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Contribution of new varieties to cereal yields in Finland between 1973 and 2003

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SUMMARY

On the basis of Finnish statutory variety trial data, the contribution of new varieties to cereal yields has been investigated. Such data have been collected since 1973. The data used contained the results of 2037 field trials testing 224 new barley cultivars, 163 new oat cultivars, 154 new spring wheat cultivars, 48 new winter wheat cultivars and 52 new winter rye cultivars. The data indicated a continuous increase in the annual yield of all the cereal species. The increase could be attributed in part to the genetic improvement of varieties and in part to changes in farming practices and environmental conditions. By using modern mixed model techniques it was possible to separate the effects due to genetic improvement from those due to the other factors. The main results show that in 1973–2003, new varieties contributed to an increase of 0·64, 0·41, 1·01, 0·63 and 0·97%, respectively, in the mean annual yield of barley, oats, spring wheat, winter wheat and winter rye. The research approach was based solely on existing data; new field experiments were not needed.

INTRODUCTION

Genetic improvement in grain yield has been studied intensively for many cultivated crops (e.g. Peng *et al.* 2000; Abeledo *et al.* 2003). The majority of these studies have been based on experiments in which historical varieties are grown in controlled environments. A typical investigation has consisted of 10 to 20 varieties from recent decades arranged in a randomized complete block design with four replicates across 3–6 years (Bulman *et al.* 1993; Morrison *et al.* 1999, 2000). Silvey (1986) has shown how a useful index for genetic gain can be calculated from national farm statistics. The research conducted and the results obtained help plant breeders to identify areas with potential for further improvement (Cuevasperez *et al.* 1995). An unavoidable problem, however, arises from the fact that the results of a single experiment or a single series of trials are relevant only to a few species and a specific growing environment.

Rekunen (1988) conducted field trials on historical oat varieties in 1977–1987 in Finland. Slafer & Peltonen-Sainio (2001) reported trends in yields of temperate cereals in high latitude countries from 1940–1998. Apart from these exceptions, a search of the current literature revealed a scarcity of well-documented information on the genetic contribution to grain yields applicable to Finnish growing conditions.

In the present study Finnish statutory variety trial data were used to investigate the contribution of new varieties to grain yields in Finland. Such data have been collected over the past 30 years. The study concentrated on the five cereals most relevant to Finnish agriculture, i.e. barley, oats, spring wheat, winter wheat and winter rye. For all these cereals, the stored data indicated a continuous increase in annual yields. As shown in many earlier studies, the increase could be attributed in part to genetic improvement of varieties and in part to changes in farming practices and environmental conditions. Modern mixed model techniques were used in the present study to distinguish between the effects due to genetic improvement and those due to the other factors.

The volume of data used was extensive compared with what can be collected from a single experiment on historical varieties. This enabled reliable results to be obtained. The use of stored statutory data made it unnecessary to conduct new experiments on historical varieties and allowed cultivars released in the most recent years to be considered. The results obtained are

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Table 1. *Number of new cultivars (cvs) released annually and number of annual trials*

