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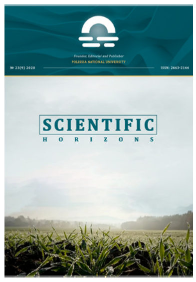

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Definition of Performance Determinants in Spring Barley by Path Analysis

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Abstract. Ambiguous results of pairwise correlation analyses and pathway analyses were obtained from different researchers. Therefore, the study of the correlation of traits and conducting a road analysis of the productivity of new genotypes using different sets of traits is relevant. The purpose of this study was to establish the correlation coefficients between the characteristics of spring barley, their direct and side effects on plant productivity, and to identify the determinants of plant selection. The research used the correlation method to determine the correlation coefficients between traits, and the method of path analysis – to establish the direct and side effects of traits on plant productivity. The positive analysis of plant productivity in the variant using quantitative traits without components of productivity revealed positive direct effects in the action on productivity and positive correlation with it traits productive bushiness as determinants of forecasting the effectiveness of high-yielding plants. In the variant using plant productivity and traits of the mass of grain from the main ear and afterspring, the path analysis found that only these two traits had a considerable direct and indirect effect in interaction with other traits on plant productivity, as well as average and high (respectively) correlation with it. Therefore, in the case of determining the mass of grain from the main ear or from the afterspring, these two separate features can also be used as determinants of the forecast of the efficiency of selection of high-yielding plants

Keywords: *Hordeum vulgare* L., quantitative trait, prediction selection efficiency, correlation, direct and effects of traits, plant performance

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INTRODUCTION

Different studies (Demidov *et al.*, 2017; Gocheva, 2014; Budacli Carpiri, 2017) on barley demonstrate the importance of determining correlations between individual traits (plant constituents, yield, weight spike) and of path analysis of the main trait, namely the plant performance. Oppositely directed (positive or negative) correlation coefficients (Hailu *et al.*, 2016; Shrimali *et al.*, 2017; Abdullah and Rihan, 2018) as well as direct and side effects of individual traits on the plant performance were determined (Gebru *et al.*, 2018; Matin *et al.*, 2019; Fatemi *et al.*, 2019). They were ambiguous depending on the accessions under study and environmental conditions. This justifies the topicality of such studies on new spring barley material, especially, on material that is used in combinatory breeding, and under various conditions of cultivation years. The authors of this paper used different sets of traits in path analysis of the performance. In analysis 1, only seven simple quantitative traits were used.

In path analysis 2, apart from simple traits (as in analysis 1), the authors used the following traits — constituents of the plant performance: grain weights per the main spike and per afterspring (i.e., from other spikes).

The grain weights per afterspring and per the main spike can be used as determinants to predict the selection of high-yielding plants.

Results of authors on the patterns of pair correlations between the individual traits of spring barley cultivars and lines as new stating material in combinatory breeding, as well as on direct and indirect effects of different traits on the plant performance are somewhat different from other researchers' results.

Availability of valuable starting material with desirable characteristics for crossing to obtain recombinant biotypes is one of the main challenges in the combinatory breeding of agricultural crops. Therefore, it is necessary to know its value both by certain traits and by their assemblages in the genotype, where they are interrelated, as the level of each of them depends on the values of other traits. In addition, relationships may depend on both genotype and growing conditions. Therefore, it is feasible to determine correlations between plant traits in cultivars and lines with different genotypic features in variable environmental conditions.

The purpose of this study was to establish the correlation between traits in spring barley cultivars and lines using pair correlation coefficients and path analysis of the plant performance (grain weight) and to define, on this basis, determinants predicting the efficiency of selection of highly productive plants.

LITERATURE REVIEW

At various stages of breeding, the selection of plants with desirable valuable traits (the effectiveness of which depends on the knowledge on correlations between them) is an essential element (Demydov *et al.*, 2017). Different researchers designed their studies to find correlations between quantitative traits of barley plants in various sets of starting materials and under various conditions. They reported positive correlations between the plant performance and other traits, in particular R. Rahimi-Baladezaie *et al.* (2011) reported positive correlations between the plant performance and productive tillering as well as between the plant performance and the grain number per spike; J. Shrimali *et al.* (2017) positive correlations were found in the plant performance with productive tillering, plant height, spike length, 1000-grain weight, and spikelet number per spike; M. Gocheva (2014) showed positive correlations of the plant performance with productive tillering, grain weight per spike, grain number per spike, and 1000-grain weight.

There were also positive correlations between other quantitative traits: between productive bushiness and the grain number per spike in R. Rahimi-Baladezaie *et al.* publication (2011); between the 1000-grain weight and grain weight per spike, between grain weight per spike and plant height, between the grain number per spike and spike length, between the grain number per spike and plant height, between the grain number per spike and spike length as well as between spike length and plant height in a study of Budacli, E. Carpici and N. Celik (2012); between the grain number per spike and grain weight per spike as well as between the grain number per spike and spike length in A. Abdullah and H. Rihan study (2018); between the total and productive tillering and plant height, between the spikelet number per spike and productive tillering, between the spikelet number per spike and plant height, between 1000-grain weight and plant height as well as between 1000-grain weight and total tillering in J. Al-Tabbal and A. Al-Fraihat study (2012); between spike length and the spikelet and grain numbers per spike, between the spikelet number per spike and grain number per spike as well as between 1000-grain weight and grain weight per spike (Gocheva, 2014).

