Path Analysis Comparison of Plant Population and Hybrid Maturity for Maize Primary and Secondary Yield Components

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Summary

Limited yield component analysis of maize (*Zea mays* L.) using path correlation analysis exists related to crop management in Europe and the United States. The objective of this study was to compare the results generated from path correlation analysis of primary to those of the primary plus secondary yield components and relate these to maize breeding and production research needs. Research was conducted in 2012 and 2013 at Zagreb, Croatia and Mead, Nebraska, United States with maize hybrids ranging from 520 to 650 FAO maturities, and plant populations ranging from 65,000 to 105,000 plants ha^{-1}. Grain yield, ears m^{-2}, rows ear^{-1}, kernels ear^{-1}, kernels row^{-1}, and kernel weight were determined. The path coefficient analysis of primary yield components of ears m^{-2}, kernels ear^{-1}, and kernel weight confirmed that yield component compensation occurred partially accounting for similar yields over a broad range of plant populations and due to hybrid maturity, with all primary grain yield components having direct effect on grain yield. The primary plus secondary indicated the important role of the number of rows ear^{-1} for maize grain yield for high plant population and early-maturity maize hybrids, and the number of kernels row^{-1} and kernels ear^{-1} importance at low plant populations and for mid- and late-maturity maize hybrids. When only primary yield components are included in the analysis, the importance of the secondary grain yield components of rows ear^{-1} and kernels row^{-1} on later occurring yield components and on yield was unavailable. Future yield component studies should use path analysis and include both primary and secondary grain yield components to better understand production and genetic factors leading to yield similarities and differences.

Key words

grain yield, yield components, yield component compensation, path analysis, plant population, hybrid maturity

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Received: November 7, 2016 | Accepted: February 21, 2017

Introduction

Grain yield of maize (*Zea mays* L.) is the product of interrelated yield components that develop sequentially and have compensatory effects (Dofing and Knight, 1992). The primary yield components ears m^{-2}, kernels ear^{-1}, and kernel weight have direct effects on maize grain yield and all except for kernel weight have indirect effects on grain yield via other primary yield components. The maize ear morphology allows measurement of numerous secondary grain yield components such as number of rows ear^{-1}, kernels row^{-1}, kernel depth, and ear length and circumference. These secondary grain yield components have only indirect effects on grain yield via one or more primary yield component. The only grain yield component studies using path correlation analysis conducted on maize have been to assist plant breeding efforts (Agrama, 1996; Mohammadi et al., 2003). Recently Milander et al. (2016; 2017) reported the first comprehensive maize yield component research for plant population and hybrid maturity classification in Croatia and Nebraska.

Comprehensive research on maize yield components to understand environmental and management influences on grain yield has been limited. Early-season stress reduces the number of ears m^{-2} (or ears $plant^{-1}$) (Evans et al., 2003), mid-season (mid-vegetative to mid grain fill stages) stress reduces the number of kernels ear^{-1} (Cicchino et al., 2010), while late-season conditions influence kernel weight as the final kernel weight is determined at physiological maturity (Novacek et al., 2013). In the literature at present, the number of kernels m^{-2} and kernel weight are the commonly reported yield components. More comprehensive yield component data is not used due to cost and labor to measure plus inconsistent results due to complex yield component compensation, thereby making data interpretation difficult.

As maize plant populations increase more ears m^{-2} are produced (Novacek et al., 2013), while the number of kernels ear^{-1}, kernels row^{-1}, and kernel weight decrease (Maddonni and Otegui, 2004; Hashemi et al., 2005; Novacek et al., 2013). Kernel weight is more stable across plant populations than the other yield components (Eichenberger et al., 2015; Svečnjak et al., 2006). Maize hybrid yield and yield component differences in response to plant population have been documented (Bavec and Bavec, 2002; Svečnjak et al., 2004), but the basis for these differences is unknown. They are likely related to different ear characteristics associated with germplasm sources used in developing maize hybrids, specifically the relative proportion of southern dent and northern flint germplasm for U.S. hybrids (Doebley et al., 1988). The southern dent maize races have ears with up to 24 rows of deep kernels, commonly with relatively short, girthy ears (Brown and Anderson, 1948) while northern flint germplasm is characterized by production of multiple ears per plant, and long, slender ears with 8 to 10 rows per ear of broad and shallow kernels (Brown and Anderson, 1947). Northern flint germplasm has been used to develop early-maturity maize hybrids.

