	0.1866 ^{ns}	0.0569 ^{ns}	-0.0517 ^{ns}	0.7077	-0.0682 ^{ns}	0.1774 ^{ns}	0.3015 ^{ns}	0.2442 ^{ns}	0.1415 ^{ns}	1

Table A33. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for 6-row barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf and hull-less cultivars and has 30 df and the minimum r significant at $p \leq 0.05$ is 0.3493.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.5412	1										
	2002	Ramada 1	-0.0559^{ns}	0.0676^{ns}	1									
		Ramada 2	0.4750	0.3722	0.3104^{ns}	1								
		Newdale 1	0.0783^{ns}	0.1432^{ns}	0.4997	0.3715	1							
		Newdale 2	0.1844^{ns}	0.2741^{ns}	0.2086^{ns}	0.4927	0.0815^{ns}	1						
AC	2001	Prodan	0.6140	0.6967	0.2255^{ns}	0.5524	0.2972^{ns}	0.4296	1					
		Newdale	0.6723	0.6403	0.0592^{ns}	0.5121	0.3740	0.3656	0.6919	1				
	2002	Ramada 1	-0.0475^{ns}	0.0786^{ns}	0.6902	0.4472	0.4368	0.1676^{ns}	0.1065^{ns}	0.0170^{ns}	1			
		Ramada 2	0.3483^{ns}	0.3947	0.3880	0.8530	0.4642	0.4456	0.5535	0.5058	0.3815	1		
		Newdale 1	0.1274^{ns}	0.2683^{ns}	0.4044	0.4981	0.8107	0.1844^{ns}	0.3897	0.4930	0.5111	0.5630	1	
		Newdale 2	0.1907^{ns}	0.4436	0.1857^{ns}	0.5132	0.2290^{ns}	0.7461	0.5154	0.4589	0.2263^{ns}	0.6168	0.3398^{ns}	1

Table A34. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for feed barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf and hull-less cultivars and has 18 df and the minimum r significant at $p \leq 0.05$ is 0.4437.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3980^{ns}	1										
	2002	Ramada 1	0.3032^{ns}	0.1296^{ns}	1									
		Ramada 2	0.5289	0.2291^{ns}	0.2722^{ns}	1								
		Newdale 1	0.1395^{ns}	0.3567^{ns}	0.5287	0.3339^{ns}	1							
		Newdale 2	0.1896^{ns}	-0.0498^{ns}	0.2485^{ns}	0.4012^{ns}	0.2694^{ns}	1						
AC	2001	Prodan	0.6788	0.6003	0.4134^{ns}	0.5965	0.4510	0.3869^{ns}	1					
		Newdale	0.6083	0.6300	0.2867^{ns}	0.5118	0.5058	0.4693	0.7779	1				
	2002	Ramada 1	0.0338^{ns}	0.0089^{ns}	0.7727	0.4061^{ns}	0.5564	0.1462^{ns}	0.1709^{ns}	0.1043^{ns}	1			
		Ramada 2	0.4629	0.2996^{ns}	0.3739^{ns}	0.8937	0.5003	0.5660	0.6444	0.6703	0.3554^{ns}	1		
		Newdale 1	0.1125^{ns}	0.2671^{ns}	0.7113	0.3672^{ns}	0.8185	0.4195^{ns}	0.4701	0.5189	0.6409	0.5805	1	
		Newdale 2	0.2042^{ns}	0.1131^{ns}	0.4253^{ns}	0.4530	0.3472^{ns}	0.8051	0.4261^{ns}	0.5364	0.3763^{ns}	0.6257	0.5443	1

Table A35. Correlation coefficients for ability to withstand competition (AWC and ability to compete (AC) across site-years for malt barley cultivars. All correlation coefficients are significant at $p \leq 0.05$ unless otherwise indicated (ns). This analysis excludes semi-dwarf and hull-less cultivars and has 42 df and the minimum r significant at $p \leq 0.05$ is 0.2973.

			AWC						AC					
			2001		2002				2001		2002			
			Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
AWC	2001	Prodan	1											
		Newdale	0.3041	1										
	2002	Ramada 1	-0.1781^{ns}	-0.1192^{ns}	1									
		Ramada 2	0.1950^{ns}	0.1785^{ns}	0.0948^{ns}	1								
		Newdale 1	-0.0033^{ns}	-0.0454^{ns}	0.2349^{ns}	0.3502	1							
		Newdale 2	-0.0506^{ns}	0.0560^{ns}	0.1252^{ns}	0.1580^{ns}	0.0121^{ns}	1						
AC	2001	Prodan	0.2865^{ns}	0.4267	-0.1919^{ns}	0.1383^{ns}	-0.0875^{ns}	-0.0097^{ns}	1					
		Newdale	0.5647	0.1420^{ns}	-0.1408^{ns}	0.2023^{ns}	0.0955^{ns}	-0.1389^{ns}	0.4590	1				
	2002	Ramada 1	0.0686^{ns}	-0.2891^{ns}	0.4869	0.2078^{ns}	0.1209^{ns}	0.0591^{ns}	0.0150^{ns}	0.0365^{ns}	1			
		Ramada 2	0.1648^{ns}	-0.0796^{ns}	0.2122^{ns}	0.4466	0.1902^{ns}	-0.0136^{ns}	0.2960^{ns}	0.4555	0.3778	1		
		Newdale 1	0.1277^{ns}	-0.1329^{ns}	0.1854^{ns}	0.1722^{ns}	0.7198	-0.0482^{ns}	0.0353^{ns}	0.2537^{ns}	0.3322	0.4168	1	
		Newdale 2	0.2336^{ns}	0.0022^{ns}	0.1905^{ns}	0.0780^{ns}	0.0555^{ns}	0.6416	0.2579^{ns}	0.2945^{ns}	0.2762^{ns}	0.4404	0.2570^{ns}	1

APPENDIX B

Table B1. Mean vigour for each cultivar in each greenhouse run. Vigour is calculated as $100*\text{biomass}_{deep}/\text{biomass}_{shallow}$. Averages for vigour are presented based on wet and dry biomass.

	Run 1		Run 2		Mean
Cultivar	Wet	Dry	Wet	Dry	
B1602	53.4	60.4	26.0	27.6	41.9
Bacon	45.0	51.5	30.8	35.9	40.8
Bedford	50.9	56.6	36.6	40.5	46.2
Candle	43.3	52.6	30.2	31.9	39.5
Condor	49.9	59.5	35.2	39.9	46.1
Dawn	38.5	46.2	23.5	26.1	33.6
Dolly	50.0	58.6	43.5	47.5	49.9
Earl	61.5	65.6	23.8	26.2	44.3
Excel	71.2	76.7	36.4	42.7	56.8
Falcon	28.8	32.9	28.8	31.8	30.6
Gainer	32.3	37.1	12.5	14.7	24.2
Harrington	50.6	57.8	21.7	24.2	38.6
Hawkeye	51.9	55.1	36.4	41.6	46.3
Kasota	35.1	39.6	29.2	34.0	34.5
Kendall	32.7	39.9	13.7	14.7	25.3
Lacombe	50.4	58.0	27.8	32.4	42.2
Manley	39.3	45.0	23.8	25.4	33.4
McGwire	36.6	40.3	28.2	31.0	34.0
Metcalfe	57.0	65.5	42.3	47.6	53.1
Oxbow	48.2	54.1	29.4	32.8	41.1
Peregrine	32.2	37.5	18.5	22.7	27.7
Phoenix	53.7	59.9	29.7	32.7	44.0
Ranger	51.2	60.6	35.7	39.9	46.9
Robust	48.7	55.3	33.7	38.0	43.9
Stander	50.9	56.8	24.3	27.2	39.8
Stein	29.1	32.8	23.4	27.0	28.1
Stratus	39.4	46.1	29.7	34.6	37.5
Thompson	26.6	30.7	42.5	45.6	36.4
Virden	50.9	57.2	33.6	38.3	45.0
Mean	45.1	51.4	29.3	32.9	39.7
LSD	17.7	20.5	19.0^{ns}	21.1^{ns}	

Table B2. A comparison of long-term averages for temperature, growing-degree days and precipitation with each site. Data are presented as means ± (standard errors) where appropriate.

Month	Long-term	2001		2002	
		Prodan	Newdale	Ramada	Newdale
	Daily Maximum Temperature (°C)				
May	18.7	19.7 (0.9)	19.1 (1.2)	17.0 (1.4)	15.5 (1.4)
Jun	23.8	21.6 (0.8)	21.1 (0.8)	24.4 (1.1)	23.7 (1.1)
Jul	26.5	25.8 (0.6)	25.1 (0.7)	27.5 (0.8)	27.7 (0.7)
Aug	25.4	27.7 (0.8)	27.0 (0.7)	23.7 (0.7)	24.5 (0.7)
	Daily Minimum Temperature (°C)				
May	4.0	5.8 (0.7)	6.8 (1.0)	-1.3 (1.1)	-0.5 (1.0)
Jun	9.5	8.8 (0.6)	9.6 (0.6)	10.7 (0.7)	10.4 (0.7)
Jul	12.0	13.3 (0.7)	9.6 (4.1)	12.9 (0.6)	12.4 (0.6)
Aug	10.5	10.7 (0.7)	11.4 (0.6)	10.8 (0.7)	10.0 (0.7)
	Daily Mean Temperature (°C)				
May	11.4	12.7 (0.7)	13.0 (1.0)	7.9 (1.2)	7.5 (1.2)
Jun	16.7	15.2 (0.6)	15.3 (0.6)	17.5 (0.8)	17.1 (0.8)
Jul	19.2	19.6 (0.6)	17.4 (2.1)	20.2 (0.6)	20.1 (0.5)
Aug	18.0	19.2 (0.7)	19.2 (0.6)	17.2 (0.6)	17.2 (0.6)
	Growing Degree-Days (5 °C)				
May	206.5	239.4	103.6	127.9	120.4
Jun	350.7	304.9	310.0	376.1	362.1
Jul	441.9	451.8	442.7	470.8	467.6
Aug	399.7	440.3	440.3	379.3	379.6
Total	1398.8	1436.4	1296.6	1354.1	1329.7
	Precipitation (mm)				
May	48.6	55.0	25.0	7.8	0.2
Jun	70.4	122.0	168.0	75.0	16.5
Jul	71.6	38.0	31.0	51.0	100.2
Aug	70.9	22.0	53.0	101.0	89.0
Total	261.5	237.0	277.0	234.8	205.9

Table B3. Significance of post-harvest quality measurements

Variable	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Yield in weed-free plots (kg ha^{-1})	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Percent dockage in weedy plots	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Yield in weedy plots (kg ha^{-1}	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Protein	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Oat 1000-kernel weight			ns	ns	ns	ns
Barley 1000-kernel weight (weed-free)				<0.0001		<0.0001
Barley 1000-kernel weight (weedy)				<0.0001		<0.0001
Barley 1000-kernel weight ratio				0.0017		0.0003

Table B4. Seed attributes measured on each cultivar in 2001.

Cultivar	Rows	Height[a]	Hull	Use	Seed Mass[b]	Day 1[c]	Day 2[d]	Day 3[e]	Day 4[f]	Day 5[g]	Day 6[h]	Day 7[i]	% Germ[j]
Candle	2	F	No	Feed	34.5	81	7	1	2	0	0	0	91
Condor	2	F	No	Feed	37.0	78	14	4	3	0	0	0	99
Dawn	2	F	No	Feed	37.3	90	6	1	0	1	0	0	98
Gainer	2	F	No	Feed	37.8	58	17	3	1	0	0	0	79
McGwire	2	F	No	Feed	37.3	88	9	2	0	0	0	0	99
Phoenix	2	F	No	Feed	33.2	66	34	0	0	0	0	0	100
Bacon	6	F	No	Feed	44.7	37	54	1	2	1	0	0	95
Falcon	6	Sd	No	Feed	32.3	94	5	0	0	0	0	0	99
Hawkeye	6	F	No	Feed	40.2	48	45	3	2	0	0	0	98
Peregrine	6	Sd	No	Feed	37.2	69	23	1	6	1	0	0	100
Dolly	2	F	Yes	Feed	51.0	36	46	3	2	0	1	0	88
Harrington	2	F	Yes	Malt	42.7	29	46	3	3	0	2	1	84
Kendall	2	F	Yes	Malt	43.9	55	40	2	1	0	0	0	98
Manley	2	F	Yes	Malt	52.4	45	38	2	6	0	1	0	92
Metcalfe	2	F	Yes	Malt	40.3	36	20	7	2	1	1	0	67
Oxbow	2	F	Yes	Malt	46.2	25	40	0	1	0	2	0	68
Stein	2	F	Yes	Malt	42.2	46	47	0	1	0	0	0	94
Stratus	2	F	Yes	Malt	47.8	58	29	0	8	0	0	0	95
Thompson	2	Sd	Yes	Feed	40.9	53	40	0	0	0	0	0	93
B1602	6	F	Yes	Malt	41.8	94	5	0	0	0	0	0	99
Bedford	6	F	Yes	Feed	39.3	12	39	23	5	0	1	0	80
Earl	6	Sd	Yes	Feed	37.9	36	43	5	3	0	0	0	87
Excel	6	F	Yes	Malt	41.8	63	12	2	2	2	1	0	82
Kasota	6	Sd	Yes	Feed	37.5	44	39	6	9	1	0	0	99
Lacombe	6	F	Yes	Feed	41.8	3	50	8	3	0	0	0	64
Ranger	6	F	Yes	Feed	42.9	27	49	6	4	0	1	0	87
Robust	6	F	Yes	Malt	37.0	10	31	4	2	2	0	1	50
Stander	6	F	Yes	Malt	43.2	56	24	5	4	0	0	0	89
Virden	6	F	Yes	Feed	42.1	7	30	18	4	0	1	2	62

a: SD = semi-dwarf
b: Seed mass given in grams per 1000 kernels
c: % germination (Day 1)
d: % germination (Day 2)
e: % germination (Day 3)
f: % germination (Day 4)
g: % germination (Day 5)
h: % germination (Day 6)
i: % germination (Day 7)
j: % germination (Total)

Table B5. Seed attributes taken on each cultivar in 2002.

