Diversity of Productivity Traits in Hybrid Lines of Aegilops L. with Triticum aestivum L.

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Abstract
Variation in productivity traits and their correlations were studied in 16 hybrid lines of Aegilops kotschyi Boiss. and A. variabilis Eig. with Triticum aestivum L. and their parental components. In comparison to the wheat cultivars, most of the hybrid lines exhibited higher tillering, whereas the length of the main tiller and spike rachis were similar to the values for the wheat cultivars. The values of other traits, such as basal stem diameter, main spike density, fertility, and a 1,000-grain weight in hybrid lines varied. In some lines, the value of these traits was higher or similar to that of wheat cultivars, whereas in others it was lower. Among the hybrids, [(A. kotschyi × ‘Rusałka’) × ‘Begra’] × ‘Turnia’ was distinguished in having the greatest basal stem diameter, longest spikes, highest fertility, and greatest 1,000-grain weight. The hybrid lines exhibited greater variation in the analyzed traits than did the wheat cultivars. In the hybrid lines, the main tiller length and basal stem diameter were positively correlated with fertility and 1,000-grain weight, whereas in wheat cultivars there were negative correlations for these traits. The results confirmed that wide hybrids can be used to eliminate the negative correlations between productivity traits in wheat. Analysis of clusters in terms of productivity traits provided information on the similarity and diversity of hybrid lines, which may prove useful in their further selection.

Keywords
Aegilops kotschyi Boiss.; Aegilops variabilis Eig.; common wheat; hybrids; quantitative traits

1. Introduction

Genetic diversity in wheat is essential for successful genetic improvement breeding programs and the creation of new genotypes. The success of a breeding program depends on the genetic variability of quantitative traits present in the plant material. The influence of such traits on wheat fertility is a frequent subject of analysis (Aharizad et al., 2012; Alemu et al., 2018; Pasandi et al., 2015). Negative correlations in yield components are one of the main barriers to increasing wheat yield (Slafer et al., 2014; Zecevic et al., 2010). In wheat hybrids with distant species, these unfavorable correlations can be eliminated. Aegilops species, which are closely related to wheat, can be a source not only of useful qualitative traits (Prażak & Krzepilko, 2018; Prażak & Molas, 2017) and resistance traits (Coriton et al., 2009; Marais et al., 2005) but of productivity traits as well (Pilch, 1996, 1997). The assessment of phenotypic variation in wheat hybrid genotypes to identify groups with similar forms is an important element of the study of diversity in breeding material (Franco et al., 2001). Cluster analysis can be used to identify genotypes that can be divided into major groups based on similarity indicators. This information is essential in choosing forms in the selection process (Aharizad et al., 2012; Alemu et al., 2018; Pasandi et al., 2015).

The goals of this study were to evaluate the variability and correlations of some quantitative traits of hybrid lines of Aegilops kotschyi Boiss. and A. variabilis Eig.
with winter wheat *Triticum aestivum* L. and their parental forms. Additionally, this evaluation was conducted to select forms that could be used as starting material in wheat breeding programs.

2. Material and Methods

The research material consisted of 16 hybrid lines of *A. kotschyi* Boiss. and *A. variabilis* Eig. with the common wheat *T. aestivum* L. and their parental components (Table 1). *Aegilops* species were obtained from the collection of the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) in Gatersleben, Germany. The research was conducted in 2012–2014. The plants for the study came from an unreplicated field experiment at the Experimental Station of the Faculty of Agricultural Sciences in Zamość, University of Life Sciences in Lublin (50°42′36.7″ N, 23°12′47.3″ E), Poland. In the early stages of breeding, there were a large number of lines to choose from, but a small number of seeds. For this reason, the standard method, but without replications, was used (Wegrzyń, 2001). The hybrid lines were compared with the parental forms. The experimental field was located on brown soil of loess origin, classified as a good wheat complex, Valuation Class 2. The seeds of lines to choose from, but a small number of seeds. For this reason, the standard method, but without replications, was used (Wegrzyń, 2001). The hybrid lines were compared with the parental forms. The experimental field was located on brown soil of loess origin, classified as a good wheat complex, Valuation Class 2.

### Table 1 Derivation of hybrid lines of *Aegilops kotschyi* Boiss. and *A. variabilis* Eig. with *Triticum aestivum* L.

| No. | Forms                                      | Traits |
|-----|--------------------------------------------|--------|
| 1.  | $F_{12-14}$ *A. variabilis* × 'Rusalka'    | VR     |
| 2.  | $F_{12-14}$ 'Rusalka' × *A. variabilis*    | RV     |
| 3.  | $F_{12-14}$ *A. kotschyi* × 'Rusalka'      | KR     |
| 4.  | $F_{12-14}$ 'Rusalka' × *A. kotschyi*      | RK     |
| 5.  | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Begra' | KRB    |
| 6.  | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Gama' | KRG    |
| 7.  | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Korweta' | KRRo   |
| 8.  | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Monopol' | KRMo   |
| 9.  | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Muza' | KRMu   |
| 10. | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Piko' | KRP    |
| 11. | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Smuga' | KRS    |
| 12. | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Turnia' | KRT    |
| 13. | $BC_1F_{8-10}$ (*A. kotschyi* × 'Rusalka') × 'Zyta' | KRZ    |
| 14. | $BC_2F_{7-9}$ [(A. kotschyi × 'Rusalka') × 'Begra'] × 'Piko' | KRBp   |
| 15. | $BC_2F_{7-9}$ [(A. kotschyi × 'Rusalka') × 'Begra'] × 'Smuga' | KRBS   |
| 16. | $BC_2F_{7-9}$ [(A. kotschyi × 'Rusalka') × 'Begra'] × 'Turnia' | KRBt   |

*Generation since the last cross.

