AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2025) 34: 1–11

https://doi.org/10.23986/afsci.153239

Comparison of spring barley (*Hordeum vulgare* L.) varieties grown in organic farming conditions: lodging and plant height

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Lodging is one of the main factors influencing yield reduction in both organic and conventional systems. In the organic system, lodging is mainly controlled by selecting varieties with increased resistance to lodging, by regulating sowing density, or by cultivation of varieties of appropriate height. The present study aimed to compare ten varieties tested in the years 2020–2022 in organic trials in terms of plant height and resistance to lodging in two growth phases (milk and harvest). Depending on the analyzed trait, a linear or cumulative link linear mixed model was fitted on plot data. The analyses showed that variety Farmer was the most resistant to lodging in the two growth phases, whereas varieties KWS Vermont and Rubaszek were less resistant to lodging in two growth phases than Farmer, but only at the milk phase, the differences were significant. Furthermore, Radek was the tallest among the tested varieties, whereas Farmer was classified as mid-tall. According to Wricke's ecovalence coefficient, Bente was the most stable, while Farmer ranked third. Therefore, varieties that are the most resistant to lodging and are the most stable in terms of height, should be promoted for cultivation.

Key words: plant height, lodging, organic trials, mixed models, stability

Introduction

Lodging is one of the main factors influencing yield reduction in both organic and conventional systems (Laidig et al. 2022). Usually, stem lodging occurs more often, although root lodging can also occur in favorable conditions (e.g., light soils). Lodging is mainly caused by weather conditions (especially long-term heavy rains or too strong wind) (see e.g. Jevtic et al. 2017, Wu et al. 2022, and the references therein). However, poor variety selection or pathogenic factors (e.g. stem base diseases) can also be responsible for lodging (see e.g. Jayesena et al. 2007, Jevtic et al. 2017, Wu et al. 2016, 2022). In a different study, Kucek et al. (2021) pointed out that tall varieties may exhibit increased risk of lodging (see also Feledyn-Szewczyk and Jończyk 2015). In conventional system, risk of lodging is mainly controlled by applying plant growth regulators or by reducing the amount of N fertilizer. In the organic system, lodging can only be controlled by selecting varieties of appropriate height or by regulating sowing density. For this reason, it is important to cultivate in organic system varieties of appropriate height and with increased resistance to lodging.

In Poland, plant breeders can register new candidate varieties for organic farming. The new varieties of major crops, including spring barley, are assessed prior to registration in value-for-cultivation-and-use (VCU) field trials, and next in organic post-registration (Porejestrowe Doświadczalnctwo Odmianowe; PDO) trials. The VCU trials are performed by the Research Centre for Cultivar Testing (COBORU), whereas the organic PDO trials are conducted in cooperation with the Institute of Soil Science and Plant Cultivation-State Research Institute (IUNG-PIB) (excluding maize, potato and winter barley). There is currently no registered organic barley variety, therefore, in organic PDO trials, conventional varieties with beneficial characteristics from the perspective of organic farming are evaluated.

The present study aimed to compare ten varieties tested in the years 2020–2022 in organic PDO in terms of plant height and resistance to lodging in two growth phases (milk and harvest). Depending on the analyzed trait, a linear or cumulative link linear mixed model was fitted on plot data. Following Edwards and Jannink (2006) and Przystalski and Lenartowicz (2023), the mixed model for plant height was fitted under the assumption of heterogeneity in error variance. Furthermore, based on the predicted variety environment interaction means, and the predicted environmental means, stability and adaptability of plant height were simultaneously assessed using the harmonic

Received 6 December 2024 / Accepted 12 March 2025

The Scientific Agricultural Society of Finland

relative performance of the genotypic values index (se e.g. Resende 2007, Colombari Filho et al. 2013, Dias et al. 2018, Przystalski and Lenartowicz 2023). Finally, using estimates from cumulative link mixed models, probabilities of given scores were obtained for each variety and lodging at the two growth stages.

Materials and methods

Field experiment

The three data sets consist of recorded plant heights and lodging scores from organic spring barley trials performed in the years 2020–2022. Each trial was laid out in a randomized complete block design with four replicates. The trials were conducted at experimental facilities (sites) belonging to COBORU and IUNG. In the three years of study the trials were performed in eight experimental sites (not necessarily in all years). The names of the sites used in this study and their locations are presented in Figure 1. A detailed description of the experimental sites, including soil types, soil fertility, forecrops and meteorological conditions, can be found in Lenartowicz et al. (2024b).