In contrast to the above positive correlations, there were negative correlations between plant height and 1000-grain weight, between plant height and spike length, between 1000-grain weight and spike length as well as between 1000-grain weight and grain number per spike Budacli, E. Carpici and N. Celik (2012); between 1000-grain weight and the spikelet and grain numbers per spike A. Abdullah and H. Rihan (2018); between the spikelet number per spike and total tillering as well as between the spikelet number per spike and 1000-grain weight J. Al-Tabbal and A. Al-Fraihat (2012); between productive tillering and grain weight and number per spike, between 1000-grain weight and spike length, between 1000-grain weight and the spikelet number per spike as well as between 1000-grain weight and grain number per spike (Gocheva, 2014).

Correlations may be changed by growing conditions: between different elements of the plant structure depending on a growing location in A. Hailu *et al.*

experiments (2016), between plant characteristics under various watering conditions (Shrimali *et al.*, 2017).

Although pair correlation coefficients are important in determining relationships between individual quantitative traits of plants, they cannot detect relationships between trait assemblages. To evaluate the contribution of each trait to the plant performance (direct effects and side or indirect effects), path analysis of the main trait is used, analysis of the plant performance (grain weight) according to Wright's method (1934). Due to this, determinant traits are defined as criteria for predicting effective selection of plants for the main trait.

Different researchers pointed out the importance of path analysis as an effective method of statistical analysis of causes and effects in the system of interrelated characteristics of barley (plant performance, its constituents, yield, etc.) (Tawfiq *et al.*, 2016; Mirosavljević *et al.*, 2016; Bocianowski *et al.*, 2016).

In researchers' different quantitative traits were found to have positive direct effect on the plant performance: productive tillering, grain number per spike, plant height, spike, and growing period in T. Setotaw *et al.* (2014) experiments; productive tillering, as R. Drikvand published (2011); and biological yield of the plant in R. Tanaka and H. Nakano study (2019).

Different researchers used path analysis and detected different determinants as criteria of selection driven by a high positive effect on the performance and a significant correlation with it: M. Ataei (2006) suggested spike length and spikelet number per spike; R. Drikvand (2011) – productive tillering; and T. Setotaw *et al.* (2014) – vegetation period.

Thus, different researchers have proven the feasibility of determining the relationships between the main and other traits of plants using both pair correlation coefficients and path analysis of the main trait to establish direct and indirect effects of interrelated traits. However, in their studies on different barley cultivars, in different geographical locations and under various growing conditions, ambiguous results (positive or negative, moreover for different traits) were obtained on pair correlations between the performance and other quantitative traits; the same can be said about the results of path analysis the performance. Therefore, studies of correlation between traits and path analysis of the performance of new genotypes with various levels of features in different years are relevant.

MATERIALS AND METHODS

Twenty-two cultivars (Vzirets, Amil, Avhur, Ahrarii, Khors, Troian, Rezerv, Sviatomykhailivskyi, Talisman Myronivskyi, KWS Bambina, Datcha, Grace, Gladys, Quench, Margret, Merlin, Gatunok, Akhiles, Yavir, Kontrast, Krechet and Modern) and three lines (15-1246, 14-561 and 15-139) of spring barley were studied. Among them, there were two-row and six-row, awny and awnless, chaffy and naked accessions.

The cultivar trials were conducted according to the methods of qualification examination of plant varieties in 2018-2020. The predecessor was grain pea. Barley was sown with a breeding seeder SSFK-7. The plot area was 10 m^2. The experiments were carried out in four replications. The farming techniques were traditional for the crop (ploughing, tilling, spraying herbicide against weeds). Grain was harvested with a breeding combine harvester Hege-125. Plants were manually selected for analysis.

During the growing periods, phenological observations were made to determine the growing period length and to assess lodging resistance on a 9-point scale.

The plant habitus was analysed on 30 plants of each accession for 8 traits (height, productive tillering, spike length, grain number per spike, grain weight per the main spike, grain weight per afterspring (i.e., from other spikes), 1000-grain weight, grain weight per plant (performance).

In 2018-2020, the weather during the growing period of spring barley was very variable: very hot and dry in 2018; hot and dry, but with significant rainfall in May in 2019; relatively favourable in 2020. This allowed for objective evaluation of the test material.

