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Maximizing Yields of Corn for Silage and Bioethanol in Hawai'i by Increasing Planting Density

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Corn can be planted and harvested year-round in Hawai'i, as it is by Hawai'i's sweet corn growers and seed producers. Maximizing economic returns of grain or silage demands that growers achieve maximum yields per unit area. A new paradigm exists for corn-based silage or bioethanol feedstock in Hawai'i that is not possible in the other 49 states. That is to have continuous plantings and regular harvests of a high-moisture corn crop. The immediate option is for use of the crop as "green-chop" silage harvested in less than 100 days. A second option is to use the wet grain alone for ethanol, while the digestible solids and plant stover (stalk) would be fed to animals. Another option is to harvest grain separately and use the stover, cobs, and husks for lignocellulosic ethanol through chemical or syngas conversion. A fourth option is the use of the entire plant for lignocellulosic ethanol, possibly exploiting low-lignin mutants.

This publication reviews research at the University of Hawai'i's College of Tropical Agriculture and Human Resources (CTAHR) to evaluate corn hybrids for the silage and bioethanol industries in Hawai'i. Maximizing yields is shown to depend on careful choice of tropically adapted hybrids and planting at suitably high plant population densities.

Background

Corn as silage and for bioenergy

Corn is the primary source of both silage and bioethanol in the United States, involving about 25 percent of the crop. Dry grain is the major current source of ethanol. However, extensive research is ongoing to evaluate the economics of ethanol extraction from whole plant tissues of crops such as corn, sorghum, guineagrass, and switchgrass. Cellulosic ethanol is derived from chemical or biophysical breakdown of cellulose, hemicellulose, and other carbohydrates from the entire plant's biomass. Following chemical digestion of corn, a valuable co-product from the processing facility is the digestible solid (referred to in the biofuels industry as dried distillers grains, or DDG) for use as a ruminant feed. Interest in the temperate corn-growing regions is thus in a single annual harvest in which the entire plant (stalk, leaves, ears) would be harvested for ethanol. Major related studies include genetic changes like those of the brown-midrib ("BMR") corns (Lee and Brewbaker 1984). These genes lower lignin and increase ethanol recovery and silage digestibility. Promising options for improved ethanol and silage economics also include the use of endocellulase transgenics (Sticklen 2007).

Year-round corn

Corn can be grown year-round in Hawai'i and in some other tropical and suptropical countries. The growers of Hawaiian Supersweet corns in Hawai'i and Thailand often plant monthly or weekly, and corn breeding nurseries in Waimānalo on O'ahu have been planted in 350 of the past 400 months. Practices of this type provide the option for continuous planting and harvest of a green crop at physiological maturity for bioethanol or silage. During the 1970s a program of this type developed near Kahuku on O'ahu, with continuous harvest of CTAHR hybrids as green chop for dairy animals. As the dairy industry declined, this became uneconomical, but it appears due for resurgence because of the high cost of shipping imported feeds.

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Continuous plantings of this type provide excellent conditions for pests and diseases. Thus a primary challenge to growers is that of finding adapted hybrids with high tolerance of the diseases and pests that thrive in Hawai‘i. The CTAHR hybrids have proven outstanding in meeting this challenge and are normally grown with no pesticide applications other than herbicides for weed control. In contrast, the Corn-Belt hybrids of temperate regions routinely fail to deliver competent yields in the tropics due to disease and insect pests.

Corn yields vary greatly through the year in Hawai‘i. In one of our studies at Waimānalo, Jong et al. (1982) planted monthly for four years and recorded annual yield variations of 100 percent. Peak yields were from spring plantings, and the lowest yields were from late-autumn plantings. The data correlated highly with solar illumination. Thus any study of this type must evaluate the impact of seasonal variations and the interaction of genetic and environment effects, as conducted by Lee (1983) at CTAHR.

Results

Identifying superior hybrids

Corn hybrids adapted to the tropics have been bred at CTAHR since the early 1960s (Brewbaker 2003). Publically available parent inbreds were collected throughout the tropics at Hawaii Foundation Seeds (www.ctahr.hawaii.edu/hfs). These inbreds were evaluated for adaptability, pest resistance, and yield in hybrids as grain or silage. Forty outstanding inbreds were converted to the Mv gene for resistance to Hawai‘i’s most serious corn disease, Maize Mosaic Virus (Brewbaker and Josue 2007). They served as parents of most hybrids that have proved superior among more than 1000 bred and evaluated by CTAHR.

