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Silage Corn Hybrid Response to Row Width and Plant Density in the Intermountain West

Mark A. Pieper
Utah State University

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SILAGE CORN HYBRID RESPONSE TO ROW WIDTH AND PLANT DENSITY IN THE INTERMOUNTAIN WEST

by

Mark A. Pieper

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

Approved:

J. Earl Creech, Ph.D. Major Professor	Grant Cardon, Ph.D. Committee Member
Ricardo Ramirez, Ph.D. Committee Member	Mark McLellan, Ph.D. Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2018

ABSTRACT

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Mark A. Pieper, Master of Science

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Major Professor: Dr. J. Earl Creech
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(72 pages)

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INTRODUCTION

History of Corn

Corn (*Zea mays L.*) is probably the most completely domesticated of all field crops because it can no longer sow its own seeds and is entirely dependent upon humans for survival (Smith, 2004). Although it is one of the most studied plants on the earth, the early history of corn is still somewhat unclear. Experts agree that corn originated in the Americas and was discovered by the western world by Columbus in 1492. At that time, corn could be found as far north as modern day Canada and south to Chile. After discovery, European traders carried corn back to Europe, and by 1575, corn had made its way into China (Gibson and Benson, 2002).

Many historians believe that the corn plant originated in Mexico. Corn is a member of the grass family, like wheat and rice, but is a unique because its male flowers (tassel) are separate from the female flowers (ear). The only other grass with a similar structure is teosinte (*Zea mays ssp. parviglumis* H.H. Litis & Doebley) (Smith, 2004). Teosinte is native to western Mexico and Guatemala, which is the reason for believing it is where corn originated. The closest relatives of the genus *Zea* are 20 species of the genus *Tripsacum,* of which all are native to the Americas. Unlike *Zea*, the flowers of *Tripsacum* species are born distinctly in the same inflorescence; male flowers are toward the tip of the spike and the female flowers basally (Dewald et al. 1987; Camara-Hernandez, 1992). When teosinte and *tripsacum* are crossed, hybrids from the two are easily produced, suggesting to many historians that this is the origin of the corn plant.

There are many types of corn, including dent corn, popcorn, sweet corn, waxy corn, flour corn, and pod corn. Dent corn feeds more people than any other plant in the Americas and is the major corn type grown in the United States (U.S). The U.S. produces 40% of the world's corn (Smith, 2004). Grain corn yields were estimated to be around 26 bu/acre in the early 1936s, while today, yields average approximately 170 bu/acre (USDA-NASS, 2017). Corn yield increase over time can be attributed to technological advances in corn breeding and improvements in agronomic practices from research. Around 90% of the corn acreage in the United States is harvested as grain corn, and the remaining 10% harvested as silage corn (Gibson and Benson, 2002).

Corn can be used in a wide array of products and applications. Corn has application as a filler for plastics, packing materials, adhesives, chemicals, explosives, paint, dyes, pharmaceuticals, solvents, soaps, livestock feed, human consumption, and many more products (Gibson and Benson, 2002).

Corn Silage

Corn silage is used as high energy roughage that can replace portions of the grain corn and alfalfa in animal diets. Silage making is an efficient method of storing large amounts of high-quality forage over a long period of time. Silage is the material produced by the controlled fermentation of a crop of high moisture (Nash, 1978). It is made by harvesting the plant biomass, chopping it into small pieces and then compressing it into a silo, pit, or pile. If ensiled in a pile or pit, the silage must be compressed and packed tightly using tractors or other heavy equipment. The primary objective of preserving silages by fermentation is to achieve an anaerobic condition, which causes fermentation and acids to form (primarily lactic and acetic) that keeps the silage from spoiling (Mcdonald, 1981). Proper harvest timing is critical for making high-quality silage because the optimum plant moisture for fermentation is 65% of total corn biomass. Another key factor in producing high quality silage is the development of the corn kernel. The kernel should be dented and at the black layer stage, meaning the starch has filled the kernel for optimum energy content. Once silage is packed tightly, the pile should be covered with plastic or other material to eliminate oxygen intake and additional spoilage (Wheaton, 1967).

The quality of the corn silage is important to farmers that feed livestock, with starch being one of the most valuable components in dairy diets. Studies with dairy cattle have shown that higher-producing cows benefited from a high-starch diet (Boerman et al., 2015). Satter (1997) suggests that corn silage should constitute one-third to two-thirds of the dietary forage dry matter when fed with alfalfa silage to derive maximal benefit.

Corn Production in the Intermountain West

Silage corn is an important feed for dairy cattle in the Intermountain West because it is a forage that produces high yields and energy (Roth, 1995). Not surprisingly, the increase in total corn hectares harvested (+44,000 ha^{-1}) in Utah and Idaho, annually, over the past 10 years corresponds to an increase of nearly 200,000 dairy cows over the same period (National Agriculture Statistics Service, 2016). To date, most corn research and management recommendations have come out of Midwest or eastern states where soil conditions, temperature, and rainfall differ greatly compared to the semi-arid, irrigated conditions typical of the West. Increased demand for silage corn by the dairy industry in the Intermountain West has created a tremendous need for verifying and improving corn production practices for the high desert (Clark, 2014).

Corn row width

The width of the rows in which corn is planted has changed over the years. In the early- to mid-1900's, corn row width varied greatly from farm to farm but was often planted in rows 102-112 cm apart (Lauer, 2006). During this period, corn row width was determined by the width of the horse pulling the planter. The development and widespread adoption of the tractor brought some standardization of corn row width from one farm to another. Research in Wisconsin identified consistent grain yield increases by narrowing rows from 102 cm to 76-cm (Lauer, 2006), and the 76-cm row has remained the most popular corn row width to the present date (National Agricultural Statistics Service, 2016).

In years past, the need for research on narrow row corn has been limited due to factors such as cultivation, flood irrigation, tractors with wide tires, and hybrids that were not adapted to narrow rows or plant crowding. Modern advances in crop production technologies, such as herbicides, hybrids, irrigation, and equipment, have created an opportunity to evaluate, and perhaps adjust, corn row width. Research in Wisconsin from 1997 to 2002 with silage corn showed an average yield increase of 5%, but ranged from -1% to 15% (Lauer, 2006). Increased yields due to narrowing row width can be attributed to corn rows closing earlier, reduced weed pressure, reduced evapotranspiration, and increased light captured (Ottman and Welch, 1989). Andrade et al. (2002) determined that grain yield increase in response to narrow rows was closely related to the improvement in light interception during the critical period for grain set. Narrow rows are also effective at decreasing weed competition (Begna et al., 2001; Teasdale, 1995; 1998).

Some studies suggest that the geography of the field location may influence how corn responds to row width. Lee (2006) concluded that narrow corn or soybean rows south of 43˚N latitude in the U.S. do not increase yields, while narrow rows north of that latitude may result in a positive yield response because the growing season is shorter and fewer heat units are available. The theory of narrow rows in northern areas is to intercept more radiation for enhanced plant growth. However, Pedersen and Lauer (2003) concluded that the use of a row width system less than 76-cm was not beneficial for either corn or soybeans in Wisconsin. Similarly, grain corn research in Minnesota found no yield advantages of narrow row corn widths (VanRoekel and Coulter, 2012).

Numerous studies have shown that individual corn hybrids can respond differently to row width (Pinter et al., 1994). Widdicombe and Thelen (2002) concluded that full-season hybrids are more likely to increase yield in narrow rows than short-season hybrids in Michigan. In Iowa, research on grain corn showed there were significant row width effects on corn yields, Farnham (2001) observed a hybrid x row width interaction among the six hybrids tested, suggests that certain hybrids may perform better at prescribed row widths. One hybrid with a 94 to 102 RM yielded more grain at 76-cm row width while another hybrid with an RM of 110 to 114 RM yielded more grain in 38-cm row widths. In Minnesota, Porter et al. (1997) found a yield advantage by narrowing the rows from 76-cm to 51-cm, or even 25-cm in some hybrids and years. A study conducted in New York using dual-purpose hybrids found that corn forage yield increased by 4.2% as row width narrowed (Cox et al., 1998). A more recent study by the same authors showed a 7.5% dry matter (DM) yield increase in silage corn when narrowing rows to 0.76 m to 0.38 m (Cox and Cherney, 2001). Hybrid does affect corn forage quality, but row width does not affect forage quality (Cox et al., 2006; Widdicombe and Thelen, 2002).

Corn plant density

Corn plant population has increased more than 50% in the past 40 years (Hodgen, 2007), and currently sits at 70,370 plants ha^{-1} in the U.S. (National Agricultural Statistics Service, 2016). The major technological advancement that has made population increase possible is improved genetics, in which new hybrids are better able to tolerate crowding stress than old hybrids (Duvick, 2005; Duvick and Cassman, 1999). Optimum plant density varies from region to region and is primarily related to moisture. In Illinois, Nafziger (1994) found that planting density has a very large effect on yield, except in very dry years or environments. Reeves and Cox (2013) suggested that inconsistent yield responses to plant population in New York were probably related to dry summer conditions during the two years of the study. Shorter season hybrids in the Midwest can achieve similar yields to longer season hybrids by increasing plant density while using 30 to 50% less water (Edwards et al., 2005).

Cox (1997) suggests that corn silage plant density should be greater than grain corn plant density by approximately 7.5% in a warm dry growing season. In a cool wet growing season silage corn and grain corn, plant densities should not differ. In New York, plant population recommendations have ranged from 86,500 to 89,000 plants ha^{-1} (Cox et al., 1998; Cox and Cherney, 2001; Cox and Cherney, 2011). A Michigan study found that total DM yield increased as plant density increased (Widdicombe and Thelen, 2002). A study in Alberta Canada, which is located in a cool short season environment, showed that achieving a plant density of approximately 100,000 plants ha^{-1} is the most important part in producing acceptable yields and quality for corn silage production (Baron et al., 2006). In evaluating yield, responses of corn to crowding stress it was determined that kernel yield per plant decreased linearly in all hybrids as plant density intensified (Hashemi et al., 2005). In addition, all yield components declined linearly in response to increased competition pressure. Research on corn plant density suggests that as corn plant density increases quality is affected adversely (Widdicombe and Thelen, 2002).

Summary and Objectives

Seed companies and Cooperative Extension occasionally evaluate plant density responses of newly released hybrids in specific growing regions to accurately adjust plant density recommendations (Cox, 1997). Row width and plant density have been shown to have a dramatic effect on yield and quality of harvested corn forage. The quality of the corn silage appears to be affected only when plant density is changed, but not when row width is changed. Narrowing corn row width offers several crop management advantages and could possibly increase yield. Research has also found that optimum plant density can differ by location, region, and hybrid.

Optimum corn row widths and plant density have been thoroughly studied in the Midwest and eastern U.S. With the increased demand for corn and corn forages in the Intermountain West, producers in need of knowledge related to optimum corn plant density and row widths to maximize quality and DM yield. There appears to be no published literature or research on corn planting density or row widths in the western U.S. The objectives of this study are to determine the row width and plant density that optimizes silage corn yield and quality in Utah and Idaho.

