Breeding Potential of Semi-dwarf Corn for Grain and Forage

in the Northern U.S. Corn Belt

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ABSTRACT

Conventional, non-dwarf corn (*Zea mays* L.) hybrids grown in the northern U.S. Corn Belt are typically more than 2 m tall and have a 75-100 day relative maturity (RM). Our objectives were to assess the potential of open-pollinated COPOP1 semi-dwarf corn for grain and forage production, estimate genetic variances and heritability in COPOP1, and develop COPOP1 subpopulations that exhibit heterosis. In 2005 and 2006, we evaluated COPOP1 with four commercial, non-dwarf hybrids at three plant population densities. Grain yield of open-pollinated COPOP1 was about half of the mean yield of the conventional hybrids. However, COPOP1 had lower grain moisture (equivalent to 62 days RM) and better forage quality than the commercial hybrids. In 2007, COPOP1 was evaluated for performance when crossed to two divergent inbred testers, LH227 and LH295. Heritability was significant for grain moisture, plant height, and ear height in testcrosses to both testers but was significant for grain yield only in testcrosses to LH227. In 2009, bulk Cycle 0 (i.e., original COPOP1) and Cycle 1 testcrosses, nine semi-dwarf hybrids, COPOP1, and three commercial hybrids were evaluated at two plant population densities. Grain yield and most agronomic and forage traits did not improve between Cycle 0 and Cycle 1 in either testcross population. None of the semi-dwarf hybrids had higher grain yields than COPOP1. While semi-dwarf COPOP1 can serve as a source of useful variation for improving elite germplasm in the northern U.S. Corn Belt, further selection in COPOP1 must be done to develop improved semi-dwarf populations.

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INTRODUCTION

In corn (*Zea mays* L.), genes such as *reduced plant 1* (*rd1*), *brachytic 2* (*br2*) and *compact plant* (*ct*) cause dwarfing (Nelson and Ohlrogge, 1957; Scott and Campbell, 1969; Modarres et al., 1997b; Neuffer et al., 1997). Semi-dwarf corn may have characteristics that make it suitable for grain and forage production in short-season environments (Dijak et al., 1999; Coors and Lauer, 2001). In particular, the limited heat units in short-season environments reduce grain yield and lessen the probability of the crop reaching physiological maturity in a given year. Semi-dwarf hybrids have required 10% fewer heat units than conventional hybrids to reach anthesis (Dijak et al., 1999) and generally reach physiological maturity earlier than conventional cultivars (Modarres et al., 1997a). Like semi-dwarf wheat (*Triticum aesivum* L.; Vogel et al., 1963), semi-dwarf sorghum (*Sorghum bicolor* L.; Windscheffel et al., 1973), and semi-dwarf rice (*Oryza sativa* L.; Hedden, 2003), semi-dwarf corn may be less prone to stalk and root lodging due to the shorter stalks and lower ear placement (Dijak et al., 1999). Semi-dwarf corn has the potential to produce high-quality forage due to its high ear-to-stover ratio, although dry matter yield was shown to be limiting in forage production (Byers et al., 1965; Hunter, 1978; Coors and Lauer, 2001).

The smaller plant structure and reduced per plant leaf area of semi-dwarf corn require high plant population densities to maximize grain and forage yield (Nelson and Ohlrogge, 1957; Begna et al., 1997; Modarres et al., 1998). Whereas conventional corn cultivars are commonly planted at 79 000 to 84 000 plants ha^{-1} in the northern U.S. Corn

Belt (Coulter, 2009), grain yield of semi-dwarf corn with the *rd1* gene was maximized at 150 000 to 200 000 plants ha^{-1} (Begna et al., 1997). Production of semi-dwarf corn at such high plant population densities may provide agroecological benefits such as reduced weed pressure, surface runoff, and evapotranspiration (Tollenaar et al., 1994; Begna et al., 2001).

In practice, the introgression of dwarfing genes in corn has been accompanied by undesirable pleiotropic effects including tassel ears, tillering, and reduced leaf number and leaf area (Scott and Campbell, 1969; Winkler and Freeling, 1994; Modarres et al., 1997b;). Selection for grain yield and other agronomic traits must therefore be conducted after the introgression of dwarfing genes. COPOP1 is an open-pollinated semi-dwarf population developed by researchers at Agriculture and Agri-Food Canada. COPOP1 was derived from BRCsyn, a synthetic population known to contain the *rd1* gene and possibly other dwarfing genes of minor effect (L.M. Reid, personal communication, 2004). COPOP1 has undergone selection for grain yield, cold and drought tolerance, early flowering, stay-green, and resistance to several diseases (L.M. Reid, personal communication, 2004). However, the usefulness of COPOP1 semi-dwarf corn in the northern U.S. Corn Belt has not been well studied.

Our primary objective was to determine the potential of the COPOP1 semi-dwarf corn population for grain and forage production in the northern U.S. Corn Belt. In this research, we first evaluated COPOP1 alongside commercial hybrids to define the improvement necessary for semi-dwarf corn to be competitive. We then estimated the genetic variance and heritability for different traits in COPOP1 to determine the potential that exists for genetic improvement by selection. Finally, we conducted one cycle of divergent testcross selection to begin to develop COPOP1 subpopulations that exhibit heterosis.