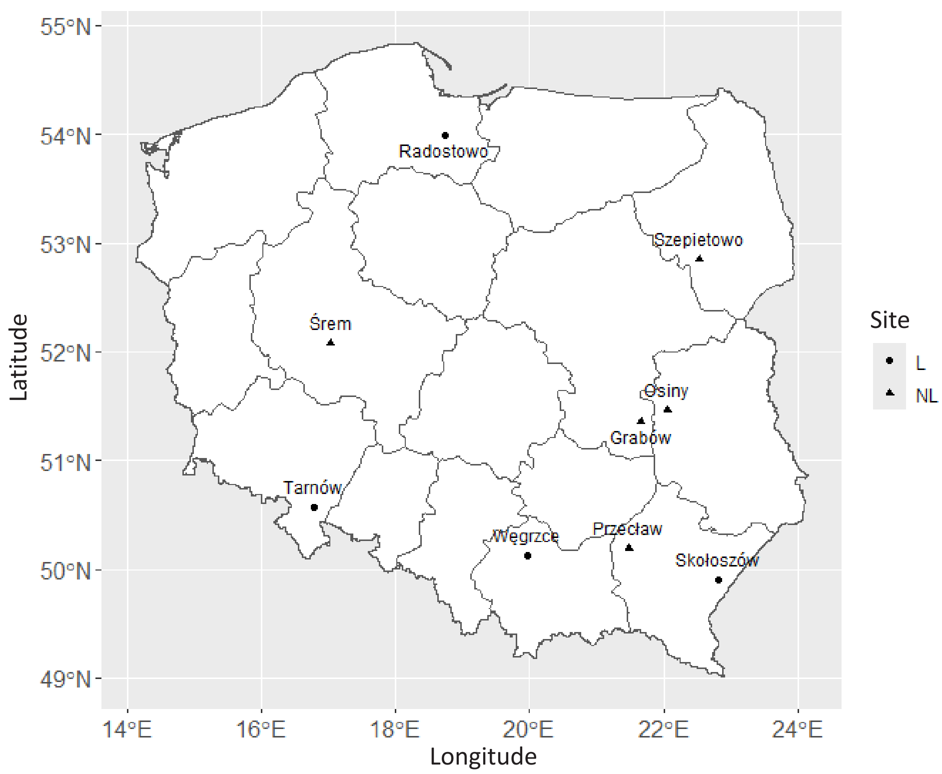

Fig. 1. Map of Poland showing the location of experimental sites used in this study. Sites where lodging was observed during the three-year study and which were included in the analyses are marked with bullets (L=Lodging observed, NL=Lodging not observed).

Usually the stability analysis of agronomic traits is based on the results of field trials conducted over several years (two, three or four) and sites. In the three-year study, a total of 12 varieties were tested. As we were also interested in assessing the stability of plant height, we selected 10 common varieties to be tested over three years. These were the varieties: Avatar, Bente, Etoile, Farmer, KWS Vermont, Mecenas, MHR Fajter, Pilote, Radek, and Rubaszek. The countries of origin and registration years for the above-mentioned varieties are given in Lenartowicz et al. (2024a).

Lodging and plant height were assessed by crop experts at different stages of plant growth, according to the BBCH code (Hack et al. 1992). In the case of lodging, measurements were taken at two growth phases: BBCH75 (medium milk: milk grain content, grain reached its final size) and BBCH89 (fully ripe: grain hard, difficult to divide with thumbnail). In the first case, the assessment was performed when several varieties reach the stage of milk maturity. In the latter case, for organizational reasons, the assessment was performed a few days before the planned harvest date. In both cases, observations were not carried out immediately after the occurrence of the phenomenon causing lodging.

In both cases lodging severity was scored on an ordinal scale from 1 to 9, where 9 means erect, standing plants (Drążkiewicz et al. 2020). A graphic diagram of the lodging assessment is shown in Figure 2.

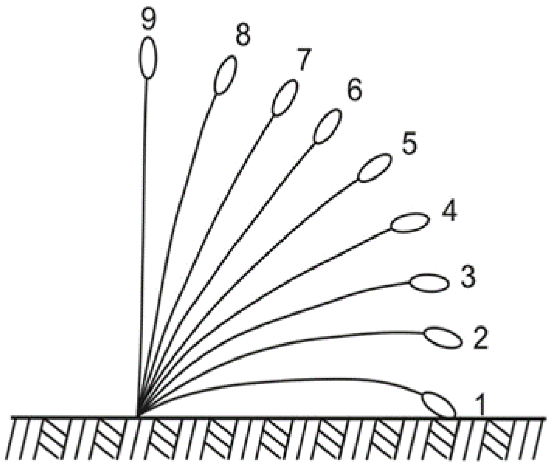

Fig. 2. Graphic diagram of the lodging assessment (Drążkiewicz et al. 2020)

The degree of lodging was estimated considering the entire plot area. Only one measurement per plot was made for each lodging phase and each variety. Lodging has been observed in almost all environments. Since we were interested in a comparison of varieties, environments (combination of year and site; E) with low intensity of lodging in a given phase were removed from further analysis. Sites included in the analyses are marked with bullets in Figure 1 (see also Supplement S1).

