academicJournals

Vol. 12(6), pp. 450-458, 9 February, 2017
DOI: 10.5897/AJAR2016.11660
Article Number: 5D9975E62695
ISSN 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Relations among phenotypic traits of soybean pods and growth habit

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Received 3 September, 2016; Accepted 20 October, 2016

This study aims to identify the phenotypic effects of traits associated with soybean pods and their growth habit. The experiments were carried out during the 2012 - 2013 agricultural year. It was done in randomized blocks arranged in a 2×20 factorial design (environments × soybean cultivars) with three replications. Data were subjected to individual analysis of variance for each environment and growth habit to verify the homogeneity of variances. Phenotypic path analysis among agronomic traits was performed for each environment within the soybean growth habits. The results showed considerable influences of growth habit via traits associated with soybean pods. The traits number of pods with two, three, and four grains directly influenced the grain yield of genotypes with indeterminate growth habit regardless of the environment. The soybean genotypes with determinate growth habit contributed greatly to grain yield through the traits number of pods with one, two, and three grains and thousand grain weight via pods with two or four grains. Indirect selection of superior genotypes for pods per plant and grain weight could provide satisfactory results for soybean yield in relation to the growth habit. The interrelationships obtained between growth habits and environments, can be applied to superior genotypes selection strategies in breeding soybean programs.

Key words: Agriculture science, biometric models, *Glycine max* L., indirect selection, grain yield, soybean breeding.

INTRODUCTION

Soybean (*Glycine max* L.) is one of the main commodities grown in Brazil due to its great range of genotypes and differential traits that enable the development and production in diverse environments (Carvalho et al., 2010). Differentiated phenotypic responses are intrinsic to the effects of genotype × environment interaction, where a particular genotype may present different associations between the traits involved

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in grain yield because of the environmental effects (Cavalcante et al., 2014).

Comprehending the interrelations between the traits associated with soybean yield potential is essential, because the degree of contribution is intrinsic to the number of pods, grains per pod, and grain weight of the genotype. Correlations among these parameters become important for the indirect selection of superior genotypes (Nogueira et al., 2012). Moreover, correlations may occur by genetic causes which are associated with the gene pleiotropism and linkage (Falconer, 1987) and phenotypical and environmental causes (Carvalho et al., 2002). Furthermore, study of Rodrigues et al. (2010), revealed that the simple correlation coefficients do not allow the exact understanding of the actions linked to the traits. Partitioning of direct and indirect effects of the traits through the path analysis is necessary for reliable interpretation of cause and effect of the correlation coefficients (Wright, 1921). The breakdown of simple correlations allows one to quantify the contribution of the explanatory traits of soybean yield and elucidate the effects attributed to environmental modifications.

This study aimed to identify the phenotypic effects of traits associated with soybean pods and its relations with growth habit.

MATERIALS AND METHODS

The experiments were carried out during the 2012 - 2013 agricultural year, in two locations in Southern Brazil: in Tenente Portela - RS, where the coordinates correspond to latitude of 27º22’10.20’’S and longitude of 53º45’23.00’’W, with an altitude of 420 m. The soil is classified as typical ferric red Oxisol. In Santa Rosa - RS, the coordinates correspond to latitude of 27º52’16.00’’S and longitude of 54º28’55.00”W, with an altitude of 268 m. The soil is classified as dystrophic Red Oxisol. According to Köppen climate classification, the climate is classified as *Cfa* subtropical humid with balanced rain system and no dry season defined for both locations.

The experimental design was randomized blocks arranged in a 2×20 factorial design (environments × soybean cultivars) with three replications. The cultivars utilized for indeterminate growth habit (IGH) were: FPS Paranapanema RR, FPS Solimões RR, FPS Netuno RR, FPS Iguaçu RR, FPS Júpiter RR, AMS Tibagi RR, BMX Magna RR, BMX Apolo RR, BMX Potência RR, BMX Alvo RR, ROOS Camino RR, NA 5909 RR, BMX Turbo RR, and TMG 7161 RR. The cultivars with determinate growth habit (DGH) were: BRS Tordilha RR, Fepagro 37 RR, Fepagro 36 RR, FPS Urano RR, A 6411 RR, and BMX Ativa RR.