MATERIALS AND METHODS

Performance of Open-Pollinated COPOP1 vs. Commercial Hybrids

In 2005 and 2006, COPOP1 was evaluated for grain production and forage quality and production in field experiments in St. Paul and Rosemount, MN. The experiments were conducted at two sites at each location in each year for a total of eight environments; the two field sites in each location differed in soil type and planting date (Table 1). COPOP1 and four early-maturing commercial hybrids were grown at three plant population densities (101 000, 138 000 and 175 000 plants ha^{-1}) for a total of 15 treatments. These 15 treatments were evaluated in a randomized complete block design with two replications per environment. The four commercial hybrids were NK N03-D8 (68 RM), Thompson's BIXXIO RR (74 RM), Pioneer 39F59 (77 RM), and Pioneer 39T66 (78 RM). The entries were evaluated in five-row plots, each row 6.10 m long and 0.30 m apart. All plots were overplanted and thinned after four weeks to achieve the target plant population density. Nitrogen fertilizer was applied at each location (Table 1) and weeds were controlled by herbicide application and mechanical means.

The grain yield and agronomic traits measured included days to anthesis (days from planting to when 50% of the plants were shedding pollen), days to silking (days from planting to when 50% of the plants had extruded silks), plant height (cm; soil surface to the collar of the top fully expanded leaf), ear height (cm; soil surface to the collar of the ear leaf), barrenness (percentage of plants that failed to produce any kernels), total lodging (percentage of plants with stalks broken below the ear or bent $\geq$ 45° at the soil surface), grain moisture (g kg^{-1}), and grain yield (Mg ha^{-1}; adjusted to 155 g H_2O kg^{-1}). Grain was hand harvested from 5.18 m of two competitive rows and mechanically shelled. Grain moisture was measured using an electronic moisture meter.

Forage traits measured included whole-plant harvest moisture (g kg^{-1}), whole-plant dry matter yield (Mg ha^{-1}), and ear-to-stover ratio. Whole-plant forage samples were taken from 5.18 m of two competitive rows when the mean whole-plant moisture of forage samples (taken periodically) was about 650 g kg^{-1}. Plants were cut at ground level and were weighed to determine total dry matter yield. Ears were then removed from half of the plants and separate weights of the ear (grain and cob) and stover (excluding grain and cob) portions were measured to determine the ear-to-stover ratio. Ear, stover, and whole-plant portions were coarse chopped individually with a modified yard chipper and approximately a 1 kg representative sample was collected of each portion. Samples were dried in a forced-air dryer at 60°C and were weighed for dry matter determination. Whole-plant samples were finely ground through a 1 mm screen for forage quality analysis.

Forage quality traits were measured on the whole-plant samples by near-infrared reflectance spectroscopy (NIRS) analysis on a Foss (Foss North America Inc., Eden Prairie, MN) model 6500 scanning monochrometer in the range of 400-2500 nm. Infrared Software International software (Foss North America, Eden Prairie, MN) was used to modify in-house predictive equations for crude protein, neutral detergent fiber (NDF), oil, starch, in vitro true digestibility (IVTD) and ash, following the guidelines of Shenk and Westerhaus (1994). The predictive equations had standard errors of cross validation (SECV) of 0.45 for crude protein, 2.5 for NDF, 1.7 for IVTD, 1.9 for starch, 0.59 for oil, and 0.45 g kg^{-1} for ash. Chemical analyses were conducted on a subset of the samples using conventional methods [crude protein as Kjeldahl N × 6.25 (AOAC, 1990); NDF and IVTD (48-hour incubation) as described by Goering and Van Soest (1970); starch as described by Hall (2000)]. Neutral detergent fiber digestibility (NDFD) was calculated (Darby and Lauer, 2002) as NDFD = 1000[NDF – (1000 – IVTD)]/NDF. Predicted milk Mg^{-1} (kg milk Mg^{-1} forage dry matter) and milk ha^{-1} (kg milk ha^{-1}) were calculated using the Milk2006 spreadsheet (Undersander et al., 1993), which uses energy intake requirements of a standard lactating dairy cow (613 kg body weight; 36 kg of milk production per day at 3.8% fat) to predict performance. The dry matter yield and harvest moisture from field measurements and crude protein, NDF, IVTD, starch, oil, and ash values from the forage quality analysis were used in calculating the performance index values; kernel processing was assumed.

Least squares estimates of trait means across environments were calculated and an analysis of variance (ANOVA) was conducted for each trait through PROC MIXED in SAS/STAT (SAS Institute, 2004). Entry, plant population density, and entry by plant population density interaction were treated as fixed effects, while environment and replication within environment were considered random. The mean square for treatment by environment interaction was used as the error term for the significance tests of the fixed effects. Fisher's protected LSD ($P = 0.05$) was used to separate entry means.

Testcross Variances and Trait Heritability in COPOP1

In 2006, 120 random S_0 plants from the COPOP1 population were self-pollinated and testcrossed to Monsanto inbreds LH227 and LH295. LH227 belongs to the Iowa

Stiff Stalk Synthetic (BSSS) heterotic group, LH295 belongs to the non-BSSS heterotic group, and LH227 × LH295 is a commercial hybrid. COPOP1 was considered as the Cycle 0 population.

In 2007, the Cycle 0 testcrosses were evaluated in yield trials at the University of Minnesota Southern Research and Outreach Center (SROC) near Waseca and the University of Minnesota Southwest Research and Outreach Center (SWROC) near Lamberton. To control spatial variation, the 120 testcrosses were divided into six sets, with 20 testcrosses per set in a randomized complete block design with one replication in each environment. Plots consisted of two rows, 6.71 m long and 0.76 m apart. Plots were planted to a target plant population density of 138 000 plants ha^{-1} and were not thinned after planting. The Waseca site was planted on 10 May and the Lamberton site on 16 May. The primary soil types were Nicollet clay loam in Waseca and Ves loam in Lamberton. Weeds were controlled with chemical herbicide and fertilizer was applied according soil test results (157-112-168 kg $N\text{-}P_2O_5\text{-}K_2O$ ha^{-1} at Waseca and 151-0-0 kg $N\text{-}P_2O_5\text{-}K_2O$ ha^{-1} at Lamberton). Data were collected for ear and plant height, root and stalk lodging, grain moisture and grain yield, in the same manner as in the 2005 and 2006 experiments. Root lodging was the percentage of plants leaning ≥45° at the soil surface and stalk lodging the percentage of plants with a broken stalk below the ear. Plots were machine harvested on 18 Sept. in Waseca and 26 Sept. in Lamberton. Trait means across environments were calculated.

