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Determination of ontogenetic selection criteria for grain yield in spring barley (*Hordeum vulgare*) by path-coefficient analysis

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Path-coefficient analysis was performed to determine the interrelationships among grain yield, yield components (spike number per m^{-2}, kernel number per spike, average kernel weight) and some phenological characteristics (duration and growing degree-days of vegetative and grain-filling periods) in spring barley genotypes in 2004-2005. Grain yield depended mainly on spike number per m^{-2} and kernel number per spike; average kernel weight had a negligible effect on grain yield in spring barley genotypes. Grain yield was significantly and positively associated with the spike number per m^{-2} and negatively correlated with other characteristics studied. Spike number per m^{-2} had considerable negative effect on the average kernel weight. A lengthening of the grain-filling period induced an increase in the average kernel weight and a positive and significant correlation was found between the two characteristics. Spike number per m^{-2} and kernel number had positive direct effects on grain yield in spring barley genotypes. The growing degree-days (GDD) for vegetative period had significant positive direct effect on kernel number, and the GDD for grain-filling period had significant positive direct effect on kernel weight. The results indicated that spike number per m^{-2}, kernel number per spike and the GDD for vegetative and grain filling period were the most reliable selection criteria for improving grain yield in spring barley in cool and short-season environments.

Key words: Correlation coefficient, path-coefficient analysis, *Hordeum vulgare*, grain yield and components, ontogenetic characteristics.

INTRODUCTION

Barley breeders are interested in developing cultivars with improved yield and other desirable characters of agronomic and phenological growth. In order to achieve this goal, the breeder has the option of selecting desirable genotypes in early generations or delaying intense selection until advanced generations (Puri et al., 1982). The selection criteria may be yield, or one or more of the yield components such as number of spikes per unit area, number of kernels per spike and kernel weight per spike (Grafius, 1964).

Grain yield is defined as the product of grain dry weight increment per unit area, per unit time and the duration of grain formation per unit time (Daynard et al., 1971). Aksel and Johnson (1961) found that barley with a long vegetative period tended to produce more kernels per spike and higher yields than those with a long grain-filling period. Bingham (1969) reported that a long vegetative period partly contributed to higher grain yield in common wheat (*Triticum aestivum* L.). Evans and Wardlaw (1976) showed that the contribution of pre-anthesis reserves to grain yield under optimal condition was 5 to 10% in wheat and 20% in barley. Garcia del Moral et al. (1991) found a positive association between the length of vegetative and grain-filling periods and grain yield in barley. Deniz (2007) found, however, a negative correlation between grain yield and the durations of vegetative and grain-filling periods in spring barley. Evans and Wardlaw (1976) indicated that there was a variation in cereals for duration

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Table 1. Average temperature, humidity and precipitation during the growing season in 2004 and 2005 in Erzurum.

Month	Precipitation (mm)			Temperature (^oC)			Humidity (%)		
	Long-term	2004	2005	Long-term	2004	2005	Long-term	2004	2005
May	70.5	121.7	92.1	10.6	9.7	10.6	60.0	63.5	72.2
June	47.9	40.7	70.0	14.9	14.5	13.9	56.0	52.8	67.9
July	27.4	2.4	20.3	19.3	17.9	20.2	50.0	41.9	55.2
August	17.1	1.3	24.3	19.4	19.6	20.2	47.0	41.1	54.8
Tot./Mean	162.9	166.1	206.7	16.1	15.4	16.2	53.3	49.8	62.5

of the vegetative and grain-filling periods. Thus, the optimum length of the two growth periods depends upon the environment, temperature in particular (Krenzer and Moss, 1975). Nass and Reiser (1975) reported that wheat genotypes with a high grain-filling rate and a short grain-filling period could produce high grain yields in short-season environments. Deniz (2007) also concluded that high yielding and short-season genotypes could be developed with short length of maturity duration.