Cultivar	Rows	Height[a]	Hull	Use	Seed Mass[b]	Day 1[c]	Day 2[d]	Day 3[e]	Day 4[f]	Day 5[g]	Day 7[h]	% Germ[i]
Bacon	6	Full	No	Feed	35.4	15	69	4	0	0	0	98
Candle	2	Full	No	Feed	35.0	80	19	0	0	0	0	99
Condor	2	Full	No	Feed	32.0	44	50	1	1	0	1	96
Dawn	2	Full	No	Feed	32.6	75	19	1	0	0	0	95
Falcon	6	SD	No	Feed	31.0	36	56	0	0	0	0	93
Gainer	2	Full	No	Feed	33.0	86	6	0	0	0	0	97
Hawkeye	6	Full	No	Feed	37.6	46	46	2	0	0	0	94
McGwire	2	Full	No	Feed	33.4	48	39	0	0	0	0	97
Peregrine	6	SD	No	Feed	30.4	75	16	0	0	0	0	91
Phoenix	2	Full	No	Feed	30.7	64	32	2	0	0	0	98
B1602	6	Full	Yes	Malt	33.1	49	44	1	0	0	0	94
Bedford	6	Full	Yes	Feed	33.9	2	77	13	0	1	0	92
Dolly	2	Full	Yes	Feed	47.5	18	69	4	1	0	0	96
Earl	6	SD	Yes	Feed	34.4	2	80	4	1	0	0	86
Excel	6	Full	Yes	Malt	39.2	1	74	9	0	1	1	86
Harrington	2	Full	Yes	Malt	41.1	27	68	1	2	0	0	99
Kasota	6	SD	Yes	Feed	30.6	12	67	4	0	0	0	86
Kendall	2	Full	Yes	Malt	39.2	23	68	1	0	1	0	93
Lacombe	6	Full	Yes	Feed	41.0	0	83	13	0	0	0	96
Manley	2	Full	Yes	Malt	42.0	26	57	6	0	0	0	89
Metcalfe	2	Full	Yes	Malt	42.3	29	54	5	0	0	2	89
Oxbow	2	Full	Yes	Malt	42.8	45	50	1	0	0	0	97
Ranger	6	Full	Yes	Feed	42.4	0	61	23	2	0	0	87
Robust	6	Full	Yes	Malt	36.8	0	79	13	1	0	0	93
Stander	6	Full	Yes	Malt	37.6	7	84	4	0	0	0	94
Stein	2	Full	Yes	Malt	37.5	7	80	4	0	0	0	91
Stratus	2	Full	Yes	Malt	42.3	25	73	2	0	0	0	100
Thompson	2	SD	Yes	Feed	40.3	40	49	0	0	0	0	90
Virden	6	Full	Yes	Feed	44.5	0	25	30	7	1	3	65

a: SD = semi-dwarf
b: Seed mass given in grams per 1000 kernels
c: % germination (Day 1)
d: % germination (Day 2)
e: % germination (Day 3)
f: % germination (Day 4)
g: % germination (Day 5)
h: % germination (Day 7)
i: % germination (Total)

Table B6. Correlation coefficient for each variable, as recorded in weedy plots, in each greenhouse trial with ability to withstand competition for each site-year in 2002. Measurements are on barley unless oat is specified. The minimum critical value for significance of correlation coefficients is 0.3672.

Greenhouse Trial 2	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Mean
Leaf area	0.2841^{ns}	0.3926	0.3736	0.2701^{ns}	0.3301
Leaf biomass (wet)	0.2845^{ns}	0.4150	0.3918	0.3083^{ns}	0.3499
Stem biomass (wet)	0.4196	0.5479	0.5251	0.4170	0.4774
Total biomass (wet)	0.3467^{ns}	0.4806	0.4568	0.3609^{ns}	0.4112
Leaf biomass (dry)	0.3368^{ns}	0.4611	0.3950	0.3367^{ns}	0.3824
Stem biomass (dry)	-0.0600^{ns}	0.2096^{ns}	0.1615^{ns}	0.0187^{ns}	0.0824
Total biomass (dry)	0.2249^{ns}	0.4086	0.3437^{ns}	0.2518^{ns}	0.3072
Plant height	0.5467	0.6392	0.5730	0.5967	0.5889
1st leaf height	0.1366^{ns}	0.1989^{ns}	0.2240^{ns}	0.1269^{ns}	0.1716
Haun stage	-0.0336^{ns}	0.0496^{ns}	-0.0939^{ns}	0.2390^{ns}	0.0403
Leaf area ratio (LAR)	-0.0663^{ns}	-0.1984^{ns}	-0.1496^{ns}	-0.2344^{ns}	-0.1622
Specific leaf area (SLA)	0.1368^{ns}	0.0121^{ns}	0.0591^{ns}	-0.0625^{ns}	0.0364
Oat wet biomass	-0.0949^{ns}	0.0713^{ns}	-0.1171^{ns}	-0.0507^{ns}	-0.0479
Oat dry biomass	-0.1153^{ns}	0.0581^{ns}	-0.1113^{ns}	-0.0749^{ns}	-0.0609
Greenhouse Trial 3					
Leaf area	0.2697^{ns}	0.4665	0.1743^{ns}	0.1724^{ns}	0.2707
Leaf biomass (wet)	0.1112^{ns}	0.3789	0.0333^{ns}	0.0635^{ns}	0.1467
Stem biomass (wet)	0.0252^{ns}	0.2781^{ns}	0.0143^{ns}	0.0547^{ns}	0.0931
Total biomass (wet)	0.0801^{ns}	0.3533^{ns}	0.0268^{ns}	0.0625^{ns}	0.1307
Leaf biomass (dry)	0.1837^{ns}	0.4820	0.0540^{ns}	0.1389^{ns}	0.2146
Stem biomass (dry)	0.1000^{ns}	0.3944	0.0161^{ns}	0.1374^{ns}	0.1620
Total biomass (dry)	0.1636^{ns}	0.4700	0.0440^{ns}	0.1431^{ns}	0.2052
Plant height	0.3450^{ns}	0.5672	0.3814	0.4609	0.4386
1st leaf height	0.3832	0.6101	0.5384	0.3246^{ns}	0.4641
Haun stage	-0.0026^{ns}	0.0455^{ns}	-0.1482^{ns}	0.1463^{ns}	0.0102
Leaf area ratio (LAR)	0.4414	0.1723^{ns}	0.3339^{ns}	0.2116^{ns}	0.2898
Specific leaf area (SLA)	0.4673	0.2705^{ns}	0.4004	0.3210^{ns}	0.3648
Oat wet biomass	-0.1089^{ns}	-0.3844^{ns}	-0.2892^{ns}	-0.2329^{ns}	-0.2539
Oat dry biomass	-0.0527^{ns}	-0.2841^{ns}	-0.1946^{ns}	-0.2318^{ns}	-0.1908
Greenhouse Trial 4					
Leaf area	0.2579^{ns}	0.4049	0.3344^{ns}	0.3801	0.3443
Leaf biomass (wet)	0.2817^{ns}	0.4474	0.3244^{ns}	0.3967	0.3626
Stem biomass (wet)	0.2781^{ns}	0.4617	0.3036^{ns}	0.4666	0.3775
Total biomass (wet)	0.2874^{ns}	0.4389	0.4518	0.4873	0.4164
Leaf biomass (dry)	0.2809^{ns}	0.4447	0.2378^{ns}	0.4551	0.3546
Stem biomass (dry)	0.2488^{ns}	0.4645	0.2441^{ns}	0.4491	0.3517
Total biomass (dry)	0.2819^{ns}	0.4723	0.251^{ns}	0.4735	0.3697
Plant height	0.4846	0.5021	0.3892	0.5011	0.4692
1st leaf height	0.3085^{ns}	0.4461	0.4303	0.2965^{ns}	0.3703
Haun stage	0.1326^{ns}	0.2493^{ns}	-0.0092^{ns}	0.3671^{ns}	0.1849
Leaf area ratio (LAR)	-0.0353^{ns}	-0.1794^{ns}	0.0336^{ns}	-0.1832^{ns}	-0.0911
Specific leaf area (SLA)	0.0424^{ns}	-0.0156^{ns}	0.1534^{ns}	0.066^{ns}	0.0615
Oat wet biomass	0.0912^{ns}	-0.0155^{ns}	0.1289^{ns}	0.0303^{ns}	0.0587
Oat dry biomass	-0.0102^{ns}	-0.0541^{ns}	0.0336^{ns}	-0.0412^{ns}	-0.0180

Table B7. Correlation coefficient for each variable, as recorded in weedy plots, in each greenhouse trial with ability to compete for each site-year in 2002. Measurements are on barley unless oat is specified.

Greenhouse Trial 2	Ramada 1	Ramada 2	Newdale 1	Newdale 2	Mean
Leaf area	0.3869	0.5067	0.4794	0.4284	0.4504
Wet leaf biomass	0.3593^{ns}	0.4879	0.4839	0.4446	0.4439
Wet stem biomass	0.487	0.5892	0.5792	0.5369	0.5481
Dry leaf biomass	0.3921	0.5032	0.4787	0.4487	0.4557
Dry stem biomass	0.019^{ns}	0.2323^{ns}	0.178^{ns}	0.1228^{ns}	0.1380
Plant height	0.5045	0.5492	0.496	0.5832	0.5332
1st leaf height	0.2003^{ns}	0.2118^{ns}	0.3198^{ns}	0.1931^{ns}	0.2313
Haun stage	-0.095^{ns}	-0.1454^{ns}	-0.2654^{ns}	-0.0534^{ns}	-0.1398
Wet total biomass	0.421	0.5435	0.5371	0.4953	0.4992
Dry total biomass	0.2923^{ns}	0.4471	0.4104	0.3695	0.3798
Leaf area ratio (LAR)	0.0104^{ns}	-0.0087^{ns}	-0.032^{ns}	-0.109^{ns}	-0.0348
Specific leaf area (SLA)	0.2472^{ns}	0.2102^{ns}	0.1587^{ns}	0.0771^{ns}	0.1733
Oat wet biomass	-0.2187^{ns}	-0.1648^{ns}	-0.2496^{ns}	-0.2021^{ns}	-0.2088
Oat dry biomass	-0.2536^{ns}	-0.1959^{ns}	-0.2777^{ns}	-0.2365^{ns}	-0.2409
Greenhouse Trial 3					
Leaf area	0.5294	0.5728	0.3473^{ns}	0.3172^{ns}	0.4417
Wet leaf biomass	0.3828	0.4614	0.2016^{ns}	0.207^{ns}	0.3132
Wet stem biomass	0.2668^{ns}	0.399	0.1639^{ns}	0.2036^{ns}	0.2583
Dry leaf biomass	0.4515	0.5119	0.2051^{ns}	0.2223^{ns}	0.3477
Dry stem biomass	0.3276^{ns}	0.4598	0.1703^{ns}	0.2326^{ns}	0.2976
Plant height	0.5187	0.6368	0.4909	0.5833	0.5574
1st leaf height	0.5638	0.7445	0.723	0.6418	0.6683
Haun stage	-0.0783^{ns}	-0.2167^{ns}	-0.3318^{ns}	-0.1812^{ns}	-0.2020
Wet total biomass	0.351^{ns}	0.4553	0.1946^{ns}	0.2145^{ns}	0.3039
Dry total biomass	0.4269	0.5121	0.201^{ns}	0.2328^{ns}	0.3432
Leaf area ratio (LAR)	0.3503^{ns}	0.1653^{ns}	0.3098^{ns}	0.151^{ns}	0.2441
Specific leaf area (SLA)	0.4309	0.3276^{ns}	0.4048	0.3058^{ns}	0.3673
Oat wet biomass	-0.172^{ns}	-0.1272^{ns}	-0.2019^{ns}	-0.1579^{ns}	-0.1648
Oat dry biomass	-0.0915^{ns}	-0.0188^{ns}	-0.0947^{ns}	-0.1211^{ns}	-0.0815
Greenhouse Trial 4					
Leaf area	0.4821	0.6081	0.5553	0.6101	0.5639
Wet leaf biomass	0.487	0.6113	0.5528	0.618	0.5673
Wet stem biomass	0.4445	0.5711	0.4627	0.6137	0.5230
Dry leaf biomass	0.4869	0.561	0.4813	0.6003	0.5324
Dry stem biomass	0.4025	0.5535	0.4075	0.5752	0.4847
Plant height	0.5142	0.5404	0.4409	0.5794	0.5187
1st leaf height	0.42	0.5669	0.5374	0.5333	0.5144
Haun stage	0.0884^{ns}	0.0429^{ns}	-0.108^{ns}	0.1018^{ns}	0.0313
Wet total biomass	0.452	0.5362	0.5734	0.6316	0.5483
Dry total biomass	0.4781	0.5839	0.4761	0.6184	0.5391
Leaf area ratio (LAR)	0.0278^{ns}	-0.0131^{ns}	0.0593^{ns}	-0.0867^{ns}	-0.0032
Specific leaf area (SLA)	0.1321^{ns}	0.1542^{ns}	0.1581^{ns}	0.1477^{ns}	0.1480
Oat wet biomass	0.1550^{ns}	0.0562^{ns}	0.2255^{ns}	0.0621^{ns}	0.1247
Oat dry biomass	0.0859^{ns}	-0.0044^{ns}	0.1175^{ns}	-0.0256^{ns}	0.0433

