ABSTRACT

Gaddy, Joshua Andrew. The Influence of Variety on Mechanical Harvesting Efficiency of Flue-Cured Tobacco. (Under the direction of W. David Smith.)

Mechanical harvesting of flue-cured tobacco is a widely used practice in North Carolina due to cost and labor savings compared to hand labor, acceptance of unaligned leaf by tobacco manufacturers, and accumulation of enough acreage by growers to justify the purchase of a mechanical harvester. Little research has been conducted to evaluate varietal effects on mechanical harvesting efficiency. Experiments evaluating current varieties were conducted at on-farm locations in North Carolina during 2003 and 2004 to investigate the influence of variety on mechanical harvesting efficiency. Ten varieties were selected to provide the widest possible range of growth characteristics. Treatments were replicated four times in a randomized complete block design. Tobacco was harvested four times. Measurements of leaf angle, leaf curvature, and internode spacing were taken before the final three harvests in order to establish differences among varieties in morphology. In addition, the number of leaves dropped on the ground behind the machine were counted after each harvest, and the fresh weight of non-harvested stem material left on the stalks within the fourth harvest position was recorded after the final harvest in order to establish differences in mechanical harvesting efficiency among varieties. Highly significant differences among varieties in leaf angle, leaf curvature, and internode spacing were found before every harvest. However, these differences did not result in highly significant differences in mechanical harvestability until the final harvest. At final harvest, significant differences in leaf and stem loss were found among varieties. Leaf angle and internode spacing were found to be

significantly related to stem loss. As leaf angle and internode spacing increased, stem loss decreased. Therefore, some varieties are better suited for mechanical harvesting systems.

THE INFLUENCE OF VARIETY ON MECHANICAL HARVESTING EFFICIENCY OF FLUE-CURED TOBACCO

By

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Biography

Joshua Andrew Gaddy, son of Dewitt and Mary Helen Gaddy, was born in Albemarle, North Carolina on February 19, 1981. He was raised in the rural community of Morven, North Carolina where he enjoyed working on his family's poultry and cattle farm and fishing. Josh attended Anson Senior High School through his junior year where he enjoyed playing football. Between Josh's junior and senior year of high school, his family moved to Stanfield, North Carolina. Josh graduated from West Stanly High School in May of 1999. He began attending North Carolina State University in the fall of 1999. Josh was involved with the NCSU Agronomy Club and the Alpha Zeta Honor Fraternity while in college. He graduated in May of 2003 with a Bachelor of Science degree in Agronomy and a minor in Agricultural Business. In the spring of 2003, Josh was admitted to graduate school at North Carolina State University where he has pursued a Master of Science degree under the direction of Dr. W. David Smith. Upon completion of his Master of Science studies, Josh will begin a career with the North Carolina Cooperative Extension Service as an agricultural agent in Sampson County.

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Lastly, the author wishes to express deep appreciation to his parents, who supported him greatly while working toward this Master of Science degree.

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INTRODUCTION

Development of a mechanical harvester for flue-cured tobacco was first initiated in 1954 at N.C. State University, and by 1961, researchers had a successful machine operating. However, USDA restrictions on unaligned leaf in the marketplace prevented farmers from adopting mechanical harvesters until the early 1970’s (21). Mechanical harvesters were used to harvest about one percent of the flue-cured tobacco grown in the Carolinas, Virginia, and Georgia in 1972 (8). In the mid 1970’s, increases in acreage per grower and changes in the institutional controls on preparation of leaf for market also helped to hasten the adoption of mechanical harvesters. For example, the lease and transfer provisions in the federal tobacco program allowed growers to accumulate enough acreage to justify the purchase of a harvester (8). Also, the tobacco industry determined that it could feasibly evaluate and process random, unaligned leaf (14, 20), and thus the requirement of hand tying of leaves into small bundles was eliminated. In 1983, enough machines had been sold to harvest about 50% of the US flue-cured crop (21). Use of mechanical harvesters continued to increase during the 1980’s and 1990’s. In 2004, a survey of North Carolina county extension personnel revealed that 56% of the acreage was harvested mechanically (Fisher 2004 Personal Communication).