Plants were harvested from the field at full maturity at the beginning of August, and the following parameters were determined for 10 plants from each form: number of productive tillers (NPT), length of main tiller (LMT), diameter of basal stem (second internode from the bottom of the plant; DBS), length of spike rachis (LSR), main spike density (number of spikelets per 10 cm of the spike rachis; MSD), fertility of main spike (number of kernels per spikelet; FMS), and 1,000-grain weight (TGW). The arithmetic mean, minimum, and maximum values of the traits were calculated, as well as the coefficients of variation (CV) and phenotypic correlations. To determine the differences between individual traits, a single classification analysis of variance was performed. Tukey’s multiple range test was used (Ansari &...
3. Results

Climatic conditions in the years 2012–2014 were varied (Table 2). Considerable variation was observed in the analyzed traits among the lines (Table 3). In the years 2012 and 2013, in the period from April to July, there was a rainfall shortage of 60% and 30%, respectively, relative to the long-term average, whereas in 2014, the total precipitation exceeded the long-term average by 3%. During all research years, the average monthly air temperature in the period from April to July was higher than the long-term average by 5.5 °C (2012) and 6.6 °C (2013 and 2014). Atmospheric conditions may have affected the productivity traits of the genotypes. The highest average rachis length, fertility, and 1,000-grain weight occurred in 2014 when the total precipitation in April–July was the highest over the 3-year study period (Table 4). The number of tillers and their length were affected by the conditions prevailing in fall. The warm fall in 2011 and 2012 enabled the emergence of plants and productive tillering. The larger number of tillers restricted access to light, which increased their elongation. The tillers were longer, but the spikes were shorter because more assimilates were used for the development of tillers and leaves (Reynolds et al., 2009). September and October were cold and rainy in 2013, which delayed sowing. The warm and humid November improved the condition of the winter crops.

Analysis of the morphological traits of hybrid lines and parental components in 2012–2014 demonstrated that the most productive tillers were produced by the RK line (mean 24.50) among the hybrid lines and by the ‘Rusalka’ cultivar (mean 15.70) among the wheat cultivars (Table 3). The lowest NPT in the hybrid lines was 3.5 and the highest was 38.1. The range of variation in this trait was smaller in wheat – from 7.8 to 23.0 (Table 4). The number of tillers and their length were affected by the conditions prevailing in fall. The warm fall in 2011 and 2012 enabled the emergence of plants and productive tillering. The larger number of tillers restricted access to light, which increased their elongation. The tillers were longer, but the spikes were shorter because more assimilates were used for the development of tillers and leaves (Reynolds et al., 2009). September and October were cold and rainy in 2013, which delayed sowing. The warm and humid November improved the condition of the winter crops.

In the hybrid lines, the average density of the main spike ranged from 12.4 to 26.3, whereas in the wheat cultivars it ranged from 17.0 to 26.2 (Table 4). The mean basal stem diameter ranged from 2.5 to 4.3 mm in the hybrid lines and from 3.2 to 4.3 mm in the wheat cultivars (Table 4). Significant differences were noted in the diameter of the basal stem between some of the hybrid lines and wheat cultivars. The greatest basal stem diameter was noted in the KRBT line (0.41 cm) and ‘Turnia’ wheat (0.40 cm). The remaining hybrid lines had similar, or somewhat lower values (lines KR

Bradley, 1960). A dendrogram was created using the unweighted pair group method with arithmetic mean (UPGMA) method using STATISTICA 12 software (Sokal & Rohlf, 1962).

### Table 2 Rainfall and temperature according to the Meteorological Station in Zamość.

| Year | April | May  | June | July | April–July | Total |
|------|-------|------|------|------|------------|-------|
| Rainfall (mm) |   |   |   |   |   |     |
| 2012 | 19.6  | 24.4 | 36.3 | 34.4 | 114.7      | 114.7 |
| 2013 | 15.6  | 35.6 | 85.6 | 63.4 | 200.2      | 200.2 |
| 2014 | 36.4  | 147.8| 50.2 | 58.5 | 292.9      | 292.9 |
| LTA  | 40    | 66   | 93   | 86   | 285        | 285   |

| Temperature (°C) | Mean |
|------------------|------|
| 2012 | 12 | 18.4 | 20 | 24.8 | 18.8 |
| 2013 | 12.4 | 20.7 | 22.6 | 24 | 19.9 |
| 2014 | 15 | 18.5 | 20.8 | 25.2 | 19.9 |
| LTA  | 6.9 | 13.4 | 15.9 | 17.1 | 13.3 |

LTA – long-term average 1979–1988.
Table 3  Mean values of selected productivity traits in hybrid lines of *Aegilops kotschyi* Boiss. and *A. variabilis* Eig. with *Triticum aestivum* L. and their parental components in 2012–2014.