Table B8. Partial correlation coefficients for AWC with variables collected in the screening trial.

Variable	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Crop Density (# m^{-2})	0.5257	0.4255	0.2238	0.3564	0.1199^{ns}	0.0422^{ns}	0.2823
Weed Density (# m^{-2})^{a}	0.0986^{ns}	-0.4711	-0.4951	-0.5197	-0.4207	-0.3991	-0.3679
Herbicide damage	-0.3722	0.0803^{ns}			-0.0467^{ns}	-0.1011^{ns}	-0.1099
Haun stage	-0.1430^{ns}	-0.1684^{ns}	0.1414^{ns}	0.0076^{ns}	-0.1281^{ns}	0.0627^{ns}	-0.0380
% Light extinction (t_1)	0.3835	0.2615	0.4040	0.4322	0.1931^{ns}	0.2671	0.3236
% Light extinction (t_2)	0.1429^{ns}	0.0688^{ns}	0.1338^{ns}	0.3783	0.1963	0.2003	0.1867
% Light extinction (t_3)				0.3374	0.2688	0.2081	0.2714
% Light extinction (t_4)					0.2471	0.1833^{ns}	0.2152
Δ % Light extinction (t_{21})^{b}	-0.2693	-0.2351	-0.4889	-0.3242	-0.0026^{ns}	-0.2621	-0.2637
Δ % Light extinction (t_{32})				-0.3005	-0.0916^{ns}	-0.1359^{ns}	-0.1760
Δ % Light extinction (t_{43})					-0.2776	-0.1585^{ns}	-0.2181
% Cover (t_1)	0.5015	0.3396	0.2876	0.3772	0.1949	0.1111^{ns}	0.3020
% Cover (t_2)			0.2883	0.4996	0.2134	0.0990^{ns}	0.2751
% Cover (t_3)	0.6620	0.38856		0.5191	0.2762	0.0426^{ns}	0.3777
% Cover (t_4)	0.6383	0.4819		0.4481	0.2540	0.1169^{ns}	0.3878
% Cover (t_5)	0.6203						0.6203
Δ % Cover (t_{21})	-0.0906^{ns}	-0.0298^{ns}	-0.0208^{ns}	-0.0818^{ns}	-0.0498^{ns}	-0.0143^{ns}	-0.0479
Δ % Cover (t_{32})	0.3023			-0.3272	-0.1354^{ns}	-0.1316^{ns}	-0.0730
Δ % Cover (t_{43})	-0.5855	-0.2188		-0.1824^{ns}	-0.1576^{ns}	0.0112^{ns}	-0.2266
Δ % Cover (t_{54})	-0.2752						-0.2752
Height (t_1)	0.5581	0.4501	0.3451	0.5733	0.3286	0.4694	0.4541
Height (t_2)	0.5275	0.4884	0.2983	0.5086	0.2325	0.4410	0.4161
Height (t_3)		0.4926	0.2775	0.5589	0.2985	0.4354	0.4126
Height (t_4)		0.5615	0.2992	0.5534	0.2062	0.3943	0.4029
Height (t_5)				0.5433	0.2556	0.4238	0.4076
Height (max)	0.5275	0.5120	0.3049	0.5509	0.2269	0.4211	0.4239
Δ Height (t_{21})	-0.2805	0.1544^{ns}	-0.1857^{ns}	-0.1900	-0.2181	-0.0351^{ns}	-0.1258
Δ Height (t_{32})		-0.1559^{ns}	0.0225^{ns}	0.0454^{ns}	0.0679^{ns}	-0.0349^{ns}	-0.0110
Δ Height (t_{43})		-0.0823^{ns}	0.0640^{ns}	-0.0616^{ns}	-0.1108^{ns}	-0.0403^{ns}	-0.0462
Δ Height (t_{54})				-0.0059^{ns}	0.2477	0.0933^{ns}	0.1117
Feekes stage (t_1)			0.0184^{ns}	-0.1563^{ns}	0.0205^{ns}	-0.1359^{ns}	-0.0633
Feekes Stage (t_2)			0.0448^{ns}	<0.00005^{ns}	0.0357^{ns}	-0.1228^{ns}	-0.0141
Lodging	-0.0409^{ns}	0.2750				0.0278^{ns}	0.0873
Disease load rating	0.0517^{ns}	0.0123^{ns}	-0.0428^{ns}	0.0811^{ns}	-0.0506^{ns}		0.0103
Yield: WF^{c}	0.3972	0.1822^{ns}	0.2282	0.2460	0.0563^{ns}	0.0439^{ns}	0.1923
Yield: Wy^{d}	0.8233	0.8164	0.6286	0.7196	0.7430	0.6921	0.7372
% Protein	-0.5601	-0.3653	-0.2920	-0.3056	-0.3443	-0.4515	-0.3865
Oat 1000-k weight			-0.0045^{ns}	-0.0588^{ns}	0.2053	-0.2588	-0.0292
Barley 1000-k wt (WF)				0.4770		0.1553^{ns}	0.3162
Barley 1000-k wt (Wy)				0.5934		0.3196	0.4565

a: Count taken as seedling density (S phase) in 2001, panicle counts after seed set (H phase) in 2002

b: Prodan 2001 was Δ % Lght extinction (t_{21})

c: Collected in weed-free plots

d: Collected in weedy plots

Table B9. Partial correlation coefficients for AC with variables collected in the screening trial.

Variable	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Crop Density (# m^{-2})	0.6064	0.6640	0.3219	0.4903	0.2771	0.1341^{ns}	0.4156
Weed Density (# m^{-2})^{a}	0.1447^{ns}	-0.3878	-0.6736	-0.7191	-0.5405	-0.4278	-0.04340
Herbicide damage	-0.3536	0.2498			-0.2237	-0.2137	-0.1353
Haun stage	-0.1632^{ns}	-0.2349	0.0572^{ns}	-0.1931	-0.2301	-0.1200^{ns}	-0.1474
% Light extinction (t_1)	0.4004	0.3072	0.4717	0.5674	0.3010	0.4206	0.4114
% Light extinction (t_2)	0.1654^{ns}	0.1998	0.3376	0.5264	0.3846	0.3431	0.3262
% Light extinction (t_3)				0.4778	0.4678	0.3292	0.4249
% Light extinction (t_4)					0.4321	0.2509	0.3415
Δ % Light extinction (t_{21})^{b}	-0.2074^{ns}	-0.1911	-0.5546	-0.3412	-0.0140^{ns}	-0.2700	-0.2631
Δ % Light extinction (t_{32})				-0.3929	-0.1730^{ns}	-0.1803^{ns}	-0.2487
Δ % Light extinction (t_{43})					-0.4065	-0.2213	-0.3139
% Cover (t_1)	0.5755	0.5720	0.3536	0.4452	0.4587	0.2427	0.4413
% Cover (t_2)			0.3727	0.6606	0.4442	0.2115	0.4223
% Cover (t_3)	0.7460	0.5991		0.6403	0.4137	0.0990	0.4996
% Cover (t_4)	0.7548	0.6368		0.6209	0.4184	0.1838^{ns}	0.5229
% Cover (t_5)	0.6762						0.6762
Δ % Cover (t_{21})	-0.1072^{ns}	-0.0633^{ns}	0.0468^{ns}	-0.0193^{ns}	-0.1974	-0.0125^{ns}	-0.0588
Δ % Cover (t_{32})	0.3293			-0.5097	-0.3079	-0.2334	-0.1804
Δ % Cover (t_{43})	-0.6404^{ns}	-0.3684		-0.3258	-0.1620^{ns}	0.0138^{ns}	-0.2966
Δ % Cover (t_{54})	-0.3849						-0.3849
Height (t_1)	0.5880	0.6631	0.4474	0.6905	0.5371	0.6418	0.5947
Height (t_2)	0.5522	0.6694	0.4647	0.6639	0.4780	0.6177	0.5743
Height (t_3)		0.5358	0.4360	0.7289	0.5192	0.6332	0.5706
Height (t_4)		0.6930	0.4498	0.6693	0.3555	0.5407	0.5417
Height (t_5)				0.7227	0.3907	0.5733	0.5622
Height (max)	0.5522	0.5596	0.4528	0.7033	0.3761	0.5652	0.5349
Δ Height (t_{21})	0.3111	0.1394^{ns}	-0.1502^{ns}	-0.1601^{ns}	-0.2570	-0.0392^{ns}	-0.0260
Δ Height (t_{32})		-0.3548	0.0081^{ns}	0.0699^{ns}	0.0349^{ns}	0.0032^{ns}	-0.0477
Δ Height (t_{43})		0.0333^{ns}	0.0104^{ns}	-0.1840^{ns}	-0.1998	-0.1114^{ns}	-0.0903
Δ Height (t_{54})				0.1771^{ns}	0.1982	0.0853^{ns}	0.1535
Feekes stage (t_1)			0.0912^{ns}	0.0458	0.1143^{ns}	-0.0504^{ns}	0.0502
Feekes Stage (t_2)			0.0776^{ns}	0.1947	0.1133^{ns}	0.0612^{ns}	0.1117
Lodging	-0.0719^{ns}	0.1483^{ns}				-0.1655^{ns}	-0.0297
Disease load rating	0.0563^{ns}	-0.0415^{ns}	-0.1430^{ns}	-0.2084	-0.1447^{ns}		-0.0963
Yield: WF^{c}	0.6767	0.5871	0.5981	0.6600	0.4869	0.4142	0.5705
Yield: Wy^{d}	0.9200	0.9203	0.8061	0.9238	0.8957	0.8281	0.8823
% Protein	-0.7259	-0.5898	-0.4012	-0.3458	-0.5340	-0.5214	-0.5197
Oat 1000-k weight			-0.0721^{ns}	-0.1150^{ns}	0.1683^{ns}	-0.1921	-0.0527^{ns}
Barley 1000-k wt (WF)				0.5949		0.2748	0.4349
Barley 1000-k wt (Wy)				0.7099		0.3564	0.5332

a: Count taken as seedling density (S phase) in 2001, panicle counts after seed set (H phase) in 2002
b: Prodan 2001 was Δ % Lght extinction (t_{21})
c: Collected in weed-free plots
d: Collected in weedy plots

Table B10. Regression slope coefficients for AWC with variables collected in the screening trial. Measurements taken at different times are subscripted in numeric order. Changes over time (Δ) in variables are calculated as $100^{*}t_{n+1}/t_n$.