Harvesting has been the last phase of tobacco production to be substantially mechanized (8). One of the primary reasons mechanical harvesters have been adopted is to reduce the amount of labor required to harvest flue-cured tobacco (21). In 1981, Grise (10) reported that harvest labor comprised 69 percent of the total labor required to produce flue-cured tobacco. Another reason is the inability to attract and retain quality labor (14). When mechanical harvesters are used, the required harvest labor can be reduced by up to 80 percent compared to that required for hand harvesting (17). Reducing required labor is one of the factors that causes mechanical harvesting to cost less than conventional harvesting. Grise (9) reported that one- and two-row mechanical harvester systems are the lowest-cost harvest systems. Labor and machinery costs were $111 less per acre for mechanical harvesting than for harvesting by hand (6).

Development of leaf removing devices on mechanical harvesters became possible when efforts to duplicate the motion of the human hand were replaced by efforts to develop separate leaf stripping and leaf recovery devices. Leaf removing devices work by either producing a downward impact near the node on the upper side of the leaf petiole or by contacting the lower side of the petiole near the stalk and cutting in an upward direction. Current leaf removal devices are termed rubber defoliators and knives (tipping heads). Defoliators are used to produce a downward impact near the leaf node. Defoliators of the spiral rubber stripper type are typically used to harvest lower and mid-stalk leaves. These defoliators consist of two members, one on each side of the row, with opposing spirals. Suggs reported that the performance of rubber defoliators is insensitive to tobacco variety (19). Because the tops of many stalks are not strong enough to support the downward leaf removing action of the rubber defoliators, a knife unit is typically used to harvest the top leaves of the plant (18). The knife units cut upward by contacting the abaxial side of the leaf petiole (19). Knife units have been reported to be less effective in removing leaves that were attached to the stalk at a sharp angle when knife velocities were slow or when the knives were kept 0.64 centimeters or more away from the stalk (19, 21).

Prior to 1950 most flue-cured tobacco varieties had a similar phenotype. Since this time, many new varieties, which display fundamentally different characteristics, have been produced. Chaplin, Graham, and Ford reported that for fifty varieties tested, internode lengths varied as much as 1.9 cm (7). In 1958, Collins and Jones (12) found that varieties differ in the angle of leaf projection from the stalk, leaf length and width, and internode spacing between leaves. Tobacco also varies considerably with respect to the strength characteristics of the leaf and some varieties are much more susceptible to “leaf drop” where the leaf may break from the stalk under its own weight. Therefore, varieties require different amounts of energy to remove leaves from the stalk (16).

Along with varietal differences, tobacco can have appreciable differences among stalk positions as well. Leaves from the upper stalk generally have more curvature than leaves from the lower part of the stalk (20). However, Splinter, Suggs, and Beeman found no differences in removal energy required among four different leaf positions (16).

Personnel at North Carolina State University conduct an Official Variety Test (NC OVT) whereby commercial varieties are evaluated to assist growers with variety selection. The NC OVT began collecting data important for mechanical harvesting ability in the 1950’s. In 1955, angle of leaf projection from the stalk was measured. Wider-angled leaves were considered to be easier to break-off mechanically (11). The NC OVT also collected data in 1963 on internode length of the basal, middle, and upper part of the plant because this information was considered useful to the engineer developing mechanical harvesting equipment (13). In more recent years, from 1996 to 2000, the NC OVT rated varieties for mechanical harvesting ability based on internode spacings. For these ratings, it was assumed that wider internode spacings would equate to better mechanical harvesting ability. However, these ratings were not in conjuction with mechanical harvesters in the field and were based only on the stated assumption (1-5). Currently, the only data the NC OVT collects on varieties relevant to mechanical harvesting ability is average internode spacing

(15). Therefore, many of the current commercial varieties have never been effectively rated for their suitability in a mechanical harvesting system.

JUSTIFICATION OF WORK

Until the 1990's, mechanical harvesters were not widely used to harvest flue-cured tobacco. However, with decreasing availability of labor, increasing production costs, and acceptance of unaligned leaf, many growers have found mechanical harvesting to be a viable option for their operation. As the number of growers harvesting mechanically has increased, more growers have asked if some varieties are more suited for their mechanized harvest system than others. Past research has shown that varieties can differ significantly in physical characteristics important to mechanical harvesting. However, no studies could be found in the literature correlating plant characteristics with mechanical harvesting efficiency.

