DIFFERENTIAL ALUMINUM TOLERANCE OF HIGH-YIELDING, EARLY-MATURING CANADIAN WHEAT CULTIVARS AND GERMPLASM

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Twenty-eight spring wheat (*Triticum aestivum*) cultivars were tested for tolerance to aluminum (Al) using solution culture techniques. Fourteen of these cultivars were also grown in the field under two different management levels, Conventional and Intensive Crop Management (ICM), to determine maximum yield potentials in the Edmonton region and to determine if individual cultivars respond differently to management levels on high fertility fallow conditions. Based upon a root weight index (RWI), seven of the 28 spring wheat cultivars tested (K.Kongoni, PT741, K.Nyumbu, PT726, Norquay, PF7748, Maringa) were more tolerant to Al than the winter wheat standard for Al tolerance, Atlas 66. The winter wheat standard for Al sensitivity, Scout 66, ranked most sensitive to Al, but 11 spring wheat cultivars were equally sensitive (Lancer, Wildcat, Columbus, Park, Bluesky, Kenyon, Benito, BW92, Neepawa, Conway, Katepwa). In the field, cultivars varied in yield potential and days to maturity in both the Conventional and ICM treatments; however, ICM provided no additional benefit in terms of yield. Six genotypes (Bluesky, Norquay, Oslo, PT726, PT741, PT742) were significantly higher yielding than Neepawa and matured as early as Park. Six of the nine highest yielding cultivars from the field trials had Al tolerance ratings (RWI values) greater than 0.80 (80% of control), while five Canadian Western Red Spring (CWRS) cultivars, the lowest yielding from the field trials, had RWI values less than or equal to 0.43. The reason for the apparent association between high yield potential and tolerance to Al is unknown.

Key words: wheat, *Triticum aestivum*, aluminum tolerance, high yield, early maturity, intensive crop management

[Tolérance différente à l'aluminium de cultivars et de matériel génétique de blé canadien précoce et à rendement élevé.]
Titre abrégé: Tolérance à l'aluminium de cultivars de blé précoce et à rendement élevé.
Nous avons déterminé la tolérance à l'aluminium (Al) de 28 cultivars de blé de printemps (*Triticum aestivum*) au moyen de méthodes de cultures en solution. Quatorze de ces cultivars ont également été produits au champ, selon deux méthodes différentes: culture classique et gestion intensive des cultures (ICM), pour déterminer les possibilités maximales de rendement dans la région d'Edmonton et vérifier si des cultivars particuliers réagissent différemment aux niveaux de gestion des cultures différents en conditions de haute fertilité sur jachère. À en juger par l'indice du poids des racines (RWI), sept des 28 cultivars de blé de printemps testés (K.Kongoni, PT741, K.Nyumbu, PT726, Norquay, PF7748 et Maringa) étaient plus tolérants à l'aluminium que le blé d'hiver étalon pour la tolérance à cet élément, Atlas 66. L'étalon de blé d'hiver pour la sensibilité à l'aluminium, Scout 66, montrait la sensibilité maximale à cet élément

mais 11 blés de printemps ont laissé voir une sensibilité équivalente (Lancer, Wildcat, Columbus, Park, Bluesky, Kenyon, Benito, BW92, Neepawa, Conway et Katepwa). Au champ, les cultivars laissaient voir un potentiel de rendement et une durée de la période de maturation variables en culture classique et en culture ICM. Toutefois, la méthode ICM ne procurait aucun avantage supplémentaire, du point de vue du rendement. Six des génotypes (Bluesky, Norquay, Oslo, PT726, PT741, PT742) donnaient un rendement significativement plus élevé que Neepawa et présentaient une période de maturation aussi courte que Park. Six des neuf cultivars au rendement le plus élevé provenant des essais au champ présentaient des valeurs de la tolérance à l'aluminium (valeurs RWI) supérieures à 0,80 (80% de celles du témoin), tandis que cinq cultivars de blé roux de printemps de l'Ouest du Canada (CWRS) ceux des cultivars testés donnant le rendement le plus bas, présentaient des valeurs de RWI inférieures ou égales à 0,43. Le rapport apparent existant entre les possibilités de rendement élevé et la tolérance à l'aluminium demeure inexpliqué.