	Barley		Oats		Spring wheat		Winter wheat		Winter rye	
Year	cvs	Trials	cvs	Trials	cvs	Trials	cvs	Trials	cvs	Trials
1973	9	12	13	4	17	5	1	1	4	2
1974	9	30	10	15	6	11	0	0	3	9
1975	7	38	7	18	12	17	7	3	4	15
1976	2	25	3	23	1	12	4	9	0	12
1977	4	19	2	19	2	11	0	7	0	12
1978	5	20	2	23	7	11	0	4	0	11
1979	6	21	3	23	5	13	0	6	3	12
1980	11	22	0	22	0	16	0	8	0	13
1981	4	24	6	20	4	14	1	3	1	9
1982	8	25	9	20	6	14	0	9	3	13
1983	7	24	1	18	5	14	1	9	0	13
1984	4	24	3	18	4	14	2	7	2	11
1985	14	26	7	23	11	17	3	9	3	11
1986	6	25	6	23	5	16	1	11	5	13
1987	5	23	9	18	3	12	0	5	4	10
1988	7	26	5	21	6	14	3	9	1	13
1989	8	27	4	19	8	12	1	8	1	15
1990	3	26	8	21	6	14	6	9	0	13
1991	7	23	2	17	7	11	1	10	1	13
1992	9	24	10	16	8	11	1	8	3	12
1993	4	23	9	16	4	8	1	6	1	9
1994	5	16	2	14	1	6	1	5	0	7
1995	3	15	3	13	2	6	2	5	2	9
1996	5	14	3	12	3	5	0	6	1	8
1997	8	15	3	12	4	6	2	5	1	7
1998	10	16	7	13	5	7	5	6	1	8
1999	10	17	5	16	3	7	2	5	2	8
2000	14	17	3	14	3	7	1	5	3	8
2001	12	13	3	14	0	7	0	6	1	9
2002	10	16	10	13	4	7	2	5	2	8
2003	8	16	4	15	2	7	0	3	0	5
Total	224	662	163	533	154	332	48	192	52	318

therefore relevant to the very latest developments and so are useful for current efforts in Finnish plant breeding.

MATERIALS AND METHODS

The study was based on data originating from statutory variety trials conducted in Finland by MTT Agrifood Research Finland since 1970. These trials are carried out according to well-documented management guidelines (Järvi *et al.* 1998). Test results from the trials are reported in a bulletin published annually (Kangas *et al.* 2003). For each cultivar considered in the present paper, the most relevant item of information is the historical date of origin. Such information was not explicitly stored in the data bank but, for each cultivar, a useful date of origin was obtained by equating the calendar year in which a cultivar was entered in the statutory variety trials with its release year. Clearly, however, some of the cultivars entered into the trials at the beginning of the testing process were developed and released before 1970. To overcome the problems arising from such old varieties, only data gathered since 1973 were used. Thus, the data actually used contained the results of 2037 field trials in which 224 new barley cultivars, 163 new oat cultivars, 154 new spring wheat cultivars, 48 new winter wheat cultivars and 52 new winter rye cultivars had been tested. The total number of yield recordings used in the present study exceeded 24 000. The structure of the data is shown in detail in Table 1. Figure 1 illustrates the connectivity of the data. It shows that, for each cereal, the annual turnover of cultivars tested is always less than 20 %. This ensures that in any well-defined linear mixed model analysis the annual variety effects are always estimable (Searle 1987).

Preliminary examination of the data indicated that it was necessary and sufficient to transform the yield recordings to logarithmic scale to justify the linear