The collection and interpretation of more detailed yield component data combined with appropriate use of path correlation analysis could lead to better understanding of yield determination and yield component compensation. Path analysis has many applications in the fields of agriculture, sociology, and epidemiology, as well as others. It was developed by Wright (1921) but first implemented in agriculture by Dewey and Lu (1959) in research on crested wheatgrass *Agropyron cristatum* L. seed production. Path correlation analysis of yield components and grain yield requires a causal relationship to exist (Dewey and Lu, 1959; Agrama, 1996), uses structural linear regression analysis that allows separation of direct and indirect effects, and in contrast to other methods, demonstrates the direction of direct and indirect effects (Li, 1975). The associations between direct and indirect effects can be difficult to dissect and path analysis provides an effective tool to be able to separate direct and indirect associations. It also allows for a critical examination of the factors acting to produce a particular correlation and measures the relative magnitude of each causal factor (Dewey and Lu, 1959).

The objective of this research was to determine the relative merit of using path correlation analysis on primary maize yield components, versus path analysis using primary plus secondary maize yield components. This article reports the comparison of path correlation analysis for primary and primary plus secondary maize grain yield components. The maize grain yield and primary plus secondary yield components results from this study are based upon plant population and hybrid maturity classification previously published (Milander et al., 2016; 2017).

Materials and methods

Field experiments were conducted in 2012 and 2013 in rainfed environments at the Faculty of Agriculture, University of Zagreb Experimental Station in Zagreb, Croatia (45°49'33.66N, 16°01'58.40E) and at the University of Nebraska Agriculture Research and Development Center (ARDC) near Mead, NE (41°09'33.95N, 96°24'44.24W). Soils had silt loam texture and research plots were planted in late April or early May. Plots were four rows wide (2.8 m wide) by 6 m long in Croatia and six rows wide (4.6 m wide) by 9.1 m long in Nebraska.

The experiments were conducted in a randomized complete block design with 3 replications. A factorial combination of three maize hybrids nested within location and five plant populations were used. Hybrids with similar genetics, maturity classifications, and significant commercial production area in Croatia and Nebraska were used. Since only non-GMO maize hybrids are allowed in Croatia, Pioneer P35F38, Pioneer P34N43, and Pioneer P34B23 were used, while in Nebraska were Pioneer P35F40, Pioneer P0876HR, and Pioneer P1151HR with a range of FAO maturities from 520 to 650 were used. Plant populations of 65,000; 75,000; 85,000; 95,000; and 105,000 plants ha^{-1} were used in both Croatia and Nebraska. Conventional disk tillage, recommended pre-emergent and post-emergent herbicides were used for weed control, and 70 to 76 cm row spacing was used at both locations.

In Croatia, an annual split application of 200 kg N ha^{-1}, and fall application of 60 kg P_2O_5 ha^{-1} and 90 kg K_20 ha^{-1} was used on plots. In Nebraska, 120 to 160 kg N ha^{-1} spring pre-plant was applied, and in 2012, 50 kg P_2O_5 ha^{-1} was applied due to a soil deficiency. The 2012 growing season in Nebraska was extremely hot and dry, thus 100 mm ha^{-1} of irrigation was furrow applied on 17 July at blister growth stage (R2) to reduce drought stress and approximate average growing conditions. More details on experimental procedures can be found in Milander et al. (2016; 2017).