MATERIALS AND METHODS

Site Description

Field experiments were conducted in 2015 and 2016 at the Utah State University Greenville Farm near North Logan, Utah (41°45′ N, 111° 48′ W; 1399.0 m elev.) and in a farmer’s field near Jerome, Idaho (42°48′ N, 114°28′ W; 1177.1 m elev.). The soil at the North Logan site is a Millville silt loam (a coarse-silty, carbonatic, mesic Typic Haploxerolls), and the soil at the Jerome, Idaho location is a Rad silt loam (a coarse-silty, mixed, superactive, mesic Durinodic xeric Haplocambids). The 2015 Utah location followed the fallow year in a wheat-fallow rotation and, in an adjacent field, followed safflower in 2016. The Idaho sites in both years had been in continuous corn for over 10 years. Both locations were sprinkler irrigated. At Idaho, the plots were irrigated with a center pivot system. At the Utah location, solid set hand pipe was used to irrigate the study.

Crop Management

The experimental design is a randomized complete block in a split-split plot arrangement with four replications. The whole plot treatment was hybrid (DKC 49-29, DKC 56-54, and DKC 61-88), the sub-plot treatment was row width (76 and 51-cm), and the sub-sub plot treatment was plant density (six final plant densities ranging from 61,776 to 123,552 plants ha^{-1} at intervals of 12,355 plants ha^{-1}). The sub-sub plots with 76-cm row width measured 3.0 m wide (4 rows), while those in the 51-cm row width were 2.6 m wide (5 rows). Plot lengths were 9.1 and 10.7 m in 2015 and 2016, respectively.

Three Dekalb (Monsanto, St. Louis, MI) hybrids were chosen with similar agronomic characteristics, but with differing relative maturity (RM) ratings of 99, 106, and 111 RM. The shortest RM Dekalb hybrid (DKC 49-29) has a RM of 99, next the 106 RM is labeled (DKC-56-54), and the longest RM hybrid is labeled (DKC 61-88). These hybrids contain the VT Triple Pro Corn RIB complete pest resistant traits against corn earworm (*Helicoverpa zea* Boddie) and European corn borer (*Ostrinia nubilalis* Hubner). Each hybrid was planted with a four-row Monosem (Monosem Inc. Edwardsville, KS) no-till NG Plus 4 precision vacuum planter at a depth of 5-cm. The 76- and 51-cm rows were planted with the same planter by adding or removing a row unit and adjusting the remaining row units to the desired spacing. Plots were planted at 131,000 plants ha^{-1} and hand thinned at the fifth leaf collar stage (Abendroth et al., 2011; Coulter et al., 2011) to the desired final plant densities (Nafziger, 1994; Cox, 1997; Bullock, et al., 1998; Stanger and Lauer, 2006; Coulter, et al., 2010; Van Roekel and Coulter, 2011, 2012). Utah was planted on 5 May 2015 and 4 May 2016. Idaho was planted on 8 May 2015 and 9 May 2016.

Both locations were conventionally tilled prior to planting using methods common to the local area. The final seedbed was prepared after N, P, and K were applied in granular form using a 3-m Gandy drop spreader (Gandy Company, Owatonna, MN).

Nitrogen fertilizer was applied in the form of urea at 280 kg N ha^{-1} and worked into the soil using a Brillion (Brillion Farm Equipment, Landoll Corporation, Brillion, WI) roller harrow before planting. At the Utah location P and K were added to reach adequate levels based on soil test results (Cardon et al., 2008). At Idaho, 34 kg N ha^{-1} of additional N fertilizer was applied as 32% urea-ammonium nitrate (UAN) through the center pivot irrigation system at the VT growth stage. At Utah, additional N was applied as 32% UAN through the irrigation system when corn was at V8 (56 kg N ha^{-1}) and VT (33.6 kg N ha^{-1}). Weeds were controlled at Utah by applying 0.84 kg acid equivalent (a.e.) ha^{-1} of glyphosate [N-(phosphonomethyl) glycine] when corn reached the V3 growth stage. Surpass [acetochlor: (2-chloro-2’-methyl-6’-ethyl-N-ethoxymethylacetanilide)] was applied as a pre-emergent at Utah in 2016. Prowl H_2O [pendimethalin: N-(1-ethylpropyl)-3,4-dimethyl-2, 6-dinitrobenzenamine] was applied at Idaho in 2015 and 2016. There were no insect or disease problems observed in both growing seasons.

When the 111 RM hybrid reached the silking stage, which occurred 3 to 6 days after the 106 RM hybrid, reached the silking stage, an AccuPAR LP-80 (Decagon Devices, Pullman, WA) ceptometer was used to measure Leaf Area Index (LAI) and Intercepted photosynthetically active radiation (IPAR) from all plots in 2015 and 2016. LAI was calculated using the AccuPAR-LP-80, while the IPAR was reported from above and below the canopy measurements of photosynthetically active radiation (Ruffo, et al., 2004). During these 3 to 6 days there were no visual differences in the canopy of the 106-d RM hybrid (Earl and Davis, 2003). Four separate IPAR and LAI measurements were taken in each plot between 1130 h and 1430 h on clear and calm days. The AccuPAR LP-80 measured 0.8-m-long, the instrument was placed diagonally across the center two 76-

cm rows and across two of the center three 51-cm rows. Measurements were taken at ground level while keeping the sensor level, above the canopy, measurements were taken before entering the plots.). Stalk diameter was measured on the first internode above the brace roots on 10 plants in the center portion of the two or three rows with an electronic caliper when the 111-d RM hybrid reached the silking stage.

The center two 76-cm rows or center three 51-cm rows of each sub-subplot were harvested with a two-row Gehl (Gehl, West Bend, WI) Model 865 pull behind corn silage chopper between 24 and 30 September 2015 and 29 September and 7 October 2016. Three individual harvest passes were required when harvesting 51-cm rows. The silage was blown into a weigh bin mounted on four load cells that were connected to a Transcell Technology (Transcell Technology INC, Buffalo Grove, IL) TI-500 SS digital weight indicator that measured silage weight for each plot. After weight measurements were recorded, corn silage was dumped and a 1-kg subsample was collected for moisture and quality analysis. Each sample was weighed, and then dried at 60°C in a forced air oven for 7 days. Samples were stirred twice daily during the first 4 days of drying to prevent molding. Samples were weighed again to determine dry matter yield before being ground through a Wiley mill (Thomas Scientific, Swedesboro, NJ) Model 3 fitted with a 2-mm screen, repeatedly passed through a splitter until sample size was reduced to 50 g, and ground through a cyclone mill (Udy Corporation, Fort Collins, CO) with a 1-mm screen. Ground samples were scanned using a FOSS XDS (NIRS) near-infrared reflectance spectroscopy instrument (FOSS, Eden Prairie, MN). The 2016 unfermented corn silage equation developed by the near infrared reflectance spectroscopy consortium (NIRSC) was used to determine the forage quality constituents of starch, crude protein (CP), amylase neutral detergent fiber (aNDF), acid detergent fiber (ADF), in vitro true digestibility at 48 hours (IVTD48), and neutral detergent fiber digestibility at 48 hours (NDFD48)(Martin, 1989). The University of Wisconsin developed the Milk 2006 worksheet which uses crude protein, aNDF, NDFD, NDFD48, starch, constants for fat and ash, and dry matter yield to determine total dietary nutrients at maintenance (TDN-1x), net energy of lactation at 3x maintenance (NEL-3x)(Shaver, 2006a; Shaver et al., 2006b; Undersander et al.,1993). The MILK2006 worksheet also predicts the Milk Mg^{-1} index (kg of milk Mg^{-1} corn silage) which is an estimate of the energy content per Mg^{-1} of forage DM. Milk ha^{-1} (kg milk ha^{-1} corn silage) is predicted from the combination of Milk Mg^{-1} and DM yield. The Milk Mg^{-1} and Milk ha^{-1} help the producer in selecting corn hybrids with high yields and high quality components (Norell, 2005).

Economic Return

An economic analysis was done using net present value (NPV) to determine the overall profitability of planting corn in narrower rows of 51-cm. NPV is commonly used to make agriculture decisions and is beneficial when making first-time investment decisions (Adusumilli et al., 2016). The NPV method uses two different formulas, one for a nonuniform or uniform series of payments to value the projected cash flows for each investment alternative at one particular point in time (Barry, 2012). NPV can be mathematically represented using the following formula:

$$\text{NPV} = -\text{INV} + \frac{P_1}{(1+i)} + \frac{P_2}{(1+i)^2} + \cdots + \frac{P_N}{(1+i)^N} + \frac{V_N}{(1+i)^N}$$

Where,

-*INV*= Initial Investment;
P_N = Cash flow in year N;
V_N = Terminal Value;
N= Time Period;
i = interest rate;

A positive net present value indicates that the projected earnings from the investment exceed the proposed costs. If the NPV is a positive value, then generally it will be a profitable investment. If there is a negative NPV it most likely will not be a profitable investment. When analyzing the investment of equipment for narrower corn row width versus conventional row width both options may show a positive cash flow. The option with the greater cash flow could potentially be the better investment long term because a dollar earned presently is worth more than a dollar earned in the future.

Initial investments of machinery cost differences include planter and tractor tire size being adjusted for narrow row width. A cost increase of (US\$92.7 ha^{-1}) for machinery on 51-cm rows versus 76-cm rows and were based on a farm size of 101 ha^{-1}. Machinery costs were taken from John Deere (Deere and Company, Moline Illinois) 24 row 76-cm and 36-row 51-cm planters were priced. Base options were utilized for all equipment and tractors except for tires, which were adjusted to 320/85R38 front tires and 320/90R54 rear tires with dual tire configuration to match the row widths of the 51-cm row width (Van Roekel and Coulter, 2012). There are no different forage harvester costs, assuming that a Kemper style forage head is used (Maschinenfabrik KEMPER Gmbh and Company. KG, Stadtlohn, Germany). Kemper forage harvester heads are row-independent harvesting headers meaning it can harvest corn at any row width. These harvesters are common in the Intermountain West and well used around larger dairies.

The cash flow in this analysis is defined as the corn silage revenue difference from the two-row width options. The revenue is estimated using partial budgets developed by the authors specific to the study regions. Currently, in the West, corn silage is not bought on the quality components but the total yield of the silage. It is difficult to determine the price of silages because of the lack of available market reports. Feuz et al. (2012) has developed formulas to determine the price of silages. Delivered corn silage value per ton as fed is said to be about 8 to 10 times the price of corn grain in dollars per bushel. If corn price is below $3/bu. use 10 times, for corn price of $4-5/ bu. use 9 times and for corn grain price of $6-8/bu. use 8 times the value of the grain. These values were used in predicting the price of silage and used in determining the cash flow.

In this NPV model, we assumed the producer would use the planter for a time period of 5 or 10 years before acquiring a new planter. The interest rate in an NPV model represents the opportunity cost of capital. Weighted Average Cost of Capital (WACC) is often used to estimate that cost of capital for individual firms (Barry, 2012). Using data collected through FINBIN[1] and Federal Reserve Bank of Kansas City, the WACC for this research is estimated to be 7.5%.

One of the key limitations of NPV analysis is the fact that inputs such as prices and yields are considered deterministic. Stochastic NPV analysis incorporates the riskiness of prices and yields in corn through stochastic distributions. @Risk (Palisades) is a Microsoft Excel add-in that incorporates stochastic simulation into the NPV model. The inputs into the stochastic simulation are the estimated price and yield distributions.