Therefore, the objectives of this study were: 1) To determine the influence of variety on mechanical harvesting efficiency by correlating plant characteristics with harvesting efficiency, and 2) To collect information which will assist in the development of a mechanical harvesting efficiency index for use in the NC OVT.

MATERIALS AND METHODS

Experiments were conducted at on-farm locations in North Carolina during 2003 and 2004 to investigate the influence of variety on mechanical harvesting efficiency. In 2003, the experiments were conducted in Wake and Wilson Counties. In 2004 studies were conducted in Wilson and Duplin Counties. Varieties were selected to provide the widest possible range of growth characteristics. The following 10 cultivars were used in the 2003 and 2004 studies: K326, K346, NC 71, NC 72, NC 606, RGH 51, RGH 4, Speight NF 3 (Spt NF 3), NC 810, and Coker 371 Gold (C 371 G).

In all experiments, treatments were replicated four times and arranged in a randomized complete block design. Plot size was 0.011 hectares and consisted of either two rows 45.7 meters long or four rows 22.9 meters long. Plants were spaced 56 centimeters apart on rows spaced 1.22 meters apart. Data were collected on 10 plants per plot. The 10 plants were tagged before the first harvest to insure that the same plants were measured each time data were collected. Tagged plants were deemed to be representative for the plot and had minimal axillary shoot growth. Tobacco in all experiments was harvested four times and data were collected before and after the final three harvests. For the first harvest, only post-harvest measurements were taken. One leaf near the top of each harvest position was measured per plant before the second, third, and fourth harvests. Leaf angle, internode spacing, and leaf curvature were measured. Leaf angle was determined by measuring the angle between the leaf petiole and the stalk using a protractor. Internode spacing was determined by measuring the distance between two successive leaf nodes. Leaf curvature was determined by measuring the distance from the leaf axil along the leaf petiole before the leaf began to curve downward thus changing the leaf angle. These three measurements were normally collected one to three days before harvest. Post-harvest measurements included a non-harvested leaf count and a fresh weight of non-harvested stem. Non-harvested leaf counts were collected the day of harvest. A leaf count was conducted after every harvest whereby the number of leaves dropped on the ground and those not removed from the stalk were counted for one row of each plot. The stem fresh weight measurement was collected within a week of the fourth harvest. Stem weight was calculated by removing and weighing the stems left on the stalks of the 10 tagged plants within the fourth harvest position.

The 2003 Wake County study was located near Fuquay-Varina, NC. The test was transplanted on May 7, 2003. A 1989 two row, four wheel drive Roanoke Tobacco Harvester[1] was used at this location. First harvest was 90 days after transplanting (DAT) using spiral rubber wiper defoliators. The second harvest was performed 98 DAT with defoliators. Third and fourth harvests were performed separately but on the same date at 112 DAT. The third harvest utilized short bar knife units. The fourth harvest was performed with long bar knife units (tipping heads). The distance between cutterbars of the tipping heads used on the final harvest was 5.2 centimeters at the bottom of the unit and 5.4 centimeters at the top of the unit. Knives on this unit were 3.2 centimeters long.

The 2003 Wilson County study was located near Wilson, NC. The test was transplanted on May 5, 2003. A Powell Generation IV Combine with a FlexBar Defoliator[2] was used at this location. The first, second, and third harvests were conducted 80, 92, and 109 DAT, respectively, using defoliators. The fourth harvest was performed 116 DAT using tipping heads. Cutterbars were 4.6 centimeters apart at the bottom of the tipping heads and

[1] Gregory Manufacturing Co., Lewiston, North Carolina
[2] Powell Manufacturing Co., Inc., Bennettsville, South Carolina.

3.1 centimeters apart at the top of the tipping heads. Knives on this unit were 3.2 centimeters long.