Variable	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Crop Density (# m^{-2})	0.1713	0.1808	0.0658	0.1597	0.0321^{ns}	0.0154^{ns}	
Weed Density (# m^{-2})	0.1455^{ns}	-0.5337	-0.2598	-0.3008	-0.2434	-0.2040	
Herbicide damage	-0.5223	0.1288^{ns}			-0.7010^{ns}	-0.1699^{ns}	
Haun stage	-5.4179^{ns}	-9.2771^{ns}	4.5355^{ns}	0.2692^{ns}	-4.0115^{ns}	1.9274^{ns}	
% Light extinction (t_1)	0.9761	0.5088	0.2782	0.6163	0.3680^{ns}	0.5043	
% Light extinction (t_2)	0.3841	0.1790^{ns}	0.1502^{ns}	0.3708	0.2654	0.3460	
% Light extinction (t_3)				0.4062	0.2127	0.1541	
% Light extinction (t_4)					0.5314	0.3313^{ns}	
Δ % Light extinction (t_{21})^{b}	-0.6631	-0.3243	-0.0204	-0.0306	-0.0003^{ns}	-0.0176	
Δ % Light extinction (t_{32})				-0.0532	-0.0066^{ns}	-0.0037^{ns}	
Δ % Light extinction (t_{43})					-0.0362	-0.0304^{ns}	
% Cover (t_1)	4.1099	1.8352	0.4429	1.3763	0.3055	0.2543^{ns}	
% Cover (t_2)	2.6736		0.2507	0.6656	0.2068	0.0832^{ns}	
% Cover (t_3)	1.4247	0.6917		0.5028	0.2876	0.0329^{ns}	
% Cover (t_4)	1.6950	0.8138		0.5470	0.3485	0.1300^{ns}	
% Cover (t_5)	1.4154						
Δ % Cover (t_{21})	-0.0312^{ns}	-0.0036^{ns}	-0.0066^{ns}	-0.0099^{ns}	-0.0086^{ns}	-0.0024^{ns}	
Δ % Cover (t_{32})	0.1078			-0.1592	-0.0314^{ns}	-0.0386^{ns}	
Δ % Cover (t_{43})	-0.3322	-0.0782		-0.06423^{ns}	-0.0933^{ns}	0.0050^{ns}	
Δ % Cover (t_{54})	-0.2704						
Height (t_1)	0.6115	0.7665	1.3048	2.1713	1.3668	2.6458	
Height (t_2)	0.6309	0.6302	0.4684	1.4993	0.5357	1.0126	
Height (t_3)		0.6778	0.3093	1.0011	0.4557	0.5838	
Height (t_4)		1.1003	0.1007	1.0128	0.2610	0.4433	
Height (t_5)				0.9790	0.3193	0.4957	
Height (max)	0.6323	0.7225	0.3348	1.0075	0.2861	0.4785	
Δ Height (t_{21})	-0.4241	0.2282^{ns}	-0.0578^{ns}	-0.2353	-0.0914	-0.0189^{ns}	
Δ Height (t_{32})		-0.1818^{ns}	0.0121^{ns}	0.0529^{ns}	0.0505^{ns}	-0.0290^{ns}	
Δ Height (t_{43})		-0.2526^{ns}	0.1708^{ns}	-0.1344^{ns}	-0.1881^{ns}	-0.0609^{ns}	
Δ Height (t_{54})				-0.0212^{ns}	1.0555	0.4211^{ns}	
Feekes stage (t_1)			0.2443^{ns}	-3.1593^{ns}	0.4120^{ns}	-2.6149^{ns}	
Feekes Stage (t_2)			1.6851^{ns}	0.0002^{ns}	2.6972^{ns}	-4.4288^{ns}	
Lodging	-0.0178^{ns}	0.1213					
Disease load rating	0.0399^{ns}	0.0118^{ns}	-0.0210^{ns}	0.0951^{ns}	-0.0454^{ns}	0.0138^{ns}	
Yield: WF^{c}	0.0084	0.0045^{ns}	0.0051	0.0069	0.0018^{ns}	0.0010^{ns}	
Yield: Wy^{d}	0.0149	0.0189	0.0135	0.0203	0.0227	0.0151	
% Protein	-8.4175	-4.6316	-2.1220	-2.7780	-4.1220	-4.7209	
Oat 1000-k wt^{e}			-0.0160^{ns}	-0.4029^{ns}	0.96789	-1.5032	
Barley 1000-k wt (WF)				1.5737		0.4202^{ns}	
Barley 1000-k wt (Wy)				1.7856		0.9193	

a: Count taken as seedling density (S phase) in 2001, panicle counts after seed set (H phase) in 2002

b: Prodan 2001 was Δ % Lght extinction (t_{21})

c: Collected in weed-free plots

d: Collected in weedy plots

e: 1000-k wt = 1000-kernel weight

Table B11. Regression slope coefficients for AC with variables collected in the screening trial.

Variable	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Crop Density (# m^{-2})	0.1982	0.2694	0.0976	0.2360	0.0677	0.0428^{ns}	
Weed Density (# m^{-2})	0.1713	-0.4194	-0.3641	-0.4471	-0.2850	-0.1910	
Herbicide damage	-0.4976	0.3824			-3.0595	-0.3137	
Haun stage	-6.2008^{ns}	-12.3372	1.8820^{ns}	-7.3332	-6.5661	-3.2195^{ns}	
% Light extinction (t_1)	0.9572	0.5708	0.3287	0.8690	0.4976	0.6885	
% Light extinction (t_2)	0.4460	0.4966	0.3905	0.5543	0.4738	0.5177	
% Light extinction (t_3)				0.6179	0.3374	0.2128	
% Light extinction (t_4)					0.8470	0.3960	
Δ % Light extinction (t_{21})^b	-0.4796^{ns}	-0.2518	-0.0234	-0.0346	-0.0014^{ns}	-0.0157	
Δ % Light extinction (t_{32})				-0.0749	-0.0114^{ns}	-0.0043^{ns}	
Δ % Light extinction (t_{43})					-0.0484	-0.0370	
% Cover (t_1)	4.7296	2.9508	0.5616	1.7447	0.6552	0.4851	
% Cover (t_2)	3.1033		0.3330	0.9453	0.3923	0.1552	
% Cover (t_3)	1.6101	1.0184		0.6661	0.3926	0.0669^{ns}	
% Cover (t_4)	2.0101	1.0268		0.8142	0.5231	0.1784^{ns}	
% Cover (t_5)	1.5471						
Δ % Cover (t_{21})	-0.0369^{ns}	-0.0073^{ns}	0.0152^{ns}	-0.0025^{ns}	-0.0312	-0.0018^{ns}	
Δ % Cover (t_{32})	0.1178			-0.2664	-0.0650	-0.0598	
Δ % Cover (t_{43})	-0.3643	-0.1256		-0.1232	-0.0874^{ns}	0.0053^{ns}	
Δ % Cover (t_{54})	-0.3792						
Height (t_1)	0.6460	1.0782	1.7444	2.8092	2.0363	3.1591	
Height (t_2)	0.6624	0.8247	0.7479	2.1020	1.0039	1.2386	
Height (t_3)		0.7040	0.5003	1.4025	0.7225	0.7415	
Height (t_4)		1.2965	0.5106	1.3156	0.4100	0.5309	
Height (t_5)				1.3988	0.4448	0.5857	
Height (max)	0.6672	0.7539	0.5121	1.3814	0.4321	0.5609	
Δ Height (t_{21})	-0.4717	0.1968^{ns}	-0.0477^{ns}	-0.2130^{ns}	-0.0981	-0.0185^{ns}	
Δ Height (t_{32})		-0.3949^{ns}	0.0044^{ns}	0.0875^{ns}	0.0237^{ns}	0.0024^{ns}	
Δ Height (t_{43})		0.0976^{ns}	0.0285^{ns}	-0.4315^{ns}	-0.3093	-0.1471^{ns}	
Δ Height (t_{54})				0.6897^{ns}	0.7698	0.3363^{ns}	
Feekes stage (t_1)			1.2382^{ns}	0.9937^{ns}	2.0930^{ns}	-0.8461^{ns}	
Feekes Stage (t_2)			3.0121^{ns}	7.6896	7.7988^{ns}	1.9279^{ns}	
Lodging	-0.0313^{ns}	0.0625^{ns}					
Disease load rating	0.0436^{ns}	-0.0382^{ns}	-0.0715^{ns}	-0.2625	-0.1183^{ns}	-0.0719^{ns}	
Yield: WF^c	0.0145	0.0139	0.0137	0.0199	0.0145	0.0085	
Yield: Wy^d	0.0167	0.0204	0.0178	0.0280	0.0250	0.0158	
% Protein	-10.9395	-7.1406	-3.0032	-3.3761	-5.8259	-4.7613	
Oat 1000-k weight			-0.2632^{ns}	-0.8473^{ns}	0.7231^{ns}	-0.9742	
Barley 1000-k wt (WF)				2.1084		0.6494^{ns}	
Barley 1000-k wt (Wy)				2.2944		0.8953	

a: Count taken as seedling density (S phase) in 2001, panicle counts after seed set (H phase) in 2002
b: Prodan 2001 was Δ % Lght extinction (t_{21})
c: Collected in weed-free plots
d: Collected in weedy plots

Table B12. Crop density for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop density data were collected in the (L) phase, but is a seed (S) attribute. Data are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	# m^{-2}						
B1602	169	135	111	124	119	101	127
Bacon	178	132	124	120	98	145	133
Bedford	183	177	124	131	117	132	144
Candle	159	131	110	124	128	132	131
Condor	132	118	119	94	110	132	118
Dawn	117	81	96	95	102	113	101
Dolly	213	163	135	105	160	123	150
Earl	177	150	117	119	126	121	135
Excel	197	155	129	130	98	116	138
Falcon	121	83	111	85	112	116	105
Gainer	189	161	127	103	116	95	132
Harrington	140	163	113	105	80	109	118
Hawkeye	120	94	118	122	90	121	111
Kasota	174	154	93	118	94	107	123
Kendall	158	152	108	125	158	121	137
Lacombe	233	190	132	126	152	144	163
Manley	130	131	95	105	164	123	125
McGwire	134	90	125	97	119	111	113
Metcalfe	179	154	111	143	95	130	135
Oxbow	142	121	124	108	107	95	116
Peregrine	116	89	87	78	114	123	101
Phoenix	161	116	99	118	135	140	128
Ranger	162	142	139	144	148	135	145
Robust	224	193	132	140	115	147	159
Stander	178	145	113	103	112	112	127
Stein	151	136	106	93	134	111	122
Stratus	160	157	129	116	92	112	128
Thompson	170	145	106	105	99	115	123
Virden	239	227	171	188	169	159	192
Mean	166	141	117	116	119	122	130
LSD	29	22	43^{ns}	32	54^{ns}	41	

Table B13. Herbicide damage for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Herbicide damage ratings are: 0 = no damage, 100 = all plants dead. Herbicide damage was rated in the seedling (L) phase and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	6.3	21.3			10.0	2.5	10.0
Bacon	6.3	23.8			3.8	5.0	9.7
Bedford	7.5	13.8			6.3	2.5	7.5
Candle	5.0	7.5			7.5	5.0	6.3
Condor	7.5	5			12.5	2.5	6.9
Dawn	10.0	5			11.3	10.0	9.1
Dolly	5.0	7.5			8.8	5.0	6.6
Earl	8.8	12.5			12.5	2.5	9.1
Excel	13.8	8.8			6.3	7.5	9.1
Falcon	37.5	18.8			11.3	15.0	20.7
Gainer	3.8	1.3			7.5	2.5	3.8
Harrington	6.3	1.3			12.5	5.0	6.3
Hawkeye	25.0	17.5			13.8	5.0	15.3
Kasota	11.3	10			21.3	12.5	13.8
Kendall	6.3	3.8			2.5	5.0	4.4
Lacombe	3.8	30			7.5	7.5	12.2
Manley	6.3	3.8			1.3	7.5	4.7
McGwire	7.5	7.5			17.5	7.5	10.0
Metcalfe	7.5	10			3.8	10.0	7.8
Oxbow	5.0	7.5			10.0	10.0	8.1
Peregrine	7.5	12.5			10.0	7.5	9.4
Phoenix	6.3	8.8			12.5	7.5	8.8
Ranger	26.3	26.3			7.5	2.5	15.7
Robust	12.5	12.5			6.3	10.0	10.3
Stander	12.5	13.8			10.0	5.0	10.3
Stein	15.0	10			12.5	7.5	11.3
Stratus	15.0	13.8			2.5	5.0	9.1
Thompson	5.0	11.3			7.5	10.0	8.5
Virden	3.8	32.5			5.0	2.5	11.0
Mean	10.2	12.4			9.0	6.5	9.5
LSD	7.3	8.6			1.0	8.9^{ns}	

