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Declining rapeseed yields in Finland: how, why and what next?

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SUMMARY

Average seed yields per hectare of *Brassica* oilseed crops in Finland, mainly summer turnip rape (*Brassica rapa* L. var. *oleifera* subvar. *annua*), which covers 0·93–0·99 of the total oil crop cultivation area depending on year, have fallen dramatically during the last 15 years. This downward trend is contrary to those in other temperate regions, where rapeseed yields have increased or levelled off after reaching a relatively high level. The 5-year moving averages for Finland show that seed yield started to diminish gradually after reaching its highest level of over 1700 kg/ha in the early 1990s. By 2005 it had fallen to 1270 kg/ha. The present study evaluated the possible reasons for the recorded collapse in Finnish turnip rape yields. All the statistical analyses were based on large, previously produced, datasets from multi-location Agrifood Research Finland (MTT) Official Variety Tests, Finnish Food Safety Authority (EVIRA) Seed Testing datasets and the Information Centre of the Ministry of Agriculture and Forestry in Finland (TIKE) national production datasets. Results from MTT trials indicated that the latest turnip rape cultivars were more sensitive to elevated temperatures at late seed set and during seed fill – and such temperatures often occurred during the years of greatest yield reduction. When taking into account how commonly sown these cultivars were at national level during the last 10 years, increased sensitivity contributed to up to two thirds of the recorded yield reduction. Even though the growing area of turnip rape has slightly exceeded 100 000 ha, after long being 60 000–70 000 ha, by extending cultivation to more northern areas of Finland, such changes do not explain the yield collapse according to data from TIKE. Furthermore, lower national yields do not stem from larger, but rather are associated with narrower within year variation in seed yield. Additional empirical work is needed to understand the causes of increased temperature sensitivity in modern cultivars (e.g. possible linkage to drought, diseases and/or drastically increased seed energy content). Furthermore, a national survey is essential for a thorough and up-to-date picture of the prevalence of pests and diseases in turnip rape and their contribution to reduced yields.

INTRODUCTION

The *Brassica* genus contains numerous important crop species, including vegetables, oilseeds, forages and feeds, many with local and traditional uses (McNaughton 1995). Annual (spring-sown) and biennial (winter-sown) forms of turnip rape (*Brassica rapa* L. var. *oleifera* subvar. *annua*) and canola rape (*Brassica napus* L. var. *oleifera* subvar. *annua*), both referred to as rapeseed, are commonly grown oil crops in temperate regions. Production areas are also vast elsewhere, including China, India, Canada and Australia, with 7·2, 6·8, 5·3 and 1·1 million ha in 2005, respectively (FAOSTAT 2006). Finland, which is in the northernmost region supporting large-scale crop production (from 60 to 65°N), was globally the 16th most important producer in 2005, based on area sown to rapeseed and, the 10th most important rapeseed producer in temperate regions above 45°N (FAOSTAT 2006).

In Finland, mean yields are generally lower than in other temperate regions (Fig. 1). This is mostly explained by the extreme northern location and the resulting short and intense growing season, but also by markedly higher production risks and large annual variation in yields (Mukula & Rantanen 1987). A short growing season makes it possible to grow

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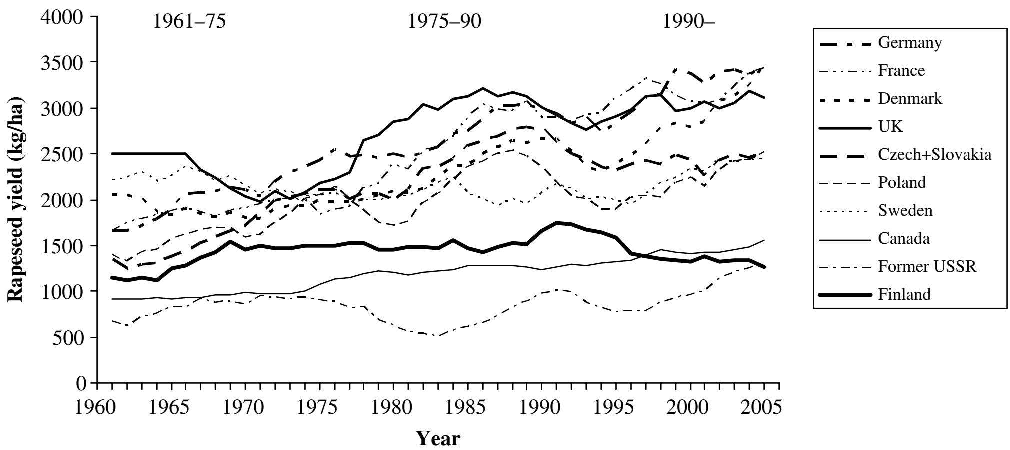

Fig. 1. National rapeseed yield trends shown as 5-year moving averages in the ten most important rapeseed producers in the temperate regions of the Northern Hemisphere (cultivation above 45°N). Source: FAOSTAT 2006 data.

only early maturing turnip rape as the main rapeseed crop and, due to excessively harsh winter conditions, only spring types. Currently, canola rape accounts for only about 0·01–0·07 of total rapeseed production in Finland. The substantial contribution of turnip rape to national vegetable oil production is exceptional in global production.

During the last 40 years, Finland has not been able to keep up with yield improvements achieved elsewhere in temperate regions: during the last 10 years, there has been a drop in rank from eighth to ninth comparing seed yield produced per hectare (Fig. 1). This is partly explained by Finland's dependence on spring turnip rape, while elsewhere canola rape, and especially its winter type, dominate rapeseed production and markets.