The 2004 Duplin County study was located near Albertson, NC. The test was transplanted on April 22, 2004. A Powell Generation IV Combine with a FlexBar Defoliator[2] was used at this location on the first three harvests. On the final harvest, a Taylor Lastover Tobacco Harvester[3] was used. The first, second, and third harvests were conducted 77, 95, and 106 DAT, respectively, using defoliators. The fourth harvest was performed 112 DAT using tipping heads. Cutterbars were 6.0 centimeters apart at the bottom of the tipping heads and 4.3 centimeters apart at the top of the tipping heads. Knives on this unit were 3.8 centimeters long. Due to inclement weather (tropical storm), only stem weight measurements were collected after the final harvest.

The 2004 Wilson County study was located near Wilson, NC. The test was transplanted on April 26, 2004. A Powell Generation IV Combine with a FlexBar Defoliator[2] was used at this location. The first, second, and third harvests were conducted 80, 100, and 113 DAT, respectively, using defoliators. The fourth harvest was performed 116 DAT using tipping heads. Cutterbars were 5.1 centimeters apart at the bottom of the tipping heads and 3.8 centimeters apart at the top of the tipping heads. Knives on this unit were 3.2 centimeters long.

All data were subjected to an analysis of variance (ANOVA), and treatment means were separated using a least significant difference value (LSD) at $p \leq 0.05$.

[3] Taylor Manufacturing Co., Inc., Elizabethtown, North Carolina.

RESULTS

Location by treatment interactions were detected for some of the parameters measured in this study. However, when present, these interactions represented only a small proportion of the total sum of squares (Tables 1-5). On the advice of our consulting statistician (Dr. Cavell Brownie – Professor of Statistics, NCSU, personal communication) these interactions were disregarded and all data were analyzed after combining over locations. Significant differences among varieties in leaf angle, leaf curvature, internode spacing, leaf loss, and stem loss were found.

Leaf Angle

Leaf angle significantly differed among varieties at every harvest position (Table 6). At second harvest, leaf angle ranged from 25 to 34 degrees with RGH 4 having a larger leaf angle than all other varieties except for Speight NF 3. NC 810 had a smaller leaf angle than all varieties except for NC 72, NC 606, and NC 71. At third harvest, leaf angle ranged from 27 to 34 degrees with varieties RGH 4 and RGH 51 having a larger leaf angle than NC 606, NC 72, NC 71, and NC 810. NC 810 had a smaller leaf angle than all varieties except NC 71. Varieties K 346, Speight NF 3, K 326 and Coker 371 Gold (C 371 G) were intermediate in leaf angle at third harvest. On the final harvest, leaf angle ranged from 32 to 50 degrees with K 346 having a larger leaf angle than all other varieties. NC 810 and Speight NF 3 had smaller leaf angles than all other varieties. Varieties RGH 4, RGH 51, C 371 G, NC 606, K 326, NC 72 and NC 71 were intermediate in leaf angle at fourth harvest. NC 810 had the narrowest leaf angle at every harvest. Leaf angles consistently increased from second to fourth harvest. Speight NF 3 changed from being one of the widest angled varieties on harvests two and three to having the narrowest angle at harvest four.

Leaf Curvature

The distance between the point at which the leaf angled downward and the leaf axil (leaf curvature) significantly differed among varieties at every harvest (Table 7). A highly curved leaf exhibited a smaller value for leaf curvature since the point of curvature occurred closer to the leaf axil. At second harvest, leaf curvature ranged from 5 to 6 cm with Speight NF 3 curving farther from the leaf axil than NC 71, C 371 G, RGH 51, NC 810, NC 72, K 326, and RGH 4. RGH 4 had a shorter distance before leaf curvature than all varieties except K 326. On the third harvest, the distance before leaf curvature ranged from 4.5 to 5.5 cm with RGH 4 curving at a shorter distance from the leaf axil than NC 72, NC 71, NC 810, K 346, NC 606, and Speight NF 3. Speight NF 3 had a longer distance before leaf curvature than all varieties except NC 606. At final harvest, the distance before leaf curvature ranged from 3.5 to 5.5 cm with K 346 having a shorter distance before leaf curvature than all other varieties. NC 810, NC 72, and Speight NF 3 had more distance before leaf curvature than all other varieties. Across all harvests, Speight NF 3 consistently had the longest distance before leaf curvature.