Correlation coefficients and path analysis of performance was conducted by Wright's (1934) method and by Bryman and Cramer's method (1990) in *STATISTICA 10* to calculate the path coefficients of direct effects, as well as by factorising the correlation coefficients between the performance and each of the seven (nine) traits on the direct effect of the trait and side effects of others to obtain a matrix of corresponding path coefficients.

RESULTS AND DISCUSSIONS

In 2018-2020, the peculiarities of the pair correlation coefficients for 10 quantitative traits in 22 cultivars and three lines of spring barley were established and path analysis of the plant performance (grain weight) was conducted.

Pair correlation coefficients of the quantitative traits

Over the three study years, the relationships between the plant performance (main trait), its constituents (productive tillering, grain number per the main spike and 1000-grain weight), its components (grain weight per the main spike and grain weight per after spring), other traits (plant height and spike length), the growing period length and lodging resistance were determined (Table 1).

***Table 1**. Correlation coefficients between the traits in spring barley*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per the main spike	Grain weight per the main spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance
Productive tillering	2018	0.44*	1	–	–	–	–	–	–	–
	2019	-0.08	1	–	–	–	–	–	–	–
	2020	0.25	1	–	–	–	–	–	–	–
Spike length	2018	0.68*	0.64*	1	–	–	–	–	–	–
	2019	0.60*	0.19	1	–	–	–	–	–	–
	2020	0.19	0.37	1	–	–	–	–	–	–
Grain number per the main spike	2018	0.24	0.15	0.03	1	–	–	–	–	–
	2019	0.03	-0.20	-0.13	1	–	–	–	–	–
	2020	0.14	-0.30	-0.03	1	–	–	–	–	–
Grain weight per the main spike	2018	0.30	0.31	0.34	0.77*	1	–	–	–	–
	2019	0.03	-0.20	-0.11	0.85*	1	–	–	–	–
	2020	0.08	-0.11	0.22	0.49*	1	–	–	–	–
Grain weight per afterspring	2018	0.43*	0.81*	0.43*	0.33	0.29	1	–	–	–
	2019	0.06	0.76*	0.23	0.18	0.28	1	–	–	–
	2020	0.13	0.49*	-0.10	-0.05	0.32	1	–	–	–
1000-grain weight	2018	0.07	-0.23	-0.07	-0.06	0.07	-0.19	1	–	–
	2019	0.37	0.04	-0.13	-0.24	-0.04	0.03	1	–	–
	2020	0.39	0.02	-0.09	-0.05	0.35	0.23	1	–	–
Growing period	2018	-0.06	0.04	0.19	-0.15	-0.13	-0.10	-0.46*	1	–
	2019	-0.18	-0.03	0.12	-0.20	-0.21	0.02	-0.29	1	–
	2020	-0.60*	0.00	0.21	-0.23	-0.04	-0.18	-0.29	1	–
Lodging resistance	2018	-0.08	0.20	0.06	0.21	0.37	0.23	-0.24	0.38	1
	2019	-0.36	-0.01	0.02	0.14	0.08	0.10	-0.35	0.31	1
	2020	-0.20	-0.16	-0.03	0.10	0.35	0.01	0.45*	-0.02	1
Performance (Grain weight per plant)	2018	0.47*	0.79*	0.48*	0.56*	0.61*	0.94*	-0.14	-0.13	0.32
	2019	0.06	0.46*	0.12	0.56*	0.71*	0.87*	0.00	-0.10	0.12
	2020	0.14	0.39	-0.03	0.10	0.57*	0.96*	0.30	-0.17	0.10

***Note**: * – significant at P=0.05*

The plant performance significantly, positively, and moderately correlated with productive tillering in 2018 and 2019 (r=0.79, 0.046 and 0.39 in 2018, 2019 and 2020, respectively); with the grain number per the main spike in 2018 and 2019 (r=0.056, 0.50 and 0.10, respectively), grain weight per the main spike (r=0.61, 0.71 and 0.57, respectively). The correlation was significant, positive and very strong between the performance and the grain weight per after spring (r=0.94, 0.87 and 0.96, respectively).

The 'performance – plant height' correlation was rather ambiguous across the years: significant in 2018 only (r=0.47, 0.06 and 0.14, respectively); the 'performance – spike length height' correlation was also significant in 2018 only (r=0.48, 0.12 and −0.03, respectively). The 'performance – 100-grain weight' correlation (r=−0.14, 0.00 and 0.30, respectively), the 'performance – lodging resistance' correlation (r=0.32, 0.12 and 0.10, respectively) and the 'performance – growing period' correlation (r=– 0.13, −0.10 and −0.17, respectively) were insignificant.

Thus, the pair correlation coefficients demonstrated positive correlations between the performance, productive tillering, and grain weight per afterspring. The correlation coefficients were also positive in 2018 and 2019 for the 'performance – grain number' correlation (significant in 2018 and 2019), for the 'performance – grain weight per the main spike' correlation, for the 'grain weight per the main spike – and the grain number per the main spike' correlation, for the 'spike length – plant height' correlation (significant in 2018 and 2019), and for the 'grain weight per afterspring – productive tillering' correlation. The '1000-grain weight – growing period' and 'grain number per the main spike – growing period' correlations were insignificant, with a negative trend.