Testcross variance and heritability (h^2) were estimated according to a one-factor design with one replication in each environment (Bernardo, 2010, p. 185). Variance components were estimated using PROC VARCOMP in SAS/STAT (SAS Insitute, 2004). Estimates of h^2 were calculated on a testcross-mean basis (Bernardo, 2010, p. 156). Confidence intervals (P = 0.05) were calculated for the testcross variance (V_{TC}) and the h^2 estimates using methods described by Knapp et al. (1987).

Selection for Divergent Combining Ability

The six testcrosses with the highest grain yield with LH227 as the tester were identified. The six S_1 lines that corresponded with the highest-yielding testcrosses were random mated in summer 2008 to form DCLH227-C1 (i.e., DC for dwarf corn). For convenience, these six S_1 lines were denoted by DCLH227-C1-1, DCLH227-C1-2, … , DCLH227-C1-6 (with DCLH227-C1-1 being the highest-yielding of the six selected lines). Likewise, the six testcrosses with the highest grain yield with LH295 as the tester were identified and their corresponding S_1 lines were random mated in 2008 to form DCLH295-C1. These six S_1 lines were denoted by DCLH295-C1-1, DCLH295-C1-2, … , DCLH295-C1-6. Predicted response to selection was calculated for grain yield in each population as $R = h^2S$, where h^2 was the heritability and S was the selection differential, i.e., the difference between the mean of the selected Cycle 0 lines and the overall Cycle 0 population.

In winter 2008, bulks of COPOP1 and of DCLH227-C1 were crossed to LH227 to produce testcross seed for evaluation. Bulks of COPOP1 and of DCLH295-C1 were likewise crossed to LH295. Also, DCLH227-C1-1, DCLH227-C1-2, and DCLH227-C1-3 were crossed in a factorial manner with DCLH295-C1-1, DCLH295-C1-2, and DCLH295-C1-3 to form nine semi-dwarf hybrids.

In 2009, testcrosses of the Cycle 0 (i.e., COPOP1) and Cycle 1 populations and the nine semi-dwarf hybrids were evaluated at two sites at SROC near Waseca and at two sites at SWROC near Lamberton, for a total of four environments. The two sites at each location differed in soil type and planting date (Table 1). Four checks were included in the experiment: open-pollinated COPOP1, NK N03-D8 (68 RM), Pioneer 39T66 (78 RM), and LH227 x LH295. Each entry was evaluated at plant population densities of 79 000 and 123 000 plants ha^{-1}. The testcrosses of DCLH227-C0, DCLH295-C0, DCLH227-C1, DCLH295-C1, and COPOP1 were replicated three times, while the dwarf hybrids were replicated only once within an environment due to limited seed availability. The plots consisted of five rows, each 6.71 m long and 0.51 m apart. Nitrogen fertilizer was applied at each location (Table 1) and weeds were controlled through chemical herbicide application and mechanical means.

The traits studied were the same as those in the comparisons of COPOP1 versus commercial hybrids in 2005 and 2006. In addition, total leaf number and stalk and root lodging were recorded. All traits were measured from the middle three rows of each plot. Total leaf number was the mean of six consecutive plants within a row; counts were taken after anthesis from the sixth leaf, which had been marked in the V6-V7 stage. Days to anthesis and days to silking were recorded at three sites, two at Waseca and one at Lamberton. Whole-plant forage samples were taken from 1 m of a competitive row, cut at ground level when plots averaged about 650 g kg^{-1} whole-plant moisture. Whole-plant forage samples were processed in the same way as in the 2005 and 2006 experiments.

Whole-plant samples were scanned by NIRS using a Perten (Perten Instruments North America Inc., Springfield, IL) model DA 7200 spectrometer in the range of 950-1650 nm. Chemical analyses were conducted using methods described previously. Commercial NIRS predictive equations (Perten Inc., Springfield, MO) were used with SECV values of 0.67 for crude protein, 2.2 for NDF, 4.7 for NDFD, 2.9 for starch, 0.35 for oil and 0.7 g kg^{-1} for ash. Predicted milk Mg^{-1} and milk ha^{-1} were calculated for the testcross populations and conventional hybrids but not for the semi-dwarf hybrids because the latter did not differ in crude protein and IVTD.

Least squares estimates of trait means were calculated and ANOVA was conducted with PROC MIXED in SAS/STAT (SAS Insitute, 2004). The nine semi-dwarf hybrids and COPOP1 were much shorter than the other entries, and separate statistical analyses were performed for the semi-dwarf entries and non-dwarf entries to allow better comparisons between material similar in height. Entry, plant population density, and entry by plant population density were considered fixed effects whereas environments and replications within environments were considered random effects. Treatment by environment mean squares were used as the denominator for significance tests of the fixed effects. Fisher's protected LSD (P = 0.05) was calculated for each significant trait for separation of entry means.