Grain yield data was determined by mechanically harvesting the middle two plot rows in Croatia and the middle three plot rows in Nebraska. Grain was weighed, water content was measured, and grain yield for each plot adjusted to a water content of 15.5 g kg^{-1}. Prior to harvest, the number of ears was counted to determine the number of ears m^{-2}. Six consecutive-ear samples were collected from each plot, stored, and used to measure the yield components. Primary grain yield components measured were ears m^{-2}, kernels ear^{-1} and kernel weight, and secondary grain yield components were rows ear^{-1}, ear circumference, kernels row^{-1}, and ear length. Rows ear^{-1} and kernels row^{-1} were hand counted, and ear length and middle-of-the ear circumference were measured. After shelling, the number of kernels ear^{-1} was hand counted and 100 kernels were randomly selected from each ear and used to determine the kernel weight. Water content was measured and 100-kernel weight was adjusted to a moisture content of 15.5 g kg^{-1}.

Data were analyzed using PROC Mixed of SAS, version 9.3 (SAS Institute, 2014). Analysis of variance indicated that low (65,000 and 75,000 plants ha^{-1}) and high (95,000 and 105,000 plants ha^{-1}) plant populations (Milander et al., 2016) and early-maturity and mid- and late-maturity hybrids (Milander et al., 2017) had significant effects on yield and yield components, thus path correlation analysis was conducted separately. Due to limited number of degrees of freedom, it was not possible to conduct the path analysis across both plant population and maize hybrid maturity simultaneously. Path correlation analysis (Agrama, 1996; Mohammadi et al., 2003) of grain yield and the primary components of ears m^{-2}, kernels ear^{-1} and kernel weight were conducted first, then the secondary yield components of rows ear^{-1} , ear circumference, kernels row^{-1}, and ear length were added afterwards using PROC Calis to determine model goodness-of-fit. Path models were developed that fit statistical analysis of data along with making biological sense. Path models and tables with direct, indirect, and total effects are presented.

Results

Primary grain yield components

With only the three primary yield components, the power-of-test and potential for indirect effects was limited. Indirect effects of primary yield components on grain yield were not present at both low and high plant populations, thus the total effects were similar to the direct effects (Table 1). However, the number of ears m^{-2} had a large negative indirect effect on grain yield of the early-maturity hybrids, thereby canceling the large positive direct effect, thus the number of ears m^{-2} had no total effect on maize grain yield (Table 2).

Path correlation models had excellent goodness-of-fit and indicated that all three primary yield components had positive direct effects on grain yield (Figs. 1 and 2; Tables 1 and 2). However, no relationships were detected among yield components across plant populations (Fig. 1; Table 1), while the number of ears m^{-2} negatively influenced the number of kernels ear^{-1} and kernel weight for early-maturity hybrids (Fig. 1A; Table 2) and the number of kernels ear^{-1} positively influenced the kernel weight for mid- and late-maturity hybrids (Fig. 1B; Table 2). The largest direct effect on grain yield was the number of kernels ear^{-1} for high plant populations (Fig. 1B; Table 1) and both the mid- and late-maturity hybrids (Fig. 2A; Table 2), while kernel weight was the largest for low plant populations (Fig. 1A; Table 1). The number of ears m^{-2}, kernels ear^{-1}, and kernel weight direct effects on grain yield were of similar magnitude for early-maturity hybrids, but much higher for the number of kernels ear^{-1} for the mid- and late-maturity hybrids (Fig. 2A; Table 2).

Primary plus secondary yield components - General

The primary plus secondary grain yield component models added the number of rows ear^{-1} and kernels ear^{-1} to the primary grain yield component model. Attempts to add ear circumference and/or ear length decreased the model statistics (data not presented), probably due to auto-correlation between the number of

Table 1. Path analysis of primary maize yield components with grain yield at low (65,000 and 75,000 plants ha^{-1}) and high plant population (95,000 and 105,000 plants ha^{-1}).