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[1] FINBIN is a database managed by the Center for Farm Financial Management at the University of Minnesota. The database includes financial data on over 5,000 farms throughout the United States.

Historical data on corn prices comes from USDA and yield distributions were estimated based on yield data from crop trials. Using @Risk, 5,000 samples were simulated using the estimated price and yield distributions.

Economic optimum plant density was determined by finding total gross revenue ha^{-1} and subtracting costs ha^{-1}. Five scenarios of silage market values ranging from (US$22.7 Mg^{-1} to US$40.8 Mg^{-1} in intervals of US$4.5 Mg^{-1}) were multiplied by total Mg^{-1} ha^{-1} to calculate gross revenue per ha^{-1}. Six cost scenarios were used to evaluate cost of seed with 80,000 seeds per bag (US$ 150/80,000 seeds to US$400/80,000 seeds at intervals US$50/80,000 seeds). It was assumed that all other operating costs were held constant.

Statistical Method

Experiments were conducted at two locations and for two years. Each experiment was a split-split-plot design in which whole plots are grouped into four blocks and randomly assigned to hybrid. Within each whole plot, two subplot were randomly assigned to row width levels (51 and 76 cm) and each subplot was further split and randomly assigned to six plant densities.

Collected data were analyzed using mixed model methodology in PROC GLIMMIX of SAS/STAT 14.2 (SAS Institute, Cary, NC). Hybrid, row width and plant density are fixed factors while location, year and block (nested within location and year) are random factors. Interactions among the fixed factors are fixed effects and interactions between fixed and random factors are random effects. Mean separations were conducted using Tukey-Kramer adjustment. Significant level is predefined at 0.05 (alpha = 0.05).

Lack of significant interaction between plant densities (seeding rates) and other factors were detected for all interested measures. When plant density showed significant impact, regression equations were developed to describe the rate of change of response variables on plant density. Raw plots on observed data indicate curvature of response over plant density. Quadratic regression model (eqn. 1.) were used to account for the inadequate, adequate and over-adequate scenarios of plant density effect on responses:

Eqn. 1 $$Y|s_i, b_j = \beta_{0(hr)} + \beta_1 x + \beta_2 x^2 + s_i + b_j + e_{ijk}$$

where *h*, *r* indicating hybrid and row width levels, *x* is the seeding rate (in 1000 plants), s_i, b_j are random effect due to *ith* site (farm) and *jth* year and e_{ijk} denotes non-explained noises. Intercept ($\beta_{0(hr)}$) changes depending on hybrid and row width when there is significant impact from the factors.

Tables (4 and 5) summarize the estimates (betas) for each response. The models were developed in PROC GLIMMIX as well. While R^2 is typical to describe predictability of a regression model, in our models however, there is no explicit R^2 as in traditional regression analysis due to random factors in the model (Nakagawa and Schielzeth 2013, Xu 2003). The covariance estimates also contribute to the percentage of variance explained by the model. For the quality measures in this study, for example, site-to-site variation counts for more than 30% of total variance. Table X listed both R^2 as calculated in traditional OLS regression explaining the variance proportion by fixed effects only and a R^2-like statistic (pseudo- R^2) calculating variance proportion explained by the mixed regression model (eqn. 1). In addition, since row width impact is not interacting with another other factors and relatively small comparing to those of hybrid and plant density, the beta0s in the table are estimates while holding row width at its average effect.

RESULTS AND DISCUSSION

Growing Conditions

Precipitation and temperature varied between locations and years, although similar trends were observed at both locations (Table 1). The 2015 and 2016 growing years were warmer than the 50-yr average at both locations. Average monthly temperature at the Utah site was 0.7˚C warmer for both growing seasons. The Idaho site was an average of 1.28˚C and 0.8˚C warmer during the 2015 and 2016 growing seasons, respectively. Temperatures for most months of the growing season were close to normal for both sites and years with the exception of June, where temperatures were 2.4 to 4.3˚C warmer than the 50-yr average.

Overall precipitation was above average for the 2015 growing season (Table 1). May precipitation was much higher than normal at both locations, with 75 and 41 mm above 50-yr average at the Utah and Idaho sites, respectively. The remainder of the 2015 growing season was at or near the long-term average. The 2016 production year was abnormally dry from June to August at both locations. May precipitation was higher than normal at the Utah site (+75 mm precip.), but lower than average at the Idaho location (-20 mm precip.). Greater than average precipitation amounts were received in September at both sites. Irrigation water was applied throughout the growing season at both locations to provide adequate moisture for corn production.

DM Yield

The hybrid × row width interaction was significant (Table 2); therefore, mean DM yields were not pooled over hybrid or row width (Fig. 1). Higher yields were measured for the 51-cm vs. the 76-cm row width for the 106 RM and 111 RM hybrids, with a 4.5% and 7% yield increase, respectively. However, the DM yield of the 99 RM hybrid in this study was not influenced by row width. Other researchers have observed silage corn yield increases from narrower row widths (Cox et al.,1998; Cox and Cherney, 2001; Cox and Cherney 2002; Porter et al. 1997). The lack of uniform hybrid yield response to row width has also been noted by others (Pinter et al. 1994; Farnham 2001). Similarly, a short season leafy hybrid in a New York study did not increase yield in narrow rows while other hybrids did (Cox et al., 1998). In Iowa, longer maturing hybrids tended to perform slightly better in narrow row environments (Farnham, 2001).Corn is almost exclusively bred in 76-cm rows, so breeders possibly may have indirectly bred corn for maximum corn DM yield in rows of that width (Tollenaar and Lee, 2002; Paszkiewicz and Butzen, 2007).

The row width × plant density interaction was not significant (Table 2). Previous studies on forage and grain corn in Minnesota (Porter et al. 1997), New York (Cox et al. 1998), Iowa (Farnham, 2001), Michigan (Widdicombe and Thelen, 2002) and Minnesota (Van Roekel and Coulter 2012) have also reported a lack of row width × plant density interaction. The main effect of plant density and hybrid were significant (Table 2). DM yield ranged from an average of 24.7 Mg $^{-1}$ ha^{-1} at 61,776 plants ha^{-1} to 28.7 Mg $^{-1}$ ha^{-1} at 123,553 plants ha^{-1} (Fig. 2). As plant density increased, silage dry matter yield increased in a quadratic response up to the highest plant density of 123,552 plants ha^{-1}. Cox and Cherney (2011) found that the maximum DM yield was also at the highest plant density at 98,000 plants ha^{-1}. Results of the study indicate that the highest yields may be achieved by increasing plant density, although it may not be cost effective according to the economic analysis that determined the optimum plant density.

Although DM yields at each population level differed between hybrids, the overall yield trends were similar (Fig. 2). Paszkiewicz and Butzen (2007) found that earlier RM hybrids possibly have higher optimum plant densities; however, Van Roekel and Coulter (2012) were unable to detect any differences between the hybrids of differing RM. It is possible that the 99 RM was not adapt to narrower row widths and having more within-row inter-plant spacing affects growth performance (Van Roekel and Coulter 2012). Greater within-row plant spacing may interfere with the plants ability to sense neighboring plant has and direct its leaves into the direction of the row enabling the plant to capture increased amounts of radiation (Girardin and Tollenaar, 1994). Because the 99 RM did not see yield increases from narrower row widths, unlike the other two hybrids, may suggest that the findings of (Lee, 2006) are applicable for this hybrid. Concluding that narrower rows located north of 43˚N latitude may see increased yields due to the shorter growing season, the narrower rows allowing the plants to intercept increased amounts of radiation.

Leaf Area Index (LAI) and Intercepted Photosynthetically Active Radiation (IPAR)

Leaf Area Index (LAI) and Intercepted Photosynthetically Active Radiation (IPAR) were affected by the main effects of hybrid, row width, and plant population, but not the interactions (Table 2). Hybrid showed small but significant differences in LAI (Table 3). Edwards (2005) suggested that hybrids may need to have had a large difference in RM to measure discrete responses of LAI and IPAR to plant density among hybrids.

The row width treatment showed a significant increase in plant canopy of 4% with LAI at the 76-cm row width compared to the 51-cm row width averaged across planting density, hybrid, and site (Table 3). DM yield, however was higher in the 51-cm row width (Fig. 1). Suggesting that the DM yield increase at 51-cm row width may not be contributed to LAI, but possibly in part in reduction of crowding stress, aiding the plants ability to utilize water and nutrients more efficiently. The findings of Van Roekel and Coulter (2012) showed otherwise, that 51-cm rows did not intercept more radiation nor produce greater leaf area. Andrade et al. (2002) and Maddonni et al. (2006) found that when LAI and IPAR were similar at the silking stage, that grain yields did not increase for rows narrower than 76 cm. At the V6 growth stage, narrow row corn showed increased interception of photosynthetically active radiation (Barbieri et al., 2000), although narrow and conventional- row corn had the same DM accumulation at the V8 stage of the study (Ma et al., 2003).

A positive linear relationship between LAI and plant density was seen at both locations (Fig. 3). LAI increased roughly 5% for every plant density increase of 12,355 plants ha^{-1}. Although plant density showed significance toward IPAR there was not a lot of difference from high to low plant densities (Table 2). The maximum IPAR was found at 123,552 plants ha^{-1} with a response of (96.7%) intercepted radiation, the minimum IPAR was at the lowest plant density of 61,776 plants ha^{-1} with a response of (95.1%) intercepted radiation (Fig. 4). These IPAR findings are similar to (Van Roekel and Coulter, 2012).

Stalk Diameter

No stalk or root lodging was noted in this study. The only significant interaction for stalk diameter was hybrid × plant population (Table 2). Stalk diameter can be represented by a quadratic model with a negative correlation between stalk diameter and increased plant density (Table 4). Stalk diameter decreased 4 to 5% as plant density increased at intervals of 12,355 plants ha^{-1} to the highest plant density (Fig. 5). In previous studies in Indiana (Boomsma et al., 2009) and in Minnesota (Van Roekel and Coulter, 2011), corn stalk diameters decreased as plant density increased. Longer RM did not necessarily correlate to a larger stalk diameter. The 99 RM hybrid had a 9% larger stalk diameter than the 106 RM hybrid, and the stalk diameter of the 111 RM hybrid was 3.5 % larger than that of the 99 RM hybrid. Given the results between LAI and stalk diameter with respect to plant density suggests that the increased yield from higher plant populations may have been affected more directly by capturing increased amounts of sunlight and utilizing water more efficiently.

The main effect of row width was also significant (Table 2). Stalk diameter showed an increase of 4% at the 51-cm row width versus 76-cm, suggesting that larger stalks may contribute to the increased DM yield of the narrower rows. A study on grain corn in Minnesota found no responses of stalk diameter among hybrids to row widths and plant density but suggested that the variability among the site years contributed to these findings (Van Roekel and Coulter 2012). The irrigation water applied to compensate for precipitation deficiencies in our study may have allowed for differences to be detected. Cox and Cherney (2001) conclude from a study in New York that despite a 7.5% yield increase and a 6% increase in milk yield at 38-cm vs. 76-cm row width, dairy farmers should produce corn silage at the same plant densities and N fertility, regardless of row width.

