Yield of spring barley mixtures as a function of varietal and environmental characteristics

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Introduction

To design good variety mixtures it is important to understand the influence of varietal and environmental characteristics on mixing effect, e.g. what characteristics are more beneficial when all mixed varieties express it highly and what characteristics are more beneficial when the mixed varieties express it to varying extent. However, as it is generally impossible to manage more than a few experimental combinations in each field trial, information on general relationships and factors of importance for the successful design of variety mixtures may be overlooked. Using meta-regression (e.g. Houwelingen *et al.* 2002), numerous results of such trials can be combined, and the influence of varietal and environmental factors on mixing effect can be elucidated.

Here, two specific hypotheses were investigated:

1. Variation in straw length among component varieties will increase mixing effect due to enhanced potential for resource utilization
2. Mixing effect will increase with more stressful environments due to increased importance of mechanisms like complementarity and compensation

Methodology

Data

We used results from 15 designed field trials of spring barley, including six three-component variety mixtures and their mainly high-yielding component varieties (part of the Danish BAR-OF trials; Østergård *et al.* 2005). Each field trial constituted an environment combined from 4 localities, 4 years and 3 management systems: conventional (incl. industrial fertilizer), organic (incl. animal manure), and ‘low-input’ organic (clover grass undersown, no manure). Fungicides were not used in any of the management types. Grain yield (hkg/ha) was assessed for all mixtures and component varieties and used as the response variable in the estimation of the effects of mixing.

Statistical analyses

Relative and absolute estimates of mixing effect on grain yield were calculated for each mixture in each environment (Table 1). As grain yields are higher in more productive environments, so are the absolute differences between varieties. The normalization of the relative measure, on the other hand, is expected to remove such scale-dependence. To illustrate this, each of the two measures was plotted against the average yield of the mixtures’ component varieties in each environment.

Table 1. Formulas for estimating absolute and relative measures of mixing effect size, as well as their variance. Here, y is the effect size estimate, x_m and $\overline{x}_c$ are LSMeans of yield measurements for a specific mixture and the average of its component varieties in a given environment, respectively, and σ^2 is the variance of LSMeans.

	Estimate	Estimate variance
Absolute measure of mixing effect	$y = x_m - \overline{x}_c$	$\sigma_y^2 = \frac{4}{3}\sigma^2$
Relative measure of mixing effect	$y = \frac{x_m - \overline{x}_c}{\overline{x}_c}$	$\sigma_y^2 = \frac{\sigma^2}{\overline{x}_c^2}\left[1 + \frac{1}{3}\left(\frac{x_m}{\overline{x}_c}\right)^2\right]$

Estimates of mixing effect were weighted according to their precision (inverse variance) and used in a number of random-effect meta-analysis models. A meta-analysis of the overall mixing effect was conducted using the model:

$$Yi = \beta_0 + U_i + e_i, \quad i = 1,\ldots, 90, \qquad (model\ 1)$$

where Y_i denotes the weighted mixing effect estimate from the specific mixture-environment combination i, β_0 the model intercept, and e_i internal experimental error with known variance. U_i captures the (normal distributed) random effects between mixture-environment combinations.

To estimate the average mixing effect of the six mixtures, the following meta-analysis model was used:

$$Yi = \beta_0 + \beta_1 Z_{1i} + \ldots + \beta_5 Z_{5i} + U_i + e_i, \quad i = 1,\ldots, 90, \qquad (model\ 2)$$

where $Z_{1i}, \ldots, Z_{5i}$ are binary (0/1) dummy variables for each of the mixtures 2 to 6, $\beta_1,\ldots, \beta_5$ are the regression estimates corresponding to factor levels, and the remaining items are defined as in model (1).

Two characteristics were then introduced as covariates in meta-analysis model (1): a varietal characteristic (variation in average straw length among component varieties) as well as an environmental characteristic (environmental yield potential, measured as 95%-quantiles of all yield measurements in the environment). Two simple and a joint regression model were used:

$$Yi = \beta_0 + \beta_1 X_{1i} + U_i + e_i, \quad i = 1,\ldots, 90, \qquad (model\ 3)$$

$$Yi = \beta_0 + \beta_2 X_{2i} + U_i + e_i, \quad i = 1,\ldots, 90, \qquad (model\ 4)$$

$$Yi = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + U_i + e_i, \quad i = 1,\ldots, 90, \qquad (model\ 5)$$

where X_{1i} denotes the value of the straw length variation for result i, X_{2i} denotes the value of the yield potential for result i, β_1 and β_2 are the according regression parameters, and the remaining items are defined as in model (1).

Goodness-of-fit of each model was examined using a chi-square test statistic, Q (Hedges and Olkin 1985), which is a measure of the variation not explained by the model (residual heterogeneity).