| Hybrid lines   | Traits | NPT | LMT (cm) | DBS (cm) | LRS (cm) | MSD | FMS | TGW (g) |
|---------------|--------|-----|---------|----------|---------|-----|-----|---------|
| VR            | NPT    | 11.23 | 85.07 | 0.34     | 8.30    | 18.38 | 1.17 | 35.88   |
| RV            | NPT    | 13.50 | 83.13 | 0.31     | 8.00    | 19.13 | 1.30 | 40.52   |
| KR            | NPT    | 18.81 | 83.69 | 0.26     | 9.50    | 14.08 | 0.98 | 28.29   |
| RK            | NPT    | 24.50 | 68.70 | 0.29     | 9.40    | 13.41 | 1.80 | 29.37   |
| KRB           | NPT    | 15.43 | 99.73 | 0.36     | 10.00   | 21.18 | 2.35 | 29.20   |
| KRG           | NPT    | 12.73 | 95.33 | 0.35     | 8.80    | 22.20 | 1.73 | 31.52   |
| KRK           | NPT    | 11.54 | 92.17 | 0.36     | 9.50    | 19.01 | 2.18 | 37.76   |
| KRKo          | NPT    | 11.03 | 108.93| 0.33     | 7.30    | 24.92 | 1.73 | 30.81   |
| KRKMo         | NPT    | 10.97 | 103.30| 0.36     | 9.20    | 20.43 | 2.52 | 38.25   |
| KRKMu         | NPT    | 13.43 | 101.67| 0.34     | 10.10   | 18.36 | 2.48 | 34.73   |
| KRBP          | NPT    | 11.53 | 98.30 | 0.40     | 9.60    | 20.32 | 2.23 | 32.66   |
| KRBS          | NPT    | 13.51 | 70.73 | 0.32     | 7.40    | 25.35 | 1.83 | 28.60   |
| KRBP          | NPT    | 10.97 | 109.67| 0.41     | 11.80   | 17.13 | 2.01 | 38.47   |
| 'Begra'       | NPT    | 14.07 | 92.57 | 0.39     | 8.40    | 23.57 | 2.12 | 38.71   |
| 'Gama'        | NPT    | 12.55 | 89.50 | 0.35     | 7.80    | 22.12 | 2.36 | 32.74   |
| 'Korweta'     | NPT    | 11.42 | 98.30 | 0.40     | 9.60    | 20.32 | 2.23 | 32.66   |
| 'Monopol'     | NPT    | 13.73 | 96.63 | 0.39     | 9.90    | 21.69 | 1.81 | 30.28   |
| 'Muza'        | NPT    | 9.14  | 90.76 | 0.37     | 9.70    | 19.35 | 2.26 | 35.08   |
| 'Piko'        | NPT    | 14.79 | 93.54 | 0.36     | 9.70    | 21.50 | 2.20 | 29.62   |
| 'Rusalka'     | NPT    | 15.70 | 75.03 | 0.34     | 7.80    | 20.35 | 2.55 | 43.64   |
| 'Smuga'       | NPT    | 12.28 | 102.70| 0.33     | 9.80    | 18.75 | 2.42 | 36.75   |
| 'Turnia'      | NPT    | 11.07 | 107.97| 0.40     | 11.40   | 18.06 | 2.58 | 33.34   |
| 'Zyta'        | NPT    | 11.87 | 101.67| 0.38     | 9.20    | 18.61 | 2.82 | 36.03   |
| *A. kotschyi*  | NPT    | 47.81 | 33.41 | 0.17     | 3.10    | 6.53  | 2.01 | 7.27    |
| *A. variabilis*| NPT   | 69.11 | 49.89 | 0.18     | 3.50    | 6.04  | 2.19 | 16.15   |
| LSD<sub>p ≤ 0.05</sub> | 17.04 | 14.78 | 0.09 | 1.90 | 3.59 | 0.90 | 8.20 |

*Least significant difference; NPT – number of productive tiller; LMT – length of main tiller; DBS – diameter of basal stem; LRS – length of spike rachis; MSD – main spike density; FMS – fertility of main spike; TGW – 1,000-grain weight.

and RK), for this trait as the wheat cultivars. The KRB line also had the longest rachises (mean 11.8 cm). Among the wheat cultivars, only ‘Turnia’ had similar rachises (mean 11.4 cm) (Table 3, Figure 1, Figure 2). In the hybrid lines, the mean length of the rachis ranged from 7.0 to 13.0 cm, and in wheat from 7.0 to 12.0 cm (Table 4, Figure 1–Figure 3). KRBS was the most fertile of the hybrid lines during the study period (mean 2.64) and ‘Zyta’ was the most fertile of the wheat cultivars (2.82) (Table 3). The mean fertility of the main spike ranged from 0.3 to 3.1 in the hybrid lines and from 1.5 to 3.1 in the wheat cultivars (Table 4).

The grains of the hybrid lines were well filled and were similar to the grains of wheat cultivars in shape and color (Figure 4–Figure 6). The 1,000-grain weight in most of the hybrid lines did not differ significantly from that of the parent wheat cultivars. The highest 1,000-grain weight among the hybrid lines occurred for RV (40.52 g) and KRB (38.47 g), and among the wheat cultivars, for ‘Rusalka’ (43.64 g) and ‘Begra’ (38.71 g) (Table 3). In the hybrid lines, the mean 1,000-grain weight ranged from 22.9 to 49.6 g and in the wheat cultivars, from 26.7 to 50.2 g (Table 4).