Mots clés: Blé (*Triticum aestivum*), tolérance à l'aluminium, rendement élevé, maturité précoce, gestion intensive des cultures

Interest in determining maximum economic yields of wheat (*Triticum aestivum* L.) cultivars in western Canada has increased in recent years. Reflecting this interest, a 3-yr Canada Grains Council research study on intensive wheat culture was initiated at the University of Alberta in 1985. Components of this research included integrated studies addressing the use of fertilizer (nitrogen and phosphate), fungicide, growth regulators, narrow row spacing, higher seeding rates, and possible interactions between these management practices and individual cultivars. One of the tests included in these studies was designed to determine (a) what maximum yields might be achieved in the Edmonton region for a range of locally adapted cultivars, given optimum agronomic management irrespective of cost, and (b) whether individual cultivars respond differently to management levels on the fallow conditions used.

In another research project, the aluminum (Al) tolerance of all wheat cultivars released in Canada, including many of the genotypes used in the maximum yield management trials described above, was determined using a rapid screening technique (Zale and Briggs 1988). Based upon this study, most of the high-yielding cultivars in the field trials possessed good tolerance to Al, despite the fact that none had been consciously selected for Al or acidity tolerance. In contrast, most Canadian Western Red Spring (CWRS) cultivars were Al-sensitive (Zale and Briggs 1988). This paper presents 3 yr of field data describing yield and maturity relationships of an array of genotypes suited for growth in the Edmonton region when grown under maximum yield conditions. Data confirming cultivar tolerance to Al as evaluated by an alternative screening technique (based on relative root yields in solution culture) and the response of two cultivars to increasing Al concentration in solution are also presented. Two cultivars suitable for use as Canadian standards for Al tolerance and Al sensitivity in further laboratory and field studies have been identified.

MATERIALS AND METHODS

Screening for Aluminum Tolerance in Solution Culture

Thirty cultivars of wheat were selected for evaluation of tolerance to Al in solution culture. Two winter wheat cultivars represented standards for tolerance (Atlas 66) and sensitivity (Scout 66) to Al (Taylor and Foy 1985a); two cultivars were of Brazilian origin (Maringa, PF7748), four were of Kenyan origin (K.Kongoni, K.Nyumbu, K.Tembo, Romany) and 22 were Canadian cultivars representing both registered CWRS cultivars and experimental lines. One hundred seeds of each cultivar were surface sterilized in 1.2% sodium hypochlorite for 20 min, and germinated overnight immersed in a solution of 0.005 g L^{-1} Vitavax to prevent fungal growth. Seedlings were grown for 3 d in a solution containing (μM) Ca (1000), Mg (300), NO_3^- (2900), and NH_4^+ (300), and for 5 d in a complete nutrient solution containing (μM) Ca (1000), Mg (300), K (800), NO_3^--N (3300), NH_4^+-N (300), PO_4^{2-} (100), SO_4^{2-} (101), Cl (34), Na (20), Fe (10), B (6), Mn (2), Zn (0.5), Cu (0.15), and Mo (0.1). Iron was supplied as Fe-EDTA prepared from equimolar amounts of $FeCl_3$ and Na_2EDTA. All growth solutions were acidified to pH 4.5 with HCl.

Twenty-four uniform, 9-d-old seedlings from each cultivar were mounted on plexiglass frames which covered each of 60 polyethylene containers of 10 L capacity. Each frame supported 12 plants in four groups of three, and shielded growth solutions from light to inhibit algal growth. Plants were grown in a controlled environment room with temperature maintained between 24 and 28°C during a 16-h light period and between 18 and 20°C during darkness. Relative humidity was maintained between 50 and 75% during the light period and between 85 and 100% during darkness. Solution temperatures were maintained between 18 and 20°C by immersing all pots in a common water bath. The growth room was illuminated by 12 HID mercury halide (400 W) and 4 HID high pressure sodium (400 W) lamps located 1.3 m above the plant bases. The photosynthetic photon flux density (PPFD) was 332 ± 28 μmol m^{-2} s^{-1} at plant base level.

A randomized block, factorial design with 30 cultivars, two Al treatments (0 μM Al, 75 μM Al), and three replicates (totalling 180 containers) was used. Due to space constraints, threefold replication was achieved in time. Control and Al treatments for each cultivar within each replicate were blocked together to minimize variation. Aluminum was supplied as $AlK(SO_4)_2 \cdot 12H_2O$, superimposed over the basal nutrient solution. The pH of aerated nutrient solutions were adjusted initially to 4.5 with HCl or KOH and were measured three times weekly. Nutrient solutions were adjusted periodically to 10 L with distilled water to compensate for water loss by evaporation and transpiration.

