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Yield trends of temperate cereals in high latitude countries from 1940 to 1998

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Wheat is the only temperate cereal for which yield trends have been exhaustively analysed on both global and national bases. This paper aims (i) to compare global yield trends of wheat, barley, oat and rye for the last five decades, (ii) to analyse their yield trends in Canada, Denmark, Norway, Sweden and Finland, the northernmost limits for extensive agriculture, and (iii) using case studies, to assess the relative contribution to yield gains made by cereal breeding. Average global yield data from FAO were regressed against years using linear or bilinear regressions. Yield gains in absolute and relative terms were calculated for comparison among countries and cereals. Data from the literature were used to assess the estimated contributions made by breeding to yield gains.

Global yield trends were not standard throughout the 1950–1998 period: rye exhibited a constant yield gain (*c.* 28 kg ha^{-1} y^{-1}), while barley and oat showed marked increases until around 1970 (*c.* 38 and 32 kg ha^{-1} y^{-1}, respectively) but quite modest increases (*c.*19 and 5 kg ha^{-1} y^{-1}, respectively) over the last 30 years. Wheat also showed a bilinear trend with only limited yield gains until the 1960s, followed by a more than 3-fold increase in rate of yield gain from then on (16 and 40 kg ha^{-1} y^{-1}, respectively). However, during the 1990s wheat yield gains have been less than previously. Hence, global yields of barley, oat and wheat have increased very slowly lately.

Trends for each combination of cereals and countries indicated consistently higher yields during the 1990s than at mid-century. In general, wheat yield tended to increase at a faster rate than yield of the other cereals. There was a trend in the last decade of low rates of yield increase compared with those of previous decades. This was clear for oat and barley, and a similar trend is emerging for wheat. This suggests that genetic and/or management improvements have had less effect in recent times. Furthermore, we found preliminary evidence to suggest that with the exception of wheat in Canada, genetic contributions in northern areas were smaller than those reported for wheat and bar-

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ley at lower latitudes. Therefore, alternative approaches must be sought for future breeding work under these high latitude conditions.

Key words: barley, breeding, northern agriculture, oat, rye, wheat, yield

Introduction

Cereals represent the major contribution to total world food production. In total their production is substantially greater than that of all other crops combined (Slafer et al. 1994). A share of that production comes from countries in which agriculture is practised at high latitudes. Under high latitude growing conditions most cereal production involves the temperate species, barley (*Hordeum vulgare* L.), oat *(Avena sativa* L.), rye (*Secale cereale* L.) and wheat (*Triticum aestivum* L.). The major factor limiting crop productivity in these marginal areas is the length of the growing season. However, these countries of these regions may be expected to make a disproportionately large contribution to future increases in crop production as they will benefit more from expected global warming than countries at lower latitudes (Kettunen et al. 1988, Carter and Saarikko 1996).

Wheat is the only temperate cereal for which yield trends have been exhaustively analysed on both global and national bases (Calderini and Slafer 1998). During the 20th century, the production of wheat increased more than 6-fold (Slafer et al. 1994). This increase was initially due to the enlargement in harvested area that occurred during the first half of the century, followed from the 1950s onwards by an increase of c. 150% in global average yield per unit land area (from 1 to 2.5 Mg ha^{-1}; Slafer et al. 1996). However, a closer inspection of the records of average yields for recent years suggests a possible levelling off of cereal yields (Slafer et al. 1996). Although the apparent levelling off should be regarded cautiously, it may indicate that new strategies for maintaining rising yields are needed, as a continued increase in productivity must be achieved to match the ongoing increase in world population (Mann 1999, Slafer and Satorre 1999). The degree to which other cereals exhibit similar decreases in yield gains during the recent decades, has not been determined. Despite their physiological-ecological similarities, trends among temperate cereals may be different, as the pressure for increasing yields and the amount of research effort expended on this has always been greater for wheat than the other temperate cereals. One of the objectives of this paper was to compare global trends for wheat, barley, oat and rye during the last five decades, as most cereals did not exhibit clear yield gains during the first half of this century (Slafer and Satorre 1999, Slafer and Otegui 2000).