The highest values for rachis length, fertility, and 1,000-grain weight in the forms were noted in 2014 when the total rainfall was the highest over the 3-year study period (Table 2, Table 4). The CV of the NPT ranged from 0.3 to 0.4 for the hybrid
Table 4 Mean, range, and variability coefficients (CV) of selected productivity traits in Aegilops L. × Triticum aestivum L. hybrid lines and their parental components – wheat cultivars and Aegilops species.

| Trait | Year | Hybrid lines | Wheat | Aegilops |
|-------|------|--------------|-------|---------|
|       |      | Mean | Range | CV | Mean | Range | CV | Mean | Range | CV |
| NTP   | 2012 | 15.1 | 3.5–38.1 | 0.4 | 13.6 | 8.4–23.0 | 0.3 | 64.2 | 51.6–73.7 | 0.5 |
|       | 2013 | 14.9 | 7.5–27.5 | 0.4 | 11.8 | 7.8–16.7 | 0.4 | 63.8 | 52.0–75.5 | 0.7 |
|       | 2014 | 10.7 | 8.1–12.8 | 0.3 | 12.6 | 8.7–17.2 | 0.2 | 49.5 | 39.8–59.1 | 0.4 |
| LMT   | 2012 | 97.2 | 70.0–119.9 | 0.1 | 96.1 | 77.9–111.9 | 0.1 | 42.3 | 34.5–50.1 | 0.1 |
|       | 2013 | 94.3 | 66.3–117.9 | 0.1 | 95.7 | 74.8–107.1 | 0.1 | 42.0 | 33.6–50.4 | 0.1 |
|       | 2014 | 92.1 | 62.1–121.0 | 0.1 | 93.2 | 72.4–106.2 | 0.1 | 40.6 | 32.1–49.0 | 0.2 |
| DBS   | 2012 | 0.34 | 0.25–0.42 | 0.2 | 0.37 | 0.32–0.41 | 0.1 | 0.18 | 0.18–0.18 | 0.2 |
|       | 2013 | 0.35 | 0.27–0.43 | 0.1 | 0.38 | 0.33–0.43 | 0.1 | 0.18 | 0.16–0.16 | 0.1 |
|       | 2014 | 0.34 | 0.25–0.38 | 0.1 | 0.36 | 0.32–0.41 | 0.1 | 0.18 | 0.16–0.19 | 0.2 |
| LRS   | 2012 | 9.0 | 7.0–11.0 | 0.1 | 9.0 | 7.0–11.0 | 0.1 | 3.0 | 3.0–3.0 | 0.2 |
|       | 2013 | 9.0 | 7.0–12.0 | 0.1 | 9.0 | 8.0–12.0 | 0.1 | 3.0 | 3.0–4.0 | 0.3 |
|       | 2014 | 10.0 | 7.0–13.0 | 0.1 | 10.0 | 8.0–12.0 | 0.1 | 4.0 | 4.0–4.0 | 0.1 |
| MSD   | 2012 | 19.2 | 14.1–25.7 | 0.1 | 20.7 | 17.8–26.2 | 0.1 | 5.6 | 5.4–5.9 | 0.3 |
|       | 2013 | 19.3 | 12.4–26.3 | 0.1 | 20.9 | 17.5–23.4 | 0.1 | 6.1 | 5.7–6.6 | 0.3 |
|       | 2014 | 19.0 | 13.3–25.7 | 0.1 | 19.7 | 17.0–23.4 | 0.1 | 7.0 | 6.7–7.2 | 0.2 |
| FMS   | 2012 | 1.7 | 0.3–2.7 | 0.3 | 2.2 | 1.5–2.5 | 0.3 | 1.9 | 1.5–2.2 | 0.5 |
|       | 2013 | 1.8 | 0.4–3.1 | 0.4 | 2.2 | 1.6–3.1 | 0.3 | 2.1 | 2.1–2.1 | 0.5 |
|       | 2014 | 2.3 | 1.4–2.9 | 0.2 | 2.6 | 2.3–3.1 | 0.1 | 2.2 | 2.1–2.3 | 0.4 |
| TGW   | 2012 | 30.4 | 22.9–35.7 | 0.2 | 31.7 | 26.7–38.0 | 0.2 | 10.7 | 7.1–14.4 | 0.1 |
|       | 2013 | 33.1 | 26.9–38.6 | 0.1 | 33.9 | 28.1–42.8 | 0.1 | 11.2 | 7.7–14.7 | 0.2 |
|       | 2014 | 38.2 | 27.1–49.6 | 0.1 | 39.1 | 34.1–50.2 | 0.1 | 13.5 | 8.0–19.0 | 0.2 |

CV – coefficient of variation; NPT – number of productive tillers; LMT – length of main tiller; DBS – diameter of basal stem; LRS – length of spike rachis; MSD – main spike density; FMS – fertility of main spike; TGW – 1,000-grain weight.

The results of the grouping of objects with similar productivity traits are presented in the form of a dendrogram (Figure 7). Cluster analysis was performed by the UPGMA method based on the Euclidean distance squared. Five homogeneous groups were distinguished. The first group and first subgroup included the VR and RV lines, characterized by high fertility and 1,000-grain weight but lower values.
for the remaining traits. The first group and second subgroup contained line KRKo and the 'Muza,' 'Gama,' and 'Begra' wheat cultivars, which were also highly fertile and had high 1,000-grain weight, but intermediate values for the remaining traits. The second group and first subgroup included the KRB, KRG, KRS, and KRZ lines and the 'Monopol,' 'Piko,' and 'Korweta' cultivars, with intermediate values for the analyzed traits. The second group and second subgroup contained KRP, KRMu, and KRBS and the cultivars 'Smuga' and 'Zyta,' with fewer productive tillers, long productive tillers, and intermediate values for the remaining traits. The third cluster consisted of lines KRT and KRBT and the 'Turnia' cultivar, with fewer productive tillers, loose spikes, and high values for the remaining traits. The third cluster also contained line KRMo, which was distinguished from the other forms in this group by its short rachises, highest spike density, low fertility, and low 1,000-grain weight. The fourth cluster and first subgroup included lines KR and RK, with the most productive tillers of all the lines, short productive tillers, intermediate rachis length, and low values for the remaining features. The fourth cluster and second subgroup consisted of line KRBP and the 'Rusalka' cultivar, with fewer productive tillers, short productive tillers and rachises, and intermediate basal stem diameter and spike density. In contrast with 'Rusalka' wheat, the KRBP line had low fertility and
Figure 2 Spikes of *Aegilops kotschyi* Boiss. × *T. aestivum* L. hybrid lines and their parental components (from left): 1–4 – hybrid lines (KRB, KRBP, KRBS, and KRBT), *A. kotschyi* Boiss., 'Rusalka,' 'Begra,' 'Piko,' 'Smuga,' and 'Turnia.'