After 14 d of treatment the longest root from each pot was measured, and plants were harvested, divided into roots and leaves, dried at 50°C, and weighed. A root weight index (RWI), leaf weight index (LWI), and root length index (RLI) were calculated by dividing the root weight, leaf weight, or root length of plants grown with Al by the respective values for plants grown in the absence of Al.

Canadian Standards for Aluminum Tolerance and Sensitivity

Based upon the results of the screening experiment, two Canadian cultivars were selected to serve as locally adapted standards for Al tolerance (PT741) and Al sensitivity (Katepwa). These cultivars were grown over a range of Al concentrations (0, 25, 50, 75, 100, 200, 300, 400, 700, 1000 μM) using the same techniques described in the screening experiment. Treatments were randomly assigned within each of three blocked replicates. After 14 d of treatment, plants were harvested, divided into roots and leaves, dried at 50°C and weighed. Data were analyzed using analysis of variance (ANOVA), Duncan's multiple range test, and simple regression. Significance was defined at the 95% confidence level.

Field Study: Cultivar × Management Trial

The objective of this trial was to evaluate the interaction between 14 spring wheat cultivars and two management levels at a single location over 3 yr. In mid-May of 1985, 1986, and 1987, the trial was seeded with a Swift Current double disc drill at 23-cm row spacing in 6-m-long plots. In 1985, the trial was replicated four times in a randomized block design. In 1986 and 1987, it was replicated four times in a split-plot design to facilitate comparison of management levels within each cultivar. The trial was seeded into fallow with blanket applications of fertilizer, intended to provide nonlimiting amounts of phosphate, potassium, and sulphate (Table 1). Base nitrogen fertility levels were also high (Table 1). Weeds were controlled with a single application of either Buctril M (bromoxynil plus MCPA) or Hoegrass II (diclofop-methyl plus bromoxynil). The majority of plots were harvested by the end of August, although in 1987 harvest was delayed until September 11 by cool, wet weather and a severe rainstorm (70 mm) on 3 Sept.

The 14 cultivars used in the field trial included five currently grown or new CWRS cultivars for the Edmonton region (Columbus, Conway, Ketepwa, Neepawa, and Park), two new utility cultivars developed at the Agriculture Canada Research Station at Beaverlodge to replace the late maturing Glenlea (Bluesky and Wildcat), and two high-yielding cultivars (Glenlea, HY320). Oslo was selected to represent the Canadian Prairie Spring quality type and because of its better adaptability to central Alberta than HY320. Norquay (a delicensed cultivar) was chosen due to its documented high yield potential and earliness in this region. Three high-yielding, early-maturing

Table 1. Base soil fertility levels (surface 30 cm), added nutrients (N, P, K, S), target yield, and rainfall for Conventional and ICM management treatments in each of 3 yr of the Edmonton field trial

Soil fertility status	1985	1986	1987
Soil test N (kg ha^{-1})	20	224	66
Added N (kg ha^{-1})†	59/119	0/78	35/111
Soil test P (kg ha^{-1})	21	15	45
Added P (kg ha^{-1})	60	90‡	90‡
Soil test K (kg ha^{-1})	391	328	439
Added K (kg ha^{-1})	0	30	30
Soil test S (kg ha^{-1})	35	38	35
Added S (kg ha^{-1})	14	10	10
Target yield (kg ha^{-1})†§	4958/6700	4958/6700	4958/6700
Rainfall (mm, May–Aug)	233	294	412

†Values represent Conventional and ICM management, respectively.
‡Banded prior to seeding.
§Estimates, not specifically stated by soil test laboratory.

lines from the University of Alberta breeding program, which had been withdrawn from testing beyond the Parkland Cooperative trial stage due to inadequate utility class quality type, were also chosen for the field study (PT726, PT741, and PT742).