RESULTS

Performance of Open-Pollinated COPOP1 versus Commercial Hybrids

The entries in the 2005 and 2006 trials had significant differences ($P < 0.05$) for all traits except barrenness and lodging (Tables 2 and 3). Compared with the conventional (i.e., non-dwarf) hybrids, COPOP1 had lower grain yield, grain moisture, plant height, ear height, days to anthesis, and days to silking, but had a greater anthesis-silking interval (ASI). Grain yield of open-pollinated COPOP1 was 46% of the mean grain yield of the four commercial hybrids. This lower grain yield was accompanied by 60 g kg^{-1} lower grain moisture at harvest. On average, COPOP1 reached anthesis and silking 6 days earlier than the four conventional hybrids. COPOP1 was half as tall as the conventional hybrids and had ears nearly 70 cm closer to the ground.

Plant population density had a significant effect on grain yield, days to anthesis, days to silking, ASI, and barrenness. Least-squares means for grain yield across all entries were 9.2 Mg ha^{-1} in the low plant population density (101 000 plants ha^{-1}) and 9.9 Mg ha^{-1} in the high plant population density (175 000 plants ha^{-1}). Means for days to silking ranged from 59.6 d in the low density to 61.2 d in the high density. Barrenness of COPOP1 was not different in the low (6.2%) and medium (6.1%) plant population densities (138 000 plants ha^{-1}) but it increased to 12.5% in the high plant population density. The entry by plant population density interaction was significant only for ear height.

Compared with the commercial hybrids, COPOP1 had significantly lower ($P < 0.05$) forage dry matter yield, forage moisture, and NDF but higher ear-to-stover ratio, crude protein, IVTD, NDFD, and starch (Table 3). In particular, COPOP1 showed a 96 % increase in ear-to-stover ratio and a 17 % increase in crude protein over the mean of the conventional hybrids. Plant population density had a significant effect on ear-to-stover ratio, crude protein, and milk Mg^{-1}. Least-squares means for ear-to-stover ratio ranged from 0.97 in the low density to 0.86 in the high density. Means for milk Mg^{-1} were 1261 kg Mg^{-1} at the low density and 1212 kg Mg^{-1} at the high density. None of the forage traits exhibited entry by plant population density interaction.

Variance and Heritability Estimates

Estimates of V_{TC} and h^2 were significant ($P < 0.05$) for grain moisture, plant height, and ear height in testcrosses of COPOP1 to both LH227 (i.e., DCLH227-C0) and LH295 (i.e., DCLH295-C0) (Table 4). Estimates of V_{TC} and h^2 for grain yield were significant only in DCLH227-C0. Estimates of h^2 in the DCLH227-C0 population ranged from 0.01 for stalk lodging to 0.63 for grain moisture; moderate heritability estimates were found for grain moisture (0.63) and ear height (0.55). In the DCLH295-C0 population, the h^2 estimates ranged from 0.02 for stalk lodging to 0.63 for grain moisture; similarly, moderate estimates for heritability were found for grain moisture (0.63), plant height (0.53), and ear height (0.48). Predicted response to selection for grain yield was 0.71 Mg ha^{-1} in DCLH227-C0 and 0.69 Mg ha^{-1} in DCLH295-C0.

Response to Selection for Divergent Combining Ability

The bulked Cycle 0 and Cycle 1 entries and the commercial hybrids differed significantly ($P < 0.05$) in their grain yield, grain moisture, plant height, ear height, days to anthesis, days to silking, and ASI (Table 5). DCLH227-C0 and DCLH227-C1 had significant differences in plant height, ear height, and ASI. However, no difference was found between DCLH295-C0 and DCLH295-C1 for grain yield or any of the agronomic traits. DCLH227-C0, DCLH227-C1, DCLH295-C0, and DCLH295-C1 were not different for grain yield from two check hybrids, Pioneer 39T66 and NK N03-D8, although all six entries had lower grain yield than LH227 × LH295. Grain moisture of DCLH227-C0, DCLH227-C1, DCLH295-C0, and DCLH295-C1 was greater than that of NK N03-D8 but was lower than that of LH227 × LH295. Plant population density had a significant effect on grain yield, plant height, ASI, and barrenness. Means for grain yield were 8.8 Mg ha^{-1} at the low density (79 000 plants ha^{-1}) and 8.0 Mg ha^{-1} at the high density (123 000 plants ha^{-1}). Barrenness ranged from 2.1% in the low density to 8.1% in the high density. Entry by plant population density interaction was not significant for grain yield or any of the agronomic traits.

The bulked Cycle 0 and Cycle 1 entries and the commercial hybrids differed significantly for all forage yield and quality traits except the milk ha^{-1} index (Table 6). Plant population density had a significant effect on harvest moisture, NDF, IVTD, NDFD, starch, and milk Mg^{-1}. Milk Mg^{-1} decreased with plant population density from 1402 kg Mg^{-1} in the low density to 1350 kg Mg^{-1} in the high density. No forage yield or quality traits had a significant entry by plant population density interaction. Cycle 1 and Cycle 0 did not differ for any of the forage traits in either population. Forage dry matter yield of the four testcross populations was not different from that of two of the check hybrids, Pioneer 39T66 and NK N03-D8.

The nine DCLH227-C1 x DCLH295-C1 semi-dwarf hybrids differed in grain yield, grain moisture, plant height, ear height, and leaf number (Table 7). Plant population density had a significant effect on days to anthesis and ASI; no entry by plant population density interaction was found for grain yield and the agronomic traits. None of the semi-dwarf hybrids had greater grain yield than open-pollinated COPOP1. Compared to COPOP1, two dwarf hybrids (DCLH227-C1-3 x DCLH295-C1-2 and DCLH227-C1-2 x DCLH295-C1-2) were taller and one dwarf hybrid (DCLH227-C1-1 x DCLH295-C1-1) was shorter. Means for ASI increased with plant population density, from 1.3 days in the low density to 2.4 days in the high density.