In the case of plant height, measurements were taken when most varieties reached the BBCH75 growth phase (medium milk: milk grain content, grain reached its final size). Plant height was measured from the soil surface to the top of the ear (excluding awns). Loose stems and hanging ears should be straightened. The measurement was made using a measuring rod with an accuracy of 1 cm in at least three most representative locations on the plot. A straightened bunch of plants was placed against the rod and the measurement was recorded. In a sample, in which early and abundant lodging occurred (score < 3), no height measurements were taken. In each plot the mean from the most representative places in the plot was taken as the final plant height. Plant height was observed in all environments

Statistical analysis

Lodging

Lodging severity was observed in the ordinal scale. Usually it is assumed that, the observed data follow a multinomial distribution, which is determined by probabilities π_{ijkl}, where π_{ijkl} is the probability that the *j*-th variety (*j* = 1..., *J*) belongs to the *i*-th category (*i* = *m*,..., *I*) and *m* is the lowest category in the series of field trials) in the *k*-th environment (*k* = 1,..., *K*) and in the *l*-th replicate (l = 1,..., *L*) and $\sum_{i=m}^{I} \pi_{ijkl} = 1$. In the present study the ordinal scores were analyzed using a cumulative link mixed model with logit link function (Tutz 2012).

Let γ_{ijkl} denote *i*-th (*i* = m, ..., *I*–1)) cumulative probability corresponding to the *j*-th variety in the *k*-th environment and in the *l*-th replicate ($\gamma_{ijkl} = \pi_{mjkl} + \pi_{m+1,ijkl} + \cdots + \pi_{ijkl}$). Then, the cumulative link mixed model can be written as

$$\eta_{ijkl} = \text{logit}(\gamma_{ijkl}) = \log\left(\frac{\gamma_{ijkl}}{1-\gamma_{ijkl}}\right) = \theta_i - \alpha_j - u_k - w_{jk} - z_{kl}\,, \qquad (1)$$

where θ_i is the fixed threshold (also known as cutpoint) on the latent scale of the *i*-th category, and α_j is the fixed effect of the *j*-th variety (G). Further, u_k ,w_{jk} , and z_{kl} denote in model (1) the random effects of environments (E), of the variety × environment interaction (G×E), and of replicates nested within environments (E×Rep), respectively. It is assumed that: $u_k \sim N(0, \sigma_u^2)$, $w_{jk} \sim N(0, \sigma_w^2)$, $z_{kl} \sim N(0, \sigma_z^2)$.

The maximum likelihood method with the Laplace approximation, under restriction $\alpha_1 = 0$ was used to estimate unknown fixed effects and variance components in (1) (Tutz and Hennevogl 1996, Christensen 2022; numerical implementation the `ordinal' R package, Christensen 2022).

Since only one standard can be used in the above model, we treated Farmer as the standard (reference) variety. In conventional post-registration trials this variety turned out to be the most resistant to lodging. Moreover, it should be noted that due to the method used to estimate unknown parameters in model (1), each variety effect can be treated as a comparison with the reference variety. In the 'ordinal' package, levels of a given factor are ordered in the lexicographical order. Therefore, the variety effect α_1 is assigned to the first variety in the ordered list of varieties. For this reason, varieties were numbered from one to ten: Farmer (1), Avatar (2), Bente (3), Etoile (4), KWS Vermont (5), Mecenas (6), MHR Fajter (7), Pilote (8), Radek (9), and Rubaszek (10) (where one denotes the standard variety). This number was further used in the analyses instead of variety names. In this way we have established the reference variety as the first variety in the list and obtained the proper variety comparisons with the reference. To test the significance of each variety effect (H_0: $\alpha_j = 0$; $j = 2, \ldots, J$), the test statistic

$$z_j = \frac{\hat{\alpha}_j}{\hat{\sigma}_j}, \qquad j = 1, \ldots, J, \tag{2}$$

was used (Christensen 2022), where $\hat{\alpha}_j$ is the estimated effect of the j-th variety and $\hat{\sigma}_j$ is the estimated standard error of $\hat{\alpha}_j$. Under the null hypothesis, the test statistic z_j has an approximate standard normal distribution.