Forage Nutritive Value

The 99 RM hybrid reached black layer 2-3 weeks before the 106 RM hybrid. At harvest, the 106 RM hybrid had reached black layer, but the 111 RM hybrid did not reach peak maturity due to freezing nighttime temperatures, which stopped further growth of the plant. Because hybrids matured at different rates, an early sampling for hybrid 99 RM was taken 14 and 21 days prior to harvesting in 2015 and 2016, respectively. Another sample was taken from the 99 RM hybrid at harvest time. Comparison of forage quality components from the early and late harvest were analyzed statistically and no significant differences were observed; therefore, only the late harvest results are shown.

Most forage quality components measured showed an effect from hybrid and plant density (Table 2). Crude Protein was the only forage quality component that showed significant row width effects. In Iowa, a similar study found no effect on corn forage quality components of silage corn (Widdicombe and Thelen 2002). Plant density affected most quality components of the silage except for dNDF48 (Table 2). The hybrid x plant population interaction was significant for starch, but row width had no effect in this study. A positive linear model (Table 5) was used to represent the increase of starch x plant density effect showing that starch increased approximately 3% from the lowest to highest plant densities tested (Fig. 6). Interestingly, these findings are opposite of the findings in New York (Cox and Cherney 2011), and Wisconsin (Cusicanqui and Lauer, 1999), which found a negative linear relation between starch concentration and plant density. And Cox and Cherney (1998), showed that plant density did not affect starch concentration. It may be possible that the maturity at the harvest timing may have affected increased starch concentration as plant density increased (Martin, 2008). Increased starch levels at higher plant densities suggest that the corn ear ratio to total plant biomass may have increased.

No interactions for crude protein (CP) were significant, but main effects of hybrid, row width, and plant density had an effect on CP (Table 2). Crude protein was the only quality component affected by row width differences (Table 3), where it was higher in silage corn grown in 76-cm than 51-cm rows (Table 4). As plant density increased, forage CP decreased by 5 g kg^{-1}(Fig. 7). These findings are consistent with the findings of (Cox et al., 1998; Cusicanqui and Lauer, 1999; Cox and Cherney, 2001; Widdicombe and Thelen, 2002; Cox and Cherney, 2011). Carter et al. (1991) stated that protein is not considered as one of the major factors for corn forage evaluation, due to low protein concentrations of corn compared with legume forages.

The NEL-3x values ranged from 1.50 Mcal kg^{-1} with the 99 RM 51-cm row width treatment up to 1.55 Mcal kg^{-1} from 111 RM 51-cm row width treatment. The higher NEL-3x values came from the longest maturity hybrid at either row width. The largest difference in NEL-3x values came from hybrid and plant density (Table 2). The regression line is represented with a quadratic model and indicates that the optimum NEL-3x was reached at 86,486 plants ha^{-1}(Table 5). TDN-1x values ranged from a low of 698.8 g kg^{-1} with the 99 RM 51-cm row width treatment to a high of 716.96 g kg^{-1} in the 111 RM 51-cm row width treatment. The highest values came from hybrids 106 RM and 111 RM at either row width treatment. The lowest values came from hybrid 99 RM at 51-cm row width. In (Table 5), 106 and 111 RM are represented by the same quadratic line, but the 99 RM had the lowest TDN-1x value. The largest differences corresponded to plant density.

ADF, NDFD, and IVTD were affected only by hybrid and plant density, but not row spacing (Table 2). Similar findings were reported by Widdicombe and Thelen (2002) and Cusicanqui and Lauer (1999). ADF showed the greatest increase when planting density was changed from 61,776 to 74,131 plants ha^{-1} (Fig. 8). When plant densities increased to the highest plant density ADF showed no difference, suggesting that ADF does not change when plant densities are above 74,131 ha^{-1} (Table 5). Hybrid was the only main effect difference observed with the 106 RM with the highest aNDF value which was 2% greater than the 111 RM, the 99 RM was 4% less than the 111d RM. Plant density significantly affected IVTD (Table 2) and no affect was seen from row width similar to findings in New York (Cox and Cherney, 2002) as plant density increased IVTD (Fig. 9) and NDFD (Fig. 10) showed a linear decrease (Table 5). The forage DMD decreased 6.9 g kg^{-1} as plant density increased from the lowest plant density to the highest, supporting the findings of Widdicombe and Thelen (2002). The decrease of NDFD in relation to plant density is not consistent with the findings of Cox and Cherney (2011), which showed no difference in NDFD in relation to plant density. Small differences were noted with aNDF (Table 2). The forage quality results varied across the range of plant densities and among different hybrids, which are consistent with the findings in Michigan (Widdicombe and Thelen 2002) and Wisconsin (Cusicanqui and Lauer 1999).

Dairy producers do not plant corn to maximize DM yields but hope to maximize milk yields (Cox et al., 2001; Undersander et al., 1993). The MILK 2006 equation was designed to help a dairy producer maximize their milk production by balancing quality components and DM yield (Shaver and Lauer, 2006). Milk Mg^{-1} and milk ha^{-1} are two different values that are given from the equation to assist farmers in making decisions regarding silage production.

Milk Mg^{-1} and Milk ha^{-1} responses to planting density are shown in Fig. 11 and 12. The relationship between plant density, Milk Mg^{-1}, and Milk ha^{-1} was best described with a quadratic model (Table 5). Milk Mg^{-1} increased quadratically from 61,776 to 86,486 plants ha^{-1} at a rate of 6.5 kg milk Mg^{-1} where maximum milk Mg^{-1} was reached, then decreased approximately 1% from 86,486 to 123,552 plants ha^{-1}(Fig. 11). Cusicanqui and Lauer’s (1999) findings were different, where the maximum milk Mg^{-1} was obtained at the lowest plant density of 44,500 plants ha^{-1}. In New York, milk Mg^{-1} had less of a negative linear response to plant density due to the NDFD and starch concentrations that did not decrease as in previous studies (Cox et al., 1998; Cusicanqui and Lauer, 1999; Cox and Cherney, 2011)

As plant density increased CP and NDFD48 values decreased causing the milk Mg^{-1} to decrease. The highest value of milk Mg^{-1} was 1634.4 kg milk Mg^{-1} when corn was planted around the 86,486 plants ha^{-1}. Milk ha^{-1} increased quadratically by 22% as plant density increased to the highest density of 123,552 plants ha^{-1}(Fig. 12). Milk ha^{-1} displayed a hybrid x row width interaction which correlates to the dry matter yield (Cox and Cherney, 2001) hybrid x row width interaction. The 99 RM displayed no effect on milk ha^{-1} from the hybrid x row width interaction. Whereas hybrids 106 RM and 111 RM showed significant increases of 4 to7 % Mg^{-1} milk ha^{-1} with corn grown in 51 versus 76-cm rows. The highest value for milk ha^{-1} was 50.45 Mg^{-1} milk ha^{-1} grown from the 111 RM at 123,552 plants ha^{-1} (Fig. 12) the longest maturity hybrid. These findings were inconsistent with the findings in Wisconsin, which found the optimum plant density for milk ha^{-1} to be around 75,000 to 85,000 plants ha^{-1} (Cusicanqui and Lauer, 1999). Cox and Cherney (2011) found maximum predicted milk yields in New York to occur at about 89,000 plants ha^{-1}, which is slightly higher than previous studies done by Cox and Cherney (Cox et al., 1998; Cox and Cherney, 2001a).

Net Return

Analysis of the initial investment of narrowing corn rows from 76-cm to 51-cm found it to be a positive investment 58% of the time (Fig. 13). This suggests that if a producer is going to upgrade old equipment, then it is probably a good investment, long term, to upgrade to equipment capable planting on narrow rows. Cox et al. (2006) reported that narrow-row corn silage can provide an increased profit over twin-row silage corn. These findings do not agree with Van Roekel and Coulter (2012) on grain corn, who found that the higher costs of machinery for narrower row widths did not significantly reduce the net return. The authors attributed this result to the lack of effect on row width in the study on DM yield increases.

The economic optimum for plant density varies on the market value of silage corn and cost of the seed (Tables 6 and 7). The net return was based on corn silage price (US$62 to US$111 Mg^{-1} at US$12.35 intervals) and seed cost (US$150 to US$400 per 80,000 seeds at US$50 intervals), while assuming all other input costs are similar at the variable plant densities. Each hybrid was analyzed separately with the corresponding DM yield at each plant density.

Net returns were greatest when plant density was planted between 74,131 and 111,197 plants ha^{-1} (Table 6 and 7). Each year the economic optimum plant population density will change based upon market prices. When prices are high, the producer has the potential to possibly increase net returns by slightly increasing plant density. Plant densities at or around 61,776 or 123,553 plants, ha^{-1} do not generally show increased net returns. When corn is planted around 86,486 plants ha^{-1} the producer will generally receive consistent maximum net returns. These finding are consistent with the findings of Van Roekel and Coulter (2012) with grain corn who found that when plant density is at 87,000 plants ha^{-1} the maximum net return is reached.

CONCLUSIONS

For this 2-year study in Utah and Idaho, DM yield, yield components, quality components, and net return were influenced by row width, hybrid, plant density, and several interactions between row width x hybrid and plant density x hybrid. Two of the three hybrids in the study produced increased DM yield when planted in 51-cm rows, with 4-7% yield improvement. Increases in DM yield at 51 cm row width are dependent on the hybrid. DM yield increased with plant population for each of the hybrids and maximum DM yield occurred at the highest planting rate of 123,552 plants ha^{-1}. Forage quality components saw little, if any, difference from row width changes. Increased plant population, on the other hand, tended to adversely affect forage quality. Maximum milk Mg^{-1} was around 86,486 plants ha^{-1}. Milk ha^{-1} showed a positive increase from the lowest to highest plant density. Economic returns favored narrow row widths of 51-cm but not all situations would be profitable by switching to narrower row widths. The economic optimum-plant population for this study was around 86,486 plants ha^{-1}.

This research suggests that planting corn on a narrower row width than the standard 76-cm row can result in a fairly consistent and significant yield increase in silage corn in the Intermountain West. Whether such a yield gain warrants the purchase of a new planter capable of narrow row planting depends on the number of acres to be planted and if the narrow row planter has utility in another crop (i.e., beans, sugarbeets, etc.) to spread the cost. Also from this research, the optimal silage corn plant density for the Intermountain West is around 86,000 plants ha^{-1}. At this plant density, we see in an increase of yield with the best forage quality components for silage corn. In years where corn market prices are above average farmers may see a larger return by increasing planting density by several thousand plants ha^{-1}above 86,000 plants ha^{-1}. Likewise, when the corn market prices are below average the farmer ought to consider decreasing plant population several thousand plants ha^{-1} below 86,000 plants ha^{-1} to increase maximum profit.

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APPENDIX. Tables and Graphs

Table 1. Monthly average temperature, total precipitation, and irrigation amounts for North Logan and Jerome for growing years 2015 and 2016 with the difference from long-term average (50 yrs.) for temperature and precipitation (1966-2016) in parenthesis.