Global yield averages may not clearly reflect the situation in particular countries or regions, and they could either highlight similarities or mask differences among them. Calderini and Slafer (1998) reported some notable coincidences in general trends for wheat yield among countries with different environments, cultures and economic/agricultural policies. However, they concentrated on major production regions rather than on particular growing conditions that define a region. In their analysis, only Canada and Sweden represented countries with virtually all production under northern growing conditions. Furthermore, only wheat was analysed and other cereals might exhibit quite different trends in specific regions. Therefore, an additional objective of this paper was to analyse yield trends for the four major temperate cereals in Canada and Nordic countries including Denmark, Norway, Sweden and Finland.

Yield statistics used in this study reflect changes in several socio-economic forces (e.g. grain prices, market demands, environmental issues) that determine modifications in both crop management and cultivar selection. When future perspectives are being sought, it is relevant to

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estimate the relative contribution of plant breeding to the total gain in yield (Slafer and Andrade 1991). As management and genetic factors interact to produce the final yield gains, recorded as averaged yield trends for a particular region, it is difficult to separate these contributions accurately (Harper 1983). Again this has been done for wheat in several regions. Genetic contributions to the total gains in wheat yield have been estimated to be *c.* 50% in USA, UK and Argentina and *c.* 30% in Australia and Mexico (Slafer et al. 1994, Bell et al. 1995). In barley approximately one third of the yield increase recorded in the UK between the 1940's and the 1980's has been attributed to genetic improvement (Silvey 1986). For neither wheat nor barley in the northernmost growing conditions, nor for other cereals anywhere, have the genetic contributions to yield gains been quantified. Hence, we also aimed to assess the relative contribution of genetic improvement to yield gains in some cases.

Material and methods

Data for this study were obtained from FAO yearbooks (the 1947 issue carried forward data from 1940 collected by the preceding organisation, The International Institute of Agriculture in Rome, and published in their Annuaires del Institut International D'Agriculture), the FAO's World Crop and Livestock Statistics published in 1987, and the FAO's web-site (www.fao.org).

Data comprised the global yield records from 1951 to 1998 and from 1940 to 1998 for each of the countries included in the analysis. Global data for the World War II period were not available for many countries and hence the trends for averaged yield were estimated from 1950 onwards. The northern countries analysed included Canada, Denmark, Finland, Norway and Sweden. In these countries most of the cereals are grown at northern latitudes. Countries with regions at high latitudes but also with temperate regions that make important contributions to the average yields of the country were not included, as both edaphic and climatic conditions, and consequently yield levels, varied widely within the north-south axis of the country.

A simple model was used to characterise the yield trend in each case. Although in some circumstances more complex models might provide a better statistical description of the actual trends, we restricted the analyses to simple models with agronomically meaningful parameters that allow comparisons to be made among countries and/or cereals. Average global yields were regressed against years using linear or bilinear regressions with an optimisation model that was fitted iteratively to the data using curve-fitting software (Jandell 1991). The regression models were y = a + bx (linear) and y = a + bc + d(x–c) (bi-linear); where 'y' represents yield, 'a' the intercept, 'b' the rate of yield gain during the first period (unique in the linear model), 'c' the year at which the inflection point occurred, 'd' the rate of yield gain during the second period, and 'x' the year. The model finally accepted for each case was that exhibiting the highest adjusted coefficient of determination, with the lowest fitted standard error.

For each country and cereal species combined simple linear regression was used to estimate the yield gains (slope) throughout the 59 years analysed. Relative yield gains were the yield gains expressed as a percentage of yields averaged for the whole period in each country-cereal combination (Slafer and Andrade 1991).

Available data from the literature on yield increases due to genetic improvement (from experiments comparing cultivars released at different times for particular combinations of countries-cereals, Calderini et al. 1999) were used to assess the estimated contributions made by breeding to the exhibited trends in yield. In these cases both total (from the data of the country-cereal under consideration) and genetic gains were assumed to be constant through the period considered in analyses and calculated in relative terms to allow for comparison (for details see Slafer and Andrade 1991).