Table B14. Haun stage for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Haun stage was rated in the seedling (L) phase and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	3.5	2.4	2.1	2.1	1.8	2.7	2.4
Bacon	3.5	2.5	2.6	2.9	2.0	3.2	2.8
Bedford	3.4	2.4	2.2	2.4	1.6	2.8	2.5
Candle	3.8	2.6	2.6	2.7	2.3	3.3	2.9
Condor	4.2	2.9	2.8	3.4	2.5	3.5	3.2
Dawn	3.7	3.0	2.9	3.3	2.5	3.3	3.1
Dolly	3.9	2.7	2.6	2.8	2.3	3.0	2.9
Earl	3.1	2.0	2.2	2.3	1.9	2.7	2.4
Excel	3.5	2.6	2.6	2.5	2.0	2.8	2.7
Falcon	3.5	2.8	2.7	2.7	1.9	3.0	2.8
Gainer	3.9	3.0	2.8	2.6	2.2	3.3	3.0
Harrington	3.9	2.6	2.7	2.9	2.2	3.4	3.0
Hawkeye	3.6	2.7	2.4	2.5	2.0	2.7	2.7
Kasota	3.5	2.4	2.3	2.5	2.1	2.8	2.6
Kendall	3.9	2.6	2.8	2.9	2.2	3.3	3.0
Lacombe	3.5	2.4	2.5	2.5	2.1	2.9	2.7
Manley	3.8	2.6	2.9	3.1	2.4	3.1	3.0
McGwire	3.8	2.8	2.7	2.8	2.3	3.4	3.0
Metcalfe	3.7	2.7	2.7	3.0	2.1	3.1	2.9
Oxbow	3.8	2.8	2.5	2.9	2.4	3.4	3.0
Peregrine	3.7	2.6	2.5	2.5	2.1	3.1	2.8
Phoenix	3.7	2.7	2.7	2.9	2.1	3.2	2.9
Ranger	3.5	2.6	2.5	2.5	1.9	2.6	2.6
Robust	3.3	2.5	2.5	2.3	1.8	2.6	2.5
Stander	3.6	2.5	2.6	2.6	2.0	2.7	2.7
Stein	3.8	2.7	2.5	2.8	2.3	3.4	2.9
Stratus	3.7	2.6	2.7	2.8	2.0	3.1	2.8
Thompson	3.5	2.5	2.7	3.2	2.4	3.0	2.9
Virden	3.2	2.2	2.5	2.5	1.5	2.5	2.4
Mean	3.6	2.6	2.6	2.7	2.1	3.0	2.8
LSD	0.4	0.3	0.3	0.3	0.4	0.3	

Table B15. Percent light extinction measured at time one (t_1) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent light extinction data were collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	86	81	35	24	9	6	40
Bacon	86	77	45	23	9	13	42
Bedford	90	83	31	25	12	13	42
Candle	92	83	47	24	13	8	45
Condor	90	82	31	18	16	8	41
Dawn	92	76	29	12	12	6	38
Dolly	92	81	48	24	13	9	45
Earl	81	80	27	17	10	3	36
Excel	83	75	49	26	15	7	43
Falcon	78	74	26	4	5	5	32
Gainer	88	80	45	19	9	8	42
Harrington	89	91	34	25	12	8	43
Hawkeye	87	82	35	27	15	18	44
Kasota	81	82	24	15	12	5	37
Kendall	86	78	38	20	12	15	42
Lacombe	88	78	46	21	11	12	43
Manley	88	77	44	21	22	8	43
McGwire	84	71	34	21	13	10	39
Metcalfe	80	76	41	33	27	15	45
Oxbow	89	82	46	19	15	6	43
Peregrine	74	74	12	11	9	3	31
Phoenix	89	79	38	27	15	12	43
Ranger	91	89	34	21	9	13	43
Robust	84	80	41	28	17	9	43
Stander	81	79	37	24	12	13	41
Stein	91	82	30	15	12	3	39
Stratus	89	83	45	23	11	8	43
Thompson	84	63	41	9	13	3	36
Virden	93	84	52	38	16	19	50
Mean	86	79	37	21	13	9	41
LSD	8	10	21^{ns}	10	9	11^{ns}	

Table B16. Percent light extinction measured at time two (t_2) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent light extinction data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	88	89	86	36	20	11	55
Bacon	88	87	80	45	17	16	56
Bedford	86	91	75	42	18	15	55
Candle	90	90	83	49	19	23	59
Condor	89	90	79	44	24	16	57
Dawn	94	85	77	31	17	10	52
Dolly	87	88	82	45	26	14	57
Earl	86	82	72	36	13	10	50
Excel	89	90	79	56	20	11	58
Falcon	86	87	78	18	13	4	48
Gainer	91	91	81	41	18	13	56
Harrington	87	93	75	27	28	14	54
Hawkeye	89	90	80	46	15	15	56
Kasota	84	90	75	34	20	14	53
Kendall	88	88	73	46	16	11	54
Lacombe	90	88	79	42	19	18	56
Manley	92	85	77	32	22	14	54
McGwire	86	79	74	38	22	11	52
Metcalfe	86	86	78	51	26	21	58
Oxbow	87	91	77	40	21	13	55
Peregrine	79	85	64	26	12	9	46
Phoenix	89	91	82	51	20	16	58
Ranger	93	89	83	47	24	17	59
Robust	84	92	78	51	18	15	56
Stander	84	85	71	40	15	12	51
Stein	93	91	79	29	19	6	53
Stratus	92	91	80	40	14	12	55
Thompson	79	82	63	30	17	10	47
Virden	88	93	78	61	30	25	63
Mean	88	88	77	40	19	14	55
LSD	5	8^{ns}	11	15	11	7^{ns}	

Table B17. Percent light extinction measured at time three (t_3) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent light extinction data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602				80	55	51	62
Bacon				85	51	70	69
Bedford				75	58	51	61
Candle				83	60	69	71
Condor				81	67	58	69
Dawn				74	51	49	58
Dolly				79	71	57	69
Earl				78	46	54	59
Excel				80	69	47	65
Falcon				67	33	54	51
Gainer				80	45	52	59
Harrington				66	57	60	61
Hawkeye				81	51	54	62
Kasota				67	51	51	56
Kendall				78	52	58	63
Lacombe				82	62	73	72
Manley				84	60	55	66
McGwire				82	60	53	65
Metcalfe				82	64	69	72
Oxbow				85	57	51	64
Peregrine				62	41	48	50
Phoenix				85	63	65	71
Ranger				87	53	65	68
Robust				81	53	58	64
Stander				74	51	47	57
Stein				75	48	48	57
Stratus				84	56	55	65
Thompson				48	51	40	46
Virden				80	62	72	71
Mean				77	55	56	63
LSD				11	18^{ns}	19	

Table B18. Percent light extinction measured at time four (t_4) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent light extinction data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602					89	87	88
Bacon					86	87	87
Bedford					84	87	86
Candle					86	90	88
Condor					88	89	89
Dawn					87	85	86
Dolly					86	87	87
Earl					82	84	83
Excel					88	82	85
Falcon					82	79	81
Gainer					83	85	84
Harrington					86	89	88
Hawkeye					84	90	87
Kasota					79	80	80
Kendall					87	89	88
Lacombe					85	86	86
Manley					88	88	88
McGwire					88	84	86
Metcalfe					88	92	90
Oxbow					84	88	86
Peregrine					77	81	79
Phoenix					87	89	88
Ranger					87	88	88
Robust					81	80	81
Stander					84	82	83
Stein					86	86	86
Stratus					86	86	86
Thompson					80	74	77
Virden					86	84	85
Mean					85	85	85
LSD					7	7	

Table B19. Percent cover measured at time 1 (t_1) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent cover data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	7	11	15	7	22	10	12
Bacon	7	9	18	10	13	16	12
Bedford	8	12	18	10	18	15	14
Candle	7	8	21	11	23	15	14
Condor	6	8	15	8	17	17	12
Dawn	4	6	12	6	14	9	9
Dolly	7	12	23	9	25	17	16
Earl	8	9	14	8	13	12	11
Excel	8	12	17	11	22	9	13
Falcon	5	8	17	5	12	13	10
Gainer	6	12	16	5	17	12	11
Harrington	6	12	15	8	16	12	12
Hawkeye	6	11	17	11	19	16	13
Kasota	7	13	12	6	13	12	11
Kendall	7	10	19	11	15	16	13
Lacombe	9	13	20	9	22	17	15
Manley	5	9	18	8	15	14	12
McGwire	6	7	17	7	20	9	11
Metcalfe	6	10	20	9	23	15	14
Oxbow	6	10	17	10	19	16	13
Peregrine	6	8	9	8	14	11	9
Phoenix	6	9	16	12	21	15	13
Ranger	6	12	22	9	22	17	15
Robust	9	13	17	10	15	13	13
Stander	6	11	12	7	17	12	11
Stein	7	10	16	6	14	9	10
Stratus	7	11	26	11	15	13	14
Thompson	7	8	16	7	19	9	11
Virden	10	16	26	15	32	20	20
Mean	7	10	17	9	18	13	12
LSD	1	3	7	5	9	6	

Table B20. Percent cover measured at time 2 (t_2) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent cover data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	13	-	32	28	44	29	29
Bacon	12	-	36	35	42	44	34
Bedford	13	-	39	35	45	51	37
Candle	12	-	43	36	55	53	40
Condor	11	-	35	34	51	45	35
Dawn	11	-	28	18	42	30	26
Dolly	14	-	47	32	54	43	38
Earl	11	-	27	25	34	36	27
Excel	13	-	33	37	48	28	32
Falcon	9	-	36	19	42	33	28
Gainer	13	-	36	26	41	36	30
Harrington	12	-	32	25	48	43	32
Hawkeye	11	-	37	34	43	45	34
Kasota	12	-	27	22	36	37	27
Kendall	11	-	36	33	40	46	33
Lacombe	17	-	39	34	53	46	38
Manley	12	-	36	28	46	42	33
McGwire	10	-	36	30	48	33	31
Metcalfe	12	-	36	39	55	45	37
Oxbow	13	-	37	33	54	50	37
Peregrine	10	-	18	19	36	31	23
Phoenix	12	-	39	43	51	44	38
Ranger	12	-	46	38	48	45	38
Robust	16	-	35	41	38	39	34
Stander	13	-	26	28	39	35	28
Stein	11	-	36	23	43	31	29
Stratus	14	-	45	37	43	42	36
Thompson	12	-	30	17	46	23	26
Virden	19	-	44	48	58	53	44
Mean	12	-	35	31	46	40	33
LSD	2	-	14	10	15^{ns}	16	

Table B21. Percent cover measured at time 3 (t_3) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent cover data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	32	45	-	55	79	54	53
Bacon	32	40	-	63	75	65	55
Bedford	31	45	-	60	73	64	55
Candle	29	39	-	69	81	77	59
Condor	25	34	-	67	83	74	57
Dawn	21	31	-	43	73	57	45
Dolly	35	49	-	66	80	78	62
Earl	26	46	-	50	61	56	48
Excel	32	42	-	66	71	50	52
Falcon	14	31	-	47	73	70	47
Gainer	31	45	-	53	79	61	54
Harrington	26	42	-	45	76	68	51
Hawkeye	27	39	-	62	62	70	52
Kasota	27	47	-	46	66	63	50
Kendall	29	36	-	58	68	68	52
Lacombe	38	47	-	63	76	73	59
Manley	29	40	-	59	78	76	56
McGwire	22	30	-	56	81	54	49
Metcalfe	27	38	-	67	82	69	57
Oxbow	31	42	-	59	78	72	56
Peregrine	21	28	-	37	59	55	40
Phoenix	31	40	-	73	76	71	58
Ranger	32	48	-	70	81	71	60
Robust	33	47	-	69	71	62	56
Stander	24	44	-	51	70	57	49
Stein	26	41	-	51	75	58	50
Stratus	31	45	-	65	76	66	57
Thompson	29	41	-	34	74	54	46
Virden	37	53	-	75	79	71	63
Mean	29	41	-	58	74	65	53
LSD	5	10	-	13	14	18^{ns}	