Not keeping up with the international yield improvement trends is not, however, the most critical and topical challenge for Finnish rapeseed production. It is obvious that making continuous progress in turnip rape yield potential is demanding – and not least as Finland is rather alone in taking care of this breeding task. However, Finnish rapeseed production represents another major reason for concern: in contrast to other rapeseed yield trends in temperate regions, the trend in Finland has been one of gradual decline – by several hundred kg/ha within the last 15 years – and without any signs of recovery (Fig. 1). Regarding other producers in temperate regions, Denmark, Germany and France are examples of countries with high rapeseed yields that have increased during the last 15 years, as demonstrated recently by Berry & Spink (2006). Some signs of recent levelling off in yield are recognized for the UK (Berry & Spink 2006), Sweden and the Czech Republic. When evaluating data gathered over 45 years, it is noticeable that other countries have also experienced some periods of yield reduction, but none has been as long lasting as that now occurring in Finland.

Comparison of rapeseed yields through relating national mean yields to averages calculated for all the ten temperate main producers reinforced the findings indicated in Fig. 1. Finnish rapeseed yield previously ranged from 0·68 to 0·83 of the temperate region mean yield, depending on decade, although in 2005 it was 0·50. A similar tendency for departure from the general yield was also obvious for Sweden, whereas, e.g., Denmark, Germany and France had both high rapeseed yields and high rates of improvement when compared with other producers.

As only spring turnip rape is grown in Finland – playing a significant role in diversifying the northern crop production – it is important to identify the reasons behind reductions in yields. Only this makes it possible for farmers to take corrective action without additional strain on producers' economy and on the environment through inappropriate production methods. Hence, the present study represents the first step in establishing the reasons for decreasing rapeseed yields in Finland.

MATERIAL AND METHODS

Yield trends

Two sources of yield data (shown as 5-year moving averages) were used: one originating from FAO (FAOSTAT 2006 data, 1961–2005) and the other from long-term datasets of MTT Agrifood Research Finland (1976–2005). In general, crop management practices were comparable with the recommended practices also used in Finnish farms. The set of experimental sites (Jokioinen, Mietoinen, Ylistaro, Anjalankoski, Tuusula, Kokemäki, Laukaa, Pälkäne,

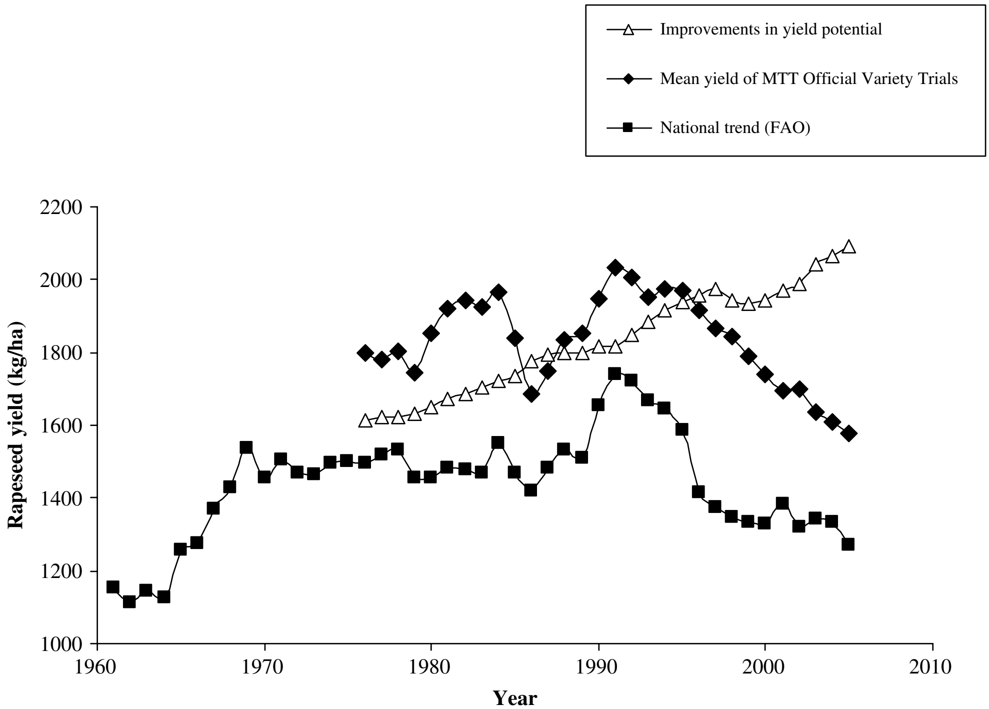

Fig. 2. Trends for annual mean yield of rapeseed according to FAOSTAT 2006 data and multi-location MTT Official Variety Trial data. Genetic yield improvements of new cultivars based on their yielding capacity compared with their predecessors. The improved yield potential is shown in the first year of introduction of a new entry into MTT Official Variety Trials. All the means are shown as 5-year moving averages.

Sipoo, Perniö, Mikkeli, Hauho, Tohmajärvi, Inkoo, Pernaja, Ruukki, Maaninka, Vihti and Jomala) and cultivars varied from year to year in the MTT multi-location Official Variety Trials. A typical trial had 12 varieties (interquartile range = 8–16 varieties) and the proportion of new varieties each year was 0·27, which ensures that differences between new and old varieties can be estimated. These trials were carried out according to management guidelines (Järvi *et al.* 1998). The data plotted in Fig. 2 take this into account by using the statistical model given as Eqn (1). This model separates the effects of new cultivars and environments, which helps to show genetics and environmental changes more precisely. The trend in Fig. 2 does not include the increased yield potential of new cultivars.