Internode Spacing

Internode spacing significantly differed among varieties at each harvest position measured (Table 8). At second harvest, internode spacing ranged from 4 to 5 cm with NC 810 having a shorter internode spacing than all varieties except K 326. K 346, Speight NF 3, RGH 4, NC 606, RGH 51, C 371 G, and NC 72 did not differ in internode spacing. On the third harvest, internode spacing ranged from 4 to 5 cm with NC 810 having a shorter internode spacing than all other varieties. RGH 4 had a longer internode spacing than all varieties except RGH 51 and K 346. At fourth harvest, internode spacing ranged from 4 to 6 cm with Speight NF 3 and NC 810 having shorter internode spacings than all other varieties. RGH 51 had a longer internode spacing than all other varieties except C 371 G. Across all harvests, NC 810 consistently had the shortest internode spacing of all varieties.

Leaf Loss at Harvest

Varieties differed significantly in the number of leaves lost behind the mechanical harvester on harvests two and four (Table 9). The number of leaves lost ranged from 2,422 to 3,611 leaves per hectare at second harvest with C 371 G, RGH 4, NC 71, and NC 72 having more non-harvested leaves behind the harvester than Speight NF 3 and NC 810. K 346, RGH 51, NC 606, and K 326 were intermediate in leaf loss at second harvest. At fourth harvest, leaf losses ranged from 852 to 2,242 leaves per hectare with Speight NF 3 losing more leaves behind the harvester than NC 71, RGH 4, K 346, C 371 G, K 326, and RGH 51. NC 810, NC 606, and NC 72 were similar to Speight NF 3 in the amount of leaves lost.

Stem Loss at Harvest

Differences among varieties in the amount of non-harvested fresh stem weight remaining on the stalk after harvesting were highly significant (Table 10). The amount of fresh stem weight per hectare ranged from 215.04 to 553.35 kilograms with NC 810 having more non-harvested stem weight than all other varieties. K 346, C 371 G, and RGH 51 had less stem loss than all other varieties except RGH 4. Speight NF 3, NC 71, K 326, NC 72, and NC 606 were intermediate in the amount of stem loss after harvest.

Stem loss was significantly affected by leaf angle, average internode spacing, and internode spacing at final harvest. Leaf angle at final harvest was negatively correlated with stem loss, having an R^2 of 0.216 (Figure 1). Average internode spacing was negatively correlated with stem loss, having an R^2 of 0.528 (Figure 2). Internode spacing at final harvest was negatively correlated with stem loss, having an R^2 of 0.441 (Figure 3). While leaf curvature significantly differed among varieties at final harvest, stem loss was not significantly correlated with leaf curvature (Figure 4).

Three models were created to predict stem loss (Table 11). The first model created used only values for average internode spacing (a) to predict stem loss (y).

$$y = 1379.91 – 218.54a$$

$$R^2 = 0.528^{**}$$

A second model was created using values for average internode spacing (a) and leaf angle (b) to predict stem loss (y).

$$y = 1414.27 – 193.40a – 3.84b$$

$$R^2 = 0.566^{**}$$

A third model was created using values for average internode spacing (a), leaf angle (b), and leaf curvature (c) to predict stem loss (y).

$$y = 1786.46 – 174.24a – 9.07b – 55.09c$$

$$R^2 = 0.622^{**}$$

DISCUSSION

Varieties in this study showed highly significant differences in leaf angle, internode spacing, and leaf curvature before each harvest (Tables 6-8). However, with respect to this study, variation among varieties in morphology means little if differences do not translate into harvestability differences. Harvestability evaluations in this study were done by assessing leaf loss after each harvest and stem loss after the final harvest. While leaf losses were significant, the most significant difference among varieties in harvestability was in stem loss (Tables 9 and 10).