Path analysis of the plant performance

As a result of determining the correlation coefficients for

2018, 2019 and 2020 between one of the 9 traits and other traits, between performance (main trait) and each of the 9 traits, as well as the path coefficients of each trait as direct effects on the performance, the correlation coefficients between the performance and each of the 9 quantitative traits were fractionalised on their direct and side (indirect) effects of the other 8 traits in the 22 varieties and three lines of spring barley under investigation.

In path analysis 1 of the performance, only seven simple quantitative traits were used (productive tillering, grain number per the main spike, 1000-grain weight, plant height, spike length, growing period, and lodging resistance). The results of the correlation fractionalisation are summarised in Table 2 – the matrix of path coefficients of each of the seven traits directly affecting the performance and side effects of the other six traits that make up a "cause-effect" system.

Table 2. *Path analysis 1 of the spring barley plant performance (Grain weight per plant) using seven traits*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	1000-grain weight	Growing period	Lodging resistance	Grain weight per plant
Plant height	2018	0.099	0.289	-0.005	0.089	0.000	0.009	-0.014	0.468*
	2019	-0.110	-0.046	0.120	0.023	0.100	-0.019	-0.012	0.056
	2020	-0.261	0.144	0.010	0.029	0.155	0.070	-0.012	0.135
Productive tillering	2018	0.043	0.662	-0.004	0.056	0.000	-0.006	0.037	0.789*
	2019	0.009	0.562	0.039	-0.160	0.011	-0.003	0.000	0.458*
	2020	-0.066	0.573	-0.047	-0.091	0.009	0.000	0.012	0.389
Spike length	2018	0.067	0.425	-0.007	0.013	0.000	-0.030	0.011	0.480*
	2019	-0.066	0.109	0.200	-0.105	-0.036	0.012	0.001	0.115
	2020	-0.049	0.212	-0.126	-0.010	-0.034	-0.025	0.002	-0.027
Grain number per spike	2018	0.023	0.099	0.000	0.375	0.000	0.025	0.037	0.560*
	2019	-0.003	-0.114	-0.027	0.789	-0.064	-0.021	0.004	0.564*
	2020	-0.036	-0.170	0.004	0.305	-0.020	0.027	-0.008	0.095
1000-grain weight	2018	0.007	-0.149	0.001	-0.023	-0.002	0.074	-0.043	-0.135
	2019	-0.040	0.023	-0.027	-0.186	0.272	-0.030	-0.012	0.000
	2020	-0.103	0.013	0.011	-0.016	0.394	0.034	-0.034	0.303
Growing period	2018	-0.005	0.024	-0.001	-0.058	0.001	-0.162	0.069	-0.133
	2019	0.020	-0.015	0.023	-0.160	-0.079	0.104	0.010	-0.097
	2020	0.156	0.000	-0.026	-0.070	-0.114	-0.117	0.001	-0.169
Lodging resistance	2018	-0.007	0.135	0.000	0.078	0.000	-0.062	0.181	0.325
	2019	0.039	-0.004	0.005	0.107	-0.096	0.032	0.033	0.115
	2020	0.053	-0.091	0.004	0.031	0.179	0.002	-0.074	0.105
Performance (Grain weight per plant)	2018	0.468	0.789	0.480	0.560	-0.135	-0.133	0.325	1.0
	2019	0.057	0.458	0.115	0.564	0.000	-0.097	0.115	1.0
	2020	0.139	0.389	-0.027	0.095	0.303	-0.169	0.105	1.0

Note: *unaccounted factors (residues) ranged from 0.001 to 0.01;* – significant at P=0.05*

The matrix structure corresponds to a system of seven equations with seven direct effects multiplied by the correlation coefficient of the respective seven traits.

Path analysis of the performance showed that the direct effects of each of the seven traits on the performance (on the central diagonal of Table 2), side effects of the other six traits in the 'each of the seven traits – performance' correlations (horizontally of each of the seven traits), and side effects of each of the seven traits in the 'performance – the other six traits' correlations (vertical of each of the seven traits) were not equal, and their values and directions depended on the years of plant cultivation.

Thus, it was found that the strong or moderate in 2018-2019 and insignificant in 2020 correlation coefficients between the performance and productive tillering (r=0.789, 0.458 and 0.389, respectively, across the years) depended on a significant direct positive effect of the latter (0.662, 0.562 and 0.573, respectively) and on insignificant in 2018 positive side effects of the plant height, grain number per main spike, and lodging resistance (0.043, 0.056 and 0.037, respectively); in 2019, on a negative effect of the grain number per main spike (−0.160) and a positive effect of the spike length (0.039); in 2020; slight negative effects of the plant height (−0.066), spike length (−0.0147) and the grain number per main spike (−0.091).