Since 1976, the basic cultivation methods of turnip rape have remained unchanged in the MTT experiments, with only modification in use of phosphorus (P) and potassium (K) fertilizers, which both were reduced when Finland became a member of the European Union. Phosphorus is a critical main nutrient, but soil P values in experimental fields suggested that P availability has been sufficient for yield formation. Preliminary statistical examination did not show any association between P application rate and seed yield in the MTT datasets (data not shown).

Factors contributing to changes in yield trends

Existing available datasets were used to analyse the role of potential contributors to the recorded turnip rape yield reduction. When a variable was demonstrated to be significant, its likely contribution to yield reduction was further analysed.

Climate conditions

MTT Official Variety Trials data and weather data of the Finnish Meteorological Institute for each trial location were used to investigate the effects of climate conditions on yields. The growing season was divided into three main phases: (1) from sowing to the beginning of flowering, (2) flowering and (3) end of flowering to yellow ripening. It was considered important to identify whether critical periods in the growing season occurred and how much the crop's responsiveness differed regarding certain main climatic variables. Therefore, the first and last main phases of the season were further divided into four, shorter, sub-phases: (i) the first 10 days after sowing, (ii) 3 weeks preceding flowering, (iii) 3 weeks following the end of flowering and (iv) 3 weeks preceding yellow ripening. Because flowering and yellow ripening are cultivar-dependent, the phases were defined separately for the five most common cultivars in the trials during the last decade: Hohto (released in 2002), Kulta (1991), Riikka (2002), Tuli (2000) and Valo (1996). The climatic variables studied were: lowest temperature, average temperature, average daily rainfall, average daily rainfall excluding the day with the highest rainfall (likely thunder and rain), standard deviation of daily temperatures and standard deviation of daily rainfall. The length of the phase was also measured if it was not fixed. The climate characteristics were available for 63 trials out of a total of 116.

The data from the five most common cultivars, seven main and sub-phases, six climatic variables and the length of phases and sub-phases were analysed separately using regression analysis; the yield was explained by a climatic characteristic in over 200 analyses. Scatter plots of yield and each climatic characteristic were used to check the results. The most explanatory climatic characteristics were chosen for extended analysis, in which all the characteristics were analysed together using regression analysis with backward elimination. The regression analyses were performed using PROC REG (SAS 1999).

Yield potential of newly introduced cultivars

Analysis of the yield potential of new cultivars was based on data from MTT Official Variety Trials (1976–2005). Cultivars and breeding lines for which there were fewer than five observations were removed. Thus, the data used comprised the results from 291 field trials, in which a total of 270 cultivars had been tested. The data were analysed statistically using the following mixed model:

$$y_{ijkl} = \mu + \text{cultivar}_i + \text{site}_j + \text{year}_k + \text{trial}_l + \varepsilon_{ijkl} \qquad (1)$$

where μ is intercept, cultivar_i is the fixed effect of ith cultivar ($i = 1, \ldots, 270$), site_j is the random effect of the jth experimental site ($j = 1, \ldots, 19$), year_k is the random effect of the calendar year ($k = 1976, \ldots, 2005$), trial_l is the random effect of a single trial ($l = 1, \ldots, 291$) and ε_{ijkl} is the residual error. The assumptions for the random effects were: $\text{site}_j \sim \text{iid } N(0, \sigma^2_{\text{site}})$, $\text{year}_k \sim \text{iid } N(0, \sigma^2_{\text{year}})$, $\text{trial}_l \sim \text{iid } N(0, \sigma^2_{\text{trial}})$, $\varepsilon_{ijk} \sim \text{iid } N(0, \sigma^2)$, and all the effects are mutually independent. Cultivars were grouped according to the year of their introduction into the testing programme of MTT. The mean yields of the cultivars in the same group were calculated for Fig. 2, in which they are shown as 5-year moving averages. The parameters of the model were estimated using the restricted maximum likelihood (REML) method with PROC MIXED (SAS 1999).

The number of cultivars released during the same year was highest during 1977–87, being 10–23 new cultivars per year. Subsequently, the annual number of new cultivars ranged from 1 to 14. Hence, the lower number of rapeseed candidate cultivars during later experiments may have biased the results by emphasizing the breeding achievements of a small number of successful cultivars.

Yield stability of newly introduced cultivars

The data from 116 MTT Official Variety Trials carried out during 1990–2005 were used to analyse the stability of cultivars. Twelve cultivars were selected for analysis: four potential cultivars accepted to the national list of cultivars for Finland during 2001–06 (Apollo, Pouta, Riikka and SW Petita), and the eight most important cultivars grown in Finland during 1990–2005 (Harmoni, Hohto, Kelta, Kova, Kulta, SW Rebus, Tuli and Valo). Each trial contained only two to eight cultivars and therefore a mixed linear model with factorial error structure (Piepho 1997; Öfversten *et al.* 2002) was used to examine the stability instead of the widely used Finlay & Wilkinson (1963) method. Stability parameters estimated by the previous method are later termed as common stability parameters.

Yield stability related to a climatic characteristic was analysed using the following regression model based on Finlay & Wilkinson (1963):

$$y_{ij} = \mu_i + \beta_i x_j + \varepsilon_{ij} \qquad (2)$$

where μ_i and β_i are the intercept and slope for ith variety ($i = 1, \ldots, 12$), x_j is a value for the studied climate characteristic at jth trial ($j = 1, \ldots, 63$), and ε_{ij} are normally distributed and mutually independent error terms. Climate conditions were available from 63 trials. The parameters of both stability models were estimated using the REML method of PROC MIXED (SAS 1999).

The relationship between yield stability and climatic characteristics was obtained by calculating theoretical yield using the following function: yield $(k, i) = \hat{\mu}_i + \hat{\beta}_i x_k$, where $\hat{\mu}_i$ and $\hat{\beta}_i$ are intercept and slope parameters estimates of the yield stability model for the ith cultivar and x_k ($k = 1976, \ldots, 2005$) is the mean of the climatic characteristic at trials conducted in year k.