Many researchers have used a linear correlation analysis to ascertain relationships between variables in barley (Rasmusson and Cannel, 1970; Rasmusson et al., 1979; Metzger et al., 1984; Garcia del Moral et al., 1985; Akkaya and Akten 1992; Deniz, 2007). Although these are helpful in determining the principal components influencing final grain yield, they provide an incomplete representation of the relative importance of the direct and indirect effects on the individual factors involved (Bhatt, 1973). Path-analysis can be used to partition the correlation coefficients obtained in such studies into direct and indirect effects. This allows separation of the direct effect of each yield component on grain yield from the indirect effects caused by the mutual associations among them (Dewey and Lu, 1959; Puri et al., 1982; Garcia del Moral et al., 1991; Dofing, 1995). Path analysis has been used successfully to clarify the interrelationships between yield and the characters of agronomic and phenological growth in barley (Tewari, 1976; Hamid and Grafius, 1978; Puri et al., 1982; Garcia del Moral et al., 1991; Dofing and Knight, 1992). Dashora et al. (1977) reported that positive and significant correlations were found between grain yield per unit area and number of kernels and kernel weight per spike. The direct effect on grain yield was positive only for kernel number per spike while kernel weight had a negative direct effect. Spring barley cultivars growing in cool and short-season environment required both early maturing and high yielding. However, negative association between these two characteristics limits their simultaneous improvement in barley (Dofing, 1995). Path-coefficient analysis was done to assess a better understanding of the relative influence of the phenological growth periods and yield components on grain yield for selection.

The main purpose of the study is to determine the interrelationships between duration and GDD of the vegetative and grainfilling periods on grain yield and yield components in spring barley genotypes.

MATERIALS AND METHODS

This field experiment was carried out in Erzurum, Turkey (40° 00´ N latitude, 1850 m altitude) over the summers of 2004 and 2005. The climate is continental and plant growing season is very short and cool (Table 1). Average temperatures along with humidity and precipitation during the growing season (May-August) were given in Table 1. In this experiment, the commercial 2-rowed spring barley (*Hordeum vulgare* L.) cultivar Tokak 157/37 and selected mutated lines from it in the M_{6-} and M_{7-} generations were evaluated.

The trials were seeded on 1 May in 2004 and 30 April in 2005. The experimental design was the randomized complete block with 3 replications. Each individual plot consisted of six rows of 3.0 m long and 0.20 m apart, with a space of 0.50 m between adjacent plots. Seeding rate was adjusted for kernel weight and 450 kernels per m^{-2} were targeted. Chemical fertilizer was applied at 40 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1} at seeding, and at another 40 kg N ha^{-1} at the beginning of stem elongation in both years. Irrigation was applied at the beginning of stem elongation and anthesis as approximately 20 mm in each stage and a total of 40 mm water in each year.

All phenological measurements of plant development were assessed using number of days from seeding (Rasmusson et al., 1979; Metzger et al., 1984; Akkaya and Akten, 1992) and growing degree-days (GDD) with a base temperature of 0^oC (CaO and Moss, 1989; Dofing, 1992, 1995). Heading date was recorded when c. 50% of spikes had completely emerged from the boot for a given plot. The grain-filling period was calculated as days from heading to maturity. Date of maturity was recorded when c. 50% of spikes had lost all green colour. A 1.0 m long section in one of the center rows was used for yield component determinations. The number of fertile spikes in this row section was counted and plants were harvested and threshed at ripe maturity. The number of kernel per spike determined on a sample of 20 spikes was taken randomly from this row section. Kernel weight per spike was recorded from the spike sample. Average kernel (1000-kernel) weight was calculated by counting and weighing 400 kernels drawn randomly from the bulk grain sample from this row section of each plot. The grain yield per unit area was calculated as the product of this row section of each plot.

ANOVA was carried out using the SPSS statistics programme (SPSS, 1999). For each variable for combined 2 years, linear correlation coefficients between all possible pairs of the eight characteristics were computed. Path coefficient analysis was made by applying these correlation coefficients and the relative importance of direct and indirect effects on grain yield was determined. The grain yield was the dependent variable and other characteristics were considered as independent. Similar definitions were applied to the other three sets of equations. The causal system assumed was based on the ontogeny of the barley plant and path coefficient diagram of relationships was shown in Figure 1.