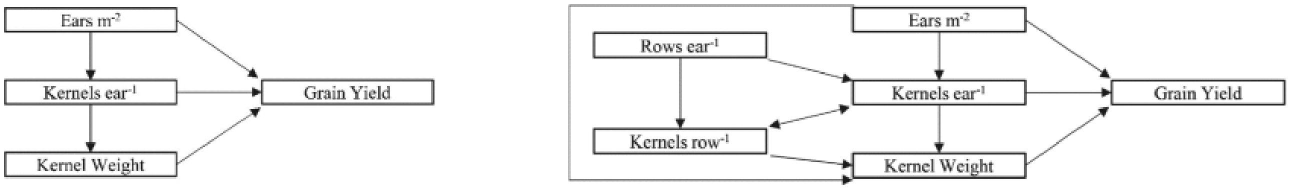
	Low Plant Populations			High Plant Populations		
Chi-Square P Value		0.62			0.98	
Goodness of Fit		1.00			1.00	
Coefficient of Determination, R^2		0.22			0.37	
Root Mean Square Error A		0.00			0.00	
Akaike Information Criterion		18.25			18.00	
Bozdogan CAIC Criterion		47.74			47.49	
Schwarz Bayesian Criterion		38.74			38.39	
Yield	Total	Direct	Indirect	Total	Direct	Indirect
Ears m^{-2}	0.39**	0.36**	0.03	0.55**	0.44**	0.11
Kernels ear^{-1}	0.40**	0.33**	0.06	0.53**	0.53**	—
Kernel weight	0.47**	0.47**	—	0.22**	0.22**	—
Kernel weight						
Ears m^{-2}	0.01	—	0.01	—	—	—
Kernels ear^{-1}	0.14	0.14	—	—	—	—
Kernels ear^{-1}						
Ears m^{-2}	0.08	0.08	—	0.21	0.21	—

* and ** indicates significance at P ≤ 0.05 and 0.01; — indicates absence of total, direct or indirect path correlation

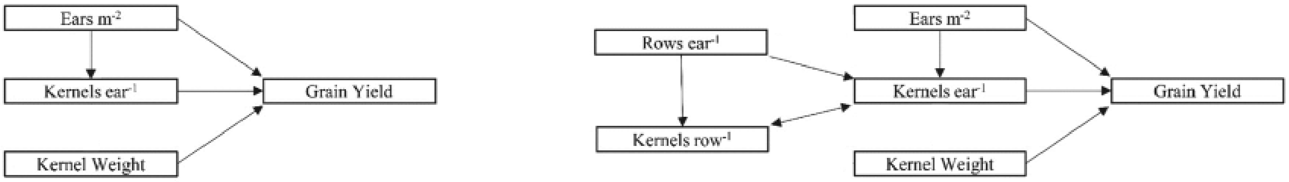
Table 2. Path analysis of primary maize yield components with grain yield by hybrid maturity.

	Early-Maturity Hybrids			Mid- and Late-Maturity Hybrids		
Chi-Square P Value	0.10			0.38		
Goodness of Fit	0.98			0.99		
Coefficient of Determination, R^2	0.46			0.45		
Root Mean Square Error	0.17			<0.01		
Akaike Information Criterion	20.71			18.77		
Bozdogan CAIC Criterion	48.56			52.86		
Schwarz Bayesian Criterion	39.56			43.86		
Yield	Total	Direct	Indirect	Total	Direct	Indirect
Ears m^{-2}	0.16	0.53**	−0.37**	0.37**	0.37**	—
Kernels ear^{-1}	0.53**	0.53**	—	0.66**	0.60**	0.06
Kernel weight	0.47**	0.47**	—	0.33**	0.33**	—
Kernel weight						
Ears m^{-2}	−0.38**	−0.38**	—	—	—	—
Kernels ear^{-1}	—	—	—	0.18*	0.18*	—
Kernels ear^{-1}						
Ears m^{-2}	−0.36**	−0.36**	—	—	—	—

* and ** indicates significance at $P \leq 0.05$ and 0.01; — indicates absence of total, direct or indirect path correlation


A. Path analysis of low plant population (65,000 and 75,000 plants ha^{-1}) primary yield components.

C. Path analysis of low plant population (65,000 and 75,000 plants ha^{-1}) for primary plus secondary yield components.


B. Path analysis of high plant population (95,000 and 105,000 plants ha^{-1}) of primary yield components.

D. Path analysis of high plant population (95,000 and 105,000 plants ha^{-1}) for primary plus secondary yield components.