Table B22. Percent cover measured at time 4 (t_4) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent cover data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	43	72		78	87	78	72
Bacon	43	70		80	81	86	72
Bedford	43	71		76	81	87	72
Candle	42	65		81	89	94	74
Condor	38	63		85	90	93	74
Dawn	37	55		69	86	81	66
Dolly	46	77		81	86	94	77
Earl	42	65		79	76	83	69
Excel	42	72		85	88	79	73
Falcon	28	57		77	84	87	67
Gainer	43	68		75	79	87	70
Harrington	40	73		64	86	89	70
Hawkeye	39	64		81	77	91	70
Kasota	40	81		62	74	88	69
Kendall	41	66		73	76	88	69
Lacombe	48	81		85	83	92	78
Manley	40	68		80	85	95	74
McGwire	35	54		83	88	84	69
Metcalfe	41	66		79	85	89	72
Oxbow	43	76		85	84	93	76
Peregrine	33	56		63	66	84	60
Phoenix	43	67		82	87	93	74
Ranger	45	78		91	83	91	78
Robust	45	73		85	80	85	74
Stander	39	64		77	82	82	69
Stein	39	68		71	87	85	70
Stratus	45	73		83	83	87	74
Thompson	41	65		48	82	68	61
Virden	46	77		84	86	93	77
Mean	41	68		77	83	87	71
LSD	4	9	-	9	10	12	

Table B23. Percent cover measured at times 5 and 6 (t_5 & t_6) for barley cultivars grown in 2001 on the Prodan. Percent cover data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001	
	% cover (t_5)	% cover (t_6)
B1602	58	85
Bacon	62	85
Bedford	60	85
Candle	60	84
Condor	56	89
Dawn	54	78
Dolly	61	83
Earl	56	75
Excel	61	85
Falcon	48	69
Gainer	59	85
Harrington	58	83
Hawkeye	55	82
Kasota	63	89
Kendall	57	79
Lacombe	70	89
Manley	56	80
McGwire	52	77
Metcalfe	57	78
Oxbow	61	85
Peregrine	49	75
Phoenix	61	84
Ranger	62	84
Robust	62	85
Stander	57	79
Stein	57	80
Stratus	61	84
Thompson	58	77
Virden	64	83
Mean	58	82
LSD	5	5

Table B24. Crop height measured at time 1 (t_1) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	95	80	21	31	20	19	44
Bacon	95	72	17	28	16	17	41
Bedford	96	78	19	29	19	17	43
Candle	88	62	18	32	20	18	40
Condor	88	68	19	28	19	17	40
Dawn	86	63	16	28	20	16	38
Dolly	86	66	18	29	18	17	39
Earl	71	54	15	25	16	16	33
Excel	88	77	18	32	21	18	42
Falcon	60	49	14	22	15	13	29
Gainer	92	74	19	29	19	18	42
Harrington	90	68	17	30	19	18	40
Hawkeye	107	77	20	34	20	18	46
Kasota	69	70	16	24	18	17	36
Kendall	90	63	19	29	19	18	40
Lacombe	95	75	19	30	19	18	43
Manley	88	63	18	29	20	18	39
McGwire	84	66	18	29	18	18	39
Metcalfe	88	67	19	31	23	19	41
Oxbow	92	71	18	28	20	17	41
Peregrine	72	55	13	25	15	14	32
Phoenix	92	65	17	30	20	18	40
Ranger	88	67	17	30	18	18	40
Robust	88	83	20	33	18	19	44
Stander	88	73	19	31	19	18	41
Stein	92	68	17	27	17	16	40
Stratus	91	70	18	28	17	16	40
Thompson	65	56	16	24	16	15	32
Virden	106	81	22	37	23	21	48
Mean	87	68	18	29	19	17	40
LSD	6	7	3	3	3	2	

Table B25. Crop height measured at time 2 (t_2) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	109	103	57	42	49	47	68
Bacon	101	89	53	40	42	42	61
Bedford	102	94	57	40	47	45	64
Candle	99	82	49	43	44	45	60
Condor	89	79	47	38	45	43	57
Dawn	93	78	47	38	45	42	57
Dolly	95	85	52	42	45	44	61
Earl	85	65	48	37	40	38	52
Excel	95	92	57	44	51	45	64
Falcon	75	58	42	30	33	31	45
Gainer	97	88	51	43	47	46	62
Harrington	94	84	47	39	44	47	59
Hawkeye	124	91	57	46	46	45	68
Kasota	80	86	44	37	42	42	55
Kendall	96	85	48	40	41	43	59
Lacombe	100	96	57	43	45	44	64
Manley	96	75	45	41	43	43	57
McGwire	97	74	48	38	42	42	57
Metcalfe	98	80	53	45	48	50	62
Oxbow	100	87	51	42	45	43	61
Peregrine	79	69	45	36	41	36	51
Phoenix	97	79	49	43	44	47	60
Ranger	95	81	51	41	41	43	59
Robust	103	98	59	47	48	48	67
Stander	90	87	57	46	49	47	63
Stein	96	80	47	38	41	39	57
Stratus	94	85	52	40	42	42	59
Thompson	78	57	50	37	41	38	50
Virden	112	95	62	50	50	49	70
Mean	95	83	51	41	44	43	60
LSD	4	9	5	3	5	4	

Table B26. Crop height measured at time 3 (t_3) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602		115	77	77	81	88	81
Bacon		107	74	72	73	83	76
Bedford		109	71	74	75	85	76
Candle		108	83	74	76	77	78
Condor		93	73	68	72	74	72
Dawn		99	75	66	73	75	72
Dolly		95	73	76	73	82	76
Earl		92	68	66	68	68	68
Excel		104	66	73	69	78	72
Falcon		80	59	53	54	56	56
Gainer		107	78	75	76	81	78
Harrington		108	73	68	73	79	73
Hawkeye		124	93	82	82	92	87
Kasota		89	58	61	60	71	63
Kendall		97	74	72	73	79	75
Lacombe		106	78	76	76	82	78
Manley		98	71	67	70	73	70
McGwire		101	77	67	70	73	72
Metcalfe		100	79	78	78	85	80
Oxbow		104	80	79	81	82	81
Peregrine		81	57	60	62	67	62
Phoenix		102	81	78	76	83	80
Ranger		98	71	69	69	75	71
Robust		110	72	78	74	85	77
Stander		100	69	70	66	74	70
Stein		98	74	66	72	73	71
Stratus		98	70	71	69	76	72
Thompson		75	59	60	60	64	61
Virden		108	78	81	76	84	80
Mean		97	73	71	72	77	73
LSD		5	4	4	5	4	

Table B27. Crop height measured at time 4 (t_4) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602			80	79	90	101	88
Bacon			78	78	78	93	82
Bedford			74	75	79	92	80
Candle			85	79	87	95	87
Condor			75	73	77	81	77
Dawn			77	75	81	85	80
Dolly			76	75	77	90	80
Earl			72	73	75	81	75
Excel			68	74	74	83	75
Falcon			60	61	63	71	64
Gainer			80	77	88	90	84
Harrington			76	73	83	92	81
Hawkeye			97	91	100	112	100
Kasota			60	60	63	73	64
Kendall			76	74	78	88	79
Lacombe			78	77	78	89	81
Manley			77	74	79	88	80
McGwire			80	76	83	89	82
Metcalfe			82	82	82	93	85
Oxbow			81	81	84	91	84
Peregrine			59	61	64	72	64
Phoenix			82	79	86	94	85
Ranger			73	73	75	87	77
Robust			76	82	78	92	82
Stander			71	73	72	80	74
Stein			76	72	81	86	79
Stratus			72	73	74	81	75
Thompson			60	63	61	68	63
Virden			80	78	79	89	82
Mean			75	75	78	87	79
LSD			3	4	4	4	

Table B28. Crop height measured at time 5 (t_5) for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602				83	90	100	91
Bacon				75	80	91	82
Bedford				76	79	92	82
Candle				75	86	92	84
Condor				72	78	80	77
Dawn				74	81	85	80
Dolly				75	76	87	79
Earl				73	75	80	76
Excel				75	75	83	78
Falcon				59	62	70	64
Gainer				75	86	90	84
Harrington				72	81	90	81
Hawkeye				89	99	110	99
Kasota				60	62	72	65
Kendall				74	79	87	80
Lacombe				78	79	90	82
Manley				74	80	87	80
McGwire				79	83	87	83
Metcalfe				80	82	94	85
Oxbow				81	87	91	86
Peregrine				62	63	70	65
Phoenix				79	85	92	85
Ranger				74	75	89	79
Robust				82	80	91	84
Stander				75	73	81	76
Stein				71	81	84	79
Stratus				74	73	82	76
Thompson				60	61	69	63
Virden				80	79	88	82
Mean				74	78	86	80
LSD				3	4	4	

Table B29. Percentage change in crop height from t_1 to t_2 for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	115	128	275	137	253	253	194
Bacon	107	124	313	139	265	254	200
Bedford	106	120	307	136	250	260	197
Candle	113	132	277	136	220	248	188
Condor	101	116	256	136	241	245	183
Dawn	109	123	301	134	230	261	193
Dolly	111	128	283	145	247	265	197
Earl	121	120	316	145	255	240	200
Excel	108	120	315	140	249	247	197
Falcon	128	117	289	137	218	232	187
Gainer	106	120	273	147	256	259	194
Harrington	105	124	275	131	236	257	188
Hawkeye	116	118	280	135	231	246	188
Kasota	117	124	280	155	240	249	194
Kendall	106	135	258	139	218	239	183
Lacombe	106	131	309	144	245	252	198
Manley	108	120	255	144	221	243	182
McGwire	115	113	273	132	242	241	186
Metcalfe	111	118	282	143	212	268	189
Oxbow	109	122	279	150	227	255	190
Peregrine	110	126	351	142	280	255	211
Phoenix	106	122	281	146	225	255	189
Ranger	109	120	295	137	227	239	188
Robust	118	119	300	142	269	260	201
Stander	104	120	303	151	261	258	200
Stein	104	118	274	143	246	252	190
Stratus	104	122	291	143	247	258	194
Thompson	120	102	322	154	258	244	200
Virden	106	118	290	136	216	233	183
Mean	110	121	290	141	241	251	192
LSD	9	14^{ns}	33	14^{ns}	32	29	

Table B30. Percentage change in crop height from t_2 to t_3 for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602		113	139	185	167	188	158
Bacon		122	141	183	174	196	163
Bedford		117	124	186	161	191	156
Candle		132	169	174	176	173	165
Condor		118	155	177	164	174	158
Dawn		130	160	175	161	176	160
Dolly		112	141	179	164	186	156
Earl		141	141	180	172	178	162
Excel		114	116	165	136	175	141
Falcon		140	142	178	165	181	161
Gainer		122	153	173	163	175	157
Harrington		129	156	177	167	170	160
Hawkeye		138	165	178	180	204	173
Kasota		103	135	166	144	172	144
Kendall		114	155	182	180	182	163
Lacombe		111	135	175	168	186	155
Manley		132	159	164	163	168	157
McGwire		139	159	177	167	174	163
Metcalfe		129	150	174	163	171	157
Oxbow		120	158	187	182	190	167
Peregrine		117	125	169	150	184	149
Phoenix		129	167	182	174	176	166
Ranger		123	140	167	170	175	155
Robust		113	124	168	155	176	147
Stander		115	122	153	135	157	136
Stein		122	156	175	173	187	163
Stratus		115	139	177	165	181	155
Thompson		134	118	163	145	170	146
Virden		114	129	162	152	171	146
Mean		123	144	174	163	179	157
LSD		15	13	13	14	14	

Table B31. Percentage change in crop height from t_3 to t_4 for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602			104	103	110	114	108
Bacon			105	107	107	111	108
Bedford			105	101	105	108	105
Candle			103	107	114	123	112
Condor			103	109	106	110	107
Dawn			103	114	110	114	110
Dolly			105	99	105	110	105
Earl			106	110	111	120	112
Excel			103	102	108	107	105
Falcon			103	114	117	126	115
Gainer			103	104	116	112	109
Harrington			104	106	113	116	110
Hawkeye			105	112	122	122	115
Kasota			102	99	104	101	102
Kendall			103	103	107	111	106
Lacombe			101	101	103	108	103
Manley			109	111	113	121	114
McGwire			105	113	118	123	115
Metcalfe			103	106	106	110	106
Oxbow			101	103	104	111	105
Peregrine			105	101	103	107	104
Phoenix			102	102	114	113	108
Ranger			103	106	108	117	109
Robust			106	104	106	109	106
Stander			103	105	108	108	106
Stein			103	108	113	117	110
Stratus			103	102	108	107	105
Thompson			101	105	103	107	104
Virden			103	96	104	107	103
Mean			104	105	109	113	108
LSD			5^{ns}	6	7	6	