Table 1 summarizes yields from 32 CTAHR corn yield trials conducted between 1995 and 2008 at the Waimānalo Research Station on O‘ahu. Data are organized by season of planting and are presented as bushels of grain at 15 percent moisture. Trials were randomized complete blocks with an average of 16 replicated entries augmented with a similar number of unreplicated hybrids. The average yield of all 32 trials was 147 bushels per acre (8.9 tons/hectare), approximately equaling that of U.S. farmers over the past decade. Average yield of the top three hybrids in each of the trials was 177 bushels.

Two of the best hybrids from CTAHR breeding were chosen for subsequent planting density evaluations. These were H1035, a singlecross of Hi63 (Philippines) x Hi26 (Colombia), and H1092, a three-way cross of (Hi26 x Hi62) x Hi63, where Hi62 is also of Philippine origin (former UH student, M. Logrono). H1035 (Photo 1) yielded 111 percent of the average and was the best performer in five of the 32 yield trials summarized above.

Seasonal data in Table 1 show the dramatic lowering of yields from autumnal plantings (average 105 bushels) with concurrent increase in variability (25% coefficient of variation). Two additional autumn trials were lost entirely to storms during this 15-year period. Maximum trial yields of 220–250 bushels/acre were from January and February plantings, when vegetative growth is slowed up to 3 weeks by cool weather, and grain matures in favorable early summer months. Outstanding individual yields were those of hybrids H1015 and H1035 (260 and 270 bu/A).

1. Ears of CTAHR hybrid H1035 (center), with parent Hi26 to left and Hi63 to right

Table 1. Corn grain yields at Waimānalo since 1995

Season	No. of trials	Yield in bushels/acre Avg.	Best three	CV
Jan–Mar	9	169.6	210.5	11.3%
Apr–June	9	144.9	162.2	10.3%
July–Sep	11	141.1	170.0	14.3%
Oct–Dec	3	104.6	142.6	24.7%

Table 2. Corn dry matter yields in tons per acre for five trials of five hybrids (Chung et al. 1982)

	Density in thousand plants per acre							
Trait	20	30	40	50	60	90	120	Average
Stover yield	3.95	4.96	5.34	5.30	5.97	5.88	6.03	5.35
Grain yield	3.00	3.28	3.31	3.45	3.44	3.35	2.63	3.21
Total yield	6.95	8.24	8.65	8.75	9.41	9.23	8.66	8.56

Corn grain yields are directly correlated with incident sunlight in Hawai‘i (Jong et al. 1982). Sunlight hours at Waimānalo averaged approximately 8 hours (385 cal/cm2/day), which was ~60 percent of similar values in the Corn Belt. Sunlight hours at Waimānalo are also exceeded greatly by those of the drier leeward regions that have been chosen by the sugarcane and corn-seed industries in Hawai‘i. The Waimānalo corn yields thus represent a low baseline for the state, as did sugarcane in this region, causing its growers to desert Waimānalo in 1940. At Waimānalo the time to silage harvest of corn (<36% grain moisture) averaged 100 days, much earlier than in temperate regions.

Identifying superior population densities

Density trials in the 1980s

Corn yields throughout the world have increased significantly as improved hybrids are planted at higher plant densities with adequate fertilization. Plant densities in U.S. cornfields have increased from 10,000 to 30,000 per acre in the past 50 years as hybrids were bred with improved standability, as stiffer stalks conferred resistance to falling over (“lodging”). The first significant study of the impact of plant density on corn yields in Hawai‘i was conducted by Chung, Brewbaker, and Ritter (1982) and entitled “Effects of increasing population density on the production of corn in Hawaii.” Five research trials were conducted, at Hāwī on the Kohala coast of the island of Hawai‘i and at Waimānalo, that each involved five hybrids planted at seven plant densities. Both grain and stover yields were measured and converted to tons of dry matter per acre, where 1 t/A = 16.5 bushels/A.