Annual changes in date of ripening and sowing

Annual date of ripening was analysed using the data from 291 MTT Official Variety Trials carried out during 1976–2005. It was modelled using Eqn (1), where the effect of the calendar year was used as a fixed effect unlike in the analysis of yields. All cultivars were sown on the same day in a trial, hence the annual dates of sowing were analysed using the model for ripening without the effect of cultivars.

Regional changes in cultivation activity

Analyses of the regional changes were based on the Information Centre of the Ministry of Agriculture and Forestry in Finland (TIKE) national production datasets during 1995–2005, which contained 37 214 results (cases). Cultivation area varied widely among cases, from 0·01 to 42·1 ha, and area was used as a weight in statistical analysis, i.e. larger cases had greater influence on the results than smaller cases. Cases were spread over 13 of 15 regions (TE-keskus), but cultivation was continuous and significant only in eight regions (Pohjanmaa, Etelä-Pohjanmaa, Satakunta, Pirkanmaa, Varsinais-Suomi, Häme, Uusimaa and Kaakkois-Suomi). Data from these eight regions were selected for statistical analysis and the statistical model used to analyse grain yields was:

$$y_{ijk} = \mu + R_i + Y_j + RY_{ij} + \varepsilon_{ijk} \quad (3)$$

where μ, R_i, Y_j, RY_{ij} and ε_{ijk} are intercept, effect of *i*th region ($i=1, \ldots, 8$), effect of *j*th year ($j=1995, \ldots, 2005$), region × year interaction and the normally distributed residual error, respectively. The parameters of the model were estimated using PROC MIXED (SAS 1999). Estimated means for different years are later termed 'corrected mean yields according to regional changes'.

Incidence of diseases

Analyses of the prevalence of sclerotinia stem rot (*Sclerotinia sclerotiorum*) were based on national seed testing data of EVIRA, the Finnish Food Safety Authority. Data were collected during 1999–2006 and included 16 cultivars and 632 records (samples) in total. Weight of the sample and the number of the infected seeds in each sample were recorded. Typical weights of the sample were 70–75 g and the weight of the heaviest sample was 140 g. The number of infected seeds was proportional to the weight of 70 g and the square root of this ratio was analysed using the following analysis of variance model:

$$y_{ijk} = \mu + \text{cultivar}_i + \text{year}_j + \varepsilon_{ijk} \quad (4)$$

where μ, cultivar_i, year_j and ε_{ijk} are intercept, effect of *i*th cultivar ($i=1, \ldots, 16$), effect of *j*th year ($j=1999, \ldots, 2006$) and the normally distributed residual error, respectively. The parameters of the model were estimated using the REML method of PROC MIXED (SAS 1999).

The risk of disease was defined as high if the number of infected seeds in a sample of 70 g was 1·5 or higher. This led to a binomial response variable (risk is high or low) and therefore the probability was analysed using logistic regression, in which risk was modelled as the effects of cultivars and years. The logistic regression was performed using PROC LOGISTIC (SAS 1999).

RESULTS

Rapeseed yields have declined in Finland, in contrast to other temperate regions of the Northern Hemisphere (Figs 1 and 2). During the last 30 years, plant breeding had, however, successfully increased yield potential of turnip rape by some 30% (i.e. 500 kg/ha) in entries adapted to northern conditions. The current realistic national potential for spring turnip rapeseed yield is around 2100 kg/ha (Fig. 2).

When regarding potential reasons for yield decline, it was seen that the most commonly grown turnip rape cultivars differed in their responsiveness to changes in the growing conditions. The common stability parameters were 0·92 for Kova and 1·00 for Kelta; both of these old cultivars were equally able to grow and yield in low and high productivity environments. Kulta (the dominant turnip rate cultivar during the 1990s) had a common stability parameter of 0·96. However, the major cultivars grown during the first decade of 2000 differed in their stability parameters, Hohto having 1·02, Valo 0·98, Tuli 0·95 and Harmoni 0·88. Furthermore, potential future cultivars showed an increasing tendency towards instability (e.g. 1·17 and 1·18).

Four climatic variables were found to be related to yields (Table 1): rainfall during a 10-day period after sowing (+1 mm/day corresponds to +8 kg/ha, $P<0·10$), average temperature during 3 weeks prior to flowering (+1 °C corresponds to +27 kg/ha, $P<0·10$), average temperature during flowering (+1 °C corresponds to –55 kg/ha, $P<0·01$) and average temperature at seed filling (+1 °C corresponds to −47 kg/ha, $P<0·001$). When all four characteristics were analysed together using backward elimination, only the temperature during seed filling remained in the model. In addition to this, cultivars differed in their sensitivity to temperature, especially from the end of flowering to ripeness (Table 1). Comparing cultivar sensitivity, it was found that an increase in mean temperature of 1 °C at seed fill did not affect seed yield of the old turnip rape cultivars Kova and Kelta, but others responded negatively to each 1 °C increment: Tuli by 27 kg/ha, Kulta by 36 kg/ha, Harmoni by 53 kg/ha, Valo by 79 kg/ha and Hohto by 87 kg/ha. Some of the new cultivar candidates lost even more yield (116 kg/ha for SW Rebus, 88 kg/ha for Petita and 65 kg/ha for Pouta) following unfavourably high temperatures at grain fill. In contrast, modern canola cultivars responded positively to increased temperatures at grain fill, with an average yield increase of 10 kg/ha per degree temperature increase.