Figure 3 Spikes (from left): *Aegilops variabilis* Eig., VR – *A. variabilis* Eig. × 'Rusalka,' 'Rusalka.'

1,000-grain weight. The fifth cluster contained the wild species *A. kotschyi* Boiss. and *A. variabilis* Eig., which had the most productive tillers, intermediate fertility, and the lowest values for the remaining features.

4. Discussion

The large variation observed between the lines was because of their hybridity and the effects of environmental conditions (Morris, 2009). Climatic conditions may have influenced the value of productivity traits. Hybrid lines each year showed greater variation in productivity traits, such as the number and diameter of productive tillers, rachis length, and fertility than did their parent wheat cultivars. However, the greatest variation in these features was noted in wild *Aegilops* species. Naghavi et al. (2014, 2015) also reported that elements of wheat yield structure are dependent on weather conditions during the growing period. Many experiments have
**Figure 4** Grains (from left): *Aegilops variabilis* Eig., *A. variabilis* Eig. × ‘Rusalka,’ ‘Rusalka.’

**Figure 5** Grains of *Aegilops kotschyi* Boiss. × *T. aestivum* L. hybrid lines and their parental components (from left): First and second rows from top – hybrid lines (KRG, KRKo, KRMo, KRMu, KRP, KRS, KRT, KRT, and KRZ), third row from top – *A. kotschyi* Boiss., ‘Rusalka,’ ‘Gama,’ ‘Korweta,’ ‘Monopol,’ and ‘Muza,’ and fourth row from top – ‘Piko,’ ‘Smuga,’ ‘Turnia,’ and ‘Zyta.’
Figure 6 Grains of *Aegilops kotschyi* Boiss. × *T. aestivum* L. hybrid lines and their parental components (from left): First row from top – hybrid lines (KRB, KRPB, KRBS, and KRBT), second row from top – *A. kotschyi* Boiss. and ‘Rusalka’, third row from top – *A. kotschyi* Boiss. and ‘Rusalka’, and fourth row from top – ‘Begra’, ‘Piko’, ‘Smuga’, and ‘Turnia’.

Figure 7 Dendrogram generated using UPGMA cluster analysis for selected productivity traits in hybrid lines of *Aegilops kotschyi* Boiss. and *A. variabilis* Eig. with *Triticum aestivum* L. and their parental components in 2012–2014 (I–V chosen clusters).
Table 5 Significant values of correlation coefficients of quantitative traits in *Aegilops* L. × *Triticum aestivum* L. hybrid lines and their parental components – wheat cultivars and *Aegilops* species in 2012–2014.

| Traits | Forms | Traits     | NPT | LMT | DBS | LRS | MSD | FMS |
|--------|-------|------------|-----|-----|-----|-----|-----|-----|
|        | Lines |            |     |     |     |     |     |     |
| LMT    | Wheats| *Aegilops* | 0.541* |     |     |     |     |     |
|        | Lines |            | −0.199* | 0.358* |     |     |     |     |
|        | Lines | *Aegilops* | −0.096** | 0.270* | 0.198* |     |     |     |
|        | Lines | *Aegilops* | −0.240* | 0.428* | 0.264* |     |     |     |
|        | Lines | *Aegilops* | −0.192* | 0.107** | −0.564* |     |     |     |
|        | Lines | *Aegilops* | −0.291* | −0.164** | 0.146** | −0.287* |     |     |
|        | Lines | *Aegilops* | −0.272* | 0.161* | 0.252* | −0.115** | 0.270* |     |
|        | Lines | *Aegilops* | −0.422* | −0.147** | −0.281* |     | 0.274* |     |
|        | Lines | *Aegilops* | 0.770* |     |     |     |     |     |

demonstrated a relationship between the elements of crop structure and weather conditions during the growing season (Brzozowska et al., 2008; Buraczyńska & Ceglarek, 2008; Glowacka, 2010; Woźniak, 2006).

Tillering in most of the hybrid lines was similar to that of wheat. The NPT in the hybrid lines and wheat cultivars was significantly lower than the NPT in the wild *Aegilops* species. In a study by Loureiro et al. (2007), tillering in hybrids of wheat with *Aegilops* L. species was similar to wheat tillering.

The shortest main tillers were noted in the *Aegilops* species (less than 50 cm), the lines RK and KRBP (about 70 cm), and the 'Rusalka' wheat cultivar (mean 75.03 cm). Short-straw wheat cultivars usually have thicker tillers and are more resistant to lodging. The KRBP line also had the densest spikes (mean 25.35). Tyrka and Stefanowska (2001) found that the length of the main tiller in wheat hybrids with *A. juvenalis* (Thell.) Eig. and *A. ventricosa* Tausch ranged from 44.4 to 118.8 cm. In a study by Knott and Dvořák (1981), the length of the main tillers in hybrid lines of *A. speltoides* Tausch. × *T. aestivum* L. ranged from 70.0 to 96.4 cm. Wheat cultivars with high spike density often have small kernels, whereas loose spike density is associated with plump kernels. However, they were more resistant to seed shedding than forms with loose spikes. Wheat forms with loose spikes have less than 17 spikelets per 10 cm of rachis, whereas forms with spikes of average density have 17–22 spikelets, and forms with dense spikes have 23 or more spikelets. In the hybrid lines, the average density of the main spike and basal stem diameter were similar or lower than that of the wheat cultivars, but their spikes were similar or longer.