Each experimental unit consisted of four rows with spacing of 0.45 m between rows and 10 m long. Plant population density for all genotypes was 300,000 plants ha^{-1}. Moreover, direct seeding system with established fertilization according to crop necessities was used in both locations. The control of insect and diseases was carried out with caution. Evaluations were performed in the central rows of each experimental unit, discarding the first few meters from each end in order to reduce the effects of borders. Later, ten random plants were sampled in order to obtain the agronomical important traits composing the average of each trait of the experimental unit. The following traits were evaluated:

i) Thousand grain weight via pods with one grain (TGW I): Traits were measured after selection of pods with only one viable grain, followed by counting of eight repetitions with one hundred grains, adjusting a thousand grain weight in grams.

ii) Thousand grain weight via pods with two grains (TGW II): Traits were measured after selection of pods with two viable grains, followed by counting of eight repetitions with one hundred grains, adjusting one thousand grain weight in grams.

iii) Thousand grain weight via pods with three grains (TGW III): Traits were measured after selection of pods with three viable grains, followed by counting of eight repetitions with one hundred grains, adjusting one thousand grain weight in grams.

iv) Thousand grain weight via pods with four grains (TGW IV): Trait was measured after selection of pods with four viable grains, followed by counting of eight repetitions with one hundred grains, adjusting a thousand grain weight in grams.

v) Number of pods with one grain (NP I G): obtained by counting of all pods per plant containing only one grain.

vi) Number of pods with two grains (NP II G): obtained by counting all pods per plant containing two grains.

vii) Number of pods with three grains (NP III G): obtained by counting all pods per plant containing three grains.

viii) Number of pods with four grains (NP IV G): obtained by counting all pods per plant containing four grains.

ix) Grain yield (YIELD): obtained by the total grain weight per experimental unit with subsequent correction of grain moisture to 13%. Ratio of the grain weight per plot by the number of plants was done. The grain weight per plant was adjusted to the plant density utilized and the results were expressed in kg ha^{-1}.

Obtained data were submitted to individual analysis of variance for each environment and growth habit to verify the homogeneity of variances. Phenotypic path analysis among agronomic traits was performed for each environment within the soybean growth habits.
For path analysis, estimates of direct and indirect effects were carried out considering the following statistical model:

$$y = p_1x_1 + p_2x_2 + ... + p_nx_n + p_eu$$

where y = grain yield or dependent variable; x_1, x_2,....,x_n = explanatory variables; p_a, p_2,...p_n = path analysis coefficients.
Estimates of the path analysis coefficients are estimated based on the following equations

$X'X\beta = X'Y$ (Li, 1975):

$$X'Y=\begin{pmatrix} r_{1y} \\ r_{2y} \\ \vdots \\ r_{ny} \end{pmatrix}, X'Y=\begin{pmatrix} 1 & r_{12} & \dots & r_{1n} \\ r_{12} & 1 & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{1n} & r_{2n} & \dots & 1 \end{pmatrix} \text{ e } \beta=\begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{pmatrix}$$

In this way, the decomposition of the correlation between the dependent variable and the explanatory variables is performed as follows (Cruz et al., 2004):

$$r_{1y} = p_1 + p_2r_{12} + \dots + p_nr_{1n}$$

$$r_{2y} = p_1r_{12} + p_2 + \dots + p_nr_{2n}$$

... ...

$$r_{ny} = p_1r_{1n} + p_{n2} + \dots + p_n$$

$$r_{iy} = p_i + \sum_{j \neq i}^{n} p_j r_{ij}$$

Where:
r_{iy}: correlation among the principal variable selected by the researcher (y) and the i-th explanatory variable;
p_i: measure of the direct effect of the i variable on the principal variable;
$p_i r_{ij}$: measure of the indirect effect of the i variable via j variable on the principal variable.