Summarized in Table 2 are the dry matter yields of the 1980s trials. The authors observed grain yields to increase significantly up to 50,000 plants per acre, with no further increase at higher populations. Yields of stover and of the entire plant continued to increase up to 60,000 plants per acre. Higher levels were accompanied by increased plant lodging, leading all regressions to be curvilinear. The regression for total dry matter yield was $Y = 5.17 + 0.96X – 0.06X^2$, where Y is yield and X is number of thousands of plants per acre. Grain yields averaged 38 percent of total dry matter, a value that has increased to about 42 percent since then for recent CTAHR hybrids. These experiments showed that year-round high-density plantings could lead to impressively high biomass yields, e.g., >30 tons of dry matter per year on an acre.

Seasonal variations related to plant density

Myoung Hoon Lee (1983) greatly expanded our studies on plant densities by evaluating yields from corn plantings at bimonthly intervals over a two-year period at the Waimānalo Research Station. Jong et al. (1982) had shown that a major source of variation in corn yields existed among seasons and was due largely to variations of incident light. Lee examined the differential response of corn yields of two superior hybrids, X304C (Pioneer) and H763 (CTAHR), at six plant densities. The 12 trials were planted over a two-year period, and data were recorded for both grain and stover. The extensive original data and regression analyses have not been published and are in Lee’s doctoral thesis (Lee 1983).

Table 3 summarizes total dry matter biomass yields for hybrid X304C at the six densities in the 12 trials. Seasons and densities both affected yields significantly, with maximal values at densities above 50,000. Yields dropped significantly in late-season trials, minimizing in the November trials. Yields were reduced only slightly at the highest density. This was explained by losses to lodging, which increased linearly with density to 20 percent at 84,000 plants per acre. A second hybrid (H763) in Lee’s study lodged over 35 percent at this high

Table 3. Corn dry matter yields in tons per acre for six densities in six seasons (Lee 1982)

Plants/acre	Jan	Mar	May	July	Sept	Nov	Average
21081	5.82	7.18	8.59	7.68	3.68	2.41	5.89
31622	6.05	8.14	8.91	8.50	4.14	2.68	6.40
42162	6.45	9.64	9.77	9.55	4.45	3.09	7.16
52703	6.77	10.00	10.95	10.32	4.09	3.32	7.58
63243	7.09	10.14	10.41	10.18	4.59	3.41	7.64
84324	7.18	10.14	9.73	9.95	4.64	3.41	7.51
Average	6.56	9.20	9.73	9.36	4.27	3.05	7.03

Table 4. Silage yields for two years in tons per acre at Mealani

	Yield trial in 2007			Yield trial in 2008		
Plants/acre	H1092	H1035	Average	H1092	H1035	Average
27,000	25.88	25.88	25.88	27.63	33.05	30.34
41,000	34.60	34.88	34.74	26.23	34.22	30.22
54,000	28.41	34.60	31.50	25.81	37.03	31.42
82,000	36.29	34.04	35.16	25.10	36.56	30.83
109,000	39.38	35.44	37.41	41.35	39.85	40.60
Average	32.90	33.00	32.94	29.22	36.14	32.68

density. It generally underperformed hybrid X304C due to this trait, illustrating the importance of selection for stiff stalk and lodging resistance as densities increase. All responses to density were curvilinear with peaks between 50 and 60 thousand plants per acre. Lee (1983) further calculated the correlations of yields and other traits to average solar radiation values during his trials. Highly significant correlation coefficients of 0.85 and 0.81 characterized grain and stover yields, respectively, in relation to solar radiation during entire growing seasons. It was concluded that the economics of silage, grain, or bioenergy production in Hawai‘i must be finely adjusted to the season of planting, the density of planting, and the cost of requisite inputs.

Density trials at Mealani

Corn density experiments were continued after 2000 in response to increasing interest in renewable bioenergy for Hawai‘i. Trials were conducted in two major ecosystems representing Hawai‘i's highlands and lowlands. Representing the highlands was the Mealani Research Station at 2800 ft elevation in Kamuela on Hawai‘i. This station has a mean annual temperature of 63°F and a single major growing season, with turcicum blight as a serious corn disease. Harvests were made at silage stage following physiological maturity. The trials involved two hybrids planted at five plant densities of 27, 43, 54, 82, and 109 thousand plants per acre (representing 70, 90, 110, 140, and 170 thousand plants per hectare). For comparison, the typical densities for silage production in Wisconsin and New Zealand are 40,000 and 50,000 per acre, respectively.