Figure 1. Comparison of primary to primary plus secondary yield components for plant population.

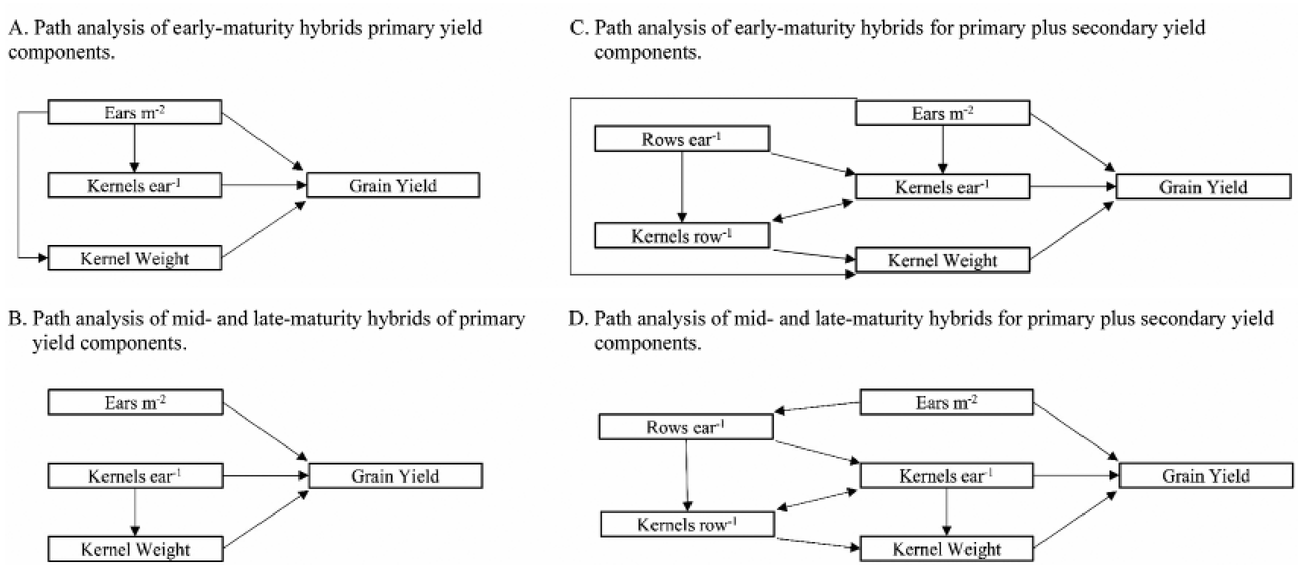
kernels ear^{-1} and kernel length (r = 0.84 to 0.90) and the number of rows $ears^{-1}$ to ear circumference (r = 0.53 to 0.67), thus these related parameters were not included in the final models.

The path analysis models selected for both the low and high plant populations, and early-maturity and mid- and late-maturity had excellent goodness-of-fit (Tables 3 and 4). The results indicated that all the primary yield components of ears m^{-2}, kernels ear^{-1}, and kernel weight had positive direct effects on grain yield across plant populations and hybrid maturity (Figs. 1 and 2; Tables 3 and 4). Adding the secondary grain yield components into the path correlation analysis for hybrid maturity classification increased information available, especially about indirect effects, without adversely affecting the path model statistics or changing the primary yield component direct effects.

The direct effects of the primary yield components on grain yield were similar for both plant population and hybrid maturity primary and primary plus secondary grain yield component models (Figs. 1 and 2; Tables 3 and 4), thereby leading to similar results as with primary yield component analysis. Likewise, the total and indirect effects were similar for the primary and primary plus secondary path analysis for low and mid- and high-plant populations (Fig.1, Tables 1 and 3) while the total and indirect effects were very different for the number of ears m^{-2} and kernels ear^{-1} (Fig. 2; Tables 2 and 4).