According to Cruz et al. (2004), when the deletion of variables is not desired by the researcher, procedures similar to ridge regression analysis are adopted. In this methodology, it is assumed that with the presence of multicollinearity, the least squares estimator obtained from X´Y may be linked to very high variances. This adverse effect can be slightly modified in the normal equations system with introduction of K constant in the diagonal of the matrix X´Y. Thus, path analysis coefficients are obtained: (X´X + KI) = X´Y;

$$\sigma = \begin{bmatrix} p_1^* \\ p_2^* \\ \ldots \\ p_n^* \end{bmatrix}$$

With the inclusion of the K constant, the decomposition of correlation between the explanatory variables and the basic variable is given by:

$$r_{1y} = (1+K)p_1^* + p_2^* r_{12} + \ldots + p_n^* r_{1n}$$

$$r_{2y} = p_1^* r_{12} + (1+K)p_2^* + \ldots + p_n^* r_{2n}$$

... ...

$$r_{ny} = p_1^* r_{1n} + p_2^* r_{n2} + \ldots + (1+K)\, p_n^*$$

Thus, we have:

$$r_{iy} = (1+K)p_{1i}^* + \sum_{j \neq i}^{n} p_j^* r_{ij}$$

Values from 0 to 1 are considered for K constant, where Cruz et al. (1997) point out that among the values it should choose for the lower value of the constant, for which most of the path analysis coefficients linked to various traits are stabilized. The determination of the path diagram is given by:

$$R^2 = p_1 r_{1y} + p_2 r_{2y} + \ldots + p_n r_{ny}$$

The residual effect is estimated by:

$$\rho_{\varepsilon} = \sqrt{1 - R^2}$$

The statistical software Genes (Cruz, 2006) was utilized in order to perform the analyses.

RESULTS AND DISCUSSION

Analysis of variance for traits

Analysis of variance revealed a significant interaction $p>0.05$ to IGH among environments x soybean cultivars for the variables TGW I, TGW II, TGW III, TGW IV, NP III G. The DGH revealed significant interaction $p>0.05$ for the traits TGW II, TGW IV, and NP III G. The obtained results demonstrated considerable influences of the growth habit via traits associated with soybean pods.

The number of grains per pod and grain weight directly influenced the soybean yield potential. These traits are responsive to the plant arrangement in the canopy, efficiency in the photosynthetically active radiation use, and considerable reduction of grain weight through water deficit (Rambo et al., 2002). Unsatisfactory water offerings provide decreases in the pod size, with negative effects on grain filling (Thomas and Costa, 2010). Moreover, research of Santos et al. (2013) reported beneficial effects of crop rotation, with the increase in the number of pods and grain yield per plant.

Direct and indirect effects between traits

Regarding the IGH for the variable TGW I, this trait does not contribute to crop yield (Table 1), observing the null correlation coefficients for direct effects in Tenente Portela -RS. According to Kurek et al. (2001), the coefficients can assume positive, negative or null magnitudes. The total Pearson correlation (r=0.441) evidenced intermediate and positive correlation coefficient, where the traits when grouped contribute to the principal variable.

The trait TGW I for IGH evidenced the direct effects, low and positive correlation coefficients to grain yield in Santa Rosa -RS. Indirect effects are obtained via TGW II with low and positive correlation coefficients. The contrasting results show the grain weight contribution to soybean yield potential, closely related to favorable environment and genotype. The Pearson correlation shows (r=0.548) intermediate and positive coefficient in relation to the principal trait. Simple correlations with high magnitudes can cause misinterpretations (Table 1), where they obtained responses are from direct or indirect effects of a particular trait or group of traits (Carvalho et al., 2002).

The TGW I for DGH demonstrated null correlation coefficients in the direct effects, with lack of response of this parameter to soybean yield in Tenente Portela -RS. The indirect effects via NP II G revealed a low and negative correlation coefficient, being low and positive via NP III G. Therefore, genotypes with DGH in this environment give preference for the formation of pods with three grains and facilitate support to soybean yield. Coimbra et al. (2005) reported that two variables are interconnected when one variable responds positively and other responds negatively for a given trait. Under these conditions the correlation of Pearson (r=-0.031) is practically null.