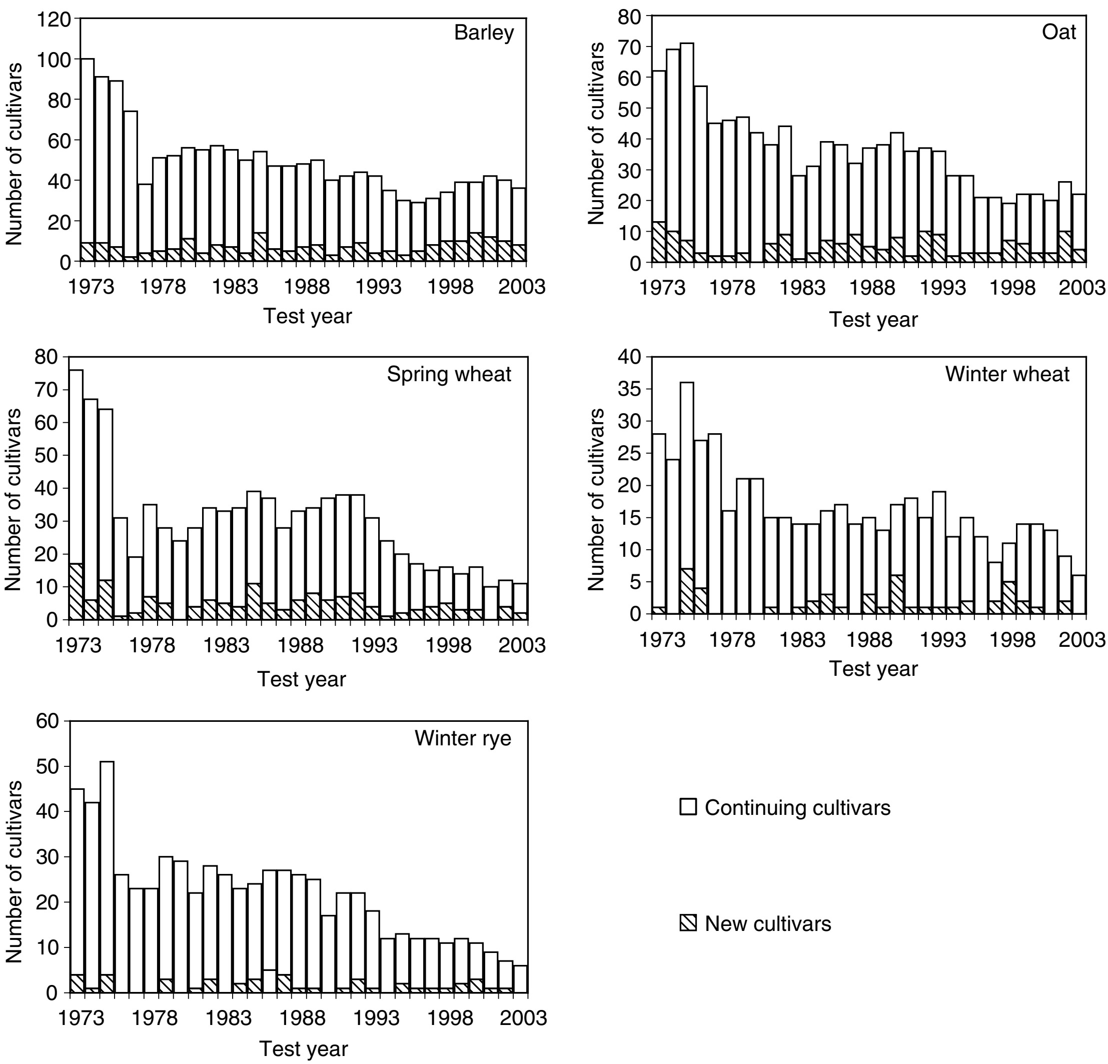

Fig. 1. Annual turnover of varieties.

relationship between the transformed yield and the explanatory variables comprising variety effects and environmental factors. This finding was well in line with the results of Calderini & Slafer (1998). From their study of trends in yield and yield stability in 21 countries throughout the 20th century, they concluded that no country exhibited a linear relationship between average wheat yields and time but that yield gains were, in general, much smaller during early decades than later ones. In fact, even if not explicitly stated, the figures presented support the conclusion of accruing cumulative growth. The findings in the present paper were also consistent with the results of Jedel & Helm (1994), whose studies on Canadian barley varieties of historical interest showed a time-dependent increase in grain yields, the responses being greater in more favourable environments. This finding likewise suggests an accrued cumulative increase that on logarithmic scale is approximately linear.