In each year, the cultivars were grown under two management levels as follows: (1) Conventional: target seeding rate 300 plants m^{-2}; nitrogen fertilizer added according to commercial soil test recommendations targeting a yield of 4958 kg ha^{-1} (74 bu acre^{-1}); no fungicides or plant growth regulators applied; (2) Intensive Crop Management (ICM): target seeding rate 500 plants m^{-2}; nitrogen fertilizer added according to commercial soil test recommendations targeting a yield in excess of 6700 kg ha^{-1} (100 bu acre^{-1}); CYCOCEL plant growth regulator applied at 1.5 L ha^{-1} at Zadoks growth stage 31 (Zadoks et al. 1974); TILT fungicide applied at 0.5 L ha^{-1} at Zadoks growth stage 49–55 (Zadoks et al. 1974). The purpose of the ICM treatment was to determine the additional benefit of these extra management inputs at the high fertility rates already existing for the Conventional treatment. Yields were determined by harvesting 5 m of the center two rows from each plot. Maturities were estimated when plots were 75% ripe visually, and by squeezing the grain, as estimated by an experienced field technician. Yield and maturity data were analyzed using ANOVA for individual years, and subsequently in a joint analysis to determine effects of year, cultivar, management level, and possible interactions.

RESULTS AND DISCUSSION

Solution Culture Studies

The 30 cultivars selected for use in the screening test differed in tolerance to Al (Table 2), confirming a number of previous reports of differential tolerance to Al in wheat (examples cited in Taylor (1988)). Exposure to Al increased root growth in several of the more tolerant cultivars, a result which has been reported for a number of species (Taylor 1988) including sorghum (*Sorghum bicolor*; Furlani and Clark 1981; Duncan et al. 1983), wheat (Taylor and Foy 1985a), and corn (*Zea mays*; Clark 1977; Bennet et al. 1987). Both root and leaf growth were depressed in all other cultivars. Symptoms of Al toxicity were most evident on roots. Aluminum-affected roots were relatively short, thick, and had numerous undeveloped laterals. Leaves of some cultivars showed chlorosis resembling iron deficiency, and others showed purple stems typical of phosphate deficiency (Foy and Brown 1964).

Analysis of variance of root weight, root length, and leaf weight data indicated significant main effects attributable to cultivar and Al treatment, as well as a significant cultivar × treatment interaction effect. Because root weight, root length, and leaf weight of cultivars differed both in the presence and

Table 2. Differential Al tolerance of 30 cultivars of *Triticum aestivum* grown in solution culture as measured by the root weight index (RWI) and root length index (RLI)

Cultivar	Root weight index	Root length index
K.Kongoni	1.10*a*	0.99*bc*
PT741	1.10*a*	1.07*ab*
K.Nyumbu	1.06*ab*	1.05*ab*
PT726	1.06*ab*	1.10*ab*
Norquay	1.04*ab*	1.21*a*
PF7748	1.02*abc*	1.06*ab*
Maringa	0.96*abc*	1.03*bc*
Atlas 66	0.96*abc*	1.07*ab*
K.Tembo	0.95*abc*	1.08*ab*
Marshall	0.90*abc*	0.88*cde*
Romany	0.85*bcd*	0.95*bcd*
PT742	0.84*bcd*	0.99*bc*
Fielder	0.84*bcd*	0.94*bcd*
Glenlea	0.80*cde*	1.04*abc*
HY320	0.80*cde*	1.02*bc*
QT8132	0.63*def*	0.81*def*
Oslo	0.61*efg*	0.70*fg*
Owens	0.51*fgh*	0.68*fg*
Lancer	0.46*fghi*	0.61*gh*
Wildcat	0.45*fghi*	0.67*fg*
Columbus	0.43*fghi*	0.47*hi*
Park	0.39*ghi*	0.37*ij*
Bluesky	0.38*hi*	0.75*efg*
Kenyon	0.33*hi*	0.36*ij*
Benito	0.30*hi*	0.36*ij*
BW92	0.29*hi*	0.46*hi*
Neepawa	0.27*i*	0.35*ij*
Conway	0.27*i*	0.41*ij*
Katepwa	0.26*i*	0.34*ij*
Scout 66	0.25*i*	0.28*j*
Standard Error	0.05	0.07

a-j Means followed by the same letters are not significantly different at the 5% level according to Duncan's multiple range test.

absence of Al, the three tolerance indices RWI, RLI, and LWI were used to evaluate cultivar differences in tolerance to Al. One-way ANOVAs for all three indices indicated significant main effects due to cultivar. Because the RWI, RLI, and LWI are expressed as growth with Al as a fraction of growth without Al, analyses of treatment effects were not appropriate.