TGW I for DGH in Santa Rosa -RS expressed by the

Table 1. Estimate of the phenotypic direct and indirect effects for thousand grain weight via pods with one grain (TGW I), pods with two grains (TGW II), and pods with three grains (TGW III) in soybean for growth habits and environments.

Effects	Indeterminate growth habit		Determinate growth habit	
	Tenente Portela-RS	Santa Rosa-RS	Tenente Portela-RS	Santa Rosa-RS
Thousand Grain Weight via Pods with one Grain (TGW I)				
Direct Effect on YIELD	0.096	0.189	-0.084	0.177
Indirect Effect via TGW II	0.026	0.117	0.009	-0.019
Indirect Effect via TGW III	0.058	0.027	-0.032	-0.060
Indirect Effect via TGW IV	0.038	0.096	0.005	0.185
Indirect Effect via NP I G	0.016	0.050	-0.021	0.040
Indirect Effect via NP II G	0.084	0.029	-0.258	-0.079
Indirect Effect via NP III G	0.016	-0.011	0.308	-0.097
Indirect Effect via NP IV G	0.076	0.011	0.049	-0.217
Total	0.441	0.548	-0.031	0.061
Thousand grain weight via pods with two grains (TGW II)				
Direct Effect on YIELD	0.034	0.128	0.122	-0.045
Indirect Effect via TGW II	0.073	0.172	-0.006	0.075
Indirect Effect via TGW III	0.067	0.031	-0.017	-0.306
Indirect Effect via TGW IV	0.042	0.114	0.020	0.219
Indirect Effect via NP I G	-0.007	0.031	0.000	0.026
Indirect Effect via NP II G	-0.009	-0.020	0.045	-0.043
Indirect Effect via NP III G	-0.004	-0.034	-0.069	-0.282
Indirect Effect via NP IV G	0.099	0.032	-0.004	-0.318
Total	0.306	0.481	0.096	0.677
Thousand grain weight via pods with three grains (TGW III)				
Direct Effect on YIELD	0.070	0.032	-0.042	-0.335
Indirect Effect via TGW II	0.079	0.158	-0.065	0.031
Indirect Effect via TGW III	0.032	0.123	0.051	-0.040
Indirect Effect via TGW IV	0.044	0.114	-0.063	0.117
Indirect Effect via NP I G	-0.013	0.014	-0.082	-0.021
Indirect Effect via NP II G	-0.023	-0.078	-0.263	-0.050
Indirect Effect via NP III G	0.018	-0.052	0.156	-0.286
Indirect Effect via NP IV G	0.107	0.039	0.047	-0.288
Total	0.337	0.357	-0.264	0.831
Coefficient of determination	0.844	0.890	0.962	0.958
K-value	0.300	0.201	5.066	5.256
Effect of the residual variable	0.394	0.322	0.193	0.203
Determining variable	0.343	6.527	6.942	2.101

direct effect with low and positive correlation coefficient, indirectly the TGW IV parameter reveals a low and positive coefficient, low and negative coefficient via NP IV G. Genotypes with DGH tend to reduce the number of pods with four grains. On the other hand, they express superiority for grain weight, contributing positively to crop yield. The Pearson correlation coefficient was (r=0.061) similar among environments (Table 1), justified by the absence of linearity in the response of traits.

The increases in the weight and number of grains per legume have high and positive correlation coefficients regarding the grain yield (Ribeiro et al., 2001). Phenotypic correlations provide different trait associations, being influenced genetically and environmentally (Falconer, 1987). The thousand grain weight via pods with two grains TGW II expressedthe directly affects null correlation coefficient for IGH in Tenente Portela -RS (Table 1). The Pearson correlation coefficient (r=0.306) evidenced positive and intermediate correlation.

Regarding the IGH in Santa Rosa -RS, direct effects are observed with low and positive coefficient of correlation via TGW II, where the contribution to the principal trait is expressed through the indirect effects of TGW I and TGW IV. For IGH, the soybean yield potential is largely dependent on the grain weight of pods with one, two, and four grains, being phenotypically more important than the number of pods per plant. Proven performance by direct and indirect effects and via Pearson correlation coefficient (r=0.481) shows a positive intermediate correlation directly contributing to grain yield. Studies of Almeida et al. (2010), found significant contribution of thousand grain weight on soybean grain yield.