The moderate in 2018 and 2019 and insignificant in 2020 correlation coefficient between the performance and grain number per the main spike (r=0.560, 0.564 and 0.095, respectively, across the years) depended on the significant direct effect of the latter (0.375, 0.789 and 0.305, respectively); in 2018, on the cumulative slight positive side effects of the plant height (0.023), productive tillering (0.099), growing period (0.025) and lodging resistance (0.037) (the sum amounted to 0.184); in 2019 – on negative side effects of productive tillering (−0.114), spike length (−0.027), 1000-grain weight (−0.064), and growing period (−0.021) (the sum amounted to −0.226); in 2020, on negative side effects, mainly of productive tillering (– 0.170), which considerably offset the direct effect (0.305), so the correlation was very weak (r=0.095).

The correlation coefficient between the performance and plant height was ambiguous across the years, reaching significance in 2018 only (r=0.468, 0.056 and 0.135, respectively). This can be attributed to the fact that in 2018 there was a positive direct effect of the plant height, a slight side effect of the grain number per the main spike, and a significant effect of productive tillering (0.099, 0.089 and 0.289, respectively).

In the three years, the direct effect of the spike length on the performance varied (−0.007, 0.200 and −0.126, respectively): it was negligibly small in 2018 (but with a significant positive side effect of productive tillering (0.425) and slight effects of the plant height and other traits), positive in 2019 (with a positive side effect of productive tillering (0.109), but with a negative effect of the grain number per spike, plant height and 1000-grain weight (−0.105, −0.066 and −0.036, respectively), negative in 2020 (with a positive side effect of productive tillering (0.212), but with negative side effects of the plant height (−0.049), 1000-grain weight (−0.034) and growing period −0.025). All this resulted in various levels of correlation between the performance and spike length: moderate in 2018, very weak in 2019 and negligibly small in 2020 (r=0.480, 0.115 and −0.027, respectively).

Thus, under the arid conditions of 2018 and 2019, was a positive direct effect of productive tillering on the performance and a positive significant correlation between the performance and productive tillering (an constituent of the performance), which may be used as a determinant for prediction and selection of highly productive plants in arid conditions (which were in 2018 and 2019, while under the more favourable conditions in 2020, we only noticed a trend).

In path analysis 2 of the performance, all possible traits were used: not only seven simple traits (as in analysis 1), but also traits – components of the performance: grain weight per the main spike and grain weight per afterspring (i.e., grain from other spikes), which sum to the plant performance.

The results of fractionalisation of the correlations between the performance and nine traits are summarised in Table 3 – the matrix of path coefficients as direct effects of each of the nine traits on the performance and side effects of the other eight traits.

***Table 3**. Path analysis 2 of the spring barley plant performance using 10 traits*

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	Grain weight per spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance	Correlation with the performance
Plant height	2018	0.011	0.002	-0.018	-0.004	0.116	0.362	-0.001	-0.001	0.001	0.468*
	2019	-0.003	-0.001	0.007	0.000	0.015	0.041	0.000	0.002	-0.004	0.056
	2020	0.006	0.001	-0.003	-0.001	0.025	0.114	-0.001	-0.001	0.003	0.135
Productive tillering	2018	0.005	0.005	-0.017	-0.002	0.121	0.682	0.002	0.000	-0.004	0.789*
	2019	0.000	0.008	0.002	0.002	-0.100	0.548	0.000	0.000	0.000	0.458*
	2020	0.002	0.003	-0.006	0.002	-0.035	0.416	0.000	0.000	0.002	0.390
Spike length	2018	0.007	0.003	-0.026	-0.001	0.134	0.358	0.001	0.002	-0.001	0.480*
	2019	-0.002	0.002	0.012	0.001	-0.056	0.168	0.000	-0.001	0.000	0.115
	2020	0.001	0.001	-0.015	0.000	0.068	-0.090	0.000	0.000	0.000	-0.027
Grain number per spike	2018	0.003	0.001	-0.001	-0.016	0.304	0.278	0.001	-0.002	-0.004	0.560*
	2019	0.000	-0.002	-0.002	-0.008	0.438	0.129	0.000	0.003	0.001	0.564*
	2020	0.001	-0.001	0.001	-0.007	0.151	-0.046	0.000	0.000	-0.001	0.095
Grain weight per spike	2018	0.003	0.002	-0.009	-0.012	0.393	0.242	-0.001	-0.001	-0.007	0.609*
	2019	0.000	-0.002	-0.001	-0.007	0.515	0.199	0.000	0.003	0.001	0.708*
	2020	0.000	0.000	-0.003	-0.003	0.308	0.276	-0.001	0.000	-0.005	0.572*
Grain weight per afterspring	2018	0.005	0.004	-0.011	-0.005	0.113	0.837	0.002	-0.001	-0.004	0.940*
	2019	0.000	0.006	0.003	-0.001	0.143	0.718	0.000	0.000	0.001	0.869*
	2020	0.001	0.001	0.002	0.000	0.099	0.858	-0.001	0.000	0.000	0.960*