Results and discussion

Global trends

Yields of the four cereals analysed exhibited some general similarities during the 1950–1998 period. The yield of each species was greatly increased during this period. Current yields (average 1990–1998) are far greater than those generally found in the mid 1950s (average 1950–1959). The relative increase was assessed as the simple ratio between these decade averages and was 47% for oat, 83% for barley, 99% for rye, and 131% for wheat (Fig. 1). However, yield trends were not similar throughout the study period. Only for rye were yields from the second half of the century best described by a linear model (Fig. 1, Table 1). The other cereals showed yield trends represented by contrary bi-linear dynamics. In wheat there were only modest yield gains until as late as the1960s, in accordance with the finding of Slafer et al. (1996) that virtually no yield gains occurred during the first half of this century. This was followed by a more than 3-fold increase in rate of yield gains by the end of the century (Fig. 1, Table 1). Yields of barley and oat exhibited marked increases until around 1970, followed by a strong reduction in yield gains, to the point that they became virtually negligible in oat (Fig. 1, Table 1).

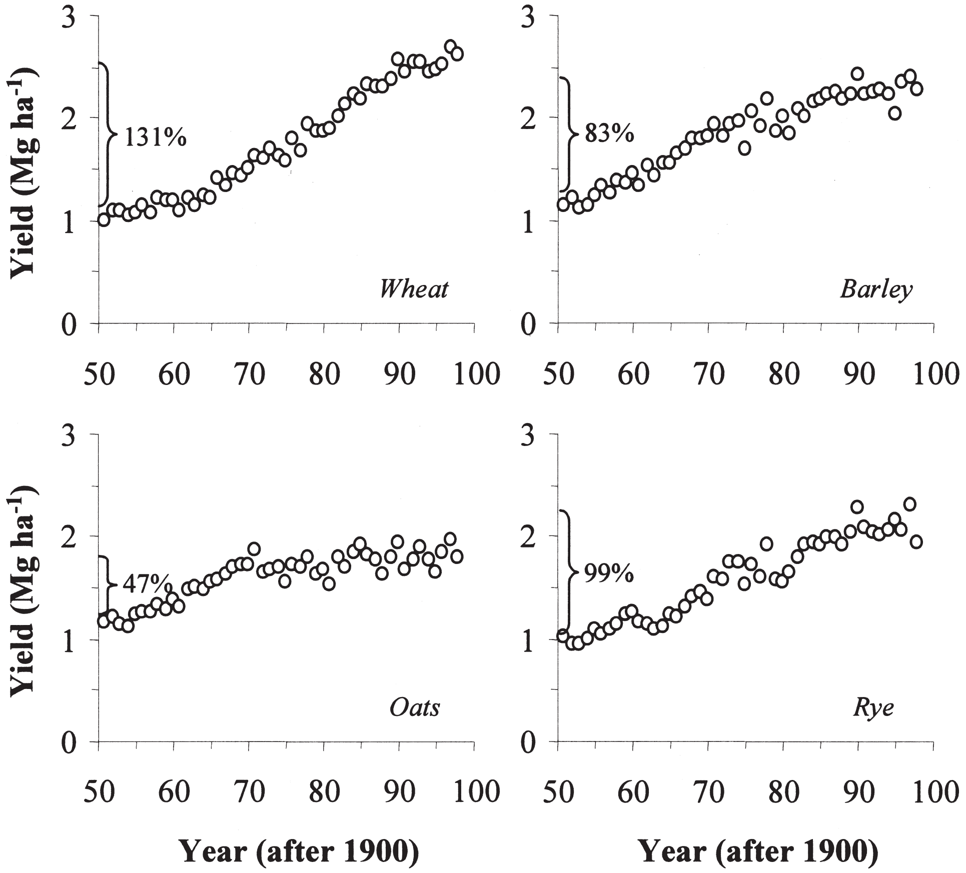

Fig. 1. Trends in global averaged yields for wheat, barley, oat and rye from 1951 to 1998. Percentages indicate the ratio of 1990–1998 to 1951–1959 yields, expressed as percentage of the latter.

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Table 1. Outputs [coefficient of determination (r^2), years when the change in slope occurred (breakpoint), and slopes (yield gains; kg ha^{-1} y^{-1})] of the regression models used to analyse yields (global averages) against years for the period 1951–1998 (inclusive) for each of the 4 major temperate cereals included in the study. Standard errors of the breakpoint (for the bi-linear model) and slopes are shown in parentheses.