Finally, for each growth phase, the cumulative probabilities and probabilities of receiving a given score for each variety were calculated using the estimates of thresholds (cutpoints) and variety effects (provided that there are no random effects). Thus, we first calculated the cutpoint for the i-th category and the j-th variety as: $\theta_i - \alpha_j$.Next, we calculated the corresponding cumulative probabilities γ_{ij} using the back-transform and the obtained cutpoints. For a given variety, the probabilities of receiving a given were calculated as: $\pi_{mi} = \gamma_{mi}$; $\pi_{Ij} = 1 - \gamma_{I-1,j}$; $\pi_{ij} = \gamma_{ij} - \gamma_{i-1,j}$, for $i = m + 1, \ldots, I - 1$. The results were plotted using the R package `lattice' (Sarkar 2008).

Plant height

Let y_{jkl} denote the observed plant height of the j-th variety ($j = 1, \ldots, J$) in the k-th environment ($k = 1, \ldots, K$) and in the l-th replicate ($l = 1, \ldots, L$). Then, the linear mixed model can be written as:

$$y_{jkl} = \mu + \alpha_j + u_k + w_{jk} + z_{kl} + e_{jkl}, \tag{3}$$

where μ denotes the general mean, and α_j is the fixed effect of the j-th variety. By u_k, w_{jk}, and z_{kl} and e_{jkl}, we denote in model (3) the random effects of environments, of the variety × environment interaction (G×E), of replicates nested within environments (E×Rep), and of errors, respectively. We assume that $u_k \sim N(0, \sigma_u^2)$, $w_{jk} \sim N(0, \sigma_w^2)$, $z_{kl} \sim N(0, \sigma_z^2)$. Finally, we assume the heterogeneity of variance between trials, i.e. it is assumed that $e_{jkl} \sim N\left(0, \sigma_{e(k)}^2\right)$.

The variance components were estimated using restricted maximum likelihood (Searle et al. 2006, numerical implementation Genstat 24, VSN International; REML). Using these variance estimates, the fixed effects were estimated by generalized least squares. To verify the null hypothesis

$$H_0: \alpha_1 = \alpha_2 = \cdots = \alpha_J = 0 \tag{4}$$

the Wald test statistic with F approximation was used. The approximate F-test statistic has an approximate F distribution with numerator degrees of freedom (n.d.f.) equal to $K - 1$ and denominator degrees of freedom (d.d.f.) calculated using the Kenward–Roger approximation (Kenward and Roger 1997). Further, provided that the null hypothesis H_0 was rejected, all possible variety comparisons at the significance level α were obtained (Hsu 1996). For this purpose, the vmcomparison function from Genstat was used. In the current study, we set options method=fpsd and probability=0.01.

To assess plant height stability, Wricke's ecovalence stability coefficient (Wricke 1962; numerical implementation Genstat 24, VSN International) was calculated on plot data as:

$$W_j = \sum_{k=1} \left(y_{jk} - \bar{y}_{j.} - \bar{y}_{.k} + \bar{y}_{..}\right)^2, \tag{5}$$

where y_{jk} is the observed mean plant height of variety j (j = 1, ... , J) in environment k (k = 1, ..., K), $\bar{y}_{j.}$ and $\bar{y}_{.k}$ denote marginal means of variety j and environment k , respectively. $\bar{y}_{.}$ denotes the overall mean of y. This stability coefficient measures the contribution of each variety in the G×E sum of squares. Varieties with the lowest values of W_j tend to be more stable.

Next, the simultaneous selection index (SSI) was calculated using the equation

$$SSI_j = rm_j + rw_j \tag{6}$$

where rm_j denotes the rank of the mean height, and rw_j is the rank of Wricke's ecovalence stability coefficient for the j-th variety. The varieties with the lowest rank sum are the most desirable.

Additionally, based on predicted G×E interaction means M_{jk} and environmental means E_k, the harmonic mean of the relative performance of genotypic values (HMRPVG) stability index (see e.g. Resende 2007, Colombari Filho et al. 2013, Dias et al. 2018) was calculated as:

$$HMPRGV_j = \frac{K}{\sum_{k=1}^{K} \frac{1}{M_{jk}/E_k}}\,. \tag{7}$$

This coefficient simultaneously measures stability and adaptability, penalizing genotype instability, similarly to the superiority measure (Lin and Binns 1988). Therefore, varieties with higher HMRPGV are those that have high adaptability and high stability simultaneously for the environments in the current study.

Results

Lodging

The estimates of variance components for both traits are summarized in Table 2.

Table 2. Estimates of variance components included in the model.