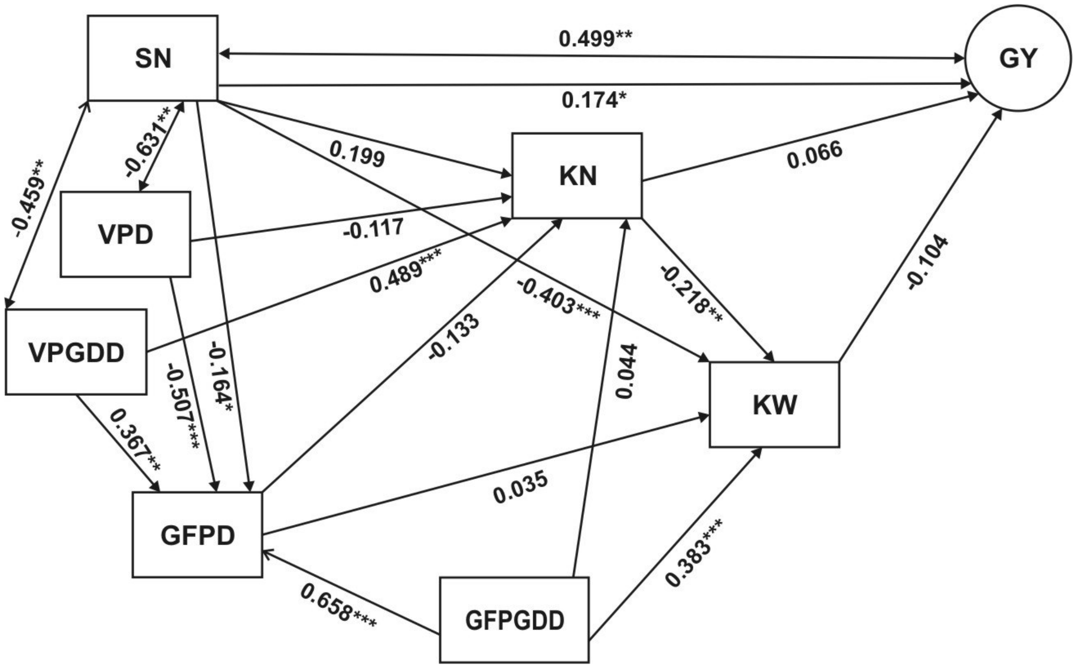

Figure 1. Path-coefficient diagram showing the interrelationships of eight characteristics in spring barley genotypes GY, grain yield per unit area; SN, spike number per m^{-2}; KN kernel number per spike; KW, 1000-kernel weight; VPD, duration of vegetative period; VPGDD, GDD for vegetative period; GFPD, duration of grain-filling period; GFDGDD, GDD for grain-filling period. The double-headed arrows indicate linear correlation coefficient and single-headed arrows indicate path-coefficient. *, **, *** Significant at P<0.05, 0.01 and 0.001, respectively.

Table 2. Mean and range values of duration (d) and growing degree-days (GDD) for phenological growth periods and grain yields (g/m^{-2}) and yield components in 19 spring barley (*Hordeum vulgare*) genotypes in 2004 and 2005.

Characteristic	2004		2005	
	Mean	Range	Mean	Range
Duration of vegetative period	61.1	59.3-65.0	61.9	56.7-66.3
GDD for vegetative period	397.7	381.7-432.0	391.9	355.3-431.3
Duration of grain – filling per.	29.7	24.7-32.0	27.5	23.7-31.0
GDD for grain-filling period	278.4	241.1-297.0	255.0	226.6-286.6
Spike number per m^{-2}	678.2	255.0-1153.3	532.7	341.7-785.0
Kernel number per spike	20.3	18.3-22.9	19.5	16.7-22.2
Average kernel weight (g)	62.2	52.1-69.7	61.9	53.7-69.8
Grain yield per m^{-2}	325.9	130.8-431.7	394.8	193.3-538.9

RESULTS

Spike number per m^{-2} mostly affected grain yield (Table 2). The spike number was positively associated with grain yield per m^{-2} (Table 3; r=0.499**) and negatively correlated with duration of vegetative period (Figure 1; r=-0,631**). The other characteristics studied, however, resulted in decreases in the grain yield in these spring barley genotypes. So, negative and significant correlations were found between grain yield and all other characteristics except the kernel number per spike (Table 3).

The path diagram showed that the spike number per m^{-2} had the highest positive direct effect ($Pc=0.174^{*}$) on grain yield followed by kernel number (Pc=0.066) and negative direct effect by kernel weight (Pc=-0.104). The ratio of the direct effect of spike number per unit area on grain yield was 29.91% in spring barley genotypes (Figure 1; Table 3). Spike number and some characteristics studied had mutual relationships (Figure 1) because these characteristics may exercise a reciprocal influence during the development of barley as described previously by Gebeyehou et al. (1982) and Garcia del Moral et al.

Table 3. Path-coefficient (Pc) analysis of grain yield in 19 spring barley (*Hordeum vulgare*) genotypes for combined two years. Direct (bold) and indirect effects of some characteristics on grain yield and correlation coefficient (r) between grain yield and the same characteristics.