Cereal	Model	r^2	Adj. r^2	Breakpoint	Yield gains	
					1st period	2nd period
Wheat	Linear	0.965	0.963	---------	38.4 (± 1.09)	---------
	Bi-linear	0.982	0.980	1963 (± 1.56)	12.9 (± 5.63)	43.6 (± 1.27)
Barley	Linear	0.913	0.909	---------	26.5 (± 1.21)	---------
	Bi-linear	0.942	0.936	1971 (± 2.90)	38.1 (± 3.49)	18.8 (± 2.39)
Oat	Linear	0.729	0.717	---------	14.0 (± 1.26)	---------
	Bi-linear	0.872	0.860	1969 (± 1.87)	31.6 (± 3.56)	5.01 (± 1.88)
Rye	Linear	0.924	0.921	---------	27.8 (± 1.17)	---------
	Bi-linear	0.924	0.917	1958 (± 15.4)	22.3 (± 17.7)	28.2 (± 1.57)

In relative terms yield gains, due to both management and breeding improvements, averaged only 0.9 and 0.3% y^{-1} for barley and oat, respectively. These rates are considerably lower than the rate of population growth (1.75% for the 1961–1998 period), and show no signs of recovery in the long term (Fig. 1). The situation seems to be much better for wheat, as its yield has been increasing on a global basis at a faster rate than the population growth during recent decades (Table 1). However, a more detailed analysis of data from the 1990s provides evidence of a slowing rate of yield increase during the last decade (Slafer et al. 1996, Slafer and Satorre 1999). We only used linear and bi-linear models in this paper, but the data for wheat were actually better represented by a tri-linear model (with an adjusted r^2 greater than that of the bi-linear model highlighted in Table 1). The tri-linear model for 1950–1998 confirms the hypotheses from a previous analysis, using only the data for 1980–1995. This work showed that wheat yields might be asymptotically approaching a ceiling (Calderini and Slafer 1998). The tri-linear model shows a significant second breakpoint at 1990 (± 2.5 y) in which the slope representing yield gains switched from a markedly high value of 47.0 (± 1.8) kg ha^{-1} y^{-1} (for the 1964–1990 period) to a much lower (and statistically non-significant) value of 22.7 (± 10.9) kg ha^{-1} y^{-1} (for 1990–1998).

As yields of the three most important temperate cereals show signs that a ceiling might be reached, there is an urgent need to acquire a much more comprehensive understanding of yield generation. This will allow new strategies to be developed to further increase yield, at least under the prevailing socio-economic conditions, either through management, breeding or combination of the two. A rate of yield increase is needed that at least keeps pace with population growth (Slafer and Satorre 1999). This is increasingly urgent (Mann 1999) if we are to meet the growing requirements for food of a population estimated to reach 8–10 billion people during the early decades of the 21st century (Rasmuson and Zetterström 1992, Evans 1998). One of these cereals, wheat, is (together with rice) the most important crop for feeding the more than 6 billion that already inhabit the planet.

Yield trends for cereals grown at high latitudes

Although for some specific combinations of cereal crops and countries other regressions may explained the yield trends better than the sim-

Table 2. Average yields for the 1940–1949 and 1990–1998 periods and outputs of linear regressions (coefficient of determination (r^2), and slope (yield gains)] of yield (averages for each cereal in each country) against years for the period 1940–1998 (inclusive, 57 degrees of freedom). Means are followed by standard errors (in parentheses).