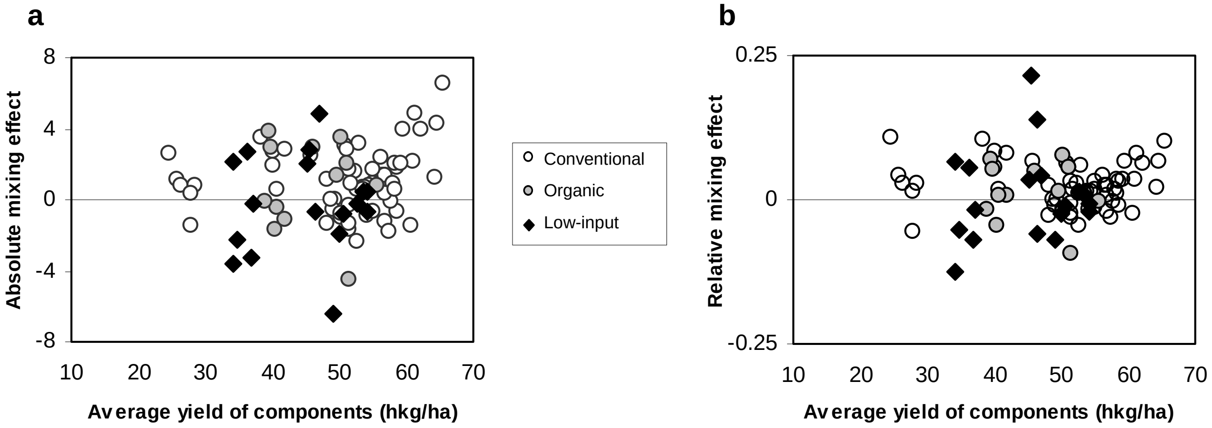

Figure 1. Absolute (a) and relative (b) estimates of mixing effect as a function of yield potential of the growing environments. Each management system is marked with distinct symbols.

Results

The relative measure of mixing effect is relatively stable across yield potentials, as indicated in Figure 1. The meta-analyses below were based on relative mixing effects.

One particular environment had extraordinarily little experimental variation, and the accordingly massive weighting of that environment in the meta-analyses had significant impact on the results. For example, the order of the class estimates for single mixtures (*model* 2) changed markedly due to its presence. Hence, that environment was excluded from the data set.

The meta-analysis without any covariates (*model* 1) showed a significant overall mixing effect of 1.1% on grain yield (Fig. 2; $p = 0.0023$). This meta-analysis model was able to explain all variation among mixture-environment combinations, i.e. there was no residual heterogeneity ($p = 0.9874$).

The meta-regression based on individual mixtures (*model* 2) revealed, nonetheless, that the effect (regression estimates) varied among mixtures, providing results in accordance with previous findings (Østergård *et al.* 2005; Kiær *et al.* 2006). For example, the mixture with grey squares in Figure 2 shows primarily positive effects, whereas the mixture with the empty circles shows equally many positive and negative effects.

The regression on mixing effect of neither variation in straw length (*model* 3; Fig. 3a; $\beta = 0.0000$; $p = 0.95$) nor environmental yield potential (*model* 4; Fig. 3b; $\beta = 0.0005$; $p = 0.53$) could be distinguished. The meta-regression using both of these (*model* 5) also did not demonstrate any significant slopes ($p = 0.83$). Similar to the model without covariates (*model* 1) these models (2-5) left no unexplained variation (not shown).

Discussion

Meta-analyses with and without covariates were applied to test hypotheses and elucidate factors of importance for mixing success.

The simple meta-analysis showed significant overall increase in yield due to mixing of varieties in spite of slightly opposing results between individual trials. However, the meta-regressions were unable to support the two hypotheses: the mixing effect was not affected by component variation in straw length, and the mixing effect was slightly increasing with environmental yield potential, which was actually arguing against the hypothesis. Further