Characteristic	Spike Number		Vegetative Period				Grain-Filling Period				Kernel Number		Kernel Weight	
	(SN)		Duration (VPD)		GDD (VPGDD)		Duration (GFPD)		GDD (GFPGDD)		(KN)		(KW)	
	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%
SN	**0.1740***	**29.91**	-0.1097	15.72	-0.0798	9.50	-0.0156	4.19	-0.0207	4.79	0.0095	3.23	-0.0859	17.88
VPD	-0.0403	6.93	**0.0640**	**9.17**	0.0487	5.80	-0.0107	2.88	-0.0042	0.97	0.0095	3.23	0.0152	3.16
VPGDD	0.2845	48.90	-0.4718	67.61	**-0.6200*****	**73.78**	-0.1147	30.83	-0.1215	28.11	-0.1816	61.73	-0.1525	31.74
GFPD	-0.0015	0.26	-0.0028	0.40	0.0031	0.37	**0.0170**	**4.57**	0.0133	3.08	-0.0001	0.03	0.0062	1.29
GFPGDD	0.0266	4.57	0.0150	2.15	-0.0439	5.22	-0.1753	47.12	**-0.2240***	**51.82**	-0.0044	1.50	-0.1019	21.21
KN	0.0036	0.62	0.0098	1.40	0.0193	2.30	-0.0003	0.01	0.0013	0.30	**0.0660**	**22.43**	-0.0147	3.06
KW	0.0513	8.82	-0.0247	3.54	-0.0255	3.04	-0.0384	10.32	-0.0473	10.94	0.0231	7.85	**-0.1040**	**21.65**
r	0.499**		-0.521**		-0.699**		-0.339**		-0.404**		-0.078NS		-0.438**	

*, **, *** Significant at p<0.05, 0.01 and 0.001, respectively.

Table 4. Path-coefficient (Pc) analysis of kernel weight in 19 spring barley (*Hordeum vulgare*) genotypes for combined two years. Direct (bold) and indirect effects of some characteristics on kernel weight and correlation coefficient (r) between kernel weight and the same characteristics.

Characteristic	Spike Number		Vegetative Period				Grain-Filling Period				Kernel Number	
	(SN)		Duration (VPD)		GDD (VPGDD)		Duration (GFPD)		GDD (GFPGDD)		(KN)	
	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%
SN	**-0.4030*****	**81.66**	0.2542	69.44	0.1849	49.52	0.0362	9.50	0.0479	10.23	-0.0221	8.57
VPD	-0.0227	4.60	**0.0360**	**9.83**	0.0273	7.31	-0.0060	1.57	-0.0024	0.51	0.0053	2.06
VPGDD	-0.0073	1.48	0.0121	3.31	**0.0160**	**4.29**	0.0029	0.76	0.0031	0.66	0.0046	1.78
GFPD	-0.0031	0.63	-0.0058	1.58	0.0064	1.71	**0.0350**	**9.18**	0.0274	5.85	-0.0002	0.08
GFPGDD	-0.0455	9.22	-0.256	6.99	0.0750	20.09	0.2998	78.65	**0.3830*****	**81.82**	0.0076	2.95
KN	-0.0119	2.41	-0.324	8.85	-0.0638	17.09	0.0013	0.34	-0.0043	0.92	**-0.2180****	**84.56**
r	-0.494**		0.238*		0.246**		0.370**		0.455**		-0.223*	

*,**,*** Significant at p<0.05, 0.01 and 0.001, respectively.

(1991). It was reported that the spike number exercised a direct influence on all other characteristics (Garcia del Moral et al., 1991).

The direct effects of spike number and kernel number on kernel weight were negative and significant. The direct effect of the GDD for grain-filling period on kernel weight was positive and significant and this caused a positive and significant correlation between the two characteristics (Figure 1; Table 4). High number of spikes per m^{-2} resulted significantly in decreased kernel weight but in a higher grain yield (Tables 3 and 4). Path analysis indicated that spike number and the GDD for vegetative and grain-filling period had positive direct effects on kernel number, while the duration of vegetative and grain-filling period had negative direct effects (Figure 1; Table 5). It was indicated that the duration of grain-filling period modified

Table 5. Path-coefficient (Pc) analysis of kernel number in 19 spring barley (*Hordeum vulgare*) genotypes for combined 2 years. Direct (bold) and indirect effects of some characteristics on kernel number and correlation coefficient (r) between kernel number and the same characteristics.