Lower Stalk Tobacco

This study found that varieties did not significantly differ in harvestability of lower stalk tobacco. While varieties showed highly significant variation in the parameters measured before each harvest (Tables 6-8), these differences did not translate into significant differences in leaf loss except at second harvest (Table 9). Even at the second harvest, differences in leaf loss were only significant at $p=0.043$, suggesting that differences among varieties in leaf loss of lower stalk tobacco is inconsistent at best. These results supported the earlier findings of Suggs (19), that performance of rubber defoliators is insensitive to tobacco variety.

Upper Stalk Tobacco

Varieties differed significantly in leaf and stem loss at final harvest. At the final harvest, defoliators were replaced with tipping heads in order to remove the upper leaves from the stalk. Earlier studies found that knives were less effective in removing leaves attached to the stalk at a sharp angle when knife velocities were slow or when the knives were more than 0.64 centimeters from the stalk (19, 21). This study supported those findings as varieties with narrow angled leaves had significantly more stem loss (Figure 1). Also, stem loss was lowest at the 2003 Wilson location where cutterbars at the top of the tipping heads were set closer together. Average stem loss across all varieties at the 2003 Wilson location was 189.93 kilograms per hectare while average stem loss across all varieties at the 2003 Wake location, 2004 Duplin location, and 2004 Wilson location was 331.98, 344.89, and 437.95 kilograms per hectare, respectively. Internode spacing also significantly correlated with stem loss confirming the assumption of the NC OVT (1-5) that short internode spacing resulted in a lowered mechanical harvesting efficiency. Average internode spacing was more highly correlated with stem loss than internode spacing within the final harvest position. While leaf curvature did not significantly affect stem loss, when added to the predicted stem loss model, it did improve this model's fit.

Average internode spacings were calculated for each variety in this study by averaging the measured internode spacings from the second, third, and fourth harvests. The average internode spacing data from the NC OVT is generated by dividing plant height by the total number of leaves per plant (Bowman 2004 Personal Communication). Despite the differences in how average internode spacings were determined, measured average internode spacings from this study are very similar to the NC OVT's average internode spacings for the varieties in this study (Figure 5). Therefore, NC OVT data should be compatible with the predicted stem loss models developed.

Since the NC OVT already measures average internode spacing, a model was created using average internode spacing alone to predict stem loss. This model lacks the power of the model combining leaf angle, average internode spacing, and leaf curvature and therefore overestimates stem loss and predicts a narrow range of stem loss among varieties (Table 11, Figures 6 and 7). Although the model using average internode spacing alone gives high estimates of stem loss for all varieties, it was able to accurately place varieties at the extremes. However, on varieties with a very wide leaf angle and moderate internode spacing, such as K 346, this model is inaccurate. When leaf angle and leaf curvature are added to the model, K 346 is more correctly placed as one of the better varieties in limiting stem loss. The incorrect placement of K 346 and the overestimation of stem loss on all varieties by the simple model illustrates the need for other parameters to be measured in addition to average internode spacing when predicting machine harvestability.

When developing a system to rate varieties, it is important to keep the system as simple as possible, while maintaining the system's accuracy. It is recommended that leaf angle and average internode spacing measurements be taken to predict stem loss. Average internode spacing data is readily available from the NC OVT. While collecting data on leaf curvature would improve the accuracy of the prediction equation, this measurement is not significantly related to stem loss and thus, was the least important plant characteristic to mechanical harvesting efficiency that was measured. Therefore, taking leaf curvature measurements is not recommended. The model using leaf angle and average internode spacing accurately predicts stem loss on all varieties (Table 11, Figure 8). Collecting data for this model would accomplish our objective of predicting stem loss and ranking varieties while keeping the data collection process as simple as possible.

In conclusion, this study illustrated that on lower stalk tobacco, differences in physical characteristics among varieties does not significantly affect mechanical harvesting efficiency. Differences in leaf angle, internode spacing, and leaf curvature among varieties are only important to harvesting efficiency on the final harvest when tipping heads are used.

Despite how varieties significantly differ in leaf angle, internode spacing, and leaf curvature, none of the varieties in this study were found unsuitable for mechanical harvesting. Some varieties, those with wider internode spacings and wider leaf angles, are better suited for a mechanical harvesting system. Since such a large percentage of the flue-cured tobacco crop in the southeastern US is mechanically harvested, rating varieties for their suitability in a mechanical harvesting system would be useful to many growers. While varietal characteristics such as yield, quality, and disease resistance are still considered to be the most important when selecting varieties, knowing how efficiently a variety can be harvested mechanically is simply another tool to aid growers when choosing varieties suitable for their operation.