Trait	E	G×E	E×Rep
Lodging in milk phase	1.67	0.94	1.10
Lodging at harvest	15.40	0.47	0.81

For both traits the highest estimates of variance components were obtained for environments. This means that environments explained most of the observed variability of both traits Furthermore for both traits the lowest values of variance components were obtained for the GE interaction. It can be noticed that the variance components for the GE interaction and for ERep effects were similar for both traits. Finally, the variances for lodging at the milk phase were almost equal.

The estimates of cutpoints, of variety effects and the values of test statistic z for lodging at two growing stages are given in Table 3.

Table 3. Estimates of cutpoints, of variety effects and values of test statistic for lodging at two growth phases.

	Parameter	Lodging at milk phase		Lodging at harvest	
		Estimate[a]	Test statistic [b]	Estimate[a]	Test statistic [b]
Cutpoint1	θ_1	–	–	-12.62 (1.91)	-6.61
Cutpoint2	θ_2	-11.98 (2.03)	-5.91	-10.10 (1.78)	-5.58
Cutpoint3	θ_3	-9.38 (1.77)	-5.30	-7.94 (1.70)	-4.66
Cutpoint4	θ_4	-8.17 (1.70)	-4.81	-6.73 (1.67)	-4.03
Cutpoint5	θ_5	-7.68 (1.68)	-4.57	-5.23 (1.64)	-3.19
Cutpoint6	θ_6	-6.30 (1.63)	-3.86	-3.20 (1.61)	-1.99
Cutpoint7	θ_7	-5.30 (1.60)	-3.31	-1.54 (1.59)	-0.97
Cutpoint8	θ_8	-4.02 (1.57)	-3.56	0.47 (1.59)	0.29

Farmer	α_1	0	–	0	–
Avatar	α_2	-6.17 (1.62)	-3. 80***	-3.12 (0.73)	-4.29***
Bente	α_3	-4.81 (1.58)	-3.04**	-1.64 (0.72)	-2.29*
Etoile	α_4	-5.25 (1.59)	-3.30***	-3.09 (0.73)	-4.22**
KWS Vermont	α_5	-3.50 (1.60)	-2.19*	-0.85 (0.74)	-1.15[ns]
Mecenas	α_6	-6.40 (1.63)	-3.94***	-4.07 (0.73)	-5.54***
MHR Fajter	α_7	-6.29 (1.64)	-3.85***	-3.91 (0.74)	-5.26***
Pilote	α_8	-6.28 (1.60)	-3.92***	-4.56 (0.75)	-6.09***
Radek	α_9	-5.69 (1.60)	-3.56***	-1.84 (0.74)	-2.50*
Rubaszek	α_{10}	-3.70 (1.58)	-2.34*	-0.78 (0.73)	-1.08[ns]

[a] The numbers in brackets denote the standard error. [b] *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; ns = non-significant

For both traits, the variety effects α_j ($j = 2, \ldots, J$) were negative. This means that the reference variety Farmer was the most resistant to lodging in the two growth stages. A different pattern can be observed for varieties Rubaszek and KWS Vermont. These two varieties were more susceptible to lodging at two growth phases than Farmer. However, only at the milk phase the differences between these two varieties and the reference variety were significant. The remaining varieties were significantly more susceptible to lodging at two growth phases.

Next, the estimates of cutpoints and variety effects(Table 3) were used to calculate the cumulative probabilities and probabilities of receiving a given score for each variety and lodging in a given growth phase. For clarity, only the probabilities of receiving a given score for each variety and lodging at a given growth phase were plotted (Fig. 3). The probabilities for lodging at the milk phase and lodging at harvest were shown in grey and black, respectively (Fig. 3). The cumulative probabilities for both data sets are shown in Supplement S2. To be consistent with the notation in model (1), in Figure 3 the numbers were used instead of variety names.