Characteristic	Spike number (SN)		Vegetative period Duration (VPD)		Vegetative period GDD (VPGDD)		Grain-filling period Duration (GFPD)		Grain-filling period GDD (GPFGDD)	
	Pc	%	Pc	%	Pc	%	Pc	%	Pc	%
SN	0.1990	**38.69**	-0.1255	19.62	-0.0913	13.00	-0.0179	6.06	-0.0236	8.57
VPD	0.0738	14.35	-0.1170	18.29	-0.0890	12.67	0.0196	6.64	0.0078	2.83
VPGDD	-0.2244	43.63	0.3721	58.16	0.4890***	69.61	0.0904	30.61	0.0958	34.80
GFPD	0.0119	2.31	0.0223	3.49	-0.0246	3.50	-0.1330	45.04	-0.1041	37.81
GFPGDD	-0.0052	1.01	-0.0029	0.45	0.0086	1.22	0.0344	11.65	0.0440	15.98
r	0.055 NS		0.149 NS		0.293**		-0.006 NS		0.020 NS	

*, **, *** Significant at p<0.05, 0.01 and 0.001, respectively.

the kernel number per spike by diminishing the abortion of pollinated florets after anthesis (Garcia del Moral, 1984). The direct effects of spike number and the duration of vegetative period on the duration of grain-filling period were negative and significant, but the direct effect of the GDD for vegetative period on the duration of grain-filling period was positive and significant (Figure 1; Table 6). This revealed that the GDD affected positively the yield components (Tables 4, 5 and 6).

Path-coefficient analysis indicated that there was a significant indirect positive effect of the spike number on grain yield via the GDD for vegetative period and significant positive correlation was found between the spike number and grain yield (Table 3). This clearly reflected the effect of the GDD for vegetative period on grain yield in spring barley genotypes. The duration of grain-filling period had the indirect positive effect on the kernel weight via the GDD for the same develop-ment period (Table 4). There was a strong indirect positive effect on kernel weight exerted by the two traits of vegetative period via spike number per m^{-2} and by the duration of grain-filling period via GDD for the same growth period on kernel weight. These relationships caused significant and positive correlations between the three characteristics and kernel weight (Table 4). The indirect effects of each variable on kernel number were mostly slight (Table 5) except for the indirect negative effect of the spike number per m^{-2} via the GDD for vegetative period and indirect positive effect of the duration of vegetative and grain-filling periods via the GDD for the two same growth periods (Table 5). The spike number had the indirect positive effect on the duration of grain-filling period, while the GDD for vegeta-tive period had the indirect negative effect on the same growth period exerted by the duration of vegetative period (Table 6).

DISCUSSION

A causal evaluation of the linear correlation coefficients failed to provide much insight into the overall relation-ships that must be involved in the sequential series of characteristics. Path-coefficient analysis was conducted in order to clarify these complex relationships. It is generally known that grain yield is the product of spike number per unit area, kernel number per spike and kernel weight. Adams (1967) cited, however, many examples of variable responses due to environmental effects on yield component expression. The correlation data from the barley experiments conducted by Rasmusson and Cannell (1970) gave additional evidence of the impor-tance of environmental variation on the relationships between the yield components. Garcia del Moral et al. (1991) emphasized that greater numbers of spikes per m^{-2} resulted in fewer kernels per spike, while the longer vegetative and grain-filling periods had higher number of kernels per spike. But, none of these relation-ships was revealed by the linear correlation analysis. Path-coefficient analysis further indicated that grain yield was dependent on the two variables, spike number per unit area and kernel number per spike in spring barley genotypes (Figure 1; Table 3). This result agreed with previous findings that barley grain yield depended on spike number per m^{-2} and kernels per spike (Ramos et al., 1982; Garcia del Moral et al., 1985, 1991; Stepherd et al., 1987). Grain yield was negatively correlated with all the characteristics studied except the spike number per m^{-2}. Increasing the spike number per unit area resulted in increase in the grain yield in spring barley genotypes (Figure 1; Table 3). The path diagram also showed that correlation coefficient between the spike number per m^{-2} and the duration of vegetative period was negative and significant (Figure 1). So, the spike number per unit area was the first characteristic in the sequence and exerted a powerful effect on subsequent characteristics. The path-coefficient analysis indicated that the spike number per m^{-2} and the kernel number per spike had positive direct effects on the grain yield (Figure 1; Table 3). This result seems to be compatible with previous findings that grain yield in barley depended on the spike number (Ramos et

Table 6. Path-coefficient (Pc) analysis of duration of grain-filling period in 19 spring barley (*Hordeum vulgare*) genotypes for combined 2 years. Direct (bold) and indirect effects of some characteristics on duration of grain-filling period and correlation coefficient (r) between the duration of grain-filling period and the same characteristics.