Primary plus secondary yield components – Plant population

Yield components of primary models for low and high plant populations were similar (Figs. 1A and 1B; Table 1). When the


A. Path analysis of early-maturity hybrids primary yield components.

C. Path analysis of early-maturity hybrids for primary plus secondary yield components.

B. Path analysis of mid- and late-maturity hybrids of primary yield components.

D. Path analysis of mid- and late-maturity hybrids for primary plus secondary yield components.

Figure 2. Comparison of primary to primary plus secondary yield components for maize hybrid maturity.

Table 3. Path analysis of primary plus secondary maize yield components with grain yield at low (65,000 and 75,000 plants ha^{-1}) and high plant population (95,000 and 105,000 plants ha^{-1}).

	Low Plant Population			High Plant Population		
Chi-Square P Value		0.28			0.52	
Goodness of Fit		0.97			0.98	
Coefficient of Determination, R^2		0.23			0.54	
Root Mean Square Error A		0.06			0.001	
Akaike Information Criterion		38.28			35.19	
Bozdogan CAIC Criterion		90.7			84.34	
Schwarz Bayesian Criterion		74.4			69.3	
Yield	Total	Direct	Indirect	Total	Direct	Indirect
Ears m^{-2}	0.37**	0.37**	0.01	0.44**	0.45**	−0.01
Kernels ear^{-1}	0.14	0.34**	−0.20	0.54**	0.54**	—
Kernel weight	0.47**	0.47**	—	0.23**	0.23**	—
Rows ear^{-1}	−0.01	—	−0.01	0.29**	—	0.29**
Kernels row^{-1}	0.29*	—	0.29*	—	—	—
Kernel weight						
Ears m^{-2}	−0.01	—	−0.01	−0.10	−0.10	—
Kernels ear^{-1}	−0.41	−0.41	—	—	—	—
Rows ear^{-1}	−0.16	—	−0.16	—	—	—
Kernels row^{-1}	0.61*	0.61*	—	—	—	—
Kernels ear^{-1}						
Ears m^{-2}	0.03	0.04	−0.01	0.03	0.03	—
Rows ear^{-1}	0.18	0.18	—	0.54**	0.54**	—
Kernels row^{-1}	0.93**	0.93**	—	0.65**	0.65**	—
Kernels row^{-1}						
Ears m^{-2}	0.01	—	0.01	—	—	—
Rows ear^{-1}	−0.14	−0.14	—	0.39**	0.39**	—
Rows ear^{-1}						
Ears m^{-2}	−0.04	−0.04	—	—	—	—

* and ** indicate significance at $P \leq 0.05$ and 0.01; — indicates absence of total, direct or indirect path correlation

primary plus secondary yield component models were considered, two major differences were present between the primary and primary plus secondary yield component path models direct effects (Figs. 1C and 1D; Table 3). First, at low plant populations, the number of kernels row^{-1} had a large direct effect on kernel weight that was absent for high plant populations; and second, at high plant populations, the number of rows ear^{-1} had a direct effect on both the number of kernels ear^{-1} and kernels row^{-1} that were absent with low plant populations. At low plant populations, the number of kernels row^{-1} had a positive indirect effect on grain yield, while the number of rows ear^{-1} has a similar magnitude positive indirect effect on grain yield in high plant

Table 4. Path analysis of primary plus secondary maize yield components with grain yield by hybrid maturity.