	Temperature †				**Precipitation**				**Irrigation**			
	North Logan‡		**Jerome**		**North Logan**		**Jerome**		**North Logan**		**Jerome**	
Month	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**
	ºC				**mm**							
April	9.1 (1.1)	10.3 (2.3)	9.1 (0.4)	11.9 (3.2)	62.9 (7.1)	55.7 (-0.1)	3.1 (-21.2)	14.9 (-9.4)	0	0	0	0
May	12.8 (-0.2)	13.0 (0)	14.7 (1)	13.9 (0.2)	134.5 (74.7)	75.7 (15.9)	68.1 (41.1)	6.9 (-20.1)	0	35	0	45
June	21.9 (3.6)	21.1 (2.9)	22.9 (4.3)	21 (2.4)	43.7 (7.7)	16.6 (-19.4)	2.6 (-15.5)	1.8 (-16.1)	141	184	145	158
July	21.6 (-1.6)	23.7 (0.5)	22.8 (-0.6)	23.1 (-0.3)	22.6 (3.7)	0.8 (-18.1)	13 (8.2)	3.1 (-1.7)	194	205	204	210
August	22.2 (-0.2)	22.5 (0.1)	23.1 (0.7)	22.5 (0.1)	28.7 (5.5)	1 (-22.2)	5.7 (-3.3)	0 (-9.0)	178	188	196	203
September	18.6 (1.9)	16.6 (-0.2)	18 (1)	16 (-1)	43.6 (6.0)	109.7 (72.1)	21 (8.8)	36.9 (24.7)	52	87	68	73
October	13.5 (3.4)	11.5 (1.4)	14.2 (3.7)	11.6 (1.1)	21.0 (-28.8)	98.4 (48.6)	20.4 (-0.6)	83.2 (62.2)	0	0	0	0

† Weather Data was obtained from the Utah Climate Center.

‡ Weather stations nearest both locations was used to obtain the temperature and precipitation data.

Table 2. The significance of *F* values for fixed sources of variation across both locations in 2015 and 2016.

Dependent Variable	**Hybrid (H)**	**Row Width (R)**	**Plant Density (P)**	**H x R**	**H x P**	**R x P**	**H x R x P**
				P > F			
Stalk diameter†	<.0001	<.0001	<.0001	0.2123	0.0475	0.4996	0.9279
IPAR‡	<.0001	0.0039	<.0001	0.1454	0.3079	0.7251	0.8924
LAI	<.0001	0.0008	<.0001	0.0878	0.3134	0.3494	0.5111
DM yield	<.0001	0.0020	<.0001	0.0009	0.2621	0.3678	0.6162
Milk Mg^{-1}	0.0362	0.7505	0.0238	0.7636	0.5104	0.8353	0.2355
Milk ha^{-1}	<.0001	0.0108	<.0001	0.0182	0.0757	0.6578	0.7579
NEL-3X	0.0271	0.7230	0.0188	0.7877	0.5617	0.7837	0.2027
TDN-1X	0.0696	0.8567	0.0188	0.7561	0.3700	0.8427	0.3097
IVTD	<.0001	0.9154	0.0036	0.2009	0.1936	0.3937	0.1954
Starch	<.0001	0.4867	0.0156	0.4331	0.0474	0.6013	0.2821
Crude protein	0.0019	0.0029	<.0001	0.2978	0.6088	0.2560	0.1294
ADF	0.0004	0.5380	<.0001	0.2585	0.0597	0.6096	0.7572
NDFD48	<.0001	0.2870	<.0001	0.2436	0.2635	0.5635	0.5029
NDF	<.0001	0.3488	0.0914	0.4116	0.1275	0.5392	0.4677
dNDF48	<.0001	0.3433	0.7937	0.5165	0.2002	0.4769	0.5353

† Measurements taken when late maturing hybrid was at silking stage.

‡ Intercepted photosynthetically active radiation (IPAR) measurements taken when the late maturing hybrid was at silking stage.

Table 3. Significance of quality measurements including crude protein (CP), acid detergent fiber (CP), amylase neutral detergent fiber (aNDF), neutral detergent fiber at 48 hours (NDFD48), in vitro true dry matter digestibility at 48 hours (IVTD48), and starch for 51-cm and 76-cm row widths, averaged across year, site, and location.

Variables	**DM Yield**	**LAI**	**IPAR**	**Stalk Diameter**	**Starch**	**IVTD**	**CP**	**Milk Mg^{-1}**	**Milk ha^{-1}**	**NDFD48**	**ADF**
	Mg ha^{-1}	m^{2} m^{-2}	%	mm	g kg^{-1}	g kg^{-1}	g kg^{-1}	Kg^{-1} Mg^{-1} DM	kg^{-1} ha^{-1}	g kg^{-1} NDF	g kg^{-1}
Row Width											
51-cm	27.6A	6.1B	4.2A	23.3A	311.0A	840.0A	67.0B	1618.3A	44.8A	605.0A	235.0A
76-cm	26.7B	6.3A	4.0B	22.5B	309.0A	841.0A	70.0A	1619.7A	43.3B	602.0 A	233.0A
Hybrid											
99-d RM	25.9 c	6.0 b	4.2 a	23.3 b	332.0 a	848.0 a	67.0 b	1601.5 b	41.3 c	609.0 a	229.0 b
106-d RM	27.1 b	5.7 c	4.4 a	21.2 c	293.0 c	835.0 b	67.0 b	1623.3 ab	44.1 b	604.0 b	237.0 a
111-d RM	28.5 a	6.7 a	3.7 b	24.2 a	304.0 b	838.0 b	70.0 a	1631.3 a	46.7 a	599.0 c	236.0 a

Table 4. Parameter estimates, R^2 values for regression models relating to intercepted photosynthetically active radiation (IPAR), leaf area index (LAI), stalk diameter, and dry matter (DM) yield of plant density on various response variables across hybrids and row spacing at North Logan, UT and Jerome, ID in 2015 and 2016.

Response variable	**Model**	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	R^2	**Pseudo-** R^2
IPAR, %	L	6.36	-0.024***	-	0.40	0.53
LAI, m^2 m^{-2}						
111 RM	L	2.84	0.051***	-	0.62	0.83
99 RM		2.10				
106 RM		1.83				
Stalk Diameter, mm						
111 RM	L	31.47	-0.079***	-	0.75	0.80
99 RM		30.63				
106 RM		28.50				
Yield, Mg ha^{-1}						
111 RM	Q	15.15	0.23***	-0.0009***	0.29	0.74
106 RM		13.79				
99 RM		12.57				

Note: * $0.01 \le p \le 0.05$; ** $0.001 \le p \le 0.01$; *** $p \le 0.001$

Table 5. Parameter estimates, R^2 values for regression models relating to Milk ha^{-1}, Milk Mg^{-1}, net energy of lactation at 3x maintenance (NEL-3x), total dietary nutrients at maintenance (TDN-1x), in vitro true dry matter digestibility at 48 hours (IVTD48), neutral detergent fiber digestibility at 48 hours (NDFD48), acid detergent fiber (ADF), amylase neutral detergent fiber (aNDF), crude protein (CP), and starch of plant density on various response variables across hybrids and row width at North Logan, UT and Jerome, ID in 2015 and 2016.

Response variable	**Model**	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	R^2	**Pseudo-** R^2
Milk ha^{-1}, kg^{-1} milk ha^{-1}						
111 RM	Q	24.39	0.40***	-0.002***	0.34	0.68
106 RM		21.88				
99 RM		19.09				
Milk Mg^{-1}, kg milk Mg^{-1}						
111 & 106 RM	Q	1526.68	2.32	-0.013	0.03	0.64
99 RM		1504.42				
NEL-3X, Mcal kg^{-1}	Q	1.47	0.0013*	-0.000007*	0.05	0.66
TDN-1X, g kg^{-1}						
111 & 106 RM	L	697.36	-	-	0.02	0.69
99 RM		691.13				
IVTD48, g kg^{-1}						
111 & 106 RM	L	84.59	-0.010**	-	0.06	0.54
99 RM		85.75				
NDFD48, g kg^{-1} NDF						
111 RM	L	61.21	-0.015***	-	0.03	0.74
106 RM		61.75				
99 RM		62.31				
ADF, g kg^{-1}						
111 & 106 RM	L	22.38	0.0014***	-	0.06	0.32
99 RM		21.60				
aNDF, g kg^{-1}						
111 & 106 RM	L	38.63	0.12*	-	0.11	0.42
99 RM		36.74				
CP, g kg^{-1}						
51-cm						
111 & 106 RM	L	7.49	-0.0074***	-	0.08	0.33
99 RM		7.26				
76-cm						
111 RM		7.78				
106 & 99 RM		7.55				
Starch, g kg^{-1}						
111 RM	L	28.86	0.016***	-	0.13	0.70
106 RM		27.83				
99 RM		31.61				

Note: * $0.01 \leq p \leq 0.05$; ** $0.001 \leq p \leq 0.01$; *** $p \leq 0.001$

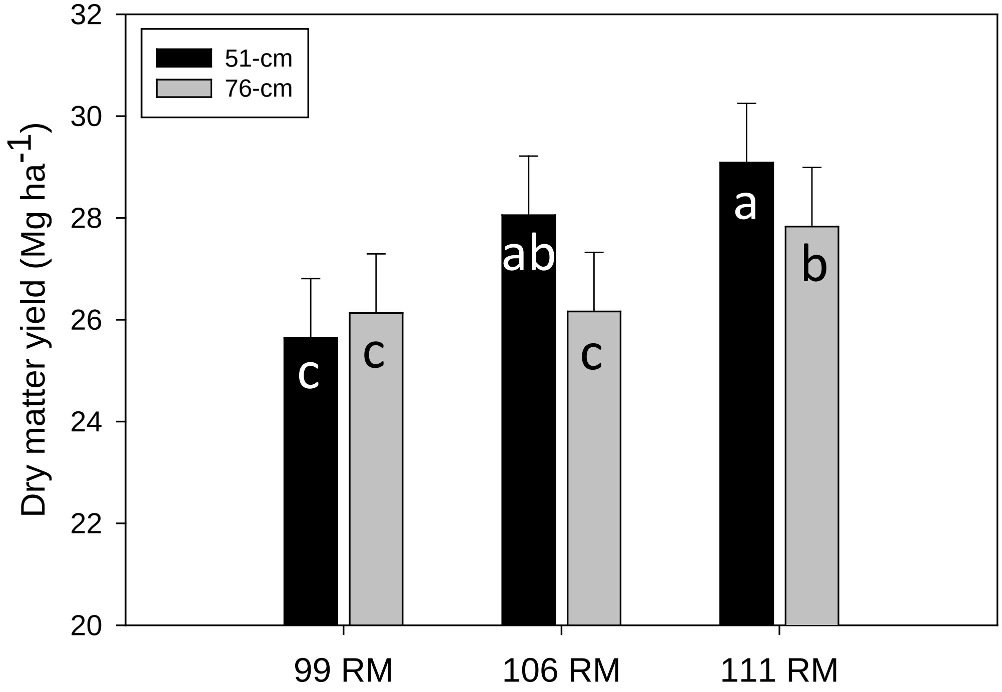

Fig. 1. Relationship between the three hybrids at each row width measuring whole plant dry matter (DM) yield. Data are averaged across location, replication, and year. Dry matter yield differences between row widths at each hybrid. The 51-cm row width yielded significantly higher for the 106 and 111 RM hybrids. The 99 RM showed no significant difference between row widths.