Values of the three tolerance indices were significantly correlated ($P < 0.001$). The RLI and RWI indices were most closely correlated (RLI = 0.85 RWI + 0.20; $R^2 = 0.81$), while correlations between LWI vs. RWI (LWI = 0.28 RWI + 0.54; $R^2 = 0.58$) and LWI vs. RLI (LWI = 0.27 RLI + 0.53; $R^2 = 0.46$) were weaker. Such results suggest that the RWI and RLI were better indicators of tolerance to Al than the LWI. Root weight is commonly regarded as a more sensitive indicator of Al toxicity than leaf weight (Taylor and Foy 1985a; Zale and Briggs 1988; Zhang and Taylor 1988). For this reason, Duncan's multiple range test was used to rank cultivars on the basis of the RWI and RLI (Table 2). Both indices gave similar results, although variation was noted for several cultivars.

On basis of the RWI (Table 2), seven cultivars (K.Kongoni, PT741, K.Nyumbu, PT726, Norquay, PF7748, Maringa) ranked higher than the Al-tolerant standard, Atlas 66. The Al-sensitive standard, Scout 66, was ranked most sensitive to Al, but 11 Canadian cultivars were equally sensitive (Lancer, Wildcat, Columbus, Park, Bluesky, Kenyon, Benito, BW92, Neepawa, Conway, Katepwa). Cultivars of Brazilian origin (Maringa, RWI = 0.96; PF7748; RWI = 1.02) and Kenyan origin (K.Kongoni, K.Nyumbu, K.Tembo, Romany; RWI = 0.85 − 1.10) were uniformly tolerant to Al. In contrast, the CWRS cultivars (Benito, BW92, Columbus, Conway, Katepwa, Kenyon, Lancer, Neepawa, Park; RWI = 0.26 − 0.46) and the two new Canadian utility cultivars from Beaverlodge (Bluesky, RWI = 0.38; Wildcat, RWI = 0.45) were sensitive. Cultivars with documented high yield potential were relatively tolerant to Al (Fielder, Glenlea, HY320, Norquay, Oslo, Owens, PT726, PT741, PT742, QT8132; RWI = 0.51 − 1.10). Marshall, a cultivar bred for rainfed high yield in the United States, also possessed good tolerance to Al (RWI = 0.90).

Two locally adapted Canadian cultivars were selected to serve as standards for Al tolerance (PT741) and Al sensitivity (Katepwa). Over the range of concentrations employed, root weight was more sensitive to Al than leaf weight (Figs 1 and 2). Differences

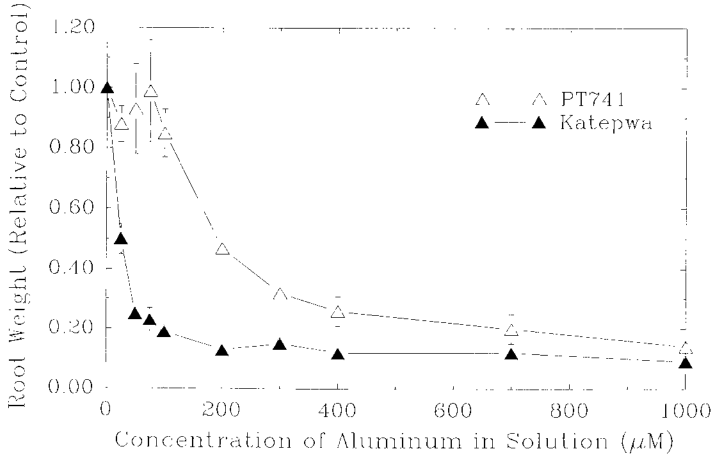

Fig. 1. The effect of Al in the nutrient solution on root weight of an Al-tolerant cultivar (PT741) and an Al-sensitive cultivar (Katepwa) of wheat. Standard errors less than 0.04 are not indicated.