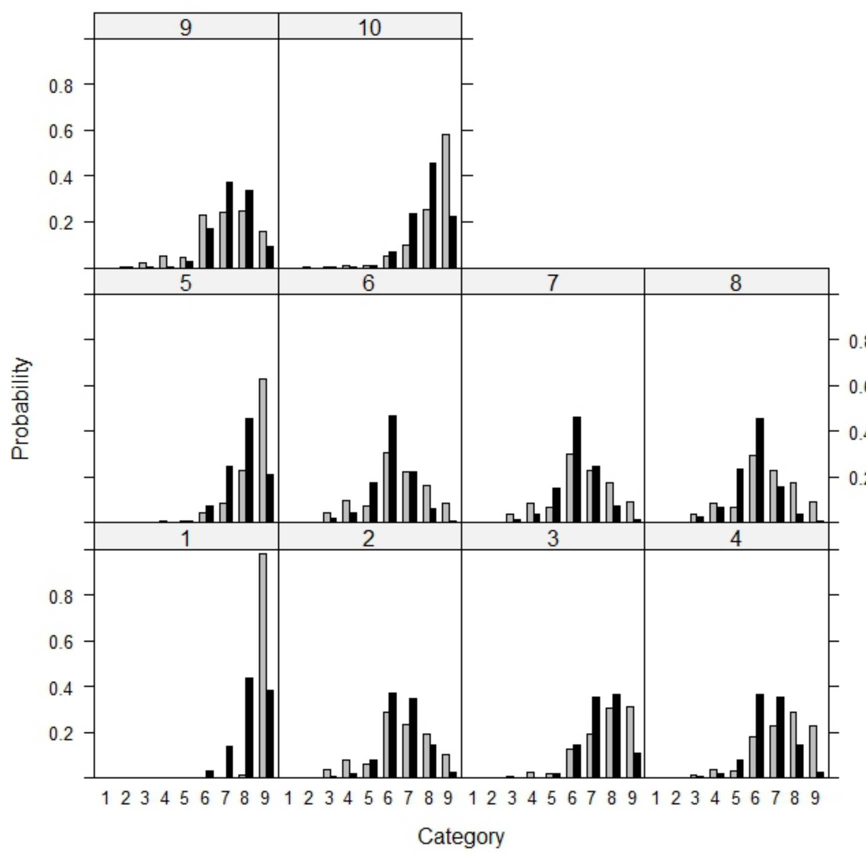

Fig. 3. Probabilities for lodging at the milk phase (grey) and lodging at harvest (black). Bars over the numbers denote probability of obtaining the score equal to a given number. Notation: 1-Farmer, 2-Avatar, 3-Bente, 4-Etoile, 5-KWS Vermont, 6-Mecenas, 7-MHR Fajter, 8-Pilote, 9-Radek, 10-Rubaszek.

It can be seen that depending on the results for lodging in the milk phase, varieties can be divided into two groups. The first group included varieties (Farmer, Bente, KWS Vermont, Rubaszek) with the most probable score of 9. Furthermore, for Farmer, KWS Vermont and Rubaszek the probability of receiving a score of 9 was greater than 0.5. The second group consisted of varieties (Avatar, Etoile, Mecenas, MHR Fajter, Pilote and Radek), for which the probabilities of obtaining scores 6, 7, 8 and 9 in lodging in the milk phase were almost equal. In the case of lodging during the harvest period the most probable score for varieties from the first group was 8. For variety Avatar the most probable score was 7, while for varieties Etoile and Radek scores 7 and 8 were almost as likely. For the other varieties from the second group, the most probable score was 6.

Plant height

The analysis of model (3) provided several estimated parameters and statistics (Table 4). The highest estimate of variance components was obtained for environments (=66.86; s.e.=22.15). This means that environments explained most of the observed variability of plant height. The variance component for the GE interaction effects was approximately ten times smaller than the variance component for environments and was equal to 6.50 (s.e.=0.97). The variance component for E×Rep was 1.54 (s.e.=0.48). The mean of error variances from the series of field trials was equal to 11.95. The highest values of error variances were recorded in environments 20Gra (i.e. Grabów in 2020), 20Os (i.e. Osiny in 2020), 20Sze (i.e. Szepietowo in 2020), 21We (i.e. Węgrzce in 2021), and 22Gra (i.e. Grabów in 2022). In all five environments the estimated values of error exceeded 20 (see Supplement S3). Finally, we checked the normality of the errors assumption. For this purpose, the expected normal quantiles were plotted against the standardized residuals (Fig. S3.1 in Supplement S3). Most of the points on the plot are located along the line . Only a few points in the upper right and lower left corners deviated slightly from this line. This means that the assumption of normality of errors was relatively well met.

The Wald test statistic used to test the null hypothesis (4) amounted to 129.65. The approximate F statistic was equal to 14.41 (n.d.f=9, d.d.f=160) and was highly significant (p< 0.001). This means that variety means differed significantly. Variety means, values of the ecovalence stability coefficient, of the simultaneous selection index and of the harmonic means of the relative performance of genotypic values index are given in Table 4. The value of the standard error of the difference is given at the bottom of Table 4.

Table 4. Variety height means, ecovalence stability coefficients (W_j, j = 1, ... , J), values of the simultaneous selection index and the harmonic mean of the relative performance of genotypic values (HMRPVG) stability index. Most favorable scores are highlighted in bold while least favorable scores are shown in italics.