Significant differences were noted in these traits between some of the hybrid lines and wheat cultivars. Plants with long, dense spikes and high numbers of spikelets and flowers per spikelet usually produce high yields. Hybrids of wheat with *A. speltoides* Tausch., *A. triumviris* L., and *A. squarrosa* L. obtained by Pilch (1996, 1997) had longer spikes, more spikelets per spike, more grains per spike, and higher 1,000-grain weight than wheat cultivars. The fertility of the main spike in the hybrids was generally lower than that of the parent wheat cultivars. Tyrka and Stefanowska (2001) found that successive generations of wheat hybrids with *A. ventricosa* Tausch. and *A. juvenalis* (Thell.) Eig. did not differ significantly from wheat in terms of fertility. In the present study, most lines did not differ significantly in fertility from that of the wheat cultivars. Tyrka and Stefanowska (2001) reported
that the 1,000-grain weight of wheat hybrids with A. ventricosa Tausch. and A. juvenalis (Thell.) Eig. ranged from 21.6 to 52.1 g, whereas that of wheat ranged from 32.6 to 42.7 g. According to the authors, the hybrid plants had a greater range of variability in 1,000-grain weight than did the winter wheat cultivars. Arain et al. (2018) noted a significant positive correlation \((r = 0.683)\) between 1,000-grain weight and grain yield.

Apart from their dependence on environmental factors, morphological traits are subject to both natural and artificial selection. Therefore, if there is an association between the loci controlling the targeted morphological trait, the influence of environmental factors will be lower (Mollasadeghi et al., 2012). In our study, the NPT in the hybrid lines and the wheat cultivars showed low negative correlations with most of the analyzed traits. The length of the main tiller was positively correlated with most of the traits in the hybrid lines but negatively correlated with those in the wheat cultivars. A similar negative correlation for the length of the main tiller and grain yield in wheat cultivars has been reported by Naghavi et al. (2015). Kociuba (2007) noted a positive correlation between the length of the main tiller in hybrid lines of triticale and wheat and 1,000-grain weight. According to the author, this may be significant in newly introduced short-straw forms of triticale. Nowosad et al. (2018) also reported a statistically positive correlation between the length of the spike and the height of the plant \((r = 0.334)\) in winter rye F\(_2\) hybrids.

Mandea et al. (2019) reported a strong negative correlation in wheat cultivars between the number of spikes per 1 m\(^2\) and the number of grains per spike. Naghavi and Khalili (2017) found wheat grain yield to be positively correlated with rachis length and the NPT.

The UPGMA method has been widely used for the analysis of morphological traits in plant breeding (Carović-Stanko et al., 2011; Dossou-Aminon et al., 2014; Silva et al., 2017). Cluster analysis performed by the UPGMA method distinguished five homogeneous groups. The distribution structure of the genotypes into five distinct clusters indicated considerable genetic diversity among the genotypes for most of the traits analyzed. Twenty-eight genotypes grouped into five clusters showed inter-cluster diversity. Cluster I consisted of six genotypes – three hybrid lines (VR, RV, and KRKo) and three parental wheat cultivars (‘Muza’, ‘Gama’, and ‘Begra’). Cluster II had the highest number of genotypes (43%) and was comprised of seven hybrid lines (KRB, KRG, KRS, KRZ, KRMu, KRP, and KRBS) and five parental forms of wheat (‘Monopol’, ‘Piko’, ‘Korweta’, ‘Smuga’, and ‘Zyta’). Cluster III was formed by three hybrid lines (KRMo, KRT, and KRBT) and a single wheat cultivar (‘Turnia’). Cluster IV was also represented by three hybrid lines (KR, RK, and KRBP) and a single wheat cultivar (‘Rusalka’). Cluster V was formed by the wild Aegilops species. UPGMA employs a sequential clustering algorithm, in which local topological relationships are inferred in order of decreasing similarity and a dendrogram is built in a stepwise manner. First, the two closest data points are identified and grouped in the dendrogram. After the first clustering, the two closest data points are treated as a single data point and new distances are computed using the average of the distances between a simple data point and the constituents of the composite data point. Then, the next closest data points are added to the dendrogram until all data points are included (Sneath & Sokal, 1973; Sokal & Rohlf, 1962).

Cluster analysis for various productivity traits provided more information about the genetic diversity among hybrid lines and their parental components. The selection of hybrid lines for higher grain yield based on these traits could be useful for further breeding.

5. Conclusions

The evaluated hybrid lines had a greater diversity of productivity traits than the wheat parental components and could be valuable starting material in wheat breeding. Particularly noteworthy are the lines KRBP, with the shortest tillers, and KRBT, with the greatest basal stem diameter, longest spikes, and a high 1,000-grain weight. In the hybrid lines, the main tiller length and basal stem diameter were positively correlated with fertility and 1,000-grain weight. In contrast, wheat showed...
negative correlations between these quantitative traits. The results confirm that wide hybrids can be used to eliminate the negative correlations between these traits in wheat to increase its fertility. The results of the research will facilitate the selection of appropriate genotypes for further breeding work.