Table 1. *Response of seed yield (kg/ha) in the most common rapeseed cultivars to accumulation of precipitation at 10 days after sowing and to temperature 3 weeks prior to flowering, at flowering and at seed filling. The standard errors (S.E.) for regression coefficients indicating the change in seed yield are shown for each period and cultivar. Data from MTT Official Variety Tests*

	Increase in precipitation by 1 mm			Increase in mean temperature by 1 °C								
	At 10 days after sowing*			Three weeks prior to flowering†			At flowering period			At seed filling period		
Cultivar	Change (kg/ha)	S.E.	*P*	Change (kg/ha)	S.E.	*P*	Change (kg/ha)	S.E.	*P*	Change (kg/ha)	S.E.	*P*
Hohto	3	7·4	0·73	−10	72·2	0·89	−72	77·6	0·29	−87	50·9	0·05
Kulta	7	4·4	0·11	46	44·7	0·30	−29	50·2	0·57	−36	35·1	0·30
Riikka	10	7·5	0·17	39	97·1	0·69	−47	62·1	0·49	−4	47·6	0·93
Tuli	14	7·8	0·07	17	82·9	0·84	−54	65·2	0·39	−27	48·2	0·57
Valo	8	4·8	0·09	45	44·2	0·31	−72	51·3	0·14	−79	31·1	0·01

* Average sowing time varied from 6 to 23 May depending on trial site.
† On an average, flowering started on 14 to 30 June and ended on 6 July to 3 August depending on trial site.

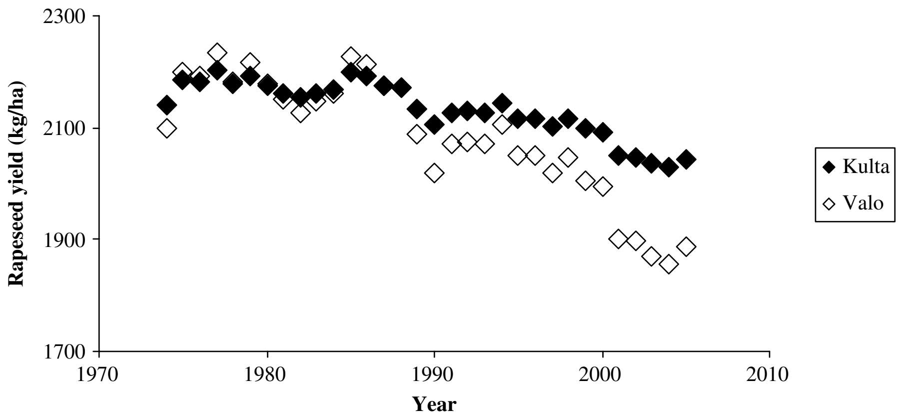

Fig. 3. Simulated seed yields over recent decades according to experienced climate for rapeseed cultivars Kulta and Valo, differing in their responsiveness to high mean temperatures during seed fill period.

Use of modern, more temperature-sensitive turnip rape cultivars explained two thirds of the collapse in yield (Fig. 2), as confirmed when simulating seed yields during growing seasons since 1976 for cultivars Kulta and Valo (Fig. 3). Such a sensitivity has been expressed because temperature conditions have been above long-term average during the last 10 years (Fig. 4). Results from MTT trials also indicated that during the last 20 years, rapeseed has ripened increasingly earlier (by 10 days), when cultivar and location effects were both excluded (Fig. 5).

Other potential reasons for yield decline were also studied. As rapeseed cultivation has expanded in Finland to areas not previously sown to *Brassica* crops, the effects of expanded cultivation both in total area and as a transition towards more northern growing conditions were studied. However, the national yield survey data (>37 000 cases during 1995–2005) indicated that this did not explain the yield collapse (Table 2).

No comprehensive, long-term data were available to allow analysis of risks related to pathogen infections and their contribution to the Finnish yield trend. However, results from the limited data available from EVIRA revealed a very rapid, almost exponential increase in the number of sclerotia particles in seed material tested in the Finnish official seed tests since 1999 (Table 3).

DISCUSSION

Yield trends and genetic gains in yield potential

The reversed rapeseed yield trend in Finland, in comparison with other temperate regions of the

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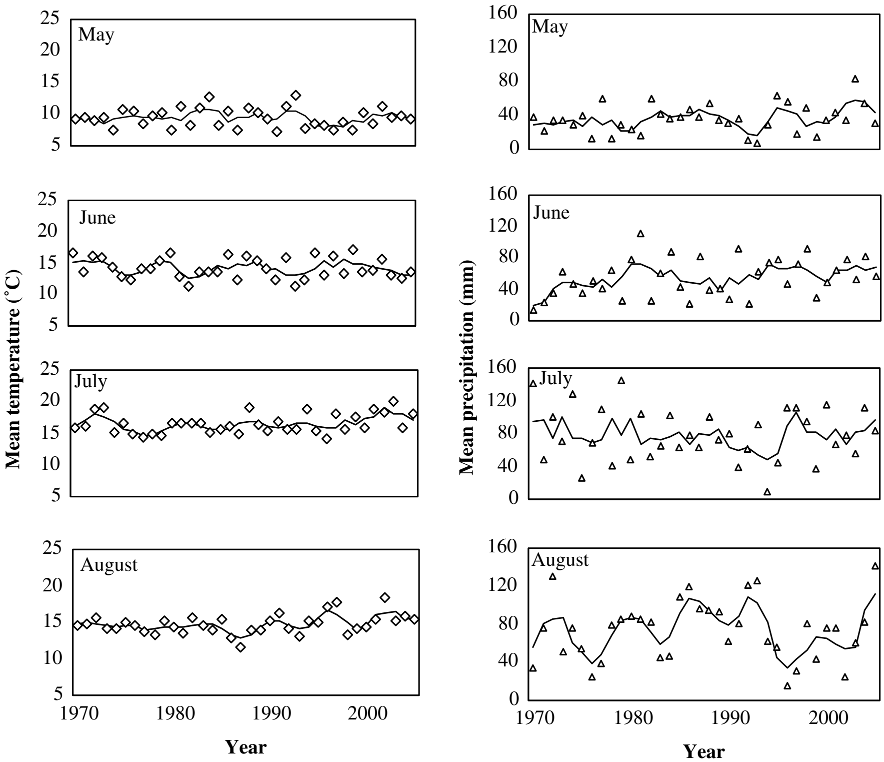

Fig. 4. Annual mean temperature and precipitation for May, June, July and August 1970–2005 for main rapeseed cultivation areas of Finland. Lines indicate 3-year moving averages. Data from the Finnish Meteorological Institute.