Variety	Mean[a,b] [cm]	W	SSI	HMRPVG
Avatar	65.77[ab] [3]	*326.2 [10]*	13	1.03
Bente	64.78[abc] [4]	64.7 [1]	5	1.02
Etoile	62.90[cde] [6]	74.9 [2]	8	0.99
Farmer	63.59[bcd] [5]	79.5 [3]	8	1.00
KWS Vermont	61.64[def] [8]	149.9 [6]	14	0.97
Mecenas	66.53[a] [2]	172.9 [7]	9	1.05
MHR Fajter	60.41[ef] [9]	107.6 [4]	13	0.95
Pilote	62.10[def] [7]	176.6 [8]	*15*	0.98
Radek	**67.15[a] [1]**	258.6 [9]	10	1.06
Rubaszek	*59.61[f] [10]*	123.9 [5]	*15*	0.94

[a] Standard error of difference: 0.9601. [b] Means not sharing any letter are significantly different at the 1% level of significance.

The mean plant heights ranged from 59.61 cm to 67.15 cm (column two of Table 4). Variety Radek was the tallest among the tested varieties, whereas. Mecenas and Avatar were the second and third tallest varieties, respectively. Based on all the pairwise comparisons, these three varieties formed a group of the tallest varieties. On the other hand, varieties KWS Vermont, MHR Fajter and Rubaszek were the smallest. Moreover, KWS Vermont and Rubaszek were also resistant to lodging at both growth stages. Finally, Farmer was ranked fifth in terms of plant height and was classified as moderately tall.

The values of ecovalence stability coefficient are given in column three of Table 4. The lowest value of the ecovalence stability coefficient was recorded for Bente. This means that this variety was the most stable among the tested varieties. Furthermore, Farmer ranked third in terms of ecovalence stability coefficient. Moreover, the shortest varieties were ranked sixth, fourth and fifth, respectively. On the other hand, the tallest varieties were among the most unstable varieties.

Now, comparing the values of the simultaneous selection index (SSI) (column four of Table 4), the lowest value of the SSI index was recorded for Bente. This means that this variety was the tallest and the most stable among the tested varieties. For Farmer this coefficient was equal to 8. Moreover, this variety ranked second together with variety Etoile. On the other hand, the highest values of the SSI index were recorded for Pilote and Rubaszek. For the tallest varieties (Avatar, Mecenas and Radek), the values of the SSI index amounted to 13, 13, and 10, respectively.

The harmonic means of the relative performance of genotypic values (HMRPVG) are given in the last column of Table 4. The tested varieties were divided into two subsets. For varieties Avatar, Bente, Farmer, Mecenas and Radek, the index values were higher than 1, whereas for the rest was less than 1. Furthermore, the highest value of the HMRPVG was obtained for variety Radek. This means that this variety exhibits the highest adaptability for the environment and at the same time, was the most stable among the tested varieties. On the other hand, the lowest value of this index was recorded for the shortest variety Rubaszek. Finally, varieties Bente and Farmer were ranked fourth and fifth in terms of the HMRPVG index, respectively.

Discussion

In this study a single stage approach was used to assess resistance to lodging and plant height of ten spring barley varieties in Polish organic field trials. In this approach the recorded measurements from all the trials are used to estimate all effects (fixed and/or random) in one model. In both models we treated environments as random. According to Yates and Cochran (1938), by treating sites or environments as random, one can extend the results to the region represented by those sites or environments. On the other hand, treating environments as fixed means that the results are valid only for those environments. Similar reasoning is valid for varieties. In this study we were interested in comparing specific varieties, so we treated varieties as fixed. A similar assumption was used in Bakinowska et al. (2016) and Zawieja et al. (2023). In these two studies, the authors were interested in finding the most resistant genotypes among the genotypes tested. Because lodging in organic trials was observed in the ordinal scale, the cumulative link mixed model according to Lenartowicz et al. (2024a) was used. This model was preferred because the results have simple interpretations in terms of probability, which can be valuable for crop experts and decision-makers. Furthermore, in our analyses, we compared the varieties with the variety most resistant to lodging. For this purpose, we used information from conventional post-registration trials and numbered the varieties from one to ten (where one indicates the standard variety) to obtain proper comparisons of varieties with reference. A similar approach was used by Zawieja et al. (2023) and Lenartowicz et al. (2024a). In these studies, they compared new lines or varieties with the most resistant variety. The opposite approach was used by Abuley et al. (2017). In that study, the authors compared cultivars with susceptible control. For this reason, depending on the goal and/or availability of information on the level of disease resistance or lodging of varieties, we recommend using prior information on the resistance level to obtain proper variety comparisons. On the other hand, if there is no prior information on the level of resistance of varieties, the order of varieties does not matter. For plant height, we tried to fit a model described in Lenartowicz et al. (2024b). However, due to convergence problems we were able to fit a model with heterogeneous errors. In this manner, we placed a greater weight on environments with high quality data (Edwards and Jannink 2006). Moreover, according to Hu et al. (2013) by applying this model one obtains more reliable variety recommendations. Because we had only a single variance component for the G×E interaction effects, we followed the approach described by Craine et al. (2023) to assess plant height stability. In that paper, the authors first calculated a stability coefficient on plot data and afterwards they calculated the harmonic mean of relative performance genotypic values based on the predicted variety × environment means and environmental means from the model. They concluded that the best linear unbiased predictor (BLUP)-based indices are reportedly robust to the unbalanced designs. Moreover, they argued that HMRPGV may be more appropriate for simultaneous selection of genotypes than the commonly used SSI index or Kang's rank-sums. In a different study, Przystalski and Lenartowicz (2023) used the HMRPGV index for simultaneous selection of potato varieties suitable either for organic or for conventional farming.