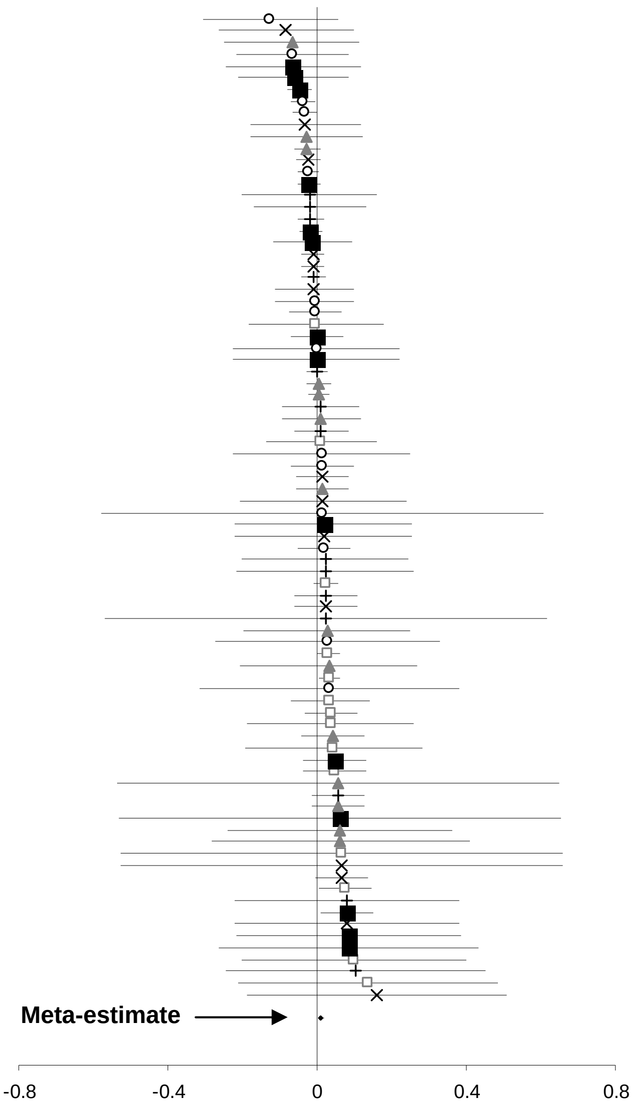

Figure 2. Plot of all estimates of mixing effect and their 95% CLs. The estimates are ordered by increasing effect size. Each of the six mixtures are plotted with a distinct symbol. The overall meta-estimate is shown at the bottom of the plot.

analyses must be done to investigate whether these trends can be found in other data sets and whether further covariates may assist interpretation.

The results also show that experimental trials with extraordinarily small experimental variation may influence the conclusions of the analysis. The excluded trial was performed at an experimental farm which is known to provide rather homogenous growing conditions. This information is not readily included in the current use of weighting. In the work to come, we will assess the appropriateness of the current application of inverse variance as weights in meta-analysis of field trial data.

Other critical issues that need further investigation include the possible lack of independence between estimates due to shared environments and common component varieties of mixtures.

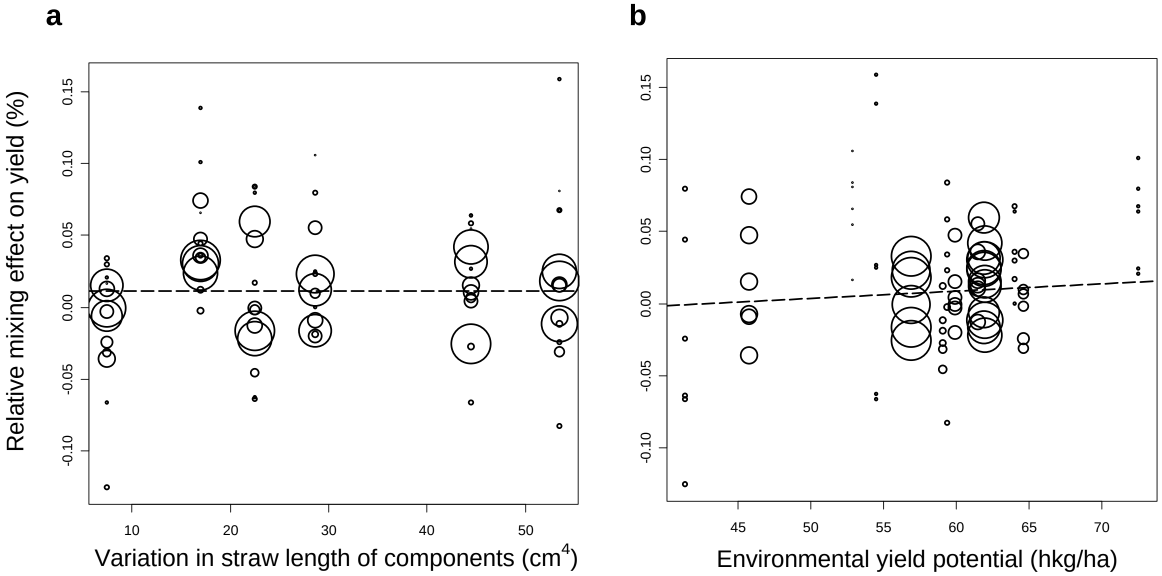

Figure 3.
Meta-regression of mixing effects against variation in straw length of the mixture's components (each averaged across environments) (a) and environmental yield potential (b).Circle diameters are proportional to the weights of the data points in the meta-regression model.

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