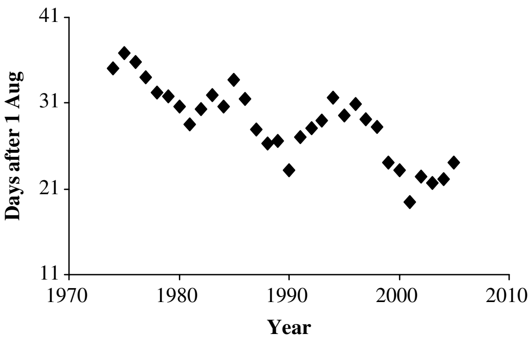

Fig. 5. Annual changes in date of ripening in rapeseed according to MTT Official Variety Trials data for 1970–2005. Means are shown as 5-year moving averages.

Northern Hemisphere (Fig. 1), was apparent in FAO statistics and in long-term, multi-location MTT Official Variety Trials carried out since 1976 (Fig. 2). As is typical for field experiments, the mean yields were somewhat higher (averaging 300 kg/ha more) than those for farmers' fields. The general similarity between Finnish national trends and MTT Official Trial data represented an interesting opportunity to determine national scale solutions to declining yields on the basis of experimental data.

During the study period, plant breeding had successfully increased yield potential of turnip rape in entries adapted to northern conditions. This was despite the fact that at the same time breeders were also successful in further modifying the chemical composition of the seed yield, especially regarding oil content and fatty acid composition. Hence, no sustained shortfalls in genetic yield potential were apparent in Fig. 2. When genetic yield achievements were measured by relating the seed yield of the newly introduced domestic and foreign cultivars to that of their predecessors, potential yield increased by some 30%, corresponding to 500 kg/ha during the last 30 years of ongoing breeding activity in turnip rape (Fig. 2). However, the lower number of rapeseed candidate cultivars during later years may have somewhat overemphasized the breeding achievements of a few successful cultivars.

The current realistic national potential for spring turnip rapeseed yield is likely to be around 2100 kg/ha (Fig. 2). If this had been realized, Finland's yield

Table 2. *National mean turnip rape yields, contribution of changes in cultivation intensity in different regions of Finland to annual mean yields, their ratio, and within year variation in national mean yields according to the national TIKE statistics for 1995–2005. The mean yield to corrected mean yield ratio indicates that regional changes in turnip rape production during the study period did not result in marked and consistent alterations in national mean yields*

Year	National mean yield (kg/ha)	Corrected mean yields according to regional changes (kg/ha)	Ratio of mean yield to corrected mean yield	Within year variation (CV)*
1995	1427	1587	0·90	0·37
1996	1485	1378	1·08	0·32
1997	1522	1526	1·00	0·28
1998	1054	1021	1·03	0·40
1999	1445	1457	0·99	0·34
2000	1433	1376	1·04	0·32
2001	1437	1408	1·02	0·29
2002	1580	1567	1·01	0·28
2003	1289	1223	1·05	0·26
2004	1069	1041	1·03	0·40
2005	1420	1378	1·03	0·27
Mean	1378	1360	1·01	0·32

* S.D.

Table 3. *Incidence of sclerotia of stem rot causing* Sclerotinia sclerotiorum *in turnip rapeseed material tested in EVIRA, the Finnish Food Safety Authority during years 1999–2006. If the odds ratio in risk analysis is higher than for the control, there is also higher risk to have more than 1·5 sclerotia per analysed 70 g seed sample. If the confidence interval (CI) for the odds ratio does not include 1·0, the difference between it and the control group or cultivar is statistically significant*

	Comparison of means			Risk analysis	
Years	*N*	Mean	95% CI	Odds ratio	95% CI
1999	56	0·1	0·0–0·1	0·00	0·00–0·07
2000	49	0·6	0·0–1·8	0·73	0·34–1·57
2001	65	0·8	0·1–2·1	1·12	0·52–2·38
2002	99	0·5	0·0–1·4	0·36	0·19–0·68
2003	86	1·4	0·4–3·0	1·00	Control group
2004	114	2·6	1·2–4·6	1·29	0·72–2·33
2005	105	4·5	2·6–7·1	4·01	1·99–8·09
2006	58	5·7	3·2–9·0	1·82	0·84–3·96
P		<0·001		<0·001	
Cultivars with $N \geqslant 20$					
Harmoni	56	4·3	2·8–6·1	1·50	0·70–3·23
Hohto	85	1·6	0·8–2·7	0·83	0·39–1·81
Pouta	21	2·3	0·8–2·2	0·53	0·18–1·54
SW Petita	23	5·8	3·1–9·4	1·06	0·29–3·85
Tuli	63	1·0	0·4–1·9	0·60	0·29–1·25
Valo	240	1·2	0·8–1·6	0·49	0·27–0·87
Kulta	119	2·8	1·9–3·9	1·00	Control cultivar
P		<0·001		0·24	

trend would have likely been one of steady increase during recent years. Yield potential in rapeseed has evidently not been realized. Comparison of the national seed yield trend with that for genetic gains showed that in the 1980s, 0·90 of the potential yield recorded in experimental rapeseed plots was also realized in farmers' fields, while this fell to only 0·50 during the first 6 years of this millennium. This

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occurred at a time when turnip rape was no longer a novel crop, when its husbandry was established.