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Table 1. ANOVA for leaf angle measurements.

	2^{nd} Harvest		3^{rd} Harvest		4^{th} Harvest	
Source	**F Value**	**PR>F**	**F Value**	**PR>F**	**F Value**	**PR>F**
Location	55.18	<0.0001	21.37	<0.0001	124.58	<0.0001
Treatment	11.26	<0.0001	5.36	0.0003	19.15	<0.0001
Location X Treatment	1.73	0.0256	2.92	<0.0001	2.25	0.0018

Table 2. ANOVA for leaf curvature measurements.

	2^{nd} Harvest		3^{rd} Harvest		4^{th} Harvest	
Source	**F Value**	**PR>F**	**F Value**	**PR>F**	**F Value**	**PR>F**
Location	45.21	<0.0001	4.87	0.0033	147.41	<0.0001
Treatment	8.59	<0.0001	8.75	<0.0001	10.60	<0.0001
Location X Treatment	1.42	0.1061	1.50	0.0758	2.12	0.0035

Table 3. ANOVA for internode spacing measurements.

	2nd Harvest		3rd Harvest		4th Harvest	
Source	**F Value**	**PR>F**	**F Value**	**PR>F**	**F Value**	**PR>F**
Location	14.44	<0.0001	67.62	<0.0001	58.10	<0.0001
Treatment	7.07	<0.0001	12.83	<0.0001	14.43	<0.0001
Location X Treatment	2.79	<0.0001	1.59	0.0503	2.17	0.0027

Table 4. ANOVA for leaf loss measurements.

	1st Harvest		2nd Harvest		3rd Harvest		4th Harvest	
Source	**F Value**	**PR>F**	**F Value**	**PR>F**	**F Value**	**PR>F**	**F Value**	**PR>F**
Location	161.55	<0.0001	82.48	<0.0001	25.70	<0.0001	30.81	<0.0001
Treatment	1.73	0.1305	2.33	0.0429	1.23	0.3199	3.17	0.0177
Location X Treatment	0.73	0.8288	1.11	0.3385	1.67	0.0347	1.98	0.0206

Table 5. ANOVA for non-harvested stem weight measurements.

	4th Harvest	
Source	**F Value**	**PR>F**
Location	82.02	<0.0001
Treatment	16.23	<0.0001
Location X Treatment	2.08	0.0042

Table 6. Effect of variety on leaf angle at three harvest positions combined over four locations, 2003-2004.

Variety	2nd Harvest	3rd Harvest	4th Harvest
	---	degrees	---
K326	31 bc	33 abc	40 cd
K346	31 bc	33 ab	50 a
NC 71	26 de	29 de	38 d
NC 72	27 de	30 cd	38 d
NC 606	27 de	31 bcd	42 bcd
RGH 51	29 cd	34 a	45 b
RGH 4	34 a	34 a	45 b
Spt NF 3	32 ab	33 ab	32 e
NC 810	25 e	27 e	32 e
C 371 G	30 bc	33 abc	44 bc
PR>F	<0.0001	0.0003	<0.0001

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table 7. Effect of variety on leaf curvature at three harvest positions combined over four locations, 2003-2004.

Variety	**2nd Harvest**	**3rd Harvest**	**4th Harvest**
	----------------------	cm	----------------------
K326	5.0 de	4.5 ef	4.5 c
K346	6.0 abc	5.0 bc	3.5 d
NC 71	5.5 bc	5.0 cd	5.0 ab
NC 72	5.5 cd	5.0 cde	5.0 a
NC 606	6.0 ab	5.5 ab	4.0 c
RGH 51	5.5 c	4.5 def	4.5 c
RGH 4	5.0 e	4.5 f	4.5 c
Spt NF 3	6.0 a	5.5 a	5.0 a
NC 810	5.5 cd	5.0 bc	5.5 a
C 371 G	5.5 c	4.5 def	4.5 bc
PR>F	<0.0001	<0.0001	<0.0001

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table 8. Effect of variety on internode spacing at three harvest positions combined over four locations, 2003-2004.