Table 3, Continued

Trait	Year	Plant height	Productive tillering	Spike length	Grain number per spike	Grain weight per spike	Grain weight per afterspring	1000-grain weight	Growing period	Lodging resistance	Correlation with the performance
1000-grain weight	2018	0.001	-0.001	0.002	0.001	0.026	-0.161	-0.011	-0.005	0.004	-0.135
	2019	-0.001	0.000	-0.002	0.002	-0.018	0.018	-0.001	0.004	-0.004	0.000
	2020	0.002	0.000	0.001	0.000	0.109	0.198	-0.003	0.000	-0.006	0.303
Growing period	2018	-0.001	0.000	-0.005	0.002	-0.052	-0.085	0.005	0.010	-0.007	-0.133
	2019	0.001	0.000	0.001	0.002	-0.110	0.012	0.000	-0.013	0.003	-0.097
	2020	-0.004	0.000	-0.003	0.002	-0.012	-0.156	0.001	0.001	0.000	-0.169
Lodging resistance	2018	-0.001	0.001	-0.002	-0.003	0.147	0.189	0.003	0.004	-0.019	0.325
	2019	0.001	0.000	0.000	-0.001	0.043	0.072	0.000	-0.004	0.011	0.115
	2020	-0.001	0.000	0.000	-0.001	0.107	0.005	-0.001	0.000	-0.013	0.105

***Note**: unaccounted factors (residues) ranged from 0.001 to 0.01; * – significant at P=0.05*

Path analysis of the performance showed that the direct effects of the nine traits and side effects of the other eight traits indirectly related to the performance through each of the nine traits unequally contributed to the performance.

The grain weight per the main spike had a positive direct effect on the performance in the three study years (2018-2020) (0.393, 0.515 and 0.308, respectively). In the relationships of this trait with the performance (horizontally), the side effect of the grain weight per afterspring (0.242, 0.199 and 0.246, relatively) was positive and the side effects of the other seven traits were insignificant. This was manifested as a significant positive correlation between the performance and the grain weight per spike (r=0.609, 0.708 and 0.572, respectively). For the three years, the side positive effect of the grain weight per spike in the relationships of the performance with other traits (vertically in Table 3) was with the grain number per spike (0.304, 0.438 and 0.151, respectively), grain weight per afterspring (0.113, 0.143 and 0.099, respectively), and lodging resistance (0.147, 0.043 and 0.107, respectively).

In all three years, the positive direct effect of the grain weight per afterspring (0.837, 0.718 and 0.858, respectively) on the performance was significant. In the relationships of this trait with the performance (horizontally), the positive side effect was exerted by the grain weight per the main spike (0.113, 0.143 and 0.099, respectively), while the side effects of the other traits were negligible. This was ultimately expressed in a very strong correlation between the performance and the grain weight per afterspring (r=0.940, 0.869 and 0.960, respectively). For all three years, the positive side effect of this trait in the relationships of the performance with other traits (vertically in Table 3) was noticed with the grain weight per spike (0.242, 0.199 and 0.246, respectively), productive tillering (0.682, 0.548 and 0.416, respectively) and plant height 0.362, 0.041 and 0.114, respectively).

The direct effects on the performance in the action of the other eight traits were negligible. Only due to significant, moderate, or weak, side effects of the grain weight per spike and the grain weight per afterspring, the correlation coefficient of some of them with the performance were positive.

Thus, there was a positive, mainly moderate, correlation between the performance and productive tillering (significant in 2018 and 2019 (r=0.793, 0.460 and 0.385, respectively), with almost zero direct effect of the latter (0.005, 0.008 and 0.003, respectively), but with a significant side effect of the grain weight per afterspring (0.682, 0.548 and 0.416, respectively). There was a moderate positive correlation between the performance and grain number per the main spike in 2018 and 2019 (r=0.563 and 0.559, respectively), which can be attributed to the side effects, mainly of the grain weight per the main spike (0.304 and 0.438, respectively) and the grain weight per afterspring (0.278 and 0.129, respectively). There was a moderate significant in 2018 and weak insignificant in 2019 correlation (r=0.477 and 0.124, respectively) between the performance and the spike length, mainly due to the positive side effect of the grain weight per afterspring (0.358 and 0.168, respectively). In 2018-2020, there was a positive correlation between the performance and the plant height (significant in 2018 (r=0.468, 0.056 and 0.135, respectively) due to the side effects, mainly of the grain weight per afterspring (0.362, 0.041 and 0.114, respectively) and the grain weight per the main spike (0.116, 0.015 and 0.025, respectively). There was a weak insignificant correlation in all three years between the performance and the growing period (r=–0.132, –0.104 and –0.171, respectively) mainly due to the negative side effects of the grain weight per the main spike (–0.052, –0.110 and –0.012, respectively) and the grain weight per afterspring (–0.085, –0.012 and –0.156, respectively). The correlation between the performance and the 1000-grain weight was insignificant and ambiguous across the years (r=–0.144, –0.002 and 0.302, respectively), with the ambiguous side effects of the grain weight per afterspring (–0.161, 0.028 and 0.198, respectively) and the grain weight per the main spike (0.096, –0.018 and 0.109, respectively).