The nine DCLH227-C1 x DCLH295-C1 semi-dwarf hybrids differed in forage harvest moisture, NDF, and starch (Table 8). Plant population density had a significant effect on forage dry matter yield; entry by plant population density interaction was not significant for any of the forage yield or quality traits. Forage dry matter yields ranged from 7.86 Mg ha^{-1} for DCLH227-C1-1 x DCLH295-C1-1 to 11.22 Mg ha^{-1} for DCLH227-C1-2 x DCLH295-C1-2. DCLH227-C1-2 x DCLH295-C1-2 had greater harvest moisture and DCLH227-C1-1 x DCLH295-C1-2 had lower harvest moisture than COPOP1. Dry matter yield increased from 8.3 Mg ha^{-1} at the low plant population density to 10.0 Mg ha^{-1} at the high plant population density.

DISCUSSION

COPOP1 Semi-Dwarf Corn for Grain Production

Three primary conclusions can be drawn from our experiments. First, open-pollinated COPOP1 has grain yields that are about half of those of commercial hybrids but exhibits useful characteristics including early flowering, reduced plant and ear height, and good forage quality. Second, significant variation is present in COPOP1 for important traits including grain yield, grain moisture, plant height, and ear height, indicating potential for improvement of these traits. Finally, one cycle of testcross selection for divergent combining ability in COPOP1 was ineffective and more cycles of selection will be needed to develop competitive semi-dwarf hybrids directly from COPOP1.

The lower grain yield of COPOP1 compared to the conventional hybrids was expected for two reasons. First, COPOP1 is an open-pollinated population that was compared to four commercial hybrids. Grain yield of open-pollinated cultivars is expected to be about 70% of that of a hybrid (Kutka and Smith, 2004). Therefore, if sufficient heterosis exists within COPOP1, we could expect a yield increase from the development of hybrids from COPOP1-derived inbreds. Second, COPOP1 has an earlier maturity rating compared to the check hybrids, which ranged in maturity from 68 to 78 RM. Results from corn maturity testing at the University of Minnesota have suggested that a 5 g kg^{-1} difference in grain moisture at harvest is roughly equivalent to a one-day difference in RM (R. Bernardo, unpublished, 2005). Given this equivalence and the RM ratings of the commercial check hybrids, COPOP1 would have a 62 day RM. Full-season cultivars generally have a greater yield potential than short-season cultivars due to the longer period of photosynthate accumulation; however, the greater yield is typically accompanied by higher grain moisture at harvest (Olson and Sander, 1988).

The response to selection for grain yield was not expected to be large due to the moderately low heritability in DCLH227-C0 and nonsignificant heritability in DCLH295-C0 for grain yield, and increases in grain yield were not observed in Cycle 1. Selections were based on experiments in 2007 and response to selection was evaluated in 2009, and we speculate that genotype × year interaction may have contributed the lack of observed response. Nevertheless, the higher grain yields of DCLH227-C0 and DCLH227-C1 than of DCLH295-C0 and DCLH295-C1 suggest that COPOP1 is related more to the non-BSSS heterotic group.

The very early maturity (approximately 62 RM) of COPOP1 makes it suitable for grain production in extremely short-season areas where limited heat units are available for the crop to reach maturity or in regions where late summer drought limits grain production. In North Dakota, early maturing hybrids (68 RM) yielded 12% higher than the later maturing hybrids (85 RM) due to their ability to avoid the late season drought conditions common in that region (Alessi and Power, 1974). Semi-dwarf corn was also found to be a potential second crop in a doublecrop system, following a small grain forage or grain first crop (Moomaw and Mader, 1991). In general, corn hybrids attain physiological maturity when the grain moisture content reaches 350 g kg^{-1}, however optimum mechanical harvesting occurs at 250 g kg^{-1} (Olson and Sander, 1988;

Sala et al., 2007). The low grain moisture of COPOP1 will lead to reduced costs of artificially drying the grain prior to storage.

While ear and plant height were significantly reduced in COPOP1 compared to the commercial hybrids, the very low ear height of many of the semi-dwarf hybrids prevented effective harvest with a combine (we harvested the plots by hand) as the ears were hanging below the reach of the combine head. For this reason, selection for increased ear height would actually be required to utilize the semi-dwarf germplasm. Root and stalk lodging were not reduced with plant stature.

COPOP1 Semi-Dwarf Corn for Forage Production

COPOP1 had high forage quality as evidenced by the superior values for crude protein, NDF, IVTD, and starch over the conventional hybrids. While the high forage quality of COPOP1 led to a high milk Mg^{-1} index (1369 kg Mg^{-1}), its low forage dry matter yield led to a low milk ha^{-1} index (13930 kg ha^{-1}). The ear-to-stover ratio of COPOP1 was nearly double that of the conventional hybrids, explaining the large difference in starch content and undoubtedly contributing to the difference in milk Mg^{-1} index. Smaller differences in crude protein, NDF, and IVTD also contributed to the difference in milk Mg^{-1}. A previous study found no significant change in dry matter consumption, milk production, or body weight between feeding treatments of dwarf corn, conventional corn, and sorghum silage on lactating cows (Byers et al., 1965). The dwarf corn silage was superior for digestibility and total digestible nutrients, however, a reduction in dry matter yield resulted in lower total digestible nutrients per acre compared to the conventional corn (Byers et al., 1965).

While the Milk2006 performance index used in the analysis required numerous assumptions regarding utilization of carbohydrates and dry matter intake, the index nevertheless provided a way to predict milk Mg^{-1} and milk ha^{-1} from forage yield and quality data. Overall, our results confirm previous findings (Byers et al., 1965) in that while the quality and digestibility of semi-dwarf corn forage is better than that of conventional hybrids, the severe reduction in dry matter yield prevents its use in most forage production systems.