TGW II in Tenente Portela-RS for DGH demonstrated direct effects of low and positive coefficient of correlation, where Pearson correlation (r=0.096) was null, with low effects of the explanatory variable on the dependent trait. According to Cruz et al. (2004), correlation coefficients reduced or equal to zero do not express absence of relation among parameters, but nonlinearity among traits. In Santa Rosa-RS for DGH, the direct effects revealed null correlation coefficient via TGW II. For the indirect effects, intermediate and negative correlation coefficients via TGW III, NP III G, and NP IV G were observed, being low and positive via TGW IV. Genotypes with DGH in this environment promoted the reduction of the number of pods with three and four grains, but potentiate the increase of grain weight in pods with four grains. This confirmed the result by Carvalho et al. (2002), where modifications in grain weight and number of grains per pod occurred because of the soybean plasticity, which can increase or reduce these traits according to environmental requirements. The contribution of TGW II to soybean yield is justified by the Pearson correlation coefficient (r = 0.677) with an intermediate and positive correlation.

Negative effects on soybean yield occur through abiotic causes via water stress, with the reduction of pods with three grains (Tavares et al., 2013), and through biotic stresses decreasing the number and weight of grains per pod (Mesquini et al., 2011). In both environments for IGH, the variable TGW III evidenced null coefficient of correlation to the direct effects (Table 1). Pronounceable effects are evidenced indirectly via NP IV for Tenente Portela-RS, where the independent variable contribution exhibited greater significance for pods with four grains than the grain weight per pod.

In Santa Rosa-RS, low and positive indirect effects were expressed via TGW I, TGW II, and TGW IV. Environmental effects on soybean pods are justified by the performance of explanatory traits linked to grain weight, which contributes with greater relevance to the principal parameter. The Pearson correlation coefficients (r=0.337 and 0.357) exhibited intermediate and positive correlations with the contribution of TGW III to soybean yield for both environments (Table 1). The comprehension of associations among traits allows indirect selection of parameters that affect the soybean yield (Carvalho et al., 2002).

The performance of TGW III to the DGH for Tenente Portela-RS demonstrated absence of response to the direct effects. Pronounceable results are expressed indirectly via NP II G with low and negative correlation coefficients. Moreover, the Pearson correlation (r=-0.264) was also similar. Therefore, genotypes with DGH in this environment have opposite behavior, where increases in pods with two grains reduce crop yield. The simple correlation shows different directions between the principal variable and the independent TGW III trait. Research carried out by Carvalho et al. (2002), found that the thousand grain weight presents greater phenotypic correlation coefficients than the genotypic ones, proving environmental influence on the secondary trait, and this trait influences grain yield.

In Santa Rosa-RS, the DGH for TGW III reveals direct effects with intermediate and negative correlation coefficient. The indirect effects were observed by low and positive correlation coefficients for TGW IV and low and negative for NP III G and NP IV G. In this environment, genotypes reduced the formation of pods with three grains and consequently their grain weight. Contribution to soybean yield is elucidated by pods with four grains that are in smaller proportions but with heavier grains. Moreover, it is justifiable by Pearson correlation (r=0.831) characterized as strong and positive. This magnitude and direction are attributable to the responses of independent traits to the principal parameter.

The variable TGW IV for IGH in Tenente Portela-RS demonstrated null direct effects on the dependent trait (Table 2). Pearson correlation coefficient (r=0.198) demonstrated low and positive correlation. Moreover, a study performed by Kurek et al. (2001), revealed coefficients with magnitude and direction similar between the number of grains per pod and grain yield. In Santa Rosa-RS, the direct effects of the variable TGW IV were observed with low and positive correlation coefficient. Indirectly, the TGW I and TGW II traits expressed low and positive coefficients, contributing to the principal trait performance.