In the present study, the observed linear relationship between the transformed yield and the above set of explanatory variables was very useful because it justified the use of mixed model techniques, which in further analyses enabled discrimination between effects due to new cultivars and those due to other factors. In statistical modelling a two-stage approach was taken. The aim of the first stage was to make certain the presence of a stable time trend due to the variety effects. The aim of the second stage was to

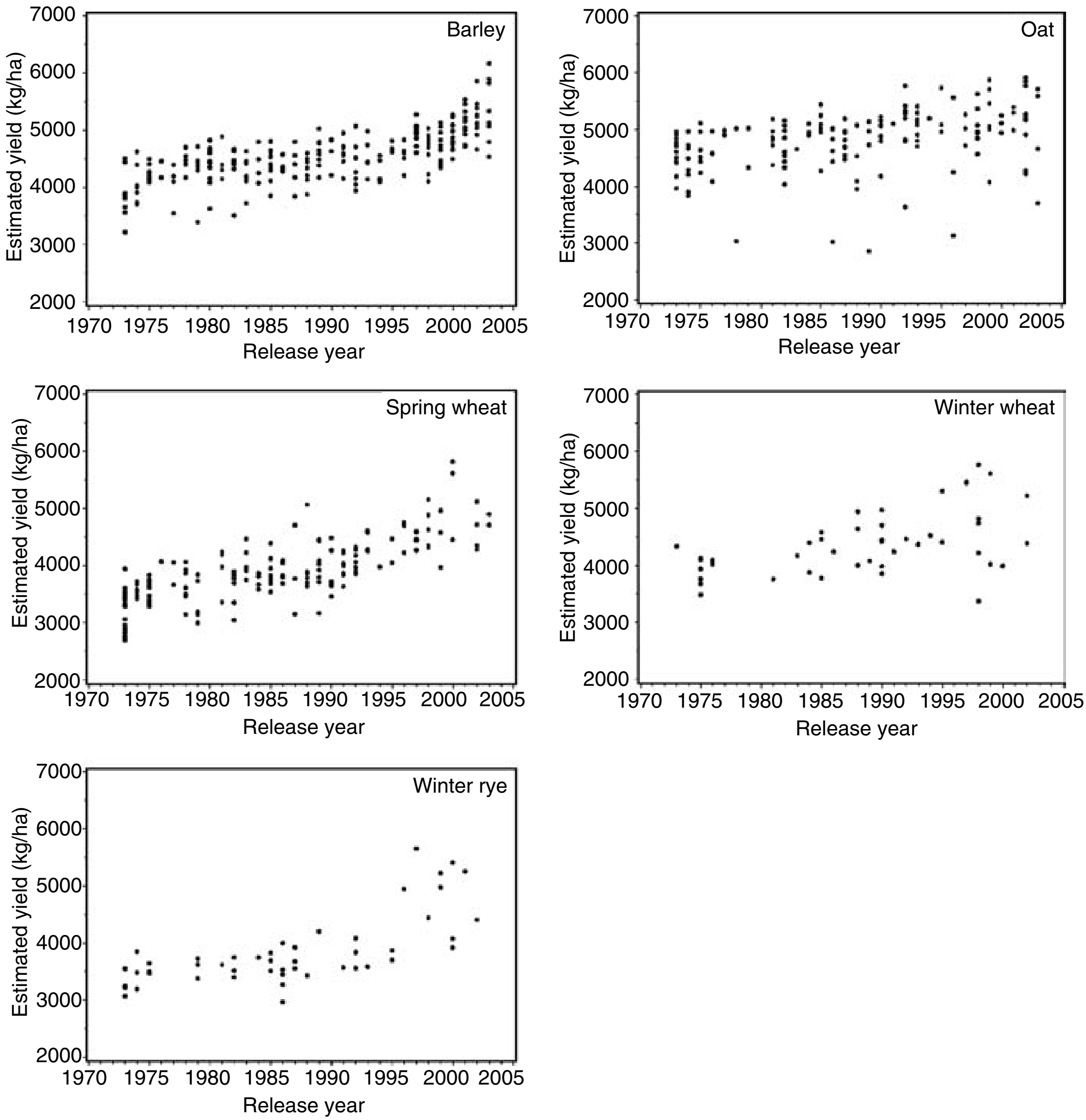

Fig. 2. Estimated yields of varieties released in different years.

provide a simple means to express and calculate the annual growth rate of the accumulating growth potential separately for each cereal species.