Characteristic	Spike Number (SN)		Vegetative Period Duration (VPD)		Vegetative Period GDD (VPGDD)		Grain-Filling Period GDD (GFPGDD)	
	Pc	%	Pc	%	Pc	%	Pc	%
SN	**-0.1640***	22.45	0.1034	11.08	0.0752	7.86	0.0195	2.49
VPD	0.3199	43.79	**-0.5070*****	54.31	-0.3858	40.32	0.0339	4.33
VPGDD	-0.1684	23.05	0.2792	29.91	**0.3670*****	38.35	0.0719	9.38
GFPGDD	-0.0783	10.72	-0.0440	4.71	0.1289	13.47	**0.6580*****	84.00
r	-0.090		-0.168		0.185*		0.783**	

*, **, *** Significant at $p<0.05$, 0.01 and 0.001, respectively.

al., 1982; Garcia del Moral et al., 1985, 1991; Stepherd et al., 1987; Dofing 1995) and, to a slight extent, on the kernel number (Rasmusson and Cannel, 1970). The path diagram indicated that kernel weight had negative direct effect on grain yield (Figure 1; Table 3; Pc =-0.104) although the spike number per m^{-2} had indirect positive effect on grain yield through its effect via the GDD for vegetative period (Table 3).

Correlation coefficients were positive and significant between kernel weight and all the phonological traits (Table 4). It was reported that kernel weight was a highly stable characteristic in barley (Gallagher et al., 1975), which may be attributed to a high degree of remobilization of reserves during kernel development (Austin et al., 1980). These results agreed with the influence of kernel weight on grain yield in barley found previously by some researchers (Garcia del Moral et al., 1985; Ramos et al., 1989). Negative and significant correlations were found between kernel weight and spike number per m^{-2} and kernel number (Table 4). The path-diagram also indicated that the spike number per m^{-2} and the kernel number per spike had significant negative direct effects on the kernel weight in spring barley genotypes (Figure 1; Table 4). These effects may well indicate a competitor effect between kernel weight and spike number per m^{-2} and kernel number per spike in spring barley. Similar relationships were found in barley (Hamid and Grafius, 1978; Dofing, 1995) and wheat (Gebeyehou et al., 1982).

Kernel number per spike was positively correlated with the GDD for vegetative period and correlation coefficient was found significant (Table 5; r = 0.293**). The path diagram also showed that the GDD for vegetative period had a direct and significant positive effect on the kernel number (Figure 1; Table 5; Pc=0.489**), which agrees with the finding of path analyses in barley (Hamid and Grafius, 1978; Garcia del Moral et al., 1991). In this concept, Dofing (1995) emphasized that increasing GDD to reach heading caused significantly higher kernel number per spike, which also had a significant positive effect on grain yield in spring barley genotypes. On the other hand, the duration of the both vegetative and grain-filling periods had negative direct effects on kernel number in spring barley genotypes (Figure 1; Table 5).

Spike number per m^{-2} influenced the GDD for vegetative period and this reflected negative indirect effect on kernel number (Figure 1; Table 5). Dofing (1995) indicated that the GDD for vegetative period recognized as being important in determining grain yield. Grain yield was negatively correlated with the durations of vegetative and grain-filling period (Table 3; r =-0.404**) although the durations of the two growth periods had negative indirect effects on the grain yield through their effects via the GDD for both growth periods (Figure 1; Table 3). The associations were supported with the results of previous researches (Kitchen and Rasmusson, 1983; Garcia del Moral et al., 1991; Dofing, 1995). The genotypes which had the high tillering capacity and the low GDD in vegetative period possessed higher grain yields than the contrary spring barley genotypes.

The spike number per unit area is the most important characteristic affecting the duration of vegetative and grain-filling periods and also grain yield and components. The spike number per m^{-2}, the kernel number and the GDD for the two growth periods seem to be the most valuable selection criteria for high grain yield in spring barley under cool and short-season environment. Consequently, in order to increase the grain yield in spring barley the two yield components and the GDD for the two growth periods have been used as selection criteria in our and similar circumstances. It will be important in the future researcher to establish the relationships between these characteristics and grain yield stability in spring barley.

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