In this environment, the genotypes with IGH promote the formation of pods with four viable grains with greater weight, contributing to the yield of genotypes. Obtained results for the Pearson correlation (r=0.337) revealed intermediate and positive correlations, where the thousand grain weight provides contribution to the soybean yield potential, regardless of the origin pod dimensions. Meotti et al. (2012), found high and positive correlation coefficient between the grain weight and soybean yield.

The performance of TGW IV variable to the DGH demonstrated low and positive coefficients to the direct effects for both environments. In Tenente Portela-RS, indirect contribution to the principal trait is revealed via NP II G and NP IV G with low and positive correlation

Table 2. Estimate of the phenotypic direct and indirect effects for thousand grain weight via pods with four grains (TGW IV), number of pods with one grain (NP I G), and number of pods with two grains (NP II G) in soybean for growth habits and environments.

Effects	**Indeterminate Growth Habit**		**Determinate Growth Habit**	
	Tenente Portela-RS	**Santa Rosa-RS**	**Tenente Portela-RS**	**Santa Rosa-RS**
Thousand Grain Weight via Pods with four grains (TGW IV)				
Direct Effect on YIELD	0.062	0.128	0.221	0.250
Indirect Effect via TGW II	0.059	0.142	-0.002	0.131
Indirect Effect via TGW III	0.023	0.114	0.011	-0.039
Indirect Effect via TGW IV	0.050	0.028	0.012	-0.237
Indirect Effect via NP I G	0.003	0.002	0.098	0.013
Indirect Effect via NP II G	-0.043	-0.065	0.237	0.004
Indirect Effect via NP III G	-0.031	-0.065	0.033	0.228
Indirect Effect via NP IV G	0.054	0.025	0.103	-0.283
Total	0.198	0.337	0.726	0.377
Number of Pods with One Grain (NP I G)				
Direct Effect on YIELD	0.089	0.197	0.131	0.155
Indirect Effect via TGW II	0.017	0.048	0.013	0.046
Indirect Effect via TGW III	-0.002	0.020	0.000	-0.007
Indirect Effect via TGW IV	-0.010	0.002	0.026	0.046
Indirect Effect via NP I G	0.002	0.001	0.165	0.021
Indirect Effect via NP II G	0.214	0.210	0.233	-0.137
Indirect Effect via NP III G	0.040	0.163	0.057	-0.008
Indirect Effect via NP IV G	-0.031	-0.018	-0.008	-0.101
Total	0.345	0.665	0.626	0.021
Number of Pods with Two Grains (NP II G)				
Direct Effect on YIELD	0.282	0.306	0.363	0.519
Indirect Effect via TGW II	0.028	0.017	0.060	-0.027
Indirect Effect via TGW III	-0.001	-0.008	0.015	0.003
Indirect Effect via TGW IV	-0.006	-0.008	0.030	0.032
Indirect Effect via NP I G	-0.009	0.027	0.144	0.002
Indirect Effect via NP II G	0.067	0.135	0.084	-0.040
Indirect Effect via NP III G	0.215	0.259	-0.108	-0.018
Indirect Effect via NP IV G	0.012	-0.036	0.026	0.035
Total	0.675	0.701	0.635	0.533
Coefficient of determination	0.844	0.890	0.962	0.958
K-value	0.300	0.201	5.066	5.256
Effect of the residual variable	0.394	0.322	0.193	0.203
Determining variable	0.343	6.527	6.942	2.101

coefficients. Pearson correlation (r=0.726) was high and positive. In this environment, genotypes promote pod formation with two and four viable grains with greater weight. For Santa Rosa-RS, indirect effects are expressed via TGW I and NP III G with low and positive correlation coefficient, and low and negative coefficient via TGW III and NP IV G.

Genotypes with DGH prefer increasing grain weight derived from pods with one to four viable grains. This behavior evidenced the reduction in the number of pods with four grains and indirect effects of these traits are observed in the intermediate and positive Pearson correlation (r=0.377). The obtained results revealed that soybean sets the number of grains per pod and grain weight due to the phenotype plasticity, derived from the genotype-environment interaction. Different responses among environments influence correlation among traits and soybean phenotype expression (Carvalho et al., 2002).