Variety	2nd Harvest	3rd Harvest	4th Harvest	Average Internode Spacing
	--	-----cm-----	--	
K326	4.0 cd	4.5 e	5.0 cd	4.5
K346	5.0 a	5.0 abc	5.5 bcd	5.0
NC 71	4.5 bc	4.5 de	5.0 d	4.5
NC 72	4.5 ab	4.5 bcd	5.5 bc	5.0
NC 606	5.0 a	4.5 cd	5.5 bc	5.0
RGH 51	5.0 a	5.0 ab	6.0 a	5.5
RGH 4	5.0 a	5.0 a	5.5 bc	5.0
Spt NF 3	5.0 a	5.0 bc	4.5 e	4.5
NC 810	4.0 d	4.0 f	4.0 e	4.0
C 371 G	4.5 ab	4.5 bcd	5.5 ab	5.0
PR>F	<0.0001	<0.0001	<0.0001	

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table 9. Effect of variety on leaves lost during harvest at four harvest positions combined over four locations, 2003-2004.

Variety	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest
	---------------------------------------	-----# leaves lost per hectare-----		---
K326	4115 a	2881 abc	2501 a	897 cd
K346	4496 a	3252 ab	2377 a	1166 bcd
NC 71	5258 a	3374 a	2747 a	1466 bcd
NC 72	4047 a	3374 a	2646 a	1555 a-d
NC 606	3981 a	2994 abc	2467 a	1600 abc
RGH 51	3656 a	3173 ab	2320 a	852 d
RGH 4	3812 a	3432 a	2287 a	1421 bcd
Spt NF 3	2646 a	2546 bc	2042 a	2242 a
NC 810	3891 a	2422 c	2669 a	1763 ab
C 371 G	4115 a	3611 a	1850 a	1001 cd
PR>F	0.13	0.043	0.32	0.018

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table 10. Effect of variety on stem weight at final harvest combined over four locations, 2003-2004.

Variety	**4th Harvest**
	--kg/ha--
K326	353.10 bc
K346	215.04 e
NC 71	367.73 bc
NC 72	328.23 cd
NC 606	314.23 cd
RGH 51	233.95 e
RGH 4	255.70 de
Spt NF 3	412.90 b
NC 810	553.35 a
C 371 G	227.61 e
PR>F	<0.0001

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table 11. Measured and predicted stem loss for varieties used in the harvesting study, 2003-2004.

Variety	Measured stem loss		AIS model[a]		AIS + LA model[b]		AIS + LA + LC model[c]	
	Stem Loss		**Stem Loss**		**Stem Loss**		**Stem Loss**	
	-kg/ha-	rank	-kg/ha-	rank	-kg/ha-	rank	-kg/ha-	rank
K326	353.10	7	910.05	8	383.94	8	389.81	8
K346	215.04	1	894.76	5	240.19	2	254.10	3
NC 71	367.73	8	905.68	7	378.43	7	369.57	7
NC 72	328.23	6	894.76	6	312.36	6	298.05	5
NC 606	314.23	5	886.01	4	290.96	5	307.25	6
RGH 51	233.95	3	857.60	1	227.09	1	222.58	1
RGH 4	255.70	4	870.72	2	241.48	3	238.53	2
Spt NF 3	412.90	9	914.42	9	385.94	9	401.70	9
NC 810	553.35	10	947.21	10	520.58	10	511.93	10
C 371 G	227.61	2	881.64	3	278.45	4	265.74	4
R^2 value	---		0.528**		0.566**		0.622**	
Equation	---		y = 1379.91 – 218.54a		y = 1414.27 – 193.40a – 3.84b		y = 1786.46 – 174.24a – 9.07b – 55.09c	

[a]Average internode spacing model where a = average internode spacing.
[b]Average internode spacing plus leaf angle model where a = average internode spacing; b = leaf angle.
[c]Average internode spacing plus leaf angle plus leaf curvature model where a = average internode spacing; b = leaf angle; c = leaf curvature.

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