Cereal	Country	$Yield_{40/49}$	$Yield_{90/98}$	r^2	Yield gains $_{(1940–1998)}$	
		kg ha^{-1}			kg ha^{-1} y^{-1}	% y^{-1}
Barley	Canada	1.30 (± 0.28)	2.96 (± 0.13)	0.850	33.7 (± 1.9)	1.65
	Denmark	3.11 (± 0.31)	5.02 (± 0.71)	0.688	35.7 (± 3.2)	0.91
	Finland	1.24 (± 0.19)	3.30 (± 0.43)	0.812	40.2 (± 2.6)	1.84
	Norway	1.80 (± 0.49)	3.61 (± 0.43)	0.754	37.2 (± 2.8)	1.31
	Sweden	1.92 (± 0.20)	4.01 (± 0.51)	0.860	42.8 (± 2.3)	1.45
Oat	Canada	1.19 (± 0.25)	2.40 (± 0.16)	0.844	23.8 (± 1.4)	1.33
	Denmark	2.85 (± 0.34)	4.96 (± 0.91)	0.632	37.4 (± 3.8)	1.01
	Finland	1.28 (± 0.23)	3.30 (± 0.33)	0.823	39.4 (± 2.4)	1.78
	Norway	1.76 (± 0.42)	3.82 (± 0.58)	0.734	44.3 (± 3.5)	1.53
	Sweden	1.45 (± 0.14)	3.71 (± 0.69)	0.779	49.5 (± 3.5)	1.84
Rye	Canada	0.79 (± 0.16)	1.93 (± 0.10)	0.792	23.1 (± 1.6)	1.70
	Denmark	2.06 (± 0.27)	4.80 (± 0.55)	0.905	56.5 (± 2.4)	1.70
	Finland	1.23 (± 0.14)	2.47 (± 0.49)	0.674	25.3 (± 2.3)	1.38
	Norway	1.68 (± 0.47)	3.36 (± 0.70)	0.664	38.9 (± 3.7)	1.40
	Sweden	1.71 (± 0.26)	4.66 (± 0.44)	0.897	59.3 (± 2.7)	1.97
Wheat	Canada	1.13 (± 0.24)	2.23 (± 0.09)	0.638	19.9 (± 2.0)	1.22
	Denmark	3.02 (± 0.58)	6.99 (± 0.42)	0.894	79.8 (± 3.6)	1.65
	Finland	1.32 (± 0.17)	3.45 (± 0.52)	0.821	43.1 (± 2.7)	1.91
	Norway	1.67 (± 0.42)	4.59 (± 0.57)	0.863	62.5 (± 3.3)	2.00
	Sweden	1.83 (± 0.41)	5.84 (± 0.37)	0.916	85.3 (± 3.4)	2.25

plest linear model ($y = a + bx$; see below), there was at least a very strong linear component in all cases, with adjusted coefficients of determination ranging from 0.63 to 0.92 (with 57 degrees of freedom, Table 2).

All combinations of cereals and countries analysed, had consistently higher yields during the 1990s than at mid-century (Table 2). Yields for the 1950–1959 decade were quite similar to those of the 1940–1949 period, and conclusions from Table 2 are not based on particularly low yields that could presumably be expected as a consequence of World War II. In all cases yields during the 1990s were also far higher than during the 1950s. Despite the large differences in average yield among countries and cereal crops, reflecting profound differences in the growing conditions, no case was found in which yield had not increased substantially. In general, the smallest absolute increases were for Canada while the highest rates of yield gain were for Sweden (Table 2). This most likely reflected the differences in environmental conditions in which cereals are grown, although some other factors such as differences in specific requirements for grain quality, could have played a role. In fact, there was a positive relationship between the rate of increase in yields in absolute terms and the average yield during the period analysed (Fig. 2, top panel). This trend, however, was not evident for individual cereals but was a general phenomenon. Barley, for example, did not exhibit a significant relationship and for the other cereals the relationship was strong but not linear (Fig. 2, top panel). By virtue of the general positive influence of the environment on the trends in yield,

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the relationship between yield gains and average yield is lost if the former is expressed in relative terms (Fig. 2, bottom panel).

With the exception of Canada, wheat yield has increased at a faster rate than that of the other cereals (Table 2), which is likely to have resulted from the greater effort directed toward improving yields of this cereal, not only in these countries but also at international centres and world-wide. The cereal species with the second-fastest rate of yield gains varied among countries, being rye in Sweden and Norway, but oat and barley in Finland, and barley in Canada (Table 2). These trends were independent of yield gains in absolute or relative terms, and differences in yield gains among countries and cereals were not related to patterns of changes in growing areas (data not shown, available in the FAO yearbooks).

In this paper we analysed the data with linear models, if they produced reasonable adjustments, because they facilitated comparison between cases and calculation of genetic contributions to yield gains (see below), while providing an estimate of the average rates of yield increase during the whole period analysed. However, this analysis prevented the identification of any indications of yields levelling off, which have been reported to be starting in most wheat growing areas of the world (Calderini and Slafer 1998).