Yields in tons of silage per acre for the two Mealani trials are summarized in Table 4. Yields in 2007 increased with density and appeared to peak between 54,000 and 82,000. In 2008, yields peaked at the highest density, but this had led to complete lodging of plants and could not have been harvested commercially (Photo 2). An optimum density would again be placed between 54,000 and 82,000. The hybrids were similar in average yield in 2007, but hybrid H1035 was quite superior in the second trial.

Density trials at Waimānalo

Waimānalo Research Station was chosen to represent Hawai‘i's lowlands. The station is at 80 ft elevation with a mean annual temperature of 74°F. Major diseases are

Table 5. Silage yields for two years in tons per acre at Waimānalo

	Yield trial in 2007			Yield trial in 2008		
Plants/acre	H1092	H1035	Average	H1092	H1035	Average
27,000	27.62	24.96	26.29	26.21	25.50	25.86
41,000	27.00	32.94	29.97	26.91	29.25	28.08
54,000	28.44	27.82	28.13	22.69	30.19	26.44
82,000	33.96	29.05	31.50	24.80	31.36	28.08
109,000	33.14	30.69	31.91	30.90	33.47	32.18
Average	30.00	29.10	29.56	26.30	29.96	28.13

southern rust and maize mosaic virus, to which each of the chosen hybrids was resistant. Two mid-summer trials were conducted in subsequent years at Waimānalo. Both trials included the same densities and hybrids. Total biomass data for the Waimānalo trials are summarized in Table 5. Responses to increased density were significant for both hybrids. While responses were somewhat irregular, H1035 showed a clear trend, with its best yield at the highest density. Data for hybrid H1092 (a three-way hybrid) were more variable. The optimum density at Waimānalo appeared to be 82,000, in part because lodging was of no significance at this station in the midsummer season (Photo 3). Strong winds and "kona" storms would make the lower density values a better choice in winter.

Data from all four trials (two locations, two years) are summarized in Table 6. The overall average yield was excellent at ~31 tons per acre for a 100$^+$-day crop. Total biomass yields at silage maturity were very similar for the two stations. Yields increased significantly with increasing density, for a regression value of R^2 = 85%. Lodging was observed in only one of the four trials and only at the highest density. In all trials we noted the thin and weak stalks of plants at densities of 82,000 and above (cf. Photo 2), and we would generally not recommend these high densities except in superior growing seasons and conditions. The gain in yield from 27,000 to 41,000 averaged 20 percent. This gain was achieved without increased inputs except for the cost of added seeds, about $15 at 2009 prices. The recommended increased density of 41,000 per acre was accepted for silage production at a dairy in ‘O‘okala, island of Hawai‘i, and empirical observations of this planting suggested a major increase in silage production.

2. Density trial at Mealani during harvest, with lowest density to right

Evaluating low-lignin corn for silage and bioenergy

Lignins strengthen tissues of most plants and increase plant biomass yields. However, they interfere with the digestion of tissues by animals and the chemical digestion for bioethanol. Four low-lignin mutants occur in corn and are recognized as a potential for improving milk gains in dairy animals and the economics of bioethanol production. Conversions of tropical corn to these mutants began at CTAHR in the 1970s and showed that yield losses could be substantial, averaging 20 percent for grain and 17 percent for stover (Lee and Brewbaker 1984). Recent studies have demonstrated that this yield reduction is offset by improved milk production, and commercial BMR hybrids came into the market in 2008.