	Early-Maturity Hybrids			Mid- and Late-Maturity Hybrids		
Chi-Square P Value	0.10			0.16		
Goodness of Fit	0.95			0.98		
Coefficient of Determination, R^2	0.58			0.58		
Root Mean Square Error	0.11			0.07		
Akaike Information Criterion	40.24			39.24		
Bozdogan CAIC Criterion	86.65			96.05		
Schwarz Bayesian Criterion	71.65			81.05		
Yield	Total	Direct	Indirect	Total	Direct	Indirect
Ears m^{-2}	0.34**	0.48**	−0.15*	0.27**	0.36**	−0.09**
Kernels ear^{-1}	0.48**	0.48**	—	0.20	0.58**	−0.37**
Kernel weight	0.41**	0.41**	—	0.32**	0.32**	—
Rows ear^{-1}	0.30**	—	0.30**	0.33**	—	0.33**
Kernels row^{-1}	0.12*	—	0.12*	0.46**	—	0.46**
Kernel weight						
Ears m^{-2}	−0.28*	−0.28*	—	0.01	—	0.01
Kernels ear^{-1}	—	—	—	−1.18**	−1.18**	—
Rows ear^{-1}	0.11	—	0.11	−0.03	—	−0.03
Kernels row^{-1}	0.29*	0.29*	—	1.44**	1.44**	—
Kernels ear^{-1}						
Ears m^{-2}	−0.07	−0.07	—	−0.16**	—	−0.16**
Rows ear^{-1}	0.53**	0.53**	—	0.59**	0.59**	—
Kernels row^{-1}	0.63**	0.63**	—	0.68**	0.68**	—
Kernels row^{-1}						
Ears m^{-2}	—	—	—	−0.13**	—	−0.13**
Rows ear^{-1}	0.36**	0.36**	—	0.46**	0.46**	—
Rows ear^{-1}						
Ears m^{-2}	—	—	—	−0.28**	−0.28**	—

* and ** indicate significance at $P \leq 0.05$ and 0.01; — indicates absence of total, direct or indirect path correlation

populations. No other indirect effects were found, thus total effects closely matched the direct effects.

Primary plus secondary yield components – Hybrid maturity

Yield components of primary models for hybrid were similar (Figs. 2A and 2B; Table 2). When the primary plus secondary path models were considered, both early-maturity, and mid- and late-maturity maize hybrids rows ear^{-1} had positive direct effects on kernels ear^{-1} and kernels row^{-1} (Table 4). In addition the number of kernels ear^{-1} and kernels row^{-1} had bi-directional effects on each other. In addition, the number of rows ear^{-1} had a large positive indirect effect on grain yield for both maturity classes, largely via positive direct effects on the number of kernels ear^{-1} and kernels row^{-1}.

Consideration of the primary and primary plus secondary path analysis models, indicated major differences in yield components between the early-maturity, and the mid-and late-maturity hybrids. The primary path analysis model indicated no total effect between the number of ears m^{-2} and yield for early maturity hybrids, since a large negative indirect effect count balanced the large direct effect of the number of ears m^{-2} on grain yield (Table 2). In addition, for the mid- and late-maturity hybrids, the primary path analysis model indicated both large positive direct and total effects of ears m^{-2} on grain yield. When the primary plus secondary path model was considered, significant indirect effect for the number of ears m^{-2} were present for early- and mid- and late maturity hybrids, which lower the magnitude of the ear m^{-2} on grain yield total effect (Table 4). Also, a large negative indirect effect of the number of kernels ear^{-1} on yield was identified, which counter-balanced the large direct effect leading to the lack of total effect mid- and late-maturity hybrids. Differences among yield components were also identified, with mid- and late-maturity hybrids with the number of ears m^{-2} having direct and total effects on rows ear^{-1}, and indirect and total effects on the number of kernels row^{-1} and kernels ear^{-1}. These were not found for the early-maturity hybrids. Also, the number of ears m^{-2} had a large negative impact on kernel weight for early-maturity hybrids, but not for mid- and late-maturity hybrids.