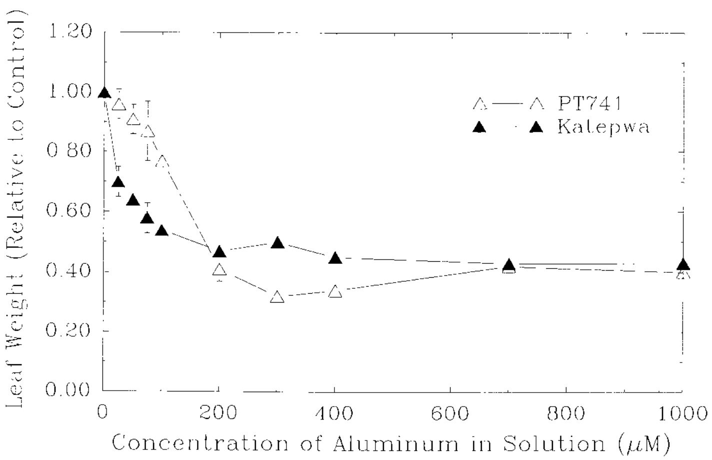

Fig. 2. The effect of Al in the nutrient solution on leaf weight of an Al-tolerant cultivar (PT741) and an Al-sensitive cultivar (Katepwa) of wheat. Standard errors less than 0.04 are not indicated.

between the two cultivars were most apparent between 25 and 200 μM Al. Katepwa showed a 50% reduction in root weight at 25 μM. In contrast, nearly 200 μM Al was required to produce the same reduction in PT741. At concentrations of 300 μM and higher, root weights of both cultivars were severely affected by Al and differences between cultivars were not as large. Nonetheless, PT741 outperformed Katepwa throughout the range of concentrations employed (Fig. 1). Differences in leaf weight were also most pronounced at concentrations below 200 μM. Katepwa outperformed PT741 at 300 and 400 μM, although leaf weights in the two cultivars were equally reduced at 700 and 1000 μM (Fig. 2). The differences between growth (root and leaf) of PT741 and Katepwa were similar in magnitude to those reported for two winter wheat standards for Al tolerance and sensitivity, Atlas 66 and Scout 66 (Zhang and Taylor 1988). The pattern of root growth being more responsive to Al stress than leaf growth is also well documented (see, for example, Mugwira et al. 1976; Campbell and Lafever 1976; Aniol and Kaczkowski 1979; Taylor and Foy 1985a,b; Zhang and Taylor 1988).

Field Study

Analysis of variance (ANOVA) for yield and maturity from the field trial in each of the 3 yr indicated that effects due to cultivar were significant, while effects of management level and the cultivar × management level interaction were not significant. Analysis of variance of the yield and maturity data for the three years pooled together indicated significant effects due to year and cultivar, while the cultivar × year and cultivar × management interaction effects were not significant (Tables 3 and 4).

The base nitrogen fertility levels of the Conventional management treatment plots were high (Table 1), and disease pressure, mainly from septoria and mildew, was very low in all 3 yr. Thus, yields were not higher in the ICM treatment. Addition of the extra nitrogen and other inputs of the ICM treatment did not result in increased yields, presumably because other factors such as moisture or heat units were limiting in individual years. Average yields were significantly different in the 3 yr (Table 3), but in inverse proportion to the number of days required to reach maturity in each year. Maturity delay in 1987 was due to cool, wet, fall conditions.

Yield and maturity performance of the 14 cultivars (Table 4) were similar to previous results from trials in the Edmonton area under

Table 3. Mean yield and days to maturity (average of 14 cultivars grown under Conventional and ICM management) in each of 3 yr (1985, 1986, and 1987) of the Edmonton field trial

Year	Yield (kg ha^{-1})	Maturity (d)
1985	5797*a*	109*a*
1986	5352*a*	113*b*
1987	4137*b*	116*c*
SE	626.8	2.7

a-c Means followed by the same letter are not significantly different at the 5% level according to Duncan's multiple range test.

Table 4. Mean yield and maturity values (averaged over 3 yr) for each of 14 cultivars in the field trial)

Cultivar	Yield (kg ha^{-1})	Maturity (d)
HY320	6234*a*	121.1*a*
PT741	5689*b*	111.8*cde*
PT742	5544*bc*	110.8*def*
Bluesky	5454*bcd*	110.6*ef*
Oslo	5421*bcd*	111.8*cde*
PT726	5362*cd*	111.1*de*
Norquay	5223*de*	110.5*ef*
Glenlea	4983*ef*	116.5*b*
Wildcat	4776*fg*	108.7*f*
Neepawa	4697*fgh*	112.9*cd*
Columbus	4581*gh*	116.6*b*
Conway	4462*h*	113.8*c*
Katepwa	4455*h*	112.4*cde*
Park	4453*h*	110.3*ef*
SE	138.3	0.9

a-h Means followed by the same letter are not significantly different at the 5% level according to Duncan's multiple range test.