References

Aharizad, S., Sabzi, M., Mohammadi, S. A., & Khodadadi, E. (2012). Multivariate analysis of genetic diversity in wheat (Triticum aestivum L.) recombinant inbred lines using agronomic traits. *Annals of Biological Research, 3*, 2118–2126.

Alemu, G., Mohammed, H., & Asnake, D. (2018). Analysis of genotype by environment interaction for agronomic traits of bread wheat (Triticum aestivum L.) genotype in Ethiopia. *Open Access Journal of Agricultural Research, 3*(8), Article 000191. https://doi.org/10.23880/OAJAR-16000191

Ansari, A. R., & Bradley, R. A. (1960). Rank-sum tests for dispersions. *Annals of Mathematical Statistics, 31*, 1174–1189. https://doi.org/10.1214/aoms/1177705688

Arain, S. M., Sial, M. A., Jamali, K. D., & Laghari, K. A. (2018). Grain yield performance, correlation, and cluster analysis in elite bread wheat (Triticum aestivum L.) lines. *Acta Agrobotanica, 71*(4), Article 1747. https://doi.org/10.5586/aa.1747

Brzozowska, I., Brzozowski, J., & Hruszka, M. (2008). Yielding and yield structure of winter wheat in dependence on methods of crop cultivation and nitrogen fertilization. *Acta Agrophysica, 11*(3), 597–611.

Buraczyńska, D., & Ceglarek, F. (2008). Yield of winter wheat cultivated after various forecrops. *Acta Scientiarum Polonorum, Agricultura, 7*(1), 27–37.

Carović-Stanko, K., Šalinowić, A., Gridiša, M., Liber, Z., Kolak, I., & Satowic, Z. (2011). Efficiency of morphological traits descriptors in discrimination of Ocimum basilicum L. accessions. *Plant Biosystems, 145*(2), 298–305. https://doi.org/10.1080/11263504.2011.558677

Coriton, O., Barloy, D., Huteau, V., Lemoine, J., Tanguy, A. M., & Jahier, J. (2009). Assignment of Aegilops variabilis Eig. chromosomes and translocations carrying resistance to nematodes in wheat. *Genome, 52*(4), 338–346. https://doi.org/10.1139/ G09-011

Dossou-Aminon, I., Loko, L. Y. E., Adjatin, A., & Dansi, A. (2014). Diversity, genetic erosion and farmer’s preference of sorghum varieties [Sorghum bicolor (L.)] in north-eastern Benin. *International Journal of Current Microbiology and Applied Sciences, 3*(10), 531–552.

Franco, J., Crossa, J., Ribaut, J. M., Betran, J., Warburton, M. L., & Khairallah, M. (2001). A method for combining molecular markers and phenotypic attributes for classifying plant genotypes. *Theoretical and Applied Genetics, 103*, 944–952. https://doi.org/10.1007/s0012200100641

Głowacka, A. (2010). Plonowanie i struktura plonu pszenicy jarej w zależności od różnych metod uprawy i pielęgnacji [Yielding and yield structure of spring wheat in dependence on different systems of cultivation and tending]. *Biuletyn Instytutu Hodowlí i Aklimatyzacji Roślin*, 256, 73–80.

Knott, D. R., & Dvořák, J. (1981). Agronomic and quality characteristics of wheat lines with leaf rust resistance derived from Triticum speltoides. *Canadian Journal of Genetics and Cytology, 23*, 475–480. https://doi.org/10.1139/g81-052

Kociuba, W. (2007). Charakterystyka zasobów genowych pszenizny zgromadzonych w latach 1998–2005 [Characterization of genetic resources of tritcale (×Triticosecale Wittmack) collected in 1998–2005]. *Zeszyty Problebowe Postępów Nauk Rolniczych*, 517(1), 369–377.

Loureiro, I., Escorial, M. C., Garcia-Baudin, J. M., & Chueca, M. C. (2007). Hybridization between wheat (Triticum aestivum) and the wild species Aegilops geniculata and A. biuncialis under experimental field conditions. *Agriculture, Ecosystems & Environment, 120*(2–4), 384–390. https://doi.org/10.1016/j.agee.2006.10.015

Mandea, V., Mustățea, P., Marinici, C. M., Șerban, G., Meluca, C., Păunescu, G., Istitioiaia, S. F., Dragomir, C., Bunta, G., Filiche, E., Voinea, L., Loboiațiu, I., Domokos, Z., Voica, M., Ittu, G., & Săulescu, N. N. (2019). Yield components compensation in winter wheats (Triticum aestivum L.) is cultivar dependent. *Romanian Agricultural Research, 36*, 27–33.

Marais, G. F., McCallum, B., Snyman, J. E., Pretorius, Z. A., & Marais, A. S. (2005). Leaf rust and stripe rust resistance genes Lr54 and Yr37 transferred to wheat from Aegilops kotschyi. *Plant Breeding, 124*, 538–541. https://doi.org/10.1111/j.1439-0523.2005.01116.x
Prażak, R., & Gawroński / Diversity of traits in Aegilops with Triticum lines

Mollasadeghi, V., Elyasi, S., & Mirzamasoumzadeh, B. (2012). Genetic variation of 12 bread wheat genotypes based on number of phonological and morphological traits. *Annals of Biological Research, 20*, 4734–4740.