The global trends in cereal yields discussed above reflect a levelling off with the exception of rye. The trend to lower rates of yield increase than in previous decades was clear for oat and barley and is emerging in wheat. Whether this is also the case for particular agricultural regions cannot be answered if the analysis is confined to linear trends. In some of the cases analysed above, a clear departure from linearity was evidenced by fitting the data to different models. This is, in part, due to the lack of clear trends of continued increasing cereal yields during the last decade. With the exception of oat in Denmark no clear positive yield trends were observed in any case for the last decade (Fig. 3). The coefficients of determination for the positive yield

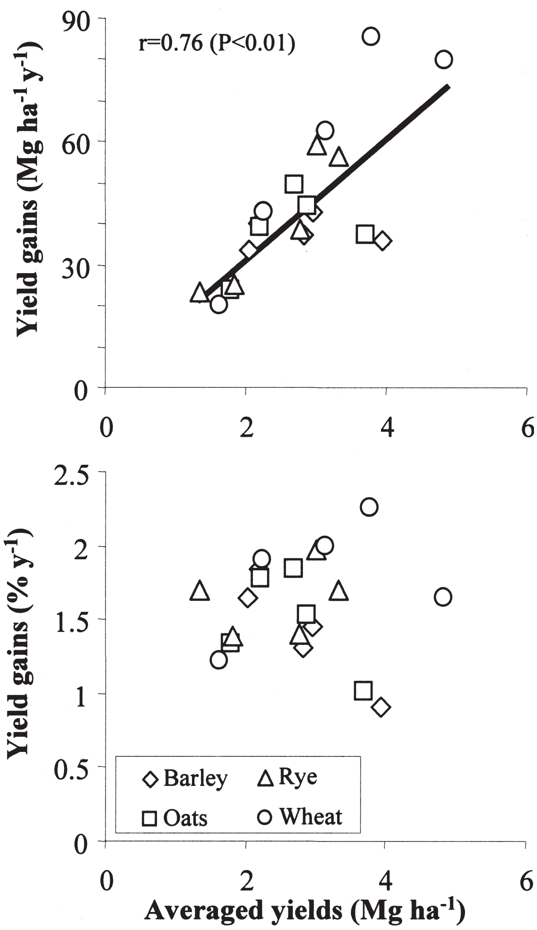

Fig. 2. Relationship between the yield gains due to both genetic and management improvements and the averaged yields from 1940 to 1998 for wheat, barley, oat and rye (symbols inside bottom panel) in Canada, Denmark, Finland, Norway, and Sweden. Line in top panel was fitted by linear regression.

trends for 1990–1998 ranged from 0.001 to 0.226 (and average yields of some cereal crops in some of these countries have tended to decline; *e.g.* rye in Finland; Fig. 3). This suggests that there has been a striking inability to improve yields through either genetic or management improvements in most combinations of cereal crops and countries analysed. All trends for the last decade must be regarded cautiously as they are based on a relatively short period. If this incipient lev-