Modern cultivars had reduced yield stability and increased temperature sensitivity

Fluctuations in occurrence of pathogens and pests, and intrinsic differences in resistance among cultivars, effects of growing conditions on their incidence and their direct effects on growth and yield formation, are all factors contributing to cultivar responsiveness to growing environment. Crop responses to these factors are ultimately expressed in yield stability. The present results indicated that the most commonly grown turnip rape cultivars differed in their responsiveness to changes in the growing conditions. Kova and Kelta were typical cultivars grown in the late 1980s and the early 1990s. The common stability parameters were 0·92 for Kova and 1·00 for Kelta. This means that they both were equally able to grow and yield in low and high productivity environments. Kulta was the dominant turnip rate cultivar during the 1990s and its common stability parameter was 0·96, indicating that it did well also under a range of conditions. However, major cultivars grown during the first decade of 2000 differed in their responsiveness to growing conditions. Hohto (1·02) and Valo (0·98) were noticeably less able to yield under unfavourable conditions when compared with Kulta, Tuli (0·95) and Harmoni (0·88). Growing seasons in the early part of this century have been exceptionally warm, often associated with lack of sufficient precipitation at critical growth phases (Fig. 4). Hence, it is likely that the collapse in national yields is at least partly attributable to such stressful growing conditions. This was further emphasized through the introduction of increasingly sensitive, less stable cultivars.

When exploring future prospects regarding turnip rape cultivar responsiveness, the present analysis is not encouraging: cultivars already tested in MTT Official Variety Trials showed an increasing tendency towards instability and some had common stability parameters as high as 1·17 and 1·18 (though there is some uncertainty due to the small number of experiments). This indicates that all the released modern cultivars were clearly targeted for cultivation in high productivity environments, while weather conditions during the last few years did not enable realization of the genetic yield potential. All the cultivars released after Kulta are growing particularly well at those MTT trial sites that are generally characterized as favourable, but they are all performing systematically worse, or at most similarly to cultivar Kulta, where average yield does not exceed 1500 kg/ha.

Four climatic variables were found to be related to yields (Table 1) and indicated that the later growth phases were particularly responsive to alterations in growing conditions. When the contribution of climate factors to the recorded reduction in yield stability of modern, high-yielding cultivars was studied further, results indicated that cultivars differed in their sensitivity to temperature, especially from the end of flowering to ripeness (Table 1). The poor performance of modern cultivars under the prevalent growing conditions is attributable to increased cultivar sensitivity to high temperatures at seed filling. Temperature sensitivity in other *Brassica* crops, including canola rape, was demonstrated earlier by Aksouh *et al*. (2001), Morrison & Stewart (2002) and Si & Walton (2004). In earlier studies, yield losses were dependent on timing and stressfulness of high temperature periods during the reproductive phase and they resulted from reduction in flower number, pod number, seed number and/or seed weight (Aksouh *et al*. 2001; Morrison & Stewart 2002; Gan *et al*. 2004). The later the occurrence of high temperatures, the more drastic were the yield losses (Gan *et al*. 2004). The present results indicate temperature sensitivity also in turnip rape (Table 1), but incidence of such stressful temperatures here in the most northern oilseed rape production area was surprising.

It was found that an increase in mean temperatures reduced seed yield of some of the newer cultivars greatly. Similarly in canola, differences in cultivar responses to high temperatures were recorded (Aksouh *et al*. 2001). However, when the present authors carried out similar analyses with canola rape cultivars, the opposite was found and modern canola cultivars responded positively to increased temperatures at grain fill, with an average yield increase of 10 kg/ha per degree temperature increase. Canola was also shown to suffer from temperature stress (Morrison & Stewart 2002), but not in the present studies where critical temperatures appeared higher for canola than for turnip rape.

During the last 20 years, rapeseed has ripened increasingly earlier, resulting in a total of 10 days earlier ripening according to MTT data, when cultivar and location effects were both excluded (Fig. 5). This was not due to earlier sowing. Mean temperatures during seed fill have been clearly higher in recent years than during the early years of the current data. Such conditions explain the poor performance of the increasingly sensitive modern cultivars. For example, when comparing the contribution of cultivar sensitivity to realization of yield potential under stressful seed fill conditions, Valo underwent yield losses of *c*. 300 kg/ha according to MTT data, while for the more stable cultivar Kulta, yield losses were 100–150 kg/ha (Fig. 5). For the most sensitive future candidate cultivar, SW Rebus, yield losses of *c*. 430 kg/ha were estimated under comparable conditions. It appears that the high yield potential of the most modern cultivars is unlikely to be realized under conditions unfavourable to seed fill. The present results underline the importance of not only assessing responsiveness of future candidate cultivars to different growing conditions, but also the need to be careful not to sow rapeseed too early in the spring with the risk of exposing it to higher temperatures at seed set and fill. In contrast to Finnish conditions, e.g. in Mediterranean climates, the later the growing season, the more temperatures and severity of drought increase; therefore, adaptation mechanisms to avoid stresses at late growth phases (Thurling & Kaveeta 1992*a*, *b*) differ from those applicable for northern temperate growing conditions.