In the present study, the overall mean plant height was 63.45 cm, while the variety means ranged from 59.61 cm to 67.15 cm. This agrees with the results obtained by Massman et al. (2022) for naked barley. In that study it was reported that the grand mean was 69.6 cm, whereas the genotype means ranged from 50.9 cm to 78 cm. In the Netherlands the variety widely grown wheat by organic farmers (Lavett) is 100 cm tall (Osman et al. 2016). In a Polish study on spring wheat, Feledyn-Szewczyk and Jończyk (2015) reported that the mean plant heights ranged from 76.8 cm to 89.1 cm. In the same study the authors showed that plant height was negatively correlated with the rate of weed infestation. They also concluded that taller cultivars exhibit a greater ability to compete with weeds. In another study Ford and Diggle (1981) argued that taller plants reduce the amount of photosynthetically active radiation in the canopy and consequently reduce the amount of light for weeds. On the other hand, in a meta-analytic study Kucek et al. (2021) showed that 16% of the samples included in their analysis showed a negative correlation between plant height and weed competitiveness. We observed similar behavior in several of our field trials (data not shown). From this perspective, the leaf area index (Hansen et al. 2008) and early vigor (Kucek et al. 2021) are the most promising traits for the selection of new lines with improved weed control abilities.

We conclude from the current work that lodging was mainly caused by environmental conditions. All environments included in the analyses experienced heavy rainfall (see Supplement S1). This is in agreement with the results obtained by Jevtic et al. (2017) and Wu et al. (2022). In these two studies, they indicated that lodging is mainly caused by weather conditions. In addition, in these environments, the cultivars were infected with leaf rust and net blotch. This may also increase the risk of crop lodging (see e.g., Wu et al. 2022 and references therein). On the other hand, we did not observe an association between lodging and weed infestation. In these environments, weed infestation was mild (data not shown). To the best of our knowledge, there are no studies in the literature on this topic. Therefore, it would be worth investigating this topic. For this purpose, the models described in Przystalski and Lenartowicz (2023) can be used to answer this question. We plan to investigate this topic in a future study.

Finally, we conclude that variety Farmer was the most resistant to lodging in two growth phases. Moreover, this variety was classified as a medium-tall variety. On the other hand, Radek was the tallest among the tested varieties. This variety was also resistant to lodging during the harvest period, but susceptible to lodging in the milk phase. According to Wricke's ecovalence stability coefficient, Bente was the most stable among the tested varieties, while Farmer ranked third. According to HMRPVG, Radek and Mecenas were the most stable and well adapted to the environments. This means that Bente, Farmer and Radek should be recommended for organic cultivation. Furthermore, these varieties may be used to breed new varieties resistant to lodging, suitable for organic farming. However, further research is needed to assess their weed-competitive abilities. For this purpose, the weed suppressive index proposed by Hansen et al. (2008) may be applied. We intend to explore this topic in future study.

Author Contributions: Conceptualization, T.L., H.B. and K.N.; methodology, M.P. and T.L.; formal analysis, M.P.; data curation, T.L.; writing—original draft preparation, T.L., H.B. and M.P.; writing—review and editing, T.L. and M.P.; visualization, M.P.; supervision K.J.; project administration, B.F.-S.; funding acquisition, K.J. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data were provided by the Institute of Soil Science and Plant Cultivation-State Research Institute (IUNG), Poland, for exclusive use in this study and are, in general, not publicly available. Reasonable requests may be addressed to the Institute of Soil Science and Plant Cultivation, State Research Institute (IUNG), Poland.

Acknowlegdements

The study was financed within the task 'Assessment of suitability for cultivation in an organic production system of varieties of spring and winter cereals and faba bean plants' from the budget grant for IUNG allocated for the implementation of the tasks of the Ministry of Agriculture and Rural Development in the years 2020–2022.

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