Among the traits that contribute to soybean yield, number of pods per plant is an emphasized attribute, which is influenced by plant arrangement and water and nutrient management (Ventimiglia et al., 1999). Research performed by Coimbra et al. (2000) found high and positive correlation coefficient between the number of pods per plant and grain yield. The NP I G for IGH in Tenente Portela-RS revealed direct effects with null coefficients. Indirectly, low and positive correlation coefficients were observed via NP II G (Table 2). Pearson correlation (r=0.345) was intermediate and positive. The magnitude of the correlation is justified by the indirect effects, where the genotype potential is linked to the emission of pods with two grains. Direct and indirect effects allow understanding of the interrelationships between traits that affect soybean yield (Perini et al., 2012).

In Santa Rosa-RS, the variable NP I G demonstrated direct and indirect effects via NP II G and NP III G, respectively, low and positive correlation coefficients. Barbaro et al. (2006) found that the number of pods per plant was the most related parameter to the genotype yield potential. The Pearson correlation (r=0.665) was intermediate and positive. In this environment, the productive performance of IGH genotypes is justified by the greater number of pods per plant, independently of the grains per pod magnitude.

The variable NP I G performance for GHD revealed direct effects with low and positive correlation coefficients for both environments (Table 2). In Tenente Portela-RS, pronounceable indirect effects were obtained via TGW IV and NP II G with low and positive correlation coefficients. Pearson correlation (r=0.626) was intermediate and positive. Genotypes with DGH contributed to the number of pods per plant conjugated to grain weight increase derived from pods with four viable grains. In Santa Rosa-RS, indirect effects were expressed via NP II G and NP G IV and low and negative correlation coefficients were observed. Pearson correlation (r=0.021) was null. The variations in pods per plant are more related to environmental effects than soybean growth habit (Perini et al., 2012).

The NP II G in both growth habits and environments revealed direct effects with intermediate and positive correlation coefficients. For Tenente Portela-RS, IGH evidenced indirect effects via NP III G and via NP I G and NP III G in Santa Rosa-RS, with low and positive correlation coefficients in relation to dependent trait. For IGH, Pearson correlations were (r=0.675) intermediate and (r=0.701) positive. Studies reported the importance of quantifying the direct and indirect effects of independent traits with the principal parameter and determine the effects linked to the environment (Gomes et al., 2007).

In Tenente Portela-RS, the DGH demonstrated indirect effects with low and positive correlation coefficient via TGW IV and low and negative coefficient via NP III G. Results justified the contribution of increased grain weight originated from pods with four grains with the reduction of number of pods with three grains. The Pearson correlations were (r=0.635) intermediate and (r=0.533) positive. Correlations with high magnitude are linked to direct and indirect effects of the independent variables in relation to the principal trait (Vencovsky and Barriga, 1992).

For both growth habits and environments, NP III G revealed direct effects with intermediate and positive correlation coefficients (Table 3). It demonstrated that the differences between the genotype traits and their interactions with the environments revealed the NP III G trait significant contribution to the principal parameter. The phenotypic correlation partitioning in direct and indirect effects allows one to quantify the influence of independent variables on soybean yield (Bizeti et al., 2004). For IGH in Tenente Portela-RS, indirect effects via NP II G and NP IV G with low and positive correlation coefficients were observed. Pearson correlation (r=0.868) was high and positive. For Santa Rosa-RS, indirect influences were expressed via NP II G with low and positive correlation coefficient. The Pearson correlation (r=0.750) was intermediate and positive for both environments with clear contribution of the independent variable NP III G to grain yield.

The trait NP III G for the DGH revealed significant indirect effects only for Santa Rosa-RS, where the TGW III and NP IV G evidenced intermediate and positive correlation coefficient, low and negative coefficient via TGW IV. Genotypes with DGH promote the formation of pods with three and four grains, where the effects on grain yield were pronounceable by the increase of grain yield via pods with three grains. This behavior is similar to the grain weight via pods with four grains. Pearson correlations were (r=0.605) intermediate and (r=0.733) positive for both environments. Positive correlations evidence increases in the principal variable through the explanatory variables effects (Nogueira et al., 2012).