Thus, the 'grain weight per the main spike' and 'grain weight per afterspring' traits as constituents of the plant performance have significant direct effects on the performance and significantly correlate with it. Therefore, these two traits are determinants predicting the effectiveness of selection of highly productive plants.

Different studies on barley demonstrated the importance of determining correlations between individual traits (plant constituents, yield, weight spike) and of path analysis of the main trait, in particular the plant performance. Oppositely directed positive correlation coefficients between different elements of the plant structure depending on a growing location (Hailu *et al.*, 2016), between the plant performance with productivity tillering, plant height, spike length, 1000-grain weight (Shrimali *et al.*, 2017), between the grain number per spike and grain weight per spike (Abdullah and Rihan, 2018) were showed. As well as direct and side effects of individual traits on the plant performance were determined (Gebru *et al.*, 2018; Matin *et al.*, 2019; Fatemi *et al.*, 2019). They were ambiguous depending on the studied accessions and environmental conditions. This justifies the topicality of such studies on new spring barley material, especially, on material that is used in combinatory breeding, and under various conditions of cultivation years.

Our results on the patterns of pair correlations between the individual traits of spring barley cultivars and lines as new stating material in combinatory breeding, as well as on direct and indirect effects of different traits on the plant performance are somewhat different from other researchers' results.

Thus, for all three years, there was a positive pair correlation between the plant performance and productive tillering and between the performance and the grain number per the main spike (significant under the arid conditions in 2018 and 2019). like in the experiments of R. Rahimi-Baladezaie *et al*. (2011), Shrimali (2017) (in addition, he found correlations of the plant performance with the plant height, spike length and 1000-grain weight), M. Gocheva (2014) (she also had a correlation between the plant performance and 1000-grain weight). In our study, there was also a positive correlation between the performance and the grain weight per the main spike, like in Gocheva' experiments (2014); and a positive correlation between the performance and the grain weight per afterspring.

These four traits (productive tillering, grain number per the main spike, grain weight per the main spike, and grain weight per afterspringt), proceeding from the positive pair correlation, but without taking into account the indirect effects of other traits, could be used as "guidepost" to select productive plants.

For all three years, there was a positive correlation between the grain weight per the main spike and the grain number per the main spike (but not between the grain weight per the main spike and the plant height) and between the spike length and the plant height (similar results were obtained by Budacli, E. Caprici and N. Celik (2012).

There was an insignificant, with a tendency to negative, correlation between the 1000-grain weight and the growing period and between the performance and the growing period. However, in Budacli Caprici and Celik' experiments (2012), there were negative correlations between other traits (plant height and 1000-grain weight, plant height and spike length, 1000-grain weight and spike length, 1000-grain weight and grain number per spike) and J. Shrimali *et al*. (2017) reported about negative correlations between the 1000-grain weight and the grain number per spike.

As different researchers pointed out, to establish the correlations between several traits, it is important to determine not only correlations between individual traits, but also their contributions to the main trait, namely to the plant performance, by their direct effects and side effects of other traits. In this regard, different researchers reported conflicting data: R. Drikvand *et al*. (2011) reported about a direct effect of productive tillering on the plant performance; M. Ataei (2006) – about direct effects of the spike length and spikelet number per spike on the performance; T. Setotaw *et al*. (2014) – about direct effects of productive tillering, grain number per spike, plant height, spike length and growing period; R. Tanaka and H. Nakano (2019) revealed the direct effect of the biological productivity of the plant. These traits also positively correlated with the plant performance and were therefore considered as predicting determinants or as selection criteria.

The authors of this study used different sets of traits in path analysis of the performance. In analysis 1, only seven simple quantitative traits were used. These traits (three constituents of the performance – productive tillering, grain number per spike ear and 1000-grain weight; other traits – plant height, spike length, growing period, and lodging resistance).

Here, the authors of this paper noticed the unequal direct and side effects of different quantitative traits on the performance; values and directions of these effects depended on the conditions of cultivation of 22 cultivars and three lines of spring barley in the study years.

In all three years, the positive direct effects on the performance were exerted by the following traits: productive tillering (0.662, 0.562 and 0.573, respectively) and the grain number per the main spike (0.375, 0.789 and 0.305, respectively).

Considering the positive and negative side effects of the other six traits, the results summed to the positive correlation coefficients between the performance and productive tillering (significant in 2018 and 2019, under the arid conditions (r=0.789, 0.458 and 0.389, respectively). These traits can be used as a predicting determinant in selection of highly productive plants, mainly under arid conditions, while under the more favourable conditions (in 2020), a tendency was only observed.