Table B32. Percentage change in crop height from t_4 to t_5 for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	-	-	-	105	101	99	102
Bacon	-	-	-	97	102	98	99
Bedford	-	-	-	102	101	100	101
Candle	-	-	-	95	99	97	97
Condor	-	-	-	98	101	99	99
Dawn	-	-	-	98	101	101	100
Dolly	-	-	-	100	99	97	99
Earl	-	-	-	100	101	99	100
Excel	-	-	-	101	101	100	101
Falcon	-	-	-	97	98	99	98
Gainer	-	-	-	97	99	100	99
Harrington	-	-	-	99	98	98	98
Hawkeye	-	-	-	98	99	98	98
Kasota	-	-	-	99	98	99	99
Kendall	-	-	-	100	101	99	100
Lacombe	-	-	-	101	101	101	101
Manley	-	-	-	100	102	99	100
McGwire	-	-	-	104	100	98	101
Metcalfe	-	-	-	98	100	101	100
Oxbow	-	-	-	100	103	100	101
Peregrine	-	-	-	101	100	98	100
Phoenix	-	-	-	99	99	99	99
Ranger	-	-	-	101	100	102	101
Robust	-	-	-	101	102	99	101
Stander	-	-	-	103	102	102	102
Stein	-	-	-	100	100	98	99
Stratus	-	-	-	101	98	101	100
Thompson	-	-	-	96	99	101	99
Virden	-	-	-	104	100	99	101
Mean	-	-	-	100	100	99	100
LSD	-	-	-	4	4^{ns}	3^{ns}	

Table B33. Maximum crop height for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Crop height data was collected in the seedling (L) and mature plant (H) phases and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	109	115	80	83	90	102	97
Bacon	101	107	78	78	80	93	90
Bedford	102	109	74	77	80	93	89
Candle	99	108	85	79	87	95	92
Condor	89	93	76	73	78	82	82
Dawn	93	99	78	75	81	86	85
Dolly	95	95	76	76	77	90	85
Earl	85	92	72	74	76	81	80
Excel	95	104	68	75	75	84	84
Falcon	75	80	60	61	63	71	68
Gainer	97	107	80	78	88	91	90
Harrington	94	108	76	73	82	92	88
Hawkeye	124	124	97	92	100	112	108
Kasota	80	89	60	63	63	73	71
Kendall	96	97	77	75	79	88	85
Lacombe	100	106	79	79	79	90	89
Manley	96	98	77	74	80	88	86
McGwire	97	101	80	79	83	90	88
Metcalfe	98	100	82	82	83	94	90
Oxbow	100	104	82	81	87	92	91
Peregrine	79	81	59	63	64	72	70
Phoenix	97	102	82	81	86	94	90
Ranger	95	98	73	74	76	89	84
Robust	103	110	76	83	80	93	91
Stander	90	100	72	75	73	82	82
Stein	96	98	76	72	81	86	85
Stratus	94	98	72	74	74	82	82
Thompson	78	75	60	63	62	69	68
Virden	112	108	81	82	79	89	92
Mean	95	100	75	76	79	88	86
LSD	4	9	3	3	4	4	

Table B34. Feekes rating at time 1 (t_1) for barley cultivars grown in 2002 on Newdale and Ramada soil series. Feekes ratings were collected in the mature plant (H) phase and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602			8.8	9.1	9.3	8.9	9.0
Bacon			8.9	9.6	9.3	9.0	9.2
Bedford			9.3	9.3	9.6	9.4	9.4
Candle			8.8	8.4	9.0	8.6	8.7
Condor			8.5	8.4	9.1	8.6	8.7
Dawn			8.0	8.5	8.9	8.8	8.6
Dolly			9.4	9.3	9.6	9.0	9.3
Earl			9.1	9.0	9.0	8.5	8.9
Excel			9.9	9.8	9.9	10.0	9.9
Falcon			8.8	7.6	8.6	8.0	8.3
Gainer			8.5	8.9	8.8	9.1	8.8
Harrington			8.3	8.5	9.0	8.5	8.6
Hawkeye			9.0	9.0	8.8	8.8	8.9
Kasota			8.9	9.3	9.5	9.6	9.3
Kendall			8.6	8.5	8.8	8.8	8.7
Lacombe			9.1	9.0	9.3	8.9	9.1
Manley			7.9	7.8	8.4	8.1	8.1
McGwire			8.5	8.5	8.9	8.3	8.6
Metcalfe			8.5	8.9	9.3	8.8	8.9
Oxbow			8.5	8.8	9.3	8.8	8.9
Peregrine			9.0	9.9	9.5	9.1	9.4
Phoenix			7.9	8.1	8.5	8.5	8.3
Ranger			9.1	9.0	9.0	8.8	9.0
Robust			9.8	9.5	9.8	9.5	9.7
Stander			9.6	9.8	9.9	9.5	9.7
Stein			7.9	8.3	9.0	8.6	8.5
Stratus			9.0	8.9	9.0	8.9	9.0
Thompson			10.0	10.1	10.0	10.0	10.0
Virden			8.6	9.0	9.1	8.8	8.9
Mean			8.8	8.9	9.2	8.9	9.0
LSD			0.7	0.4	0.6	0.4	

Table B35. Feekes rating at time 2 (t_2) for barley cultivars grown in 2002 on Newdale and Ramada soil series. Feekes ratings were collected in the mature plant (H) phase and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602			11.2	11.0	11.2	11.2	11.2
Bacon			11.3	11.2	11.3	11.2	11.3
Bedford			11.2	11.2	11.3	11.2	11.2
Candle			11.1	10.9	11.0	11.1	11.0
Condor			11.0	10.4	11.2	10.8	10.9
Dawn			10.8	10.8	11.2	10.6	10.9
Dolly			11.2	11.1	11.2	11.0	11.1
Earl			11.0	10.7	11.2	11.2	11.0
Excel			11.2	11.2	11.2	11.2	11.2
Falcon			10.8	10.7	11.0	11.0	10.9
Gainer			10.9	11.0	11.0	11.2	11.0
Harrington			11.2	10.8	11.2	10.8	11.0
Hawkeye			11.2	10.8	11.1	10.8	11.0
Kasota			11.0	11.0	11.3	11.2	11.1
Kendall			11.0	10.4	11.2	11.2	11.0
Lacombe			10.9	11.0	11.3	10.9	11.0
Manley			10.8	10.3	11.2	10.6	10.7
McGwire			11.0	10.8	11.2	11.0	11.0
Metcalfe			11.0	11.0	11.2	11.2	11.1
Oxbow			11.2	10.9	11.0	11.1	11.1
Peregrine			11.2	11.0	11.2	11.2	11.2
Phoenix			11.1	10.7	11.0	11.2	11.0
Ranger			10.9	11.0	11.2	11.0	11.0
Robust			10.8	11.2	11.2	11.1	11.1
Stander			11.1	11.1	11.2	11.2	11.2
Stein			11.0	10.3	11.2	10.6	10.8
Stratus			11.2	10.6	11.2	10.6	10.9
Thompson			11.0	10.8	11.2	11.0	11.0
Virden			11.2	11.0	11.2	11.0	11.1
Mean			11.1	10.9	11.2	11.0	11.0
LSD			0.3^{ns}	0.4	0.2^{ns}	0.3	

Table B36. Lodging ratings for barley cultivars grown in 2001 on Prodan and Newdale soil series. No lodging was observed in 2002. Lodging ratings were collected in the mature plant (H) phase and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	43	56					50
Bacon	45	70					58
Bedford	44	51					48
Candle	25	70					48
Condor	35	3					19
Dawn	26	33					30
Dolly	43	19					31
Earl	24	16					20
Excel	49	1					25
Falcon	49	8					29
Gainer	30	51					41
Harrington	33	89					61
Hawkeye	25	56					41
Kasota	36	73					55
Kendall	45	44					45
Lacombe	21	41					31
Manley	4	4					4
McGwire	20	1					11
Metcalfe	10	10					10
Oxbow	23	68					46
Peregrine	28	4					16
Phoenix	35	49					42
Ranger	14	51					33
Robust	24	1					13
Stander	19	1					10
Stein	24	51					38
Stratus	26	40					33
Thompson	5	3					4
Virden	26	24					25
Mean	29	34					31
LSD	42^{ns}	36					

Table B37. Disease load ratings for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Disease load ratings were collected in the mature plant (H) phase and are presented as means with protected LSD. Ratings range from 0, for no disease, to 100 for death due to disease. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	69	49	59	70	70	48	61
Bacon	64	64	76	80	83	56	71
Bedford	49	53	89	79	83	53	68
Candle	53	35	81	88	84	70	69
Condor	68	41	84	84	85	81	74
Dawn	55	43	68	85	74	61	64
Dolly	69	54	81	86	88	60	73
Earl	50	54	51	70	63	45	56
Excel	74	46	66	70	71	30	60
Falcon	48	46	60	76	79	48	60
Gainer	58	41	86	95	81	80	74
Harrington	86	79	86	95	89	79	86
Hawkeye	54	50	59	76	74	28	57
Kasota	95	84	94	94	94	83	91
Kendall	70	43	83	88	80	70	72
Lacombe	61	64	74	75	90	63	71
Manley	65	59	73	85	78	49	68
McGwire	55	43	48	73	60	49	55
Metcalfe	79	59	69	80	84	64	73
Oxbow	73	51	68	84	83	66	71
Peregrine	80	65	70	68	83	50	69
Phoenix	61	48	70	83	83	55	67
Ranger	46	55	50	63	63	36	52
Robust	59	59	65	73	66	35	60
Stander	55	46	45	66	70	35	53
Stein	71	61	84	95	86	83	80
Stratus	68	50	93	91	90	54	74
Thompson	85	88	95	95	95	78	89
Virden	55	55	78	88	83	58	70
Mean	65	55	73	81	80	57	68
LSD	17	17	21	9	13	23	

Table B38. Yield in weed-free plots for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Yield data were collected after harvest and are presented as means with protected LSD. Ratings range from 0, for no disease, to 100 for death due to disease. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	kg ha^{-1}						
B1602	3951	3635	2999	2756	2863	3669	3312
Bacon	3664	3333	2615	1830	2425	3076	2824
Bedford	4390	3853	2562	2430	2751	3658	3274
Candle	3347	2891	2012	1594	2134	2683	2444
Condor	3316	3276	2095	1899	2246	2432	2544
Dawn	3344	2613	1964	1653	1947	2597	2353
Dolly	3467	4078	2659	2184	2459	3243	3015
Earl	3787	3809	2658	2543	2823	3575	3199
Excel	4203	4435	2839	2758	2930	3548	3452
Falcon	2198	2431	2035	1815	1967	2579	2171
Gainer	3313	3073	2174	1873	2228	2810	2579
Harrington	3537	2701	1992	1551	2092	2759	2439
Hawkeye	3426	3090	2534	2378	2507	3367	2884
Kasota	3887	2899	1870	1458	1997	2856	2495
Kendall	4423	3542	2309	2174	2380	3235	3011
Lacombe	4500	3820	2944	2606	2505	3432	3301
Manley	4106	3198	2078	1819	2079	2894	2696
McGwire	3775	3309	2602	2478	2361	3220	2958
Metcalfe	4010	3446	2532	2260	2328	3564	3023
Oxbow	3515	3595	2350	2171	2393	3344	2895
Peregrine	3053	2793	1858	1765	2078	2736	2381
Phoenix	3482	2977	2253	2055	2404	2782	2659
Ranger	4462	4070	3080	2796	2946	3855	3535
Robust	4367	4098	2644	2702	2490	3354	3276
Stander	4554	4344	3043	2845	2743	3445	3496
Stein	4162	3239	2053	1559	2138	2671	2637
Stratus	4586	4249	2642	2312	2389	2975	3192
Thompson	3670	2996	2007	1500	2113	2790	2513
Virden	3880	4069	2737	2512	2385	3202	3131
Mean	3806	3444	2419	2147	2383	3116	2886
LSD	372	476	285	236	282	398	

Table B39. Percent dockage in weedy plots for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Percent dockage data were collected after harvest and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	17	28	18	30	29	23	24
Bacon	22	41	19	40	39	30	32
Bedford	22	39	21	31	36	28	30
Candle	29	48	21	36	35	30	33
Condor	36	54	22	42	37	32	37
Dawn	48	66	28	55	43	35	46
Dolly	20	31	17	31	35	28	27
Earl	27	45	21	42	36	36	35
Excel	23	37	12	22	25	26	24
Falcon	70	83	30	59	47	44	56
Gainer	33	43	26	48	45	25	37
Harrington	21	39	23	46	37	31	33
Hawkeye	31	42	21	32	38	27	32
Kasota	27	42	40	70	46	37	44
Kendall	29	42	24	41	37	31	34
Lacombe	12	28	18	27	27	20	22
Manley	28	39	19	41	36	32	33
McGwire	33	45	27	40	35	27	35
Metcalfe	22	45	15	27	26	21	26
Oxbow	25	44	17	32	33	30	30
Peregrine	56	82	52	70	57	52	62
Phoenix	25	47	19	31	35	24	30
Ranger	21	35	10	27	23	18	22
Robust	19	30	17	25	26	22	23
Stander	24	40	19	39	37	30	32
Stein	26	41	26	49	37	33	35
Stratus	20	34	17	27	39	33	28
Thompson	34	63	33	52	52	44	46
Virden	11	18	12	17	18	16	15
Mean	28	44	22	39	36	30	33
LSD	4	8	4	7	9	8	