At the first stage, to ascertain the presence of time dependent trends due to the variety effects, an observed yield y_{ikl} of variety i tested in year k at site l was modelled as

$$\log(y_{ikl}) = \mu + \tau_i + \alpha_k + \beta_l + \phi_{kl} + \varepsilon_{ikl}$$

where μ is the general mean, τ_i, α_k and β_l are, respectively, fixed effects due to the ith variety, the kth trial year and the lth site, ϕ_{kl} is a random effect due to the interaction between the kth trial year and the lth site and ε_{ikl} is a random error term. All the effects defined as random were assumed to be normally distributed with zero mean.

Inclusion of the explanatory terms related to environmental conditions permitted the effects of changing farming practices and weather conditions to be removed from the changes in the response variable. This resulted in estimated variety effects $\hat{\tau}_i$ that were free from changes in environmental conditions. In Fig. 2 the estimated yields of varieties are plotted against the release year, i.e. the year the respective

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variety was entered into the field tests. It can be seen that, for each cereal, there exists a stable ascending trend due to the variety effects.

At the second stage, in order to provide a simple means to express and calculate the annual growth rate of the accumulating growth potential, the release year was incorporated into the model. In this case, an observed yield y_{ijkl} of variety i entered into field tests in year j (release year) and tested in year k at site l was modelled as

$$\log(y_{ijkl}) = \mu + \lambda t_{ij} + \alpha_k + \beta_l + \phi_{kl} + \varphi_{ij} + \varepsilon_{ijkl}$$

where λ is an unknown regression coefficient, t_{ij} is the release year j of variety i measured in the ordinary interval scale of calendar years and φ_{ij} is a normally distributed random effect with zero mean due to the ith variety nested within the jth release year. The rest of the terms are as above.

The rationale for incorporation the new random term φ_{ij} was just to absorb inconvenient variation and so improve the accuracy of the model. Since each random term has an expected value of zero all the material changes in the yielding potential due to the genetic evolution of the varieties is now expressed by the fixed term λt_{ij}.

Note that in the above model specifications it was possible to define some terms as random because they all included a large number of randomly distributed effects. Note, too, that both of the above models could have been further expanded by adding more interaction terms. Inclusion of such terms was tested but their contribution to model fitting was found to be not statistically significant.

The latter model provides a simple means to calculate the annual growth rate of the accumulating growth potential. To see this, let $y_{kl}(t_j)$ denote the expected mean yield of cultivars released in year t_j and grown in year k at site l. From the model specification it then follows that, for each cereal, we can write $y_{kl}(t_j) = \exp(\mu + \lambda t_j + \alpha_k + \beta_l)$. Thus, because the parameter λ can take only small values, the ratio of the expected annual yields from 2 consecutive years, say t_0 and t_1, can be expressed as $y_{kl}(t_1)/y_{kl}(t_0) = \exp[\lambda(t_1 - t_0)] = \exp(\lambda) \approx 1 + \lambda$. The growth rate of the mean annual yield due to genetic evolution can therefore be assessed simply by a proper estimate of the model parameter λ. Such estimates were obtained for each cereal species by fitting the above model separately to the respective data using the procedures of SAS/STAT software (SAS Institute Inc. 1999).

To study the fit of the model to the data, box whisker plots were produced separately for each cereal (Fig. 3). In these plots the residuals are plotted against the release years. The plots were produced using the SAS/GPLOT procedure (Friendly 1991).