conditions of lower fertility, but for which no consistent data were available (i.e., breeding trials, Parkland Cooperation trials, Western Wheat Cooperative trials, Alberta Regional trials, etc.). These data confirm the high yield potential of rainfed wheat at this location. The range in yield averaged over the 3 yr was from 4453 kg ha^{-1} for Park to 6234 kg ha^{-1} for HY320. There were no significant differences in the average yield among the five CWRS cultivars (Columbus, Conway, Katepwa, Neepawa, and Park) in the trial. As expected, Park was significantly earlier to mature than Neepawa, which was in turn earlier than Columbus (Table 4). This trial also confirmed the well-established earliness of Neepawa compared to Glenlea (3–6 d later) and HY320 (8–12 d later) at this location. The high yield conditions of the 3-yr trial magnified differences in maturity.

From an agronomic perspective, the most important result from the field trial was the identification of six genotypes that were significantly higher yielding than Neepawa, but that were not significantly later maturing than Park under these high fertility conditions. These genotypes (Bluesky, Norquay, Oslo, PT726, PT741, and PT742) are of widely diverse genetic origin and quality type, but all are characterized by lower protein content than CWRS cultivars (University of Alberta, unpublished data).

General Discussion

Comparison of the solution culture studies and the field studies indicates an apparent association between high yield potential and tolerance to Al. Of the nine highest yielding cultivars of lines used in the field trials, six had RWI values equal to or greater than 0.80. In contrast, the five CWRS cultivars had RWI values equal to or less than 0.43. The CWRS cultivars Conway, Katepwa, and Neepawa were the lowest ranked spring wheat cultivars for tolerance to Al. If the field study had been carried out on an acid, Al-toxic soil, superior performance of Al-tolerant cultivars would have been expected. The high pH (6.0) of our experimental plots, however, rules out Al toxicity as a growth limiting factor.

The reason for the observed association between high yield potential and tolerance to Al is unexplained. Cultivars developed in regions dominated by acid soils often show tolerance to Al (Foy et al. 1974). This could account for the high ranking of the Brazilian (Maringa, PF7748) and Kenyan (K.Kongoni, K.Nyumbu, K.Tembo, and Romany) cultivars used in this study. Lack of selection of Al tolerance, however, has been associated with the development of Al-sensitive cultivars (Foy et al. 1974); none of the cultivars in the field trials were specifically bred for Al tolerance. It is possible that the group differences for yield and Al tolerance were a result of different breeding objectives, strategies, and conditions. The CWRS cultivars have been developed by repeated backcrossing with a narrow germplasm base lacking Al tolerance. The high-yielding cultivars were developed by selecting specifically for high yield from a broader base of germplasm under generally high fertility field conditions. A common characteristic of the cultivars with high yield potential used in the field study, however, is the presence of Brazilian or Mexican germplasm in their background. This is true of the Al-tolerant cultivars HY320, PT741, PT742, PT726, Norquay, and Glenlea, as well as Oslo, Bluesky, and Wildcat which were ranked sensitive to intermediate in tolerance to Al (RWI = 0.38 − 0.61).

It is also possible that the relationship between high yield potential and tolerance to Al might be related to nitrogen use efficiency. In a number of species, Al tolerance has been associated with differences in ammonium and nitrate uptake (Fleming 1983; Taylor and Foy 1985c; Keltjens 1987; Keltjens and van Ulden 1987), high nitrate reductase activity (Foy and Fleming 1982), and high protein content of grain (Mesdag et al. 1970). Perhaps breeding and selection for yield under high fertility conditions (such as in the University of Alberta breeding program) favors cultivars with high nitrogen use efficiency and, hence, tolerance to Al. To test the possible association between tolerance and yield potential, a backcross program to introduce Al tolerance into CWRS and other cultivars has been initiated. This material will be useful for further field and solution culture studies to evaluate the relationship between Al tolerance, nitrogen use efficiency, and yield potential. In such studies, the locally adapted cultivars PT741 and Katepwa can be used as Canadian standards for Al tolerance and Al sensitivity, replacing the previously accepted standards, Atlas 66 and Scout 66, which are not suited for field studies in Western Canada.

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