The NP IV G for IGH revealed direct and indirect effects via NP III G with low and positive correlation coefficients for both environments (Table 3). The DGH in Tenente Portela-RS revealed direct and indirect effects via TGW IV with low and positive correlation coefficients. Pearson correlation (r=0.035) was null. For Santa Rosa, intermediate and positive coefficient was observed in the direct effects. Indirectly, low and positive coefficients via TGW III and NP III G and low and negative coefficients via TGW I and TGW IV were observed. The results expressed in these conditions and growth habit evidenced the soybean plasticity and its ability to change depending on environmental conditions. The Pearson correlation (r=0.679) was intermediate and positive regarding the principal trait.

Phenotypic estimates of traits linked to soybean pods evidenced high coefficients of determination and lower residual effects. Moreover, the results justify the associations with grain yield regardless of the growth

Table 3. Estimate of the phenotypic direct and indirect effects for number of pods with three grains (NP III G) and number of pods with four grains (NP IV G) in soybean for growth habits and environments.

Efeitos	Indeterminate Growth Habit		Determinate Growth Habit	
	Tenente Portela-RS	**Santa Rosa-RS**	**Tenente Portela-RS**	**Santa Rosa-RS**
Number of Pods with Three Grains (NP III G)				
Direct Effect on YIELD	0.464	0.395	0.663	0.303
Indirect Effect via TGW II	0.003	-0.005	-0.039	-0.057
Indirect Effect via TGW III	0.000	-0.011	-0.012	0.042
Indirect Effect via TGW IV	0.002	-0.004	-0.010	0.315
Indirect Effect via NP I G	-0.004	-0.021	0.011	-0.188
Indirect Effect via NP II G	0.007	0.081	0.011	-0.004
Indirect Effect via NP III G	0.131	0.201	-0.059	-0.031
Indirect Effect via NP IV G	0.122	0.034	0.007	0.338
Total	0.868	0.750	0.605	0.733
Number of Pods with Four Grains (NP IV G)				
Direct Effect on YIELD	0.195	0.134	0.169	0.369
Indirect Effect via TGW II	0.037	0.015	-0.024	-0.104
Indirect Effect via TGW III	0.017	0.030	-0.003	0.039
Indirect Effect via TGW IV	0.039	0.009	-0.011	0.261
Indirect Effect via NP I G	0.017	0.023	0.135	-0.191
Indirect Effect via NP II G	-0.014	-0.027	-0.006	-0.042
Indirect Effect via NP III G	0.017	-0.084	0.057	0.050
Indirect Effect via NP IV G	0.292	0.102	0.028	0.277
Total	0.661	0.232	0.035	0.679
Coefficient of determination	0.844	0.890	0.962	0.958
K-value	0.300	0.201	5.066	5.256
Effect of the residual variable	0.394	0.322	0.193	0.203
Determining variable	0.343	6.527	6.942	2.101

habit.

Conclusions

The traits number of pods with two, three, and four grains directly influenced the grain yield of genotypes with indeterminate growth habit regardless of the environment. The soybean genotypes with determinate growth habit express greater contributions to grain yield through the traits number of pods with one, two, and three grains and thousand grain weight via pods with two or four grains. Indirect selection of superior genotypes for pods per plant and grain weight could provide satisfactory results for soybean yield in relation to the growth habit. The interrelationships obtained between growth habits and environments, can be applied to superior genotypes selection strategies in breeding soybean programs.

Conflict of Interests

The authors have not declared any conflict of interests.

Abbreviations: TGW I, thousand grain weight via pods with one grain; **TGW** II, thousand grain weight via pods with two grains; **TGW** III, thousand grain weight via pods with three grains; **TGW** IV, thousand grain weight via pods with four grains; **NP** I G, number of pods with one grain; **NP** II G, number of pods with two grains; **NP** III G, number of pods with three grains; **NP** IV G, number of pods with four grains; **YIELD**, grain yield; **IGH**, indeterminate growth habit; **DGH**, determinate growth habit.

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