Future Utilization of Semi-Dwarf Corn

The use of semi-dwarf corn in a grain or forage production system would be accompanied by changes in the typical production practices. The plant architecture of semi-dwarf corn is conducive to high plant population densities due to reductions in plant stature and, consequently, leaf number and size. Previous results have shown that optimum grain production of semi-dwarf inbreds and hybrids is attained at much higher population densities than conventional hybrids (Begna et al., 1997; Modarres et al., 1998). In our 2005 and 2006 experiments, grain yield of COPOP1 did not change with plant population density. Barrenness, an indicator of stress due to plant density, was not different between the low and medium plant densities, although it increased at the high density for COPOP1. Further studies are needed to determine the optimum plant population density for semi-dwarf corn, although it is evident that semi-dwarf corn can be produced at greater plant population densities to optimize grain production. Entry by plant population density interaction was not significant for grain yield or a majority of the traits measured, indicating that these semi-dwarf populations and hybrids do not need to be evaluated at multiple, high plant population densities for an accurate assessment of grain yield.

COPOP1 can be utilized in corn breeding in two ways. First, COPOP1 can be used as an open-pollinated cultivar. In recent years, there has been a renewed interest from public breeders in developing improved populations and population hybrids as an alternative to single-cross hybrids (Kutka and Smith, 2004; Carena, 2005). As previously mentioned, COPOP1 will be most useful in very short-season environments, in areas prone to late-season drought, or in a doublecrop system.

Second, COPOP1 can serve as an adapted source of variation for grain moisture, ear height, and flowering time to improve temperate germplasm (Goodman, 1985; Hallauer, 1978; Stuber, 1979). This approach will exploit the prebreeding that already has been done in COPOP1. The corn breeding project at the University of Minnesota is currently investigating the use of genomewide molecular markers to introgress desirable traits from COPOP1 into elite, early-season and full-season corn inbreds. Also, selection for divergent combining ability is continuing on populations derived from COPOP1 for population improvement and the development of semi-dwarf inbreds.

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Table 1 – Primary soil type and planting and harvest dates (grain and forage) for field experiments of COPOP1.

	2005				2006				2009			
	St. Paul		Rosemount		St. Paul		Rosemount		Waseca		Lamberton	
	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
Primary soil type	Richwood silt loam	Waukegan silt loam	Waukegan silt loam	Kenebec silt loam	Richmond silt loam	Waukegan silt loam	Waukegan silt loam	Kenebec silt loam	Clarion loam	Nicollet clay loam	Webster clay loam	Ves loam
Fertilizer application	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	140-0-0 kg N-P_2O_5-K_2O ha^{-1}	157-0-0 kg N-P_2O_5-K_2O ha^{-1}	157-0-0 kg N-P_2O_5-K_2O ha^{-1}	160-67-67 kg N-P_2O_5-K_2O ha^{-1}	160-67-67 kg N-P_2O_5-K_2O ha^{-1}
Planting date	9 May	3 Jun.	6 May	3 Jun.	4 May	1 Jun.	28 Apr.	1 Jun.	22 Apr.	22 May	7 May	28 May
Harvest date (forage)	9 Aug.	22 Aug.	10 Aug.	22 Aug.	31 Jul.	18 Aug.	1 Aug.	21 Aug.	17 Aug	3 Sep.	17 Aug., 2 Sep.	2 Sep.
Harvest date (grain)	30 Aug.	14 Sep.	1 Sep.	20 Sep.	5 Sept.	4 Oct.	7 Sep.	5 Oct.	9 Oct.	9 Oct.	9 Oct.	9 Oct.

Table 2 – Significance of effects and least squares means of grain yield and agronomic traits, averaged across plant population densities and environments, for COPOP1 evaluation with commercial hybrids in Rosemount and St. Paul, MN, in 2005 and 2006.

Entry	Grain yield	Grain moisture	Plant height	Ear height	Days to anthesis	Days to silking	ASI†	Barrenness	Lodging
	Mg ha^{-1}	g kg^{-1}	---------- cm ----------		------------------ d -------------------			------------ % -----------	
COPOP1	5.0	196	127	41	54	56	1.98	8.3	15.8
NK N03-D8	9.4	246	230	99	60	62	1.46	10.6	12.4
Thompson's BIXXIO RR	11.1	260	266	106	59	61	1.50	9.8	10.9
Pioneer 39F59	11.7	259	261	120	61	62	0.95	8.2	12.7
Pioneer 39T66	10.9	259	262	108	60	62	1.54	7.8	12.9
Mean of conventional hybrids	10.8	255	254	108	60	62	1.36	9.1	22.9
LSD (0.05)‡	0.7	15	5	4	1	1	0.6	NS	NS
			Significance of effects						
Source of Variation									
Entry	***	*	***	***	***	***	*	NS	NS
Density	*	NS	NS	NS	**	***	***	***	NS
Entry x Density	NS	NS	NS	*	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonignificant at the 0.05 level.
† ASI, Anthesis-silking interval.
‡ Least significant difference at the 0.05 probability level for comparisons within columns

Table 3 – Significance of effects and least squares means of forage traits and milk performance indices, averaged across plant population densities and environments, for COPOP1 evaluation with commercial checks in Rosemount and St. Paul, MN, in 2005 and 2006.