Table B40. Net yield in weedy plots for barley cultivars grown over two years on Prodan, Newdale and Ramada soil series. Yield data were collected after harvest and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
	kg ha^{-1}						
B1602	3466	2753	2346	1969	2070	2816	2570
Bacon	3012	2353	2172	1271	1725	2251	2131
Bedford	3623	2491	2169	1837	1840	2837	2466
Candle	2656	1880	1754	1307	1691	2101	1898
Condor	2204	1750	1743	1384	1629	2006	1786
Dawn	1910	1170	1536	1062	1414	1969	1510
Dolly	2882	2930	2130	1699	1811	2388	2307
Earl	2776	2185	2117	1545	1924	2171	2120
Excel	3302	2651	2522	2137	2359	2663	2606
Falcon	895	660	1596	919	1266	1648	1164
Gainer	2191	2017	1699	1172	1422	2364	1811
Harrington	3025	2061	1616	1100	1507	2071	1897
Hawkeye	2496	1998	2055	1683	1715	2594	2090
Kasota	3006	2090	1421	655	1428	1951	1759
Kendall	3064	2347	1855	1412	1664	2415	2126
Lacombe	3932	2754	2459	2035	2020	3025	2704
Manley	3129	2297	1858	1415	1591	2363	2109
McGwire	2566	2163	2021	1622	1761	2526	2110
Metcalfe	3262	2234	2202	1731	1951	2969	2392
Oxbow	2833	2175	1989	1607	1804	2434	2140
Peregrine	1522	588	1070	721	1140	1360	1067
Phoenix	2917	1904	1953	1579	1730	2223	2051
Ranger	3410	2489	2810	2152	2341	3280	2747
Robust	3432	2649	2280	2035	2196	2554	2524
Stander	3438	2287	2589	1732	1851	2570	2411
Stein	3135	2056	1600	1131	1757	2122	1967
Stratus	3599	2853	2058	1867	1698	2134	2368
Thompson	2534	1153	1530	938	1212	1748	1519
Virden	3620	3262	2504	2325	2078	2859	2775
Mean	2891	2145	1988	1519	1745	2359	2108
LSD	266	463	292	241	312	385	

Table B41. Barley 1000-kernel weight (g m^{-2}) in weedy, weed-free plots and the ratio between weedy and weed-free plots, for barley cultivars grown in 2002 on Newdale and Ramada soil series. Data are from the Ramada 2 and Newdale 2 locations only. Barley 1000-kernel weight data were collected after harvest and are presented as means with protected LSD. Non-significant LSDs are denoted by ^{ns}.

Cultivar	Ramada2			Newdale2		
	Weed-free	Weedy	Ratio	Weed-free	Weedy	Ratio
	g m^{-2}			g m^{-2}		
B1602	34	35	102	39	39	100
Bacon	32	32	101	39	38	99
Bedford	32	33	100	38	38	100
Candle	29	30	102	35	36	104
Condor	32	33	101	36	39	106
Dawn	31	30	99	35	35	102
Dolly	39	41	105	48	48	101
Earl	35	34	97	39	39	100
Excel	37	36	97	39	37	95
Falcon	28	26	92	36	36	100
Gainer	31	30	96	35	39	109
Harrington	35	32	91	40	39	96
Hawkeye	34	35	103	41	40	97
Kasota	26	23	88	32	33	103
Kendall	34	33	96	40	39	98
Lacombe	37	36	97	43	43	101
Manley	38	37	96	41	43	104
McGwire	35	35	99	37	38	102
Metcalfe	39	37	96	44	43	97
Oxbow	38	37	96	44	45	101
Peregrine	30	28	92	34	33	97
Phoenix	30	30	100	35	36	102
Ranger	35	36	100	42	42	101
Robust	38	36	95	38	40	104
Stander	38	37	99	39	38	98
Stein	36	33	92	37	40	108
Stratus	38	37	98	44	41	94
Thompson	38	36	96	44	43	98
Virden	41	41	101	44	44	99
Mean	32.63	33.33	91.42	37.93	38.13	94.26
LSD	2	2	7	2	2	6

Table B42. Percent protein for barley cultivars in weedy plots grown over two years on Prodan, Newdale and Ramada soil series. Barley 1000-kernel weight data were collected after harvest and are presented as means with protected LSD. Ratings range from 0, for no disease, to 100 for death due to disease. Non-significant LSDs are denoted by ^{ns}.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
B1602	11.5	10.6	12.0	12.6	10.6	12.0	11.6
Bacon	11.8	12.2	13.8	15.2	11.4	12.8	12.9
Bedford	10.8	10.4	11.8	12.7	10.5	11.7	11.3
Candle	12.0	13.0	12.8	14.2	11.6	12.7	12.7
Condor	12.3	12.3	12.7	14.8	11.2	13.1	12.7
Dawn	11.7	12.5	11.8	13.5	10.7	12.2	12.1
Dolly	11.4	11.0	11.9	13.5	10.9	11.9	11.8
Earl	11.2	11.0	12.6	13.2	11.1	12.3	11.9
Excel	10.8	10.2	11.8	12.6	10.1	11.6	11.2
Falcon	13.9	15.8	16.7	18.5	13.8	15.8	15.8
Gainer	10.7	11.0	11.6	12.2	9.9	11.5	11.2
Harrington	11.4	11.7	12.1	12.9	11.0	11.8	11.8
Hawkeye	12.7	13.4	14.4	15.7	11.3	13.6	13.5
Kasota	11.0	10.3	12.7	13.1	11.6	12.1	11.8
Kendall	11.6	11.2	12.6	13.7	11.3	12.0	12.1
Lacombe	10.4	10.7	11.3	11.9	10.6	11.4	11.1
Manley	11.2	11.3	12.0	13.0	11.2	12.4	11.9
McGwire	11.8	12.0	11.8	13.5	10.6	13.0	12.1
Metcalfe	11.6	11.1	12.6	13.3	11.5	12.3	12.1
Oxbow	11.8	11.6	13.0	13.6	11.4	12.4	12.3
Peregrine	13.3	12.4	15.1	15.9	13.5	14.7	14.2
Phoenix	12.4	12.9	13.2	14.9	11.2	13.0	12.9
Ranger	10.5	10.1	11.3	12.2	9.9	11.1	10.9
Robust	11.3	10.8	12.4	13.4	10.6	12.1	11.8
Stander	11.0	10.1	11.4	12.6	10.5	11.8	11.2
Stein	11.5	11.3	12.2	13.3	10.8	11.7	11.8
Stratus	11.5	11.7	12.1	13.4	11.2	12.4	12.1
Thompson	11.3	10.8	12.4	12.9	11.9	12.3	11.9
Virden	10.7	10.3	11.7	12.6	10.3	11.5	11.2
Mean	11.6	11.5	12.5	13.6	11.1	12.4	12.1
LSD	0.3	0.7	0.8	0.7	0.5	0.5	

APPENDIX C

Table C1. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect barley ability to withstand competition for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide	ns	ns	ns	ns	ns	ns
Cultivar	ns	ns	ns	ns	ns	ns
Fungicide x Cultivar	ns	ns	ns	ns	ns	ns

Table C2. Ability to withstand competition (AWC) for each cultivar by fungicide treatment. Data are presented as means ± standard error for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002. Yes and no in parentheses indicate whether fungicides were applied.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	87	67	86	92	92	92	86
Ranger (Yes)	77	70	100	95	97	96	89
Metcalfe (No)	82	65	94	99	102	93	89
Metcalfe (Yes)	80	64	97	95	91	93	87
Stander (No)	76	58	98	95	96	88	85
Stander (Yes)	79	67	88	86	90	94	84
Gainer (No)	83	68	91	86	90	93	85
Gainer (Yes)	89	70	93	90	90	89	87
Harrington (No)	82	75	89	92	87	93	86
Harrington (Yes)	80	74	84	96	91	95	87
Candle (No)	81	74	89	107	96	94	90
Candle (Yes)	81	66	101	89	89	93	87
Mean	81	68	93	94	93	93	87
LSD	5	7	7	10	6	6	

Table C3. Ability to compete (AC) for each cultivar by fungicide treatment. Data are presented as means ± standard error for sites on Prodan, Newdale and Ramada soil series in 2001 and 2002. Yes and no in parentheses indicate whether fungicides were applied

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	83	66	98	99	97	98	90
Ranger (Yes)	81	66	100	99	97	98	90
Metcalfe (No)	79	56	99	99	94	98	88
Metcalfe (Yes)	82	61	100	100	95	98	89
Stander (No)	75	54	99	97	94	96	86
Stander (Yes)	78	60	98	97	93	96	87
Gainer (No)	78	55	98	94	91	97	86
Gainer (Yes)	83	67	99	95	92	96	89
Harrington (No)	78	58	98	97	91	97	87
Harrington (Yes)	81	65	98	96	94	97	89
Candle (No)	76	53	99	98	94	95	86
Candle (Yes)	79	56	99	98	92	97	87
Mean	79	60	99	97	94	97	88
LSD	8	5	1	1	3	1	

Table C4. Percent protein for each cultivar by fungicide treatment (fungicide application indicated by Yes/No). Data are presented as means with LSD.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	10.5	9.8	12.0	11.6	10.4	11.0	10.9
Ranger (Yes)	10.3	9.7	11.7	12.0	10.4	10.8	10.8
Metcalfe (No)	11.5	11.3	13.3	13.3	11.4	12.2	12.2
Metcalfe (Yes)	11.8	11.2	13.2	13.6	11.4	12.2	12.2
Stander (No)	11.0	10.0	12.3	12.8	11.0	11.7	11.5
Stander (Yes)	10.8	9.8	12.4	12.9	11.0	11.5	11.4
Gainer (No)	10.6	10.6	12.6	12.9	10.4	11.3	11.4
Gainer (Yes)	10.5	10.4	12.1	12.9	10.8	11.3	11.3
Harrington (No)	11.4	11.5	12.6	12.7	11.4	11.9	11.9
Harrington (Yes)	11.2	11.2	12.3	12.4	11.3	11.8	11.7
Candle (No)	11.8	12.6	14.1	14.0	11.4	12.4	12.7
Candle (Yes)	11.9	12.2	13.6	13.7	11.2	12.4	12.5
Mean	11.1	10.9	12.7	12.9	11.0	11.7	11.7
LSD	0.3	0.4	0.4	0.5	0.2	0.2	

Table C5. Percent dockage for each cultivar by fungicide treatment. Data are presented as means with LSDs.

Cultivar	2001		2002				Mean
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2	
Ranger (No)	16.7	34.1	1.8	1.1	3.1	1.6	9.7
Ranger (Yes)	18.8	33.5	0.4	0.7	3.1	1.6	9.7
Metcalfe (No)	21.5	44.0	0.8	0.7	5.8	2.1	12.5
Metcalfe (Yes)	18.4	39.1	0.5	0.4	4.6	2.2	10.9
Stander (No)	25.4	46.5	1.4	2.8	6.0	4.3	14.4
Stander (Yes)	22.1	40.3	1.7	2.7	6.7	4.2	13.0
Gainer (No)	21.8	45.3	2.0	6.1	8.6	2.7	14.4
Gainer (Yes)	17.2	33.1	1.0	4.9	7.9	3.6	11.3
Harrington (No)	22.0	42.3	1.6	3.0	8.7	3.4	13.5
Harrington (Yes)	18.6	34.6	1.6	4.5	6.0	2.5	11.3
Candle (No)	24.2	47.3	0.9	1.8	6.1	4.7	14.2
Candle (Yes)	21.5	44.2	0.8	2.2	7.7	3.3	13.3
Mean	20.7	40.4	1.2	2.6	6.2	3.0	12.3
LSD	2.8	5.1	0.6	1.1	2.5	1.4	

Table C6. P-values for the null hypotheses that fungicide application, cultivar or the fungicide x cultivar interaction did not significantly affect oat 1000-kernel weight from weedy plots.

	2001		2002			
	Prodan	Newdale	Ramada 1	Ramada 2	Newdale 1	Newdale 2
Fungicide			ns	ns	ns	ns
Cultivar			ns	0.0014	ns	ns
Fungicide x Cultivar			ns	ns	ns	ns