In path analysis 2 of the performance, we used, in addition to simple signs (as in analysis 1), the following traits – constituents of the plant performance: grain weights per the main spike and per afterspring (i.e., from other spikes).

These two components of the performance had significant direct and side (in interaction with other traits) effects on the performance. The positive side effect of these traits was with each other: grain weight per the main spike – grain number per the main spike, grain weight per afterspring – productive tillering; in two years, the positive side effects were with the plant height, spike length and grain number per the main spike. This was expressed in their positive correlations with the performance. The other traits did not have significant direct or side effects on the performance.

Another component of the performance, the grain weight per aftespting had a very strong direct effect (0.837, 0.718 and 0.858, respectively) on the plant performance and strongly correlated with it (r=0.940, 0.718 and 0.858, respectively). The grain weight per the main spike, as a component of the performance, had a significant direct effect on the performance (0.393, 0.515 and 0.308, respectively) and moderately correlated with it (r=0.609, 0.708 and 0.572, respectively). Therefore, the grain weights per afterspring and per the main spike can be used as determinants to predict selection of high-yielding plants.

CONCLUSIONS

According to the purpose of this study and the task to establish independence of the plant traits for three years (2018-2020), there were positive moderate coefficients of pair correlation between the plant performance and productive tillering (significant for 2018 and 2019 (r=0.789, 0.458 and 0.390, respectively, across the years), moderate coefficients (2018-2019) between the plant performance and the grain number per the main spike (r=0.789 and 0.458, respectively; insignificant r=0.095 in 2020), moderate coefficients (2018-2020) between the plant performance and the grain weight per the main spike (r=0.609, 0.708 and 0.572, respectively), and high coefficients between the plant performance and the grain weight per afterspring (r=0.940, 0.869 and 0.960, respectively). The positive interdependence of the following three traits was revealed: plant performance, productive tillering, and grain weight per afterspring.

The study established direct and side effects of the traits in path analysis of the plant performance using seven simple traits (productive tillering, grain number per the main spike, 1000-grain weight, plant height, spike length, growing period, and lodging resistance) and for all three years (2018-2020), the results showed the significant positive direct effects of productive tillering on the performance (significant in arid 2018 and 2019 [0.662, 0.562 and 0.573, respectively, across the years]) and positive moderate correlations with it (r=0.789, 0458 and 0.389, respectively), and therefore productive tillering constitutes a determinant predicting selection of highly productive plants.

Path analysis of the plant performance using both simple traits of plants and traits – constituents of the plant performance (grain weight per the main spike and grain weight per afterspring) established that only these two traits-components had significant direct effects (0.393, 0.515 and 0.308, respectively, and 0.837, 0.718 and 0.858, respectively, by traits and years) and side effects in interaction with other traits on the plant performance and moderately or strongly, respectively, correlated with it (r=0.609, 0.708 and 0.572, respectively, and r=0.940, 0.869 and 0.860, respectively). Therefore, the grain weights per the main spike and per afterspring can also be used as determinants to predict the effectiveness of selection of high-yielding plants, which are able to become valuable lines in the breeding process.

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Визначення детермінантів продуктивності ячменю ярого шляховим аналізом

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Анотація. В різних дослідників було одержано неоднозначні результати аналізів парної кореляції та шляхового аналізу. Тому дослідження кореляції ознак і проведення шляхового аналізу продуктивності нових генотипів з використанням різних наборів ознак є актуальним. Метою дослідження було встановлення коефіцієнтів кореляції між ознаками ячменю ярого, прямих і побічних їх ефектів на продуктивність рослини та визначення детермінантів добору рослин. У дослідженнях використано метод кореляції для визначення коефіцієнтів кореляції між ознаками, а метод шляхового аналізу — для встановлення прямих і побічних ефектів ознак на продуктивність рослини. Шляховим аналізом продуктивності рослин у варіанті з використанням кількісних ознак без складових продуктивності установлено позитивні прямі ефекти в дії на продуктивність і позитивну кореляцію з нею ознаки продуктивна кущистість як детермінанти прогнозу ефективності добору високопродуктивних рослин. У варіанті з використанням в шляховому аналізі продуктивності рослин також і ознак-складових її (маси зерна з основного колоса та підгону) установлено, що лише ці дві ознаки-складові мали значний прямий і побічний у взаємодії з іншими ознаками ефект в дії на продуктивність рослини, а також середній та високий (відповідно) рівень кореляції з нею. Тому, в разі визначення маси зерна з основного колоса або з підгону, ці дві окремі ознаки також можна використати як детермінанти прогнозу ефективності добору високопродуктивних рослин

Ключові слова: *Hordeum vulgare* L., кількісна ознака, прогноз ефективності добору, кореляція, прямий і побічний ефект ознак, продуктивність рослини