Morris, J. R. (2009). Characterization of sesame (*Sesamum indicum* L.) germplasm regenerated in Georgia, USA. *Genetic Resources and Crop Evolution, 56*, 925–936. https://doi.org/10.1007/s10722-009-9411-9

Naghavi, M. R., & Khalili, M. (2017). Evaluation of genetic diversity and traits relations in wheat cultivars under drought stress using advanced statistical methods. *Acta Agriculturae Slovaca, 109*(2), 403–415. https://doi.org/10.14720/ajas.2017.109.2.23

Naghavi, M. R., Moghaddam, M., Toorchi, M., & Shakiba, M. R. (2014). Evaluation of the relationship between morphological and agronomic traits with grain yield in spring wheat cultivars under drought stress. *International Journal Biosciences, 5*(3), 88–93. https://doi.org/10.12692/ijb/5.3.88-93

Naghavi, M. R., Toorchi, M., Moghaddam, M., & Shakiba, M. R. (2015). Evaluation of diversity and traits correlation in spring wheat cultivars under drought stress. *Notulae Scientiae Biologicae, 7*(3), 349–354. https://doi.org/10.15835/nlb.7.3.9592

Nowosad, K., Łącka, A., & Bocianowski, J. (2018). Charakterystyka mieszańców *F* motyli w *Secale cereale* L. pod względem wybranych cech ilościowych [Characteristic of selected qualitative traits for *F*₂ hybrids of winter rye (*Secale cereale* L.)]. *Fragmenta Agronomica, 35*(2), 71–78. https://doi.org/10.26374/fa.2018.35.17

Pasandi, M., Jannohammadi, M., Movahedi, Z., & Sabaghnia, N. (2015). Gruping bread wheat genotypes and lines based on some morphological traits using multivariate analysis. *Cercetări Agronomice în Moldova, 3*(163), 13–22. https://doi.org/10.1515/cerce-2015-0037

Pilch, J. (1996). Performance of interspecific and intergeneric hybrids of *Triticum aestivum* L. for wheat improvements. Part I. Performance of winter generations *F*₂–*F*₃ of *T. aestivum* L. with *Aegilops* (*2x, 4x*), *Secale* (*2x, 4x*) and *Elymus* (*4x*) species in respect of some characters of spike. *Plant Breeding and Seed Science, 40*(3–4), 73–82.

Pilch, J. (1997). Performance of interspecific and intergeneric hybrids of *Triticum aestivum* L. for wheat improvements. Part II. Breeding value of spring-type generations *F*₁₀ of *T. aestivum* L. with *Aegilops* (*2x, 4x*), *Secale* (*2x*) and *Hordeum* (*2x*) species in respect of some characters of spike. *Plant Breeding and Seed Science, 41*(1), 3–15.

Prażak, R., & Krzepilko, A. (2018). Evaluation of iron and zinc content in grain of *Aegilops L.* × *Triticum aestivum* L. hybrid lines. *Journal of Elementology, 23*(2), 545–557. https://doi.org/10.5601/jelem.2017.22.3.1486

Prażak, R., & Molas, J. (2017). Evaluation of protein content in grain of *Aegilops L.* × *Triticum aestivum* L. hybrid lines. *Polish Journal of Agronomy, 29*, 35–42. https://doi.org/10.5601/jelem.2016.21.1.1124

Reynolds, M., Foulkes, M. J., Slafer, G. A., Berry, P., Parry, M. A. J., Snape, J. W., & J, A. W. (2009). Raising yield potential in wheat. *Journal of Experimental Botany, 60*(7), 1899–1918. https://doi.org/10.1093/jxb/erp016

Silva, A. D. C. C. D., Sabiá, R. R., Chiamolera, F. M., Segantini, D. M., & Martins, A. B. G. (2017). Morphological traits as tool to verify genetic variability of interspecific dragon fruit hybrids. *Revista Brasileira de Fruticultura, 39*(1), Article e-168. https://doi.org/10.1590/0100-29452017168

Slafer, G. A., Savin, R., & Sadras, V. O. (2014). Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crop Research, 157*, 71–83. https://doi.org/10.1016/j.fcr.2013.12.004

Sneath, P. H., & Sokal, R. R. (1973). *Numerical taxonomy*. W. H. Freeman and Company.

Sokal, R. R., & Rohlf, F. J. (1962). The comparison of dendrograms by objective methods. *Taxon, 11*, 33–40. https://doi.org/10.2307/1217208

Tyrka, M., & Stefanowska, G. (2001). Ocena zróżnicowania cech płonotwórczych mieszańców *Aegilops juvenalis* i *Aegilops ventricosa* z pszenicą [Estimation of diversity of yield forming traits in hybrids of *Aegilops juvenalis* and *Aegilops ventricosa* with wheat]. *Buletyn Instytutu Hodowli i Aklmatyzacji Roślin, 2001*(218–219), 57–68.

Woźniak, A. (2006). The yield and quality of grain of spring wheat (*Triticum aestivum* L.) and hard wheat (*Triticum durum* Desf.) in dependence on agrotechnical level. *Acta Agrophysica, 8*(3), 755–763.

Węgrzyn, S. (2001). Możliwości wykorzystania metod statystycznych do opracowania wyników doświadczeń w hodowli roślin [An application of some statistical methods in plant breeding trial]. *Biuletyn Instytutu Hodowli i Aklmatyzacji Roślin, 2001*(218–219), 5–14.
Zecevic, V., Boskovic, J., Dimitrijevic, M., & S, P. (2010). Genetic and phenotypic variability of yield components in wheat (Triticum aestivum L.). Bulgarian Journal of Agricultural Science, 16, 422–428.