Entry	Dry matter yield	Harvest Moisture	Ear-to-stover ratio	Crude protein	NDF†	IVTD	NDFD	Starch	Milk Mg^{-1}	Milk ha^{-1}
	Mg ha^{-1}	g kg^{-1}		-------------------------------	-------------------------------	g kg^{-1}	-------------------------------	-------------------------------	kg Mg^{-1}	kg ha^{-1}
COPOP1	10.1	703	1.50	92	458	758	474	253	1369	13930
NK N03-D8	17.4	718	0.77	82	473	749	470	221	1270	22413
Thompson's BIXXIO RR	17.7	732	0.72	81	466	756	476	206	1208	21730
Pioneer 39F59	18.6	709	0.86	76	483	728	437	235	1217	22893
Pioneer 39T66	18.3	735	0.72	75	491	728	446	186	1113	20510
Mean of conventional hybrids	18.0	724	0.77	79	478	740	457	212	1202	21887
LSD (0.05)‡	1.0	9	0.10	3	12	9	10	17	50	1530
					Significance of effects					
Source of Variation										
Entry	***	***	***	***	***	***	***	***	***	***
Density	NS	NS	*	***	NS	NS	NS	NS	*	NS
Entry x Density	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonsignificant at the 0.05 level.
† NDF, neutral detergent fiber; IVTD, in-vitro true digestibility; NDFD, neutral detergent fiber digestibility.
‡ Least significant

Table 4 – Testcross variance (V_{TC}), error variance (V_{error}), and heritability (h^2) on an entry-mean basis for grain yield and agronomic traits of DCLH227-C0 and DCLH295-C0 populations evaluated in Lamberton and Waseca, MN, in 2007.

		Grain yield	Grain moisture	Plant height	Ear height	Stalk lodging	Root lodging
DCLH227-C0	V_{TC}	0.21	223.69	53.91	29.35	1.59	1.67
		(0.03, 0.42)†	(139.41, 337.63)	(2.02, 112.76)	(15.98, 46.73)	(-64.17, 63.15)	(-0.45, 3.97)
	V_{error}	0.80	257.55	234.91	47.51	326.04	9.88
	h^2	0.35	0.63	0.31	0.55	0.01	0.25
		(0.06, 0.55)	(0.47, 0.75)	(0.01, 0.52)	(0.36, 0.69)	(-0.43, 0.31)	(-0.08, 0.48)
DCLH295-C0	V_{TC}	0.21	100.31	63.10	19.67	3.02	0.27
		(-0.18, 0.38)	(62.19, 151.76)	(32.76, 102.10)	(8.72, 33.34)	(-60.67, 62.99)	(-0.54, 1.09)
	V_{error}	1.36	117.48	111.33	43.13	315.54	3.98
	h^2	0.24	0.63	0.53	0.48	0.02	0.12
		(-0.26, 0.39)	(0.47, 0.74)	(0.33, 0.67)	(0.25, 0.64)	(-0.41, 0.32)	(-0.27, 0.39)

† 95% confidence intervals in parenthesis.

Table 5 – Significance of effects and least squares means of grain yield and agronomic traits, averaged across plant population densities and environments, of Cycle 0 and Cycle 1 populations and check hybrids evaluated in Waseca and Lamberton, MN, in 2009.

Entry	Grain yield	Grain moisture	Plant height	Ear height	Days to anthesis	Days to silk	ASI†	Leaf number	Barrenness	Root lodging	Stalk lodging
	Mg ha^{-1}	g kg^{-1}	---------- cm -----------		------------------- d -------------------				------------------- % --------------------		
DCLH227-C0	8.2	275	175	88	71	74	3.2	16	6.7	4.4	0.8
DCLH227-C1	8.0	279	184	96	72	75	2.5	16	8.5	6.7	1.7
DCLH295-C0	7.5	257	156	85	71	73	2.2	16	5.2	3.7	1.5
DCLH295-C1	7.8	257	158	84	72	74	1.8	16	4.4	6.4	0.6
NK N03-D8	7.3	241	169	91	73	74	1.2	17	4.7	8.9	0.0
Pioneer 39T66	8.1	246	181	105	70	73	2.2	16	3.7	9.7	1.7
LH227 x LH295	11.8	339	186	106	82	84	1.2	18	2.7	1.3	0.0
LSD$_A$ (0.05)‡	0.9	9	8	5	1	2	0.9	0.4	NS	NS	NS
LSD$_B$ (0.05)	1.2	13	12	7	2	2	1.4	0.7	NS	NS	NS
LSD$_C$ (0.05)	1.5	15	15	9	3	3	1.7	0.8	NS	NS	NS
					Significance of effects						
Source of Variation											
Entry	***	***	***	***	***	***	*	***	NS	NS	NS
Density	*	NS	*	NS	NS	NS	*	NS	***	NS	NS
Entry x Density	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonsignificant at the 0.05 level.
† ASI, Anthesis-silking interval.
‡ Least significant difference at 0.05 probability level within columns; LSD$_A$, for comparisons within the bulk testcrosses; LSD$_B$, for comparisons between the bulk testcrosses and the check hybrids; LSD$_C$, for comparisons within the check hybrids.

Table 6 – Significance of effects and least squares means of forage yield and quality and milk performance indices, averaged across plant population densities and environments, of Cycle 0 and Cycle 1 populations and check hybrids evaluated in Waseca and Lamberton, MN, in 2009.