Table 2. *Estimated annual growth rates* ($\hat{\lambda}$) *of mean annual yield and their standard errors*

Cereal	$\hat{\lambda}$	S.E. ($\hat{\lambda}$)	*P* value
Barley	0·0064	0·0007	$<0·001$
Oat	0·0041	0·0010	$<0·001$
Spring wheat	0·0101	0·0010	$<0·001$
Winter wheat	0·0063	0·0024	$<0·01$
Winter rye	0·0097	0·0019	$<0·001$

RESULTS

The estimated annual growth rates ($\hat{\lambda}$) of mean annual yield and their standard errors are listed in Table 2. Derived as they are from trial data, these estimated values cannot be applied as such to practical farming because the deployment of new varieties is often irregular and delayed. Moreover, improved new varieties of cereals are not released every year. The contribution of new varieties to practical crop production therefore tends to be erratic. Nevertheless, commercial imperatives imply that the genetically superior varieties will ultimately be adopted. Under this premise, the modelling techniques used in the present study ensure that the above figures represent the level of the mean annual contribution of new varieties to practical farming. This contribution depends on the prevailing yield level. The recent contribution can be approximated by national yield statistics. Table 3 summarizes the mean annual contribution of variety improvement during the past 10 years.

The data show that, for all cereal species, the yielding potential is positively correlated with growth time. As a side-effect of increased yield, the mean growth times of cultivars therefore tend to increase. More precisely, during the period of 3 decades considered here, the mean growing cycles for barley, spring wheat, winter wheat, oats and rye have increased by 3·4, 0·7, 0·0, 0·5, 0·2 days, respectively.

None of the box whisker plots shows any kind of systematic interdependence between the magnitude of the residuals and the release time. This ensures that, for each cereal, the fit of the model to the data is good over the whole time period of 30 years considered in the present study and the use of the model is justified.

DISCUSSION

During the 3 decades covered by the study, breeding activities on barley, spring wheat and winter wheat have been continuous and consistent. The steady parallel genetic improvement of these species observed here therefore complies well with expectations.

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Table 3. *Variety contribution to practical farming during the past 10 years*

Cereal	National yield mean (kg/ha)	Annual growth rate of mean annual yield due to genetic evolution (%)	Annual yield gain due to genetic evolution (kg/ha)
Barley	3242	0·64	20·7
Oat	3203	0·41	13·1
Spring wheat	3509	1·01	35·4
Winter wheat	3356	0·63	21·1
Rye	2363	0·97	22·9