In assessing the significance of increased temperature sensitivity in modern cultivars and the national yield trend, cultivar responsiveness data were linked to the extent of cultivation. This revealed that use of modern, more temperature-sensitive turnip rape cultivars, together with the high temperature conditions of the last 10 years, explained two thirds of the reduction in yield (Fig. 2). This was also clearly demonstrated by simulating seed yields during growing seasons since 1976 for cultivars Kulta and Valo on the basis of their estimated temperature sensitivity (Fig. 3).

The existing datasets did not enable further study of the recorded increased temperature sensitivity of modern turnip rape cultivars. It is possible that other interacting stresses are involved in the sensitivity. Possibly breeding-induced changes in seed composition, towards increased energy value (both higher oil and protein content), together with high yield potential, resulted in extreme demands for energy metabolism and failures when high temperatures occurred during seed fill. According to MTT long-term experiments, the average oil content of turnip rape cultivars has increased by 1·9% since 1976. One hypothesis is that this, in conjunction with lack of constant selection pressure for high temperatures during the reproductive phase (especially seed filling), resulted in problems in yield stability of the modern turnip rape cultivars. Furthermore, drought may have interfered with temperature sensitivity (Mogensen *et al*. 1997), but the present work was not successful in demonstrating it – possibly as water shortage often progresses gradually with some recovery periods until plant stands are at the seed fill phase. The detrimental effects of drought on canola flowering, seed set and/or seed yield have also been demonstrated by, e.g., Wright *et al*. (1995) and Si & Walton (2004). Drought and high temperature effects are also seen at the global scale, with rapeseed yields in temperate regions, above 45°N, generally being higher than those in Mediterranean or tropical climates (FAOSTAT 2006 data). Moreover, diseases may also interfere with and contribute to the national yield trend (FAOSTAT 2006 data), though this is least likely to be true regarding MTT yield trend, as in MTT trials increase in disease incidence would have been recorded and quantified.

Signs of more severe sclerotinia stem rot infections

Turnip rape can be infected by many diseases and significant yield losses can occur even under the northernmost growing conditions. *Plasmodiophora brassicae*, causing clubroot disease, *S. sclerotiorum*, causing sclerotinia stem rot, and *Peronospora parasitica*, causing downy mildew, are among the more usual diseases associated with yield losses and reduced stability in turnip rape. Crop rotation of *Brassica* crops is not now sufficient, being sown to the same field about every third year instead of the recommended 5 years, and fungicides are not commonly used. Diseases are consequently a potentially important contributor to yield collapse, especially as rapeseed area has tended to increase. However, rapeseed cultivation has expanded to areas not previously sown to *Brassica* crops. When studying the effects of expanded cultivation both in total area and as a transition towards more northern growing conditions, the national yield survey data, with over 37 000 cases during 1995–2005, indicated that this did not explain the yield collapse (Table 2).

No comprehensive, long-term data were available to allow analysis of risks related to pathogen infections and their contribution to the Finnish yield trend. However, results from the limited data available from EVIRA revealed a very rapid, almost exponential increase in the number of sclerotia particles in seed material tested in the Finnish official seed tests since 1999 (Table 3). It is, however, probable that *S. sclerotiorum* infections have not increased accordingly in Finnish turnip rape fields, but the results somewhat overestimate the prevalence of the disease, as sclerotias might have been easily broken during seed cleaning and sorting processes that are typical for seed preparation. Furthermore, they might have appeared more frequently in seed harvested during warm and dry conditions typical during the last years. Such an exponential increase in sclerotia particles in turnip rapeseed underlines the need for estimating turnip rape disease prevalence in Finland through a national survey. This would also serve to quantify the potential contribution to national yield reduction, of which one third remained unexplained after this study. The last Finnish survey on diseases of turnip rape was from 1984 to 1987 (Hannukkala 1988) and not comprehensive. No up-to-date information on *Brassica* crops is available from the Nordic countries (see e.g. Wallenhammar 1996; Twengström *et al*. 1998). On the other hand, in MTT trials, as in practical cultivation, insect pests are commonly controlled with insecticides and hence they are not likely to contribute to increased yield losses, unlike for diseases. Resistance to the major diseases has not played an important role in recent Finnish rapeseed breeding programmes. Plant breeders, however, make careful observations while selecting the breeding lines and it is unlikely that tolerance to major diseases, sclerotinia stem rot and club root had decreased in new cultivars. In MTT official variety testing, incidence of diseases is not systemically scored, but all abnormalities in crop are recorded and hence exceptionally susceptible cultivars would have been pointed out. However, incidence of diseases which are more difficult to detect, such as downy mildew, might have been underestimated.

It is essential that rapeseed yields in Finland stop declining. Levelling off is, however, also unacceptable as in this case genetic gains in yield potential remain clearly unrealized. Hence, the national rapeseed yield trend needs to be increased; otherwise prominent improvements will not be achieved both regarding sustainability and competitive ability of rapeseed production for food–feed chain and, in future, for biodiesel production. Achieving improvements in yield requires identification of the most important diseases through a national survey as well as breeding for improved yield stability by decreasing temperature sensitivity while improving resistance against detected, most important diseases.

The main conclusions from the present work were that the dominating *Brassica* crop in Finland, summer turnip rape, was demonstrated to be temperature-sensitive during the reproductive phase, especially seed fill. Such an increased sensitivity was emphasized in modern, high-yielding and high quality cultivars and explained about two thirds of the national seed yield collapse in Finland during the last 15 years. Another potential contributor might be increased infections caused by pathogens, as sclerotia particles of *Sclerotinia* stem rot have become a more common problem in Finnish seed material during recent years. The potential role and contribution of diseases need to be investigated through a national survey. As canola rape cultivars did not respond negatively to temperatures that were stressful to turnip rape, canola could substitute for turnip rape to some extent in the most advantageous growing areas of Finland.

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