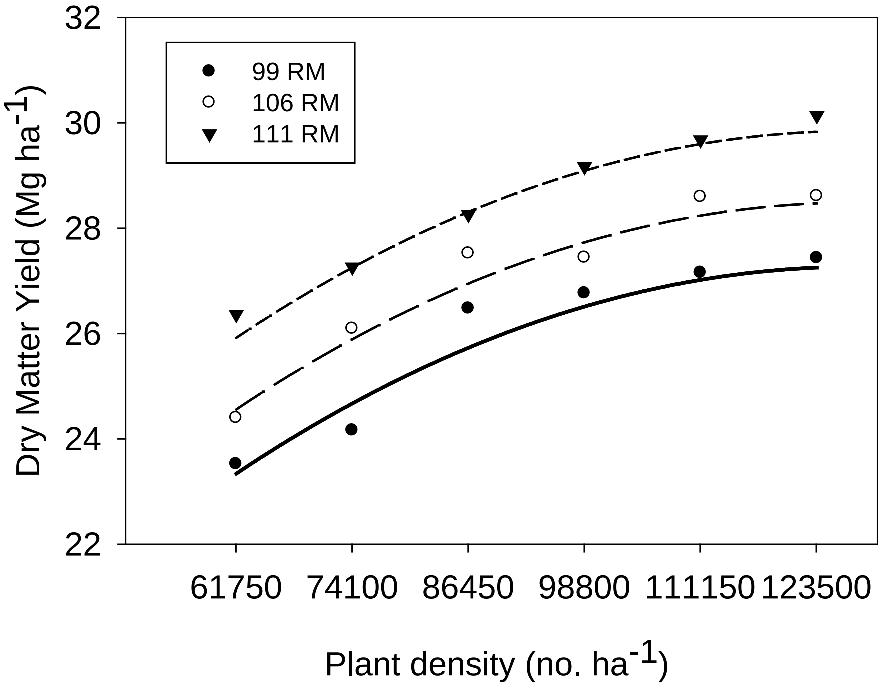

Fig. 2. Effect of plant density and hybrid type on forage dry matter (DM) yield. The relationship between the three hybrids at each row width (51-cm and 76-cm) measuring whole plant dry matter yield. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 4.

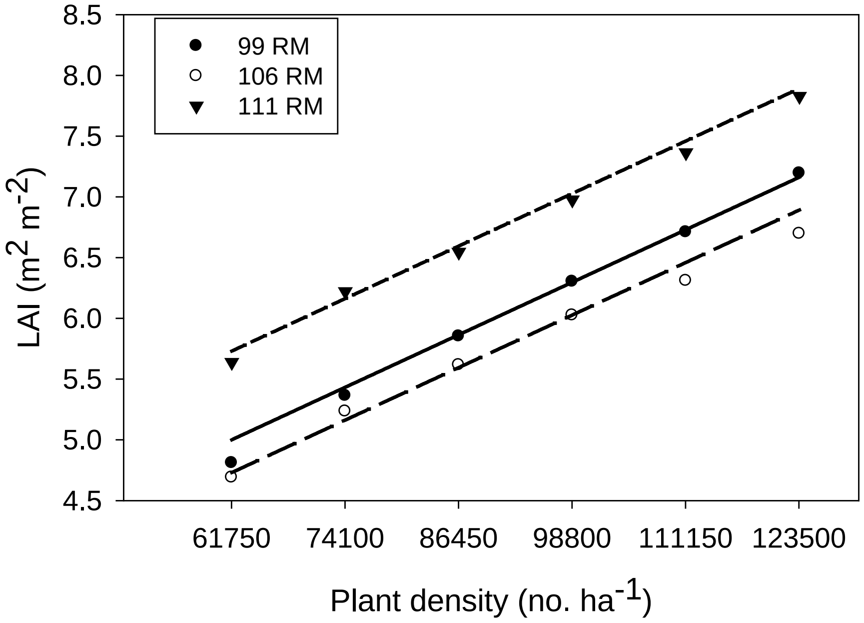

Fig. 3. Effect of plant density and hybrid type on Leaf Area Index (LAI). The relationship between the three hybrids averaging the mean row width (51-cm and 76-cm) measuring total LAI. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 4.

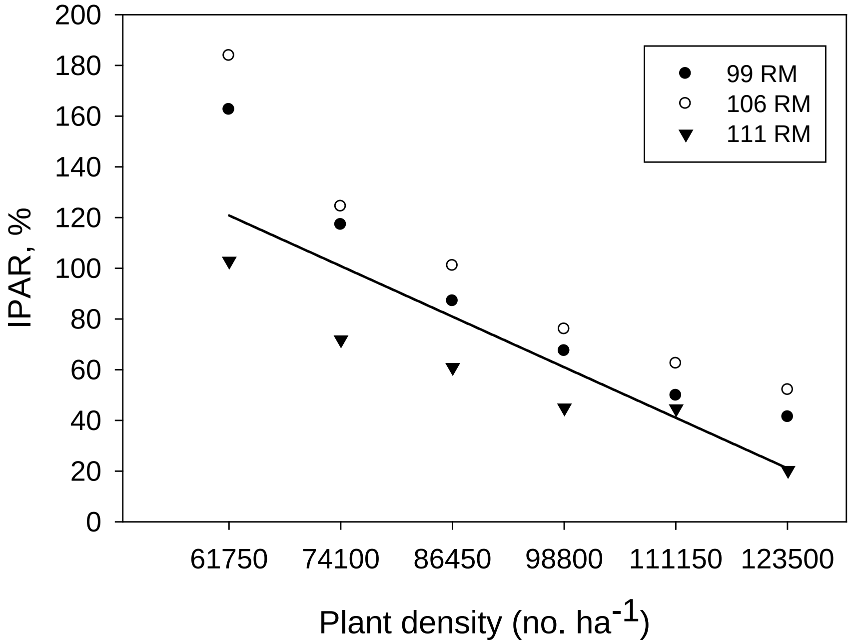

Fig. 4. Intercepted Photosynthetic active radiation (IPAR) response to plant density. Data are averaged across location, year, hybrid, row width, and replication. Parameter estimates and (R^2) values are in Table 4.

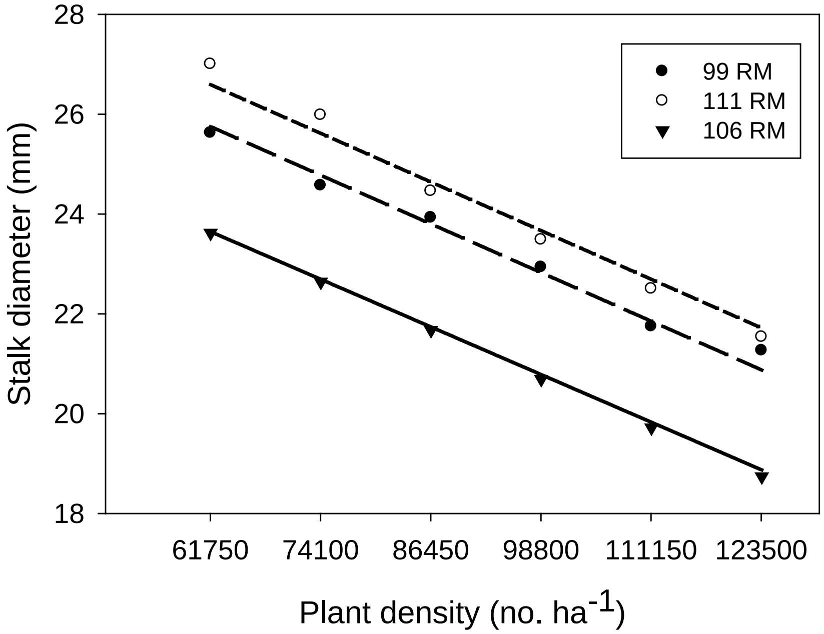

Fig. 5. Effect of plant density and hybrid type on stalk diameter. The relationship between the three hybrids, averaging row width (51-cm and 76-cm) measuring stalk diameter at the silking stage. Data are averaged across location, year, and replication. Parameter estimates and (R2) values are in Table 4.

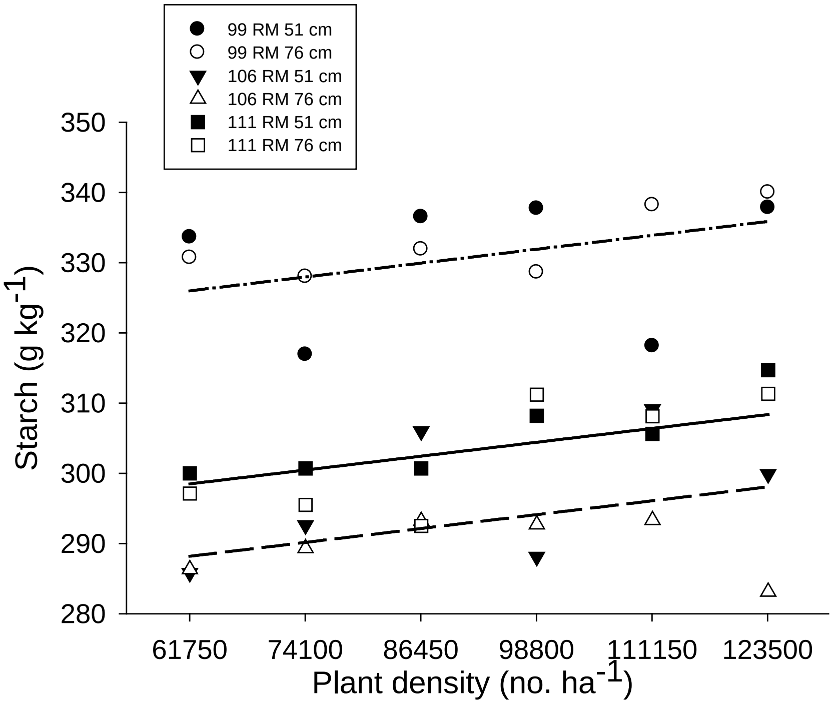

Fig. 6. Effect of plant density, hybrid type, and row width on corn silage starch content. The relationship between the three hybrids at each row width (51-cm and 76-cm) measuring starch. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 5.