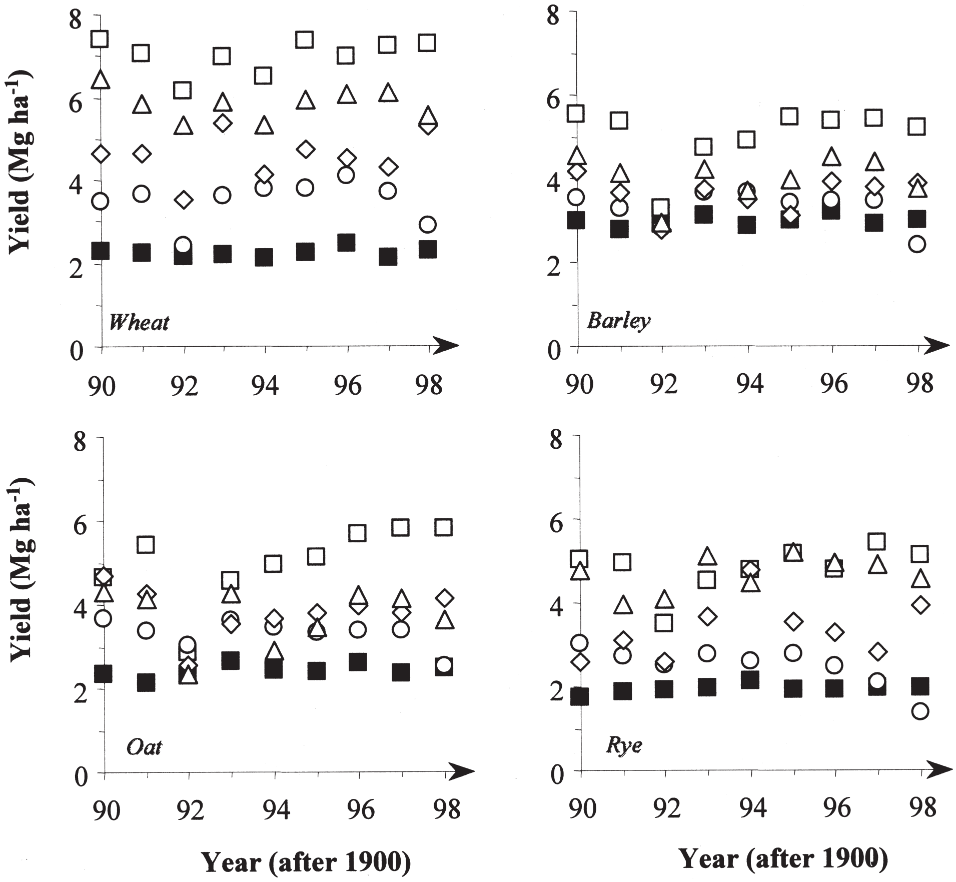

Fig. 3. Yield trends for wheat, barley, oat and rye during the last decade in Canada (■), Denmark (□), Finland (○), Norway (◇) and Sweden (△).

elling off is confirmed, however, in agreement with findings for wheat trends in most of growing regions of the world (Calderini and Slafer, 1998), and if the prevailing socio-economic situations are not strongly modified, new strategies for further increasing yields will be needed (Araus 1996, Richards 1996, Slafer et al. 1996, Mann 1999).

Genetic contributions to yield gains

The influence of breeding on the yield gains discussed above (Table 2) may be sought by comparing them (in relative terms) with the magnitude of the relative genetic gains in yield calculated from experiments in which cultivars released at different times have been grown together (Slafer and Andrade 1991). We found only a few of these studies in the literature. Those that do exist help to draw only a preliminary, and clearly incomplete, picture of the genetic improvement contributions to yield gains in cereal production made at the highest latitudes. They were two independent Canadian studies on barley, two independent evaluations of oat improvement effects carried out in Finland, and two estimates of breeding effects on wheat yield,

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Table 3. Genetic gains in yield assessed in absolute (slopes of the relationships between yield and the year of introduction of the cultivars) and relative (genetic gains as a percentage of the averaged yield of the study) terms for some cereals in some northern agricultural systems. Only data for cultivars released after 1940 in each study were included in the analysis.

Cereal	Country	Genetic gains in yield		Source
		kg ha^{-1} y^{-1}	% y^{-1}	
Barley	Canada	25.0	0.59	Bulman et al. 1993
		12.9	0.30	Jedel and Helm 1994
Oat	Finland	13.4	0.29	Rekunen 1988
		7.6	0.19	Peltonen-Sainio 1990
Wheat	Canada	25.0	0.82	Hucl and Baker 1987
	Sweden	23.1	0.33	Ledent and Stoy 1988*

* Only the experiment conducted in the normal year was included in the analysis

one for Canada and the other for Sweden (Table 3).

The cases of barley in Canada and oat in Finland clearly illustrate that estimates of genetic gains are strongly related to the conditions of the study. The estimated genetic gains for barley in Canada were 13 or 25 kg ha^{-1} y^{-1}, depending on the studies that reported results from two regions clearly differing in weather, particularly water availability. The difference was not apparent if the relative genetic gain was calculated (Table 3). The same was true for oat in Finland (Table 3). Genetic gains in wheat yields in Canada and Sweden appeared to have been similar (*c.* 25 kg ha^{-1} y^{-1}, Table 3). However, as wheat growing environments in Sweden and in Canada are quite different (not only for their average national yields shown in Table 2, but also in their specific experimental conditions), the relative genetic gains were far greater in Canada than in Sweden (Table 3).

Consequently, there seems not to be a similar genetic contribution to yield gains across these conditions (cereal crops and high latitude countries). It ranges from c. 15% for oat in Finland and wheat in Sweden to c. 65% for wheat in Canada. Intermediate relative contributions were made by barley breeding in Canada (*c.* 25%). With the exception of wheat in Canada, these contributions are clearly smaller than those reported in the literature for wheat and barley in temperate areas such as USA, UK, Argentina, Australia and Mexico (where *c.* 30–60% of the on-farm yield gains were attributed to breeding; Silvey 1986, Slafer et al. 1994, Bell et al. 1995). It may be considered that either (i) the conditions under which breeding is done in these high-latitude countries results in a relatively low contribution in terms of improving yield potential (e.g. by focussing the breeding programs on adaptation and yield stability rather than on yield potential), or (ii) the efficiency of breeding itself has been markedly lower than at other sites, indicating that new alternatives must be sought for future breeding in these conditions. This is particularly critical if future gains in yield are expected, due to economic and environmental reasons, to come more from breeding than from management improvement (Slafer et al. 1996).