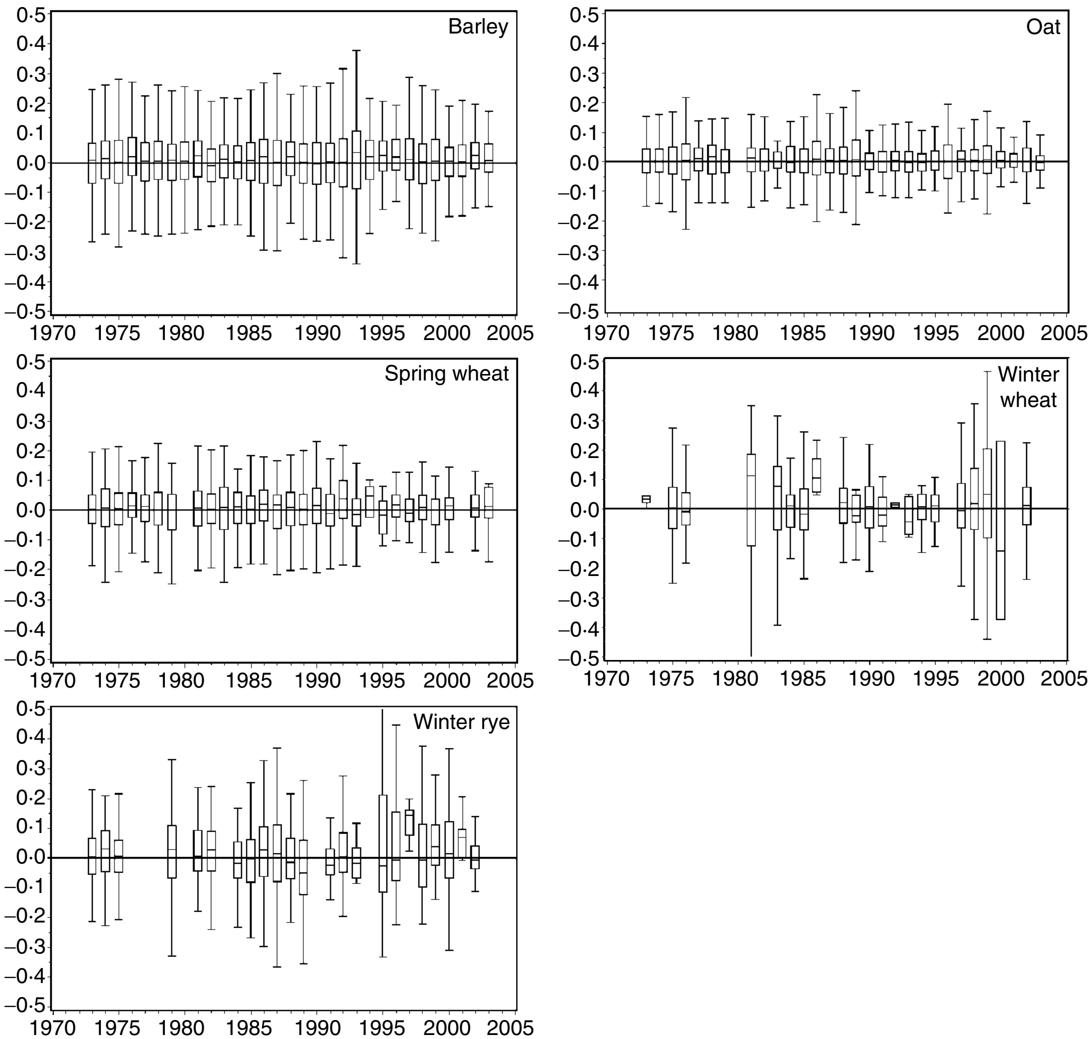

Fig. 3. Box whisker plots of the residuals. In each panel the residuals are plotted against the release years of the cereal specified in the heading. The bottom and top edges of each box are located at the sample 25th and 75th percentiles (lower and upper quartiles). The centre horizontal lines are located at the 50th percentile (median). Vertical lines are drawn from the box to the most extreme point within 1·5 interquartile ranges.

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Breeding activities on oats were intensive and productive long before the period considered here. Moreover, in the 1970s, high-yielding foreign varieties were widely imported and tested in statutory variety trials.

Breeding activities on rye have been modest in the last few decades. The observed high genetic improvement of rye was not therefore expected. One possible explanation for this improvement may be the introduction of hybrid varieties in the 1990s. Such varieties may play an overly important role in the present study because of the small total number of new rye cultivars and trials on rye. The genetic improvement of rye is not therefore likely to remain as high as implied here.

Slafer & Peltonen-Sainio (2001) report that the yields of most cereals tend to level off at high latitudes. The present study suggests that the most likely reason is changes in farming practices, as inferred from the fact that our model fits well to the data from the very recent years (see Fig. 3). This indicates that the contribution of plant breeding to yield gains of all commercially important cereals has remained at a statistically significant and practically important level in the very recent years, too.

The present study concentrated solely on the genetic improvement of cereals. The mixed model techniques used can, however, be applied to study the genetic improvement of other plant species of agricultural interest as well. The same techniques can further be used to explore the effects of new varieties on the many quality determinants of agricultural crops. As to the cereals themselves, Finnish statutory variety trial data contain long series of test recordings of crude protein content, plant height, specific weight, Hagberg falling number and growing cycles. The breeding policies of many quality determinants have, however, varied over time (Rekunen 1988; Bulman *et al*. 1993; Abeledo *et al*. 2003) and we cannot therefore assume constant time trends in their changes. When studying longitudinal changes in quality determinants it is therefore important to carefully adjust the mixed models to ensure that they comply with the changes implied by the actual data.

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