Table 6. Silage yields in tons per acre summarized for two locations over two years

	Waimänalo yield trials		Mealani yield trials		
Plants/acre	2007	2008	2007	2008	Average
27,000	26.29	25.88	25.86	30.34	27.09
41,000	29.97	34.74	28.08	30.22	30.75
54,000	28.13	31.50	26.44	31.42	29.37
82,000	31.50	35.16	28.08	30.83	31.40
109,000	31.91	37.41	32.18	40.60	35.53
Average	29.56	32.94	28.13	32.68	30.83

The four low-lignin genes in corn are designated bm1 to bm4. They produce a brownish color in the midribs of leaves and are classified as brown-midrib (BMR) mutants. Collaborative studies were initiated in 2008 with the University of Wisconsin to evaluate these four genes in identical hybrid backgrounds. Preliminary grain yield data from a 2009 trial at Waimānalo ranged from 17 percent to 30 percent reduction for mutants bm2 and bm4, respectively. Multi-year studies of these hybrids will include data on whole-plant biomass yield, in-vitro digestibility, milk gains, and economics of bioethanol extraction. Concurrent studies by Sticklen (2009) encourage the view that endocellulase transgenes may similarly enhance the economics of lignocellulosic bioethanol by affecting lignin and cellulose levels.

Discussion

Higher plant densities lead to higher corn yields, but with limits set by the hybrid itself. Hybrids released in recent years show much better response to high planting densities (Hammer et al. 2009). At least five factors appear to be involved—prolificacy, resistance to lodging, light interception, erect leaf angle, and increased root penetration. Older hybrids often failed to produce an ear at high densities, and breeders selected more prolific (two-eared) types. Similarly, breeders selected for stiff-stalked plants with high resistance to lodging and tolerance of mechanical harvesters. Early investigators emphasized that light interception by corn leaves must be nearly 100 percent for maximal yields, involving the concept of high leaf-area indices. Spacing between rows of corn was thus reduced in the 20th century from the width of a horse to 2.5 feet, for which most farm machinery is now designed. Hybrids with the leafy gene lfy had up to 25 percent more leaf area but proved less tolerant of high plant densities (Subedi et al. 2006). Erect plants with low leaf angle have come to characterize most temperate hybrids based on evidence that this permits higher density without interplant shading. Recent research emphasizes that these newer hybrids also are more effective at extracting soil moisture from deep in the soil profile, relating to root penetration of the erect-plant types (Hammer et al. 2009). Continued improvement in these traits is desirable for tropical corn hybrids that tend to be prolific and large-leaved but overly tall, weak-stalked, and poorly rooted.

The studies reported here suggest that densities between 40,000 and 50,000 plants per acre will maximize total biomass yields of Hawai‘i-bred hybrids. They also confirm the earlier observations of Chung et al. (1982) and Lee (1983) that very high densities in Hawai‘i's fields can lead to lodging and significant reduction of ear size and grain yield. The data are of equal interest in planning for bioethanol production and for production of corn silage. Seasonal variations in corn growth can exceed 100 percent in Hawai‘i and must be factored in to decisions about suitable hybrids and densities.

There appears to be great potential for corn silage or green-chop to support the feeding of dairy and beef animals with the restoration of Hawai‘i's feedlots. Corn is a versatile crop that is easily grown and has many products. Modern hybrids like H1035 (Photo 1) from CTAHR are superior in yield and can be grown without any pesticides (www.ctahr.hawaii.edu/hfs). The present option of harvesting grain for ethanol and stover for silage on the island of Hawai‘i may encourage Hawai‘i's ranchers to return to the process of fattening range animals. In turn it may help undergird the development of bioethanol production.

3. Density trial at Waimānalo, with Rommel Corrales

Conclusions

These studies focused on the potential of corn-based silage and bioethanol production in Hawai'i. Trials and field demonstrations sought to maximize corn biomass yields by the choice of outstanding hybrids and by increasing plant densities. Hybrids with resistance to Hawai'i's maize mosaic virus were essential. Superior yields were from CTAHR hybrids like H1035, with international parentage, that could be grown pesticide-free. All density trials showed significant yield response to increased densities. While the accepted present level is 27,000/acre, yield increases averaged 20 percent with densities of 41,000 and above. Responses were similar near sea level (Waimānalo) and at 2700 ft elevation (Mealani) and were similar for tested hybrids. Other data are summarized that show the seasonal effects to be so great in Hawai'i that these responses to densities will maximize in spring and summer plantings. The data are shown to be equally applicable to bioethanol production of corn and to its use as silage by Hawai'i's dairy and beef producers.

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