Conclusions

Results from the present study confirmed the absence of any significant yield gain in wheat during approximately the last decade when analysed globally. They also showed that the global yields for the two other major temperate cereals, barley and oat, have been increasing very slowly during a longer period. Only rye exhibited a trend of increased yields equivalent to the increase in world population, even during the last decade.

Trends in cereal yields for the five nations producing them, virtually exclusively at very high latitudes, showed that in general the better the environmental conditions the faster the rate of yield improvement. Comparing cereals grown in these high latitude environments, wheat showed the greatest yield gains in virtually all conditions, while the ranks of the other cereals varied among the countries. A more detailed analysis of the latter period (from 1990 to 1998) revealed that in virtually all these regions yields of most cereals tended to level off. All analyses were done when the data were available until 1998, but even using the latest data for 1999, the trends were unchanged. This latest trend to a reduced or negligible increase in yield is particularly relevant to the scenario of environmental warming – benefiting agriculture in northern regions – and the rise in CO_2 concentrations enhancing yield and water use efficiency.

Based on the very few cases reported in the literature, it seems that, with the exception of wheat in Canada, the genetic gains in these high latitude environments were smaller than expected from results with wheat and barley under temperate conditions. Determining the reasons for these unexpectedly small contributions from cereal breeding may allow identification of alternative strategies that will promote further yield increases in the future.

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SELOSTUS

Viljojen satoisuuden kehitys pohjoisen viljelyn alueilla vuosina 1940–1998

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Vehnä on ainoa lauhkean vyöhykkeen vilja, jonka satoisuuden kehitystä on aiemmin tarkasteltu kattavasti maailmanlaajuisesti ja viljelyalueittain. Tämän tutkimuksen tarkoituksena oli verrata kauran, ohran, rukiin ja vehnän satoisuuden kehittymistä viimeisen viiden vuosikymmenen ajan erityisesti pohjoisen viljelyn alueilla (Kanada, Norja, Ruotsi, Suomi ja Tanska). Lisäksi arvioitiin kasvinjalostuksen osuutta satoisuuden kehittymisessä. Aineistona käytettiin FAO:n tilastoja.

Verrattaessa eri viljalajien satoisuuden muutoksia tutkitulla ajanjaksolla (1950–1998), havaittiin, että rukiin hehtaarisadot kasvoivat tasaisesti noin 28 kg vuodessa. Sen sijaan ohran (38 kg/ha/vuosi) ja kauran sadot (32 kg/ha/vuosi) kasvoivat ensin huomattavasti 1970-luvun paikkeille saakka, ja kasvu tasaantui voimakkaasti viimeisen 30 vuoden aikana. Myös vehnän satoisuuden kehitystä kuvasi parhaiten bi-lineaarinen malli; vähäistä satoisuuden kasvua 1960-luvulle saakka seurasi satoisuuden kolminkertaistuminen 1990-luvulle mentäessä tosin tästä edelleen kasvun tasaantuminen.

Tutkittaessa satoisuuskehitystä niin pohjoismaissa kuin Kanadassakin voitiin havaita, että yleisesti ottaen vehnän satoisuus kehittyi muita viljoja nopeammin. Tämä kuvastanee vehnän arvostusta ja kehitystyöhön käytettyjen tutkimusvarojen runsautta. Toisaalta kauran ja ohran, mutta vähissä määrin myös vehnän, osalta voidaan havaita satoisuuskehityksen hidastumista viime vuosikymmenenä. Alustavat tuloksemme antoivat myös viitettä siitä, että kasvinjalostuksen rooli tutkittujen viljalajien satoisuuden parantamisessa oli pohjoisilla viljelyalueilla pienempi (poikkeuksena vehnän tuotanto Kanadassa) kuin mitä on raportoitu viljeltäessä vehnää ja ohraa alhaisemmilla leveysasteilla.