Discussion

The collection of secondary maize yield component data is expensive and labor intensive, but as shown in this study, this provides additional information beyond that of primary yield components alone. This information includes evaluation of direct and indirect effects of secondary yield components on each other, and on grain yield. The secondary yield component rows ear^{-1} is determined at the V7 growth stage (Abendroth et al., 2011), and thus this data allow one to consider more precisely the timing of stress or crop management practice on yield. Path correlation analysis provides a statistical modeling technique that enhances the descriptive value of the data, and gives an opportunity to visually present magnitude and direction of complex yield component data. Many differences were observed between the primary plus secondary yield component models, largely related to the presence or absence of indirect effects and the consequent influence on total effects, which are the sum of the direct and indirect effects (Table 4). This gives the opportunity to better understand yield component compensation, and relate this compensation to yield similarities and/or differences caused by genetics, environment, and management.

Specifically, in this study, the primary plus secondary yield components path analysis models (Fig. 1; Table 3) allowed better understanding of the lack of maize yield response when the plant population was increased from 65,000 to 105,000 plants ha^{-1} (Milander et al., 2016). At high plant populations, the number of row ear^{-2} positively influenced the number of kernels ear^{-1} and indirectly grain yield. This was likely due to intra-specific plant competition at high plant populations at the V7 growth stage early in the growing season when the number of rows ear^{-1} is determined (Abendroth et al., 2011). In contrast, at low population, the ear size as measured by the number of kernels row^{-1} and kernels ear^{-1} had large impacts on grain yield.

The primary plus secondary path analysis models (Fig. 2; Table 4) allowed better understanding about the similar grain yields produced by early-, mid-, and late-maturity maize hybrids (Milander et al., 2017). Early-maturity maize hybrids produced fewer rows ear^{-1}, lighter kernels, and more kernels row^{-1} and kernels ear^{-1} than mid- and late-maturity hybrids. This led to multiple differences between yield component total, direct and indirect effects between the early-maturity and mid- and late-maturity hybrids, likely due to differences in the proportion of northern flint (more in early-season hybrids) and southern dent (more in mid- and late maturity hybrids) present in the genetic background.

Collection of primary yield components is important, but not adequate to understand grain yield determination, yield component compensation, and interpret responses of maize hybrids to environment, management, or genetic background. Measurement and path analysis of primary plus secondary yield components allows detection and direction of direct, indirect and total effects of yield components on yield, and relatively early yield components on later occurring yield components. Especially relevant is the fact that the primary yield component of the number of ears m^{-2} occurs by the V6 growth stage, and the secondary yield component number of rows ear^{-1} occurs specifically at the V7 growth stage (Abendroth et al., 2011), both of these allowing for better understanding of early seasons stress or competition on maize yield. Measuring both primary and secondary yield components along with yield and use of path analysis is useful to interpreting production and genetic research with maize and other crops.

Conclusion

Yield component responses are environmentally specific and hybrid differences are common, therefore, results can be complex and confusing. Path correlation analysis has been used widely for other crops, but only limited use has been reported for maize, and these studies focused on primary yield components with occasional inclusion of one secondary yield component (Agrama, 1996; Mohammadi et al., 2003). In the field research (Milander et al., 2016, 2017) it was found that rainfed maize yield was influenced to a limited degree across locations, years, plant populations, and hybrid maturity, but yield component compensation occurred leading to resilient grain yield production across plant populations and hybrid maturity. Primary and primary plus secondary yield component path analyses models for both plant population and hybrid maturity had excellent goodness-of-fit in this study. The path coefficient analysis results presented confirm that yield component compensation occurred for both plant population and hybrid maturity differences, with all primary grain yield components having direct effect on grain yield. The primary plus secondary indicated differential yield component response to plant population and hybrid maturity, especially the important role of the largely genetically controlled number of rows ear^{-1} determined at the V7 growth stage (Abendroth et al., 2011) for high plant population and early-maturity. Also, the number of kernels row^{-1} and kernels ear^{-1}, which occurs between the V7 and R2 growth stages, have an important role in grain yield at low plant populations and for mid- and late-maturity maize hybrids. When only primary yield components were included in the analysis, then the importance and different responses of these secondary yield components on later occurring yield components and grain yield were unavailable. Future grain yield component studies should use path analysis and include both primary and secondary grain yield components to help better understand production and genetic factors leading to grain yield differences.

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