Entry	Dry matter yield	Harvest moisture	Crude protein	NDF†	IVTD	NDFD	Starch	Milk Mg^{-1}	Milk ha^{-1}
	Mg ha^{-1}	g kg^{-1}	------------------------------	------------------------------	g kg^{-1}	------------------------------	------------------------------	kg Mg^{-1}	kg ha^{-1}
DCLH227-C0	13.8	705	75	463	727	410	240	1382	42967
DCLH227-C1	14.3	708	73	470	726	417	233	1363	44046
DCLH295-C0	12.4	697	79	452	729	399	254	1394	38892
DCLH295-C1	12.7	692	77	453	726	394	258	1398	39511
NK N03-D8	12.6	690	76	442	741	412	257	1413	40052
Pioneer 39T66	14.1	690	69	447	733	402	263	1408	44290
LH227 x LH295	15.5	730	71	497	710	418	197	1277	44655
LSD_A (0.05)‡	1.4	14	3	11	7	10	15	43	NS
LSD_B (0.05)	2.0	20	5	16	10	14	22	62	NS
LSD_C (0.05)	2.4	24	6	19	11	17	26	74	NS
				Significance of effects					
Source of Variation									
Entry	*	**	***	***	***	**	***	**	NS
Density	NS	**	NS	***	**	**	***	**	NS
Entry x Density	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonsignificant at the 0.05 level.
† NDF, neutral detergent fiber; IVTD in-vitro true digestibility; NDFD, neutral detergent fiber digestibility.
‡ Least significant difference at 0.05 probability level within columns; LSD_A, for comparisons within the bulk testcrosses; LSD_B, for comparisons between the bulk testcrosses and the check hybrids; LSD_C, for comparisons within the check hybrids.

Table 7 – Significance of effects and least squares means of grain yield and agronomic traits, averaged across plant population densities and environments, of nine dwarf hybrids and COPOP1 evaluated in Waseca and Lamberton, MN, in 2009.

Entry	Grain yield	Grain moisture	Plant height	Ear height	Days to anthesis	Days to silk	ASI†	Leaf number	Stalk lodging	Root lodging
	Mg ha^{-1}	g kg^{-1}	----------- cm ----------		------------------- d -------------------				----------- % -----------	
DCLH227-C1-1 x DCLH295-C1-1	3.4	183	82	46	63	65	2.8	14	0.3	0.6
DCLH227-C1-1 x DCLH295-C1-2	3.9	173	102	50	64	66	2.3	14	6.6	-1.3
DCLH227-C1-1 x DCLH295-C1-3	4.8	201	101	46	63	65	2.0	14	1.8	-0.5
DCLH227-C1-2 x DCLH295-C1-1	4.4	179	92	51	63	65	1.9	14	3.4	0.5
DCLH227-C1-2 x DCLH295-C1-2	4.8	201	112	57	65	66	0.9	15	3.4	0.5
DCLH227-C1-2 x DCLH295-C1-3	4.6	181	101	50	64	66	1.6	15	2.4	-0.3
DCLH227-C1-3 x DCLH295-C1-1	4.3	185	90	50	63	65	1.4	14	4.0	3.4
DCLH227-C1-3 x DCLH295-C1-2	4.1	208	110	54	63	66	2.8	15	3.8	1.7
DCLH227-C1-3 x DCLH295-C1-3	5.1	201	99	48	63	65	1.7	14	-0.2	1.8
COPOP1	4.6	190	94	47	64	66	1.5	15	3.4	0.5
LSD_A (0.05)‡	1.0	16	9	6	NS	NS	NS	0.8	NS	NS
LSD_B (0.05)	0.7	12	7	5	NS	NS	NS	0.7	NS	NS
				Significance of effects						
Source of Variation										
Entry	**	**	***	*	NS	NS	NS	***	NS	NS
Density	NS	NS	NS	NS	**	NS	*	NS	NS	NS
Entry x Density	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonsignificant at the 0.05 level.
† ASI, Anthesis-silking interval;
‡ Least significant difference at 0.05 probability level within columns; LSD_A, for comparisons within the semi-dwarf hybrids; LSD_B, for comparisons between the semi-dwarf hybrids and COPOP1.

Table 8 – Significance of effects and least squares means of forage yield and quality, averaged across plant population densities and environments, of nine dwarf hybrids and COPOP1 evaluated in Waseca and Lamberton, MN, in 2009.

Entry	Dry matter yield	Harvest moisture	Crude protein	NDF†	IVTD	NDFD	Starch
	Mg ha^{-1}	g kg^{-1}	-------------------------------- g kg^{-1} --------------------------------				
DCLH227-C1-1 x DCLH295-C1-1	7.9	540	90	447	730	440	239
DCLH227-C1-1 x DCLH295-C1-2	9.3	523	87	424	712	400	297
DCLH227-C1-1 x DCLH295-C1-3	8.0	568	93	428	701	468	288
DCLH227-C1-2 x DCLH295-C1-1	8.2	554	92	474	688	584	227
DCLH227-C1-2 x DCLH295-C1-2	11.2	629	94	447	747	476	246
DCLH227-C1-2 x DCLH295-C1-3	8.8	543	93	422	772	411	232
DCLH227-C1-3 x DCLH295-C1-1	9.0	574	92	431	763	375	286
DCLH227-C1-3 x DCLH295-C1-2	10.9	615	85	457	722	383	238
DCLH227-C1-3 x DCLH295-C1-3	8.0	566	93	416	741	454	303
COPOP1	10.2	578	91	450	731	411	263
LSD$_A$ (0.05)‡	NS	59	NS	33	NS	NS	47
LSD$_B$ (0.05)	NS	48	NS	27	NS	NS	38
		Significance of effects					
Source of Variation							
Entry	NS	*	NS	*	NS	NS	*
Density	**	NS	NS	NS	NS	NS	NS
Entry x Density	NS	NS	NS	NS	NS	NS	NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.
NS, nonsignificant at the 0.05 level.
† NDF, neutral detergent fiber; IVTD in-vitro true digestibility; NDFD, neutral detergent fiber digestibility;
‡ Least significant difference at 0.05 probability level within columns; LSD$_A$, for comparisons within the semi-dwarf hybrids; LSD$_B$, for comparisons between the semi-dwarf hybrids and COPOP1.