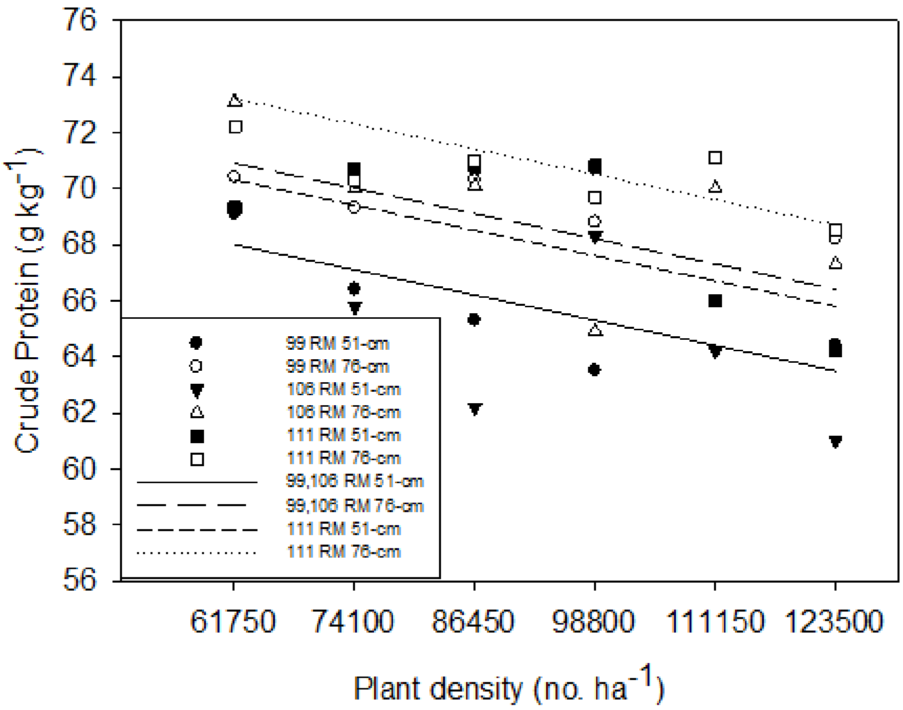

Fig. 7. Effect of plant density, hybrid type, and row width on forage component crude protein (CP). The relationship between the three hybrids at each row width (51-cm and 76-cm) measuring CP. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 5.

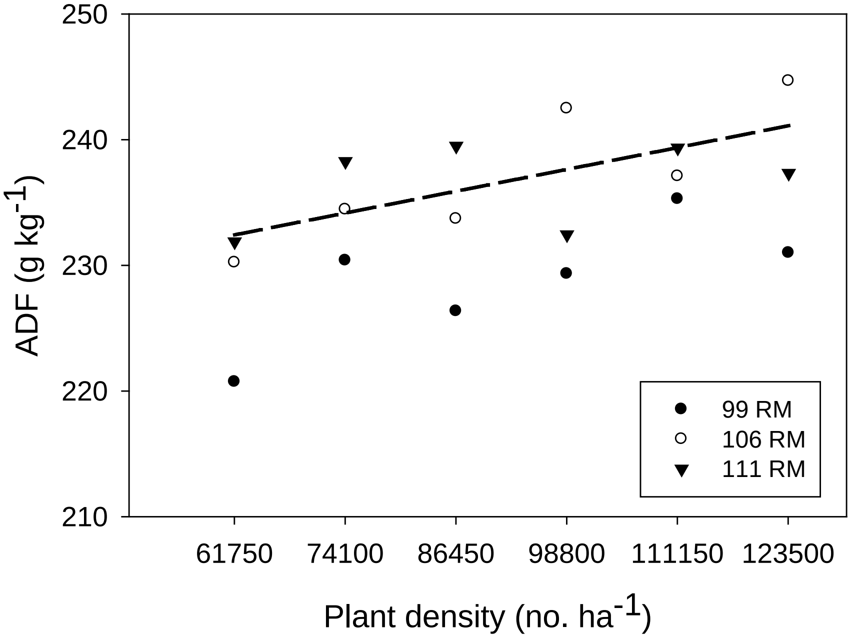

Fig. 8. Effect of plant density averaged across hybrid type in correspondence to Acid Detergent Fiber (ADF). Data are averaged across location, year, row width, and replication. Parameter estimates and (R^2) values are in Table 5.

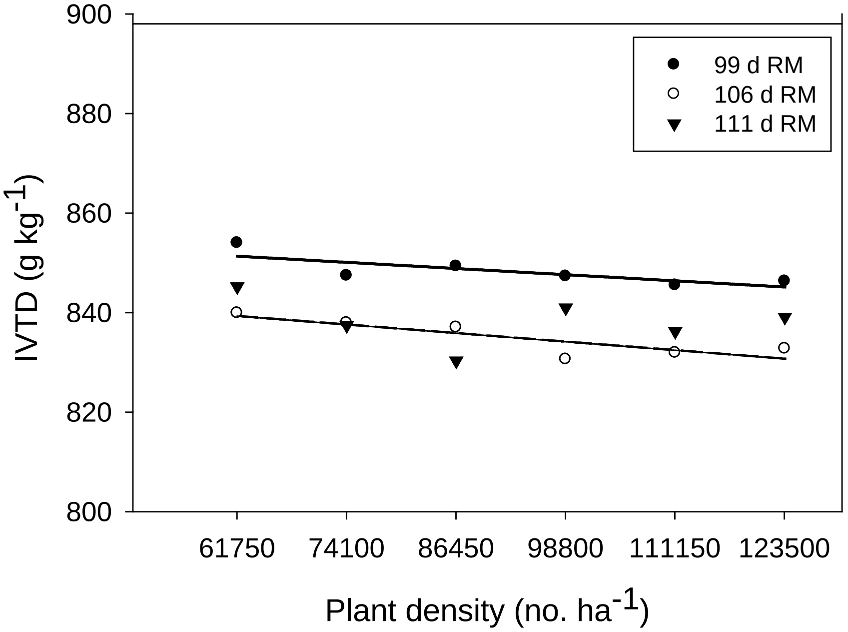

Fig. 9. Effect of plant density and hybrid type on In Vitro True Digestibility (IVTD). Data are averaged across location, year, row width, and replication. Parameter estimates and (R2) values are in Table 5.

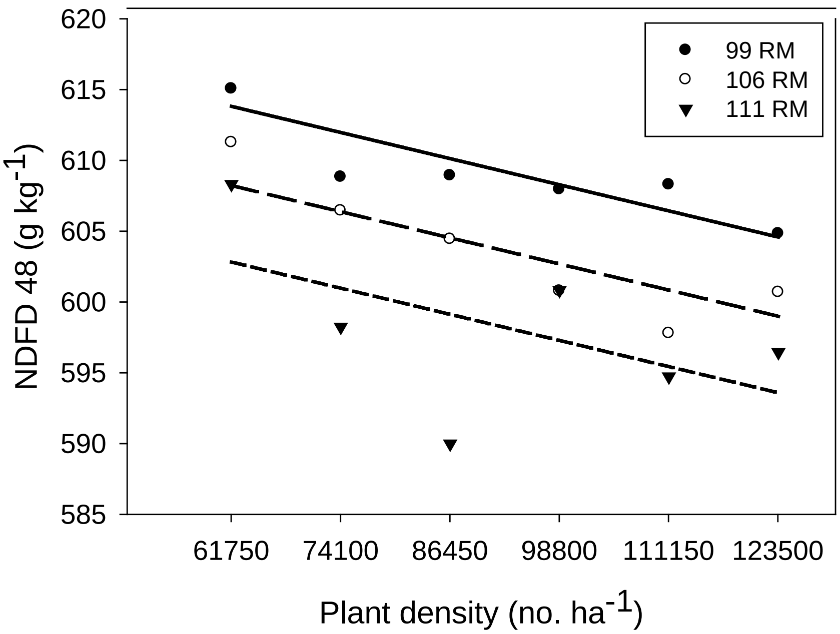

Fig. 10. Effect of plant density and hybrid type on Neutral Detergent Fiber Digestible at 48 hours (NDFD48). Data are averaged across location, year, row width, and replication. Parameter estimates and (R^2) values are in Table 5.

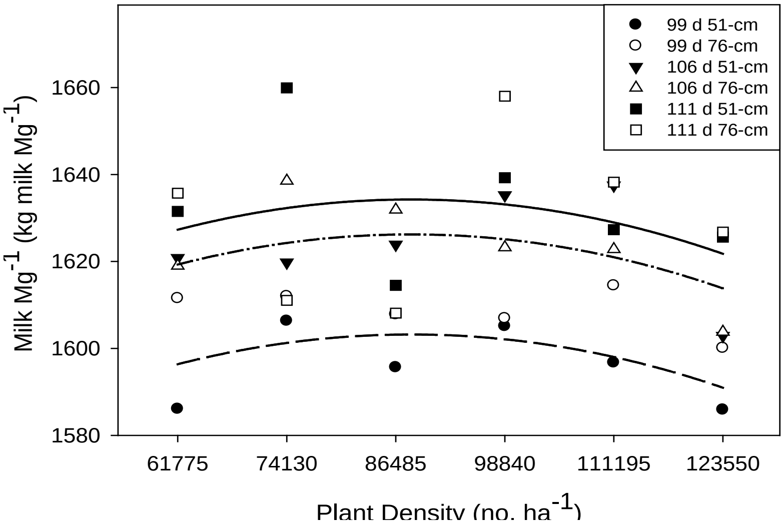

Fig. 11. Effect of harvest plant density on corn forage Milk Mg^{-1}, for each hybrid at both row widths, averaged across location, year, and replication. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 5.

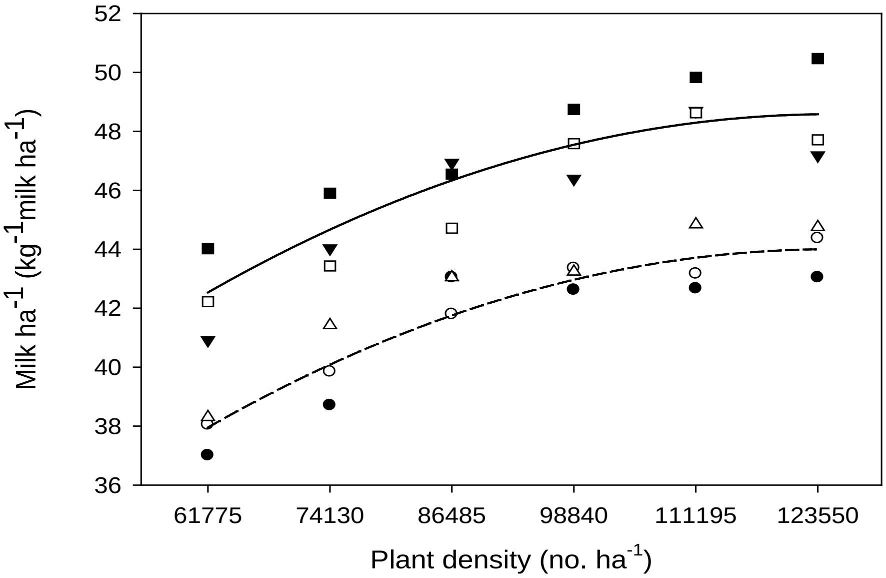

Fig. 12. Effect of harvest plant density on corn forage Milk ha^{-1}, for each hybrid at both row widths, averaged across location, year, and replication. Data are averaged across location, year, and replication. Parameter estimates and (R^2) values are in Table 5.

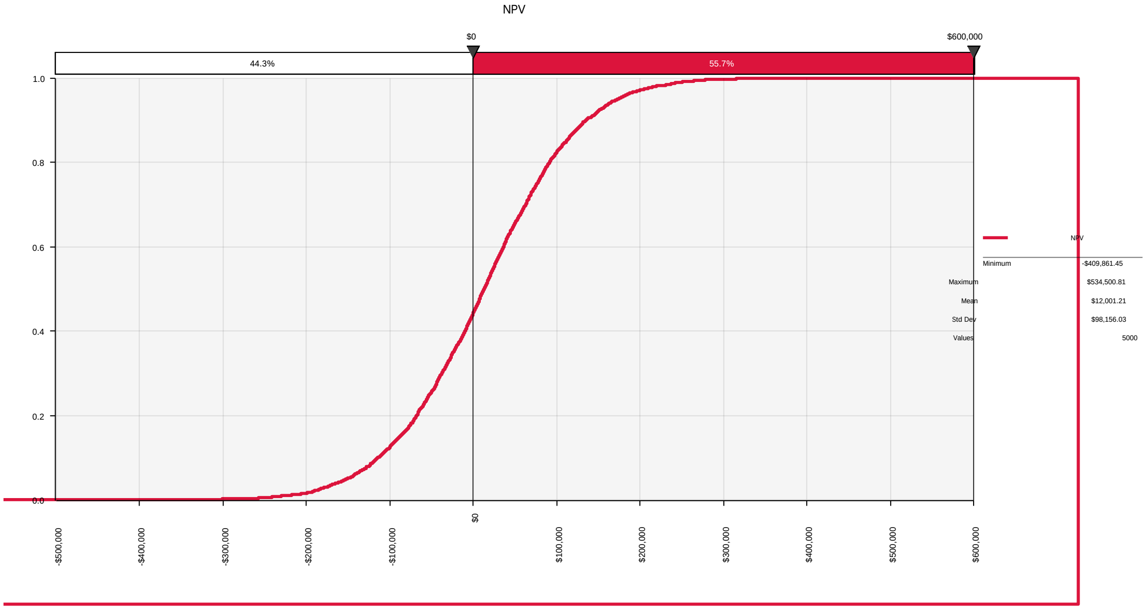

Fig 13. The net present value (NPV) for switching to 51-cm row widths. Indicating that the investment may be profitable 58% of the time. In addition, 44% of the time the investment may not be profitable.

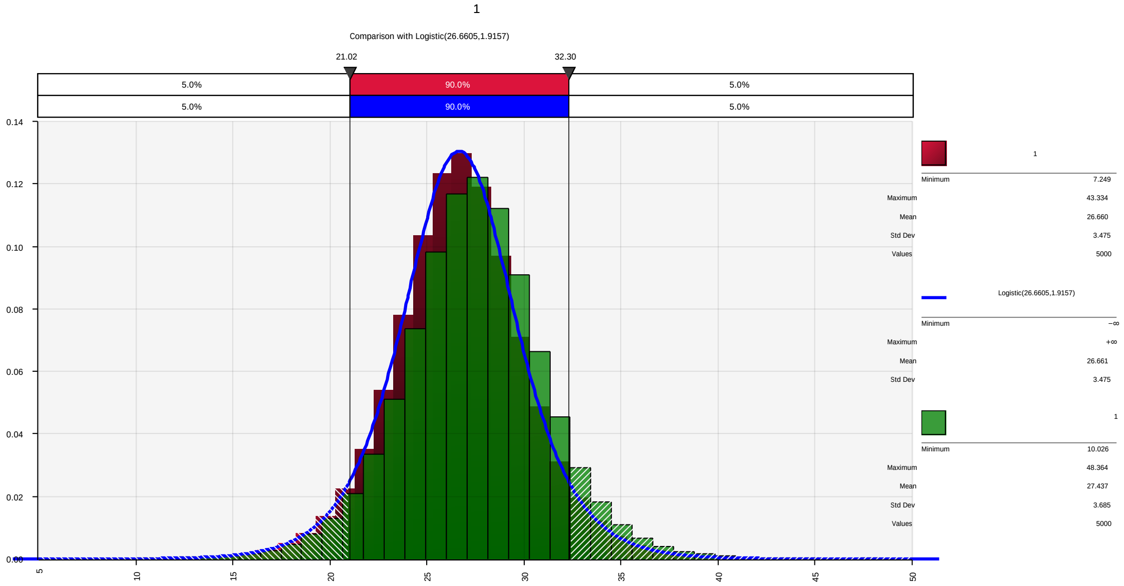

Fig. 14. The parabolic curve is represented with two colors. The green represents the 51-cm, and red 76-cm row widths. The green curve is slightly shifted to the right indicating the possible increased return on investment.

Table 6. Gross return (-seed cost) from three different hybrids Dekalb 49-29 (99 RM), Dekalb 56-54 (106 RM), and Dekalb 61-88 (111 RM) at six plant populations. At three different seed costs ($150-$250 per. 80,000 seeds). Returns are calculated from yield averages at each plant population, location, and year (2015 and 2016) growing seasons.

Silage Market Value	*Plant Population*	*$150/80,000 seeds*			*$200/80,000 seeds*			*$250/80,000 seeds*		
	Plants/ha^{-1}	99-d	106-d	111-d	99-d	106-d	111-d	99-d	106-d	111-d
$25/ton	61776	215.0	224.7	241.4	199.3	209.1	225.8	183.7	193.5	210.1
	74131	212.7	232.8	247.3	194.0	214.1	228.5	175.2	195.3	209.8
	86486	225.8	230.6	249.0	203.9	208.7	227.1	182.1	186.8	205.3
	98842	219.1	227.5	249.7	194.1	202.5	224.7	169.1	177.5	199.7
	111197	217.9	232.0	246.0	189.8	203.9	217.9	161.7	175.8	189.8
	123552	211.7	224.8	241.8	180.4	193.5	210.5	149.2	162.3	179.3
$30/ton	61776	267.3	279.1	299.0	251.7	263.4	283.4	236.1	247.8	267.8
	74131	266.5	290.6	308.0	247.7	271.9	289.2	229.0	253.1	270.5
	86486	284.1	289.8	311.9	262.2	267.9	290.1	240.4	246.0	268.2
	98842	277.9	287.9	314.7	252.9	262.9	289.7	227.9	237.9	264.7
	111197	278.4	295.3	312.1	250.3	267.2	284.0	222.2	239.0	255.9
	123552	272.7	288.5	308.9	241.5	257.2	277.6	210.2	226.0	246.4
$35/ton	61776	319.7	333.4	356.7	304.1	317.8	341.1	288.4	302.1	325.4
	74131	320.3	348.4	368.7	301.5	329.7	349.9	282.8	310.9	331.2
	86486	342.4	349.0	374.9	320.5	327.2	353.0	298.6	305.3	331.1
	98842	336.7	348.4	379.6	311.7	323.4	354.6	286.7	298.4	329.6
	111197	338.9	358.6	378.2	310.7	330.4	350.1	282.6	302.3	321.9
	123552	333.8	352.2	376.0	302.6	320.9	344.7	271.3	289.7	313.5

$40/ton	*61776*	*372.1*	*387.7*	*414.3*	*356.4*	*372.1*	*398.7*	*340.8*	*356.5*	*383.1*
	74131	374.1	406.2	429.4	355.3	387.5	410.6	336.6	368.7	391.9
	86486	400.7	408.3	437.8	378.8	386.4	415.9	356.9	364.5	394.0
	98842	395.5	408.9	444.6	370.5	383.9	419.6	345.5	358.9	394.6
	111197	399.3	421.8	444.3	371.2	393.7	416.1	343.1	365.6	388.0
	123552	394.9	415.9	443.1	363.7	384.6	411.8	332.4	353.4	380.6
$45/ton	61776	424.4	442.0	472.0	408.8	426.4	456.4	393.2	410.8	440.7
	74131	427.9	464.0	490.1	409.1	445.3	471.3	390.4	426.5	452.6
	86486	459.0	467.5	500.7	437.1	445.6	478.8	415.2	423.8	457.0
	98842	454.4	469.4	509.5	429.4	444.4	484.5	404.4	419.4	459.5
	111197	459.8	485.1	510.3	431.7	457.0	482.2	403.5	428.9	454.1
	123552	456.0	479.6	510.2	424.7	448.3	478.9	393.5	417.1	447.7

Table 7. Gross return (-seed costs) from three different hybrids Dekalb 49-29 (99 RM), Dekalb 56-54 (106 RM), and Dekalb 61-88 (111 RM) at six plant populations. At three different seed costs ($300-$400 per. 80,000 seeds). Returns are calculated from yield averages, at each plant population, location, and year (2015 and 2016) growing seasons.

Silage Market Value	*Plant Populations*	*$300/80,000 seeds*			*$350/80,000 seeds*			*$400/80,000 seeds*		
	Plants/ha^{-1}	99-d	106-d	111-d	99-d	106-d	111-d	99-d	106-d	111-d
$25/ton	61776	168.1	177.9	194.5	152.5	162.2	178.9	136.8	146.6	163.3
	74131	156.5	176.6	191.0	137.7	157.8	172.3	119.0	139.1	153.5
	86486	160.2	164.9	183.4	138.3	143.1	161.5	116.4	121.2	139.6
	98842	144.1	152.5	174.7	119.1	127.5	149.7	94.1	102.5	124.7
	111197	133.6	147.6	161.7	105.4	119.5	133.5	77.3	91.4	105.4
	123552	117.9	131.0	148.0	86.7	99.8	116.8	55.4	68.5	85.5
$30/ton	61776	220.5	232.2	252.2	204.8	216.6	236.5	189.2	200.9	220.9
	74131	210.2	234.4	251.7	191.5	215.6	233.0	172.7	196.9	214.2
	86486	218.5	224.2	246.3	196.6	202.3	224.4	174.7	180.4	202.6
	98842	202.9	212.9	239.7	177.9	187.9	214.7	152.9	162.9	189.7
	111197	194.0	210.9	227.7	165.9	182.8	199.6	137.8	154.7	171.5
	123552	179.0	194.7	215.1	147.7	163.5	183.9	116.5	132.2	152.6
$35/ton	61776	272.8	286.5	309.8	257.2	270.9	294.2	241.6	255.3	278.6
	74131	264.0	292.2	312.4	245.3	273.4	293.7	226.5	254.7	274.9
	86486	276.8	283.4	309.2	254.9	261.5	287.4	233.0	239.7	265.5
	98842	261.7	273.4	304.6	236.7	248.4	279.6	211.7	223.4	254.6
	111197	254.5	274.2	293.8	226.4	246.1	265.7	198.2	217.9	237.6
	123552	240.1	258.4	282.2	208.8	227.2	251.0	177.6	195.9	219.7

$40/ton	*61776*	*325.2*	*340.8*	*367.5*	*309.6*	*325.2*	*351.8*	*293.9*	*309.6*	*336.2*
	74131	317.8	350.0	373.1	299.1	331.2	354.4	280.3	312.5	335.6
	86486	335.1	342.6	372.2	313.2	320.8	350.3	291.3	298.9	328.4
	98842	320.5	333.9	369.6	295.5	308.9	344.6	270.5	283.9	319.6
	111197	315.0	337.5	359.9	286.8	309.3	331.8	258.7	281.2	303.6
	123552	301.2	322.1	349.3	269.9	290.9	318.1	238.7	259.6	286.8
$45/ton	61776	377.6	395.1	425.1	361.9	379.5	409.5	346.3	363.9	393.9
	74131	371.6	407.8	433.8	352.9	389.0	415.1	334.1	370.3	396.3
	86486	393.3	401.9	435.1	371.5	380.0	413.2	349.6	358.1	391.3
	98842	379.4	394.4	434.5	354.4	369.4	409.5	329.4	344.4	384.5
	111197	375.4	400.7	426.0	347.3	372.6	397.8	319.2	344.5	369.7
	123552	362.2	385.8	416.4	331.0	354.6	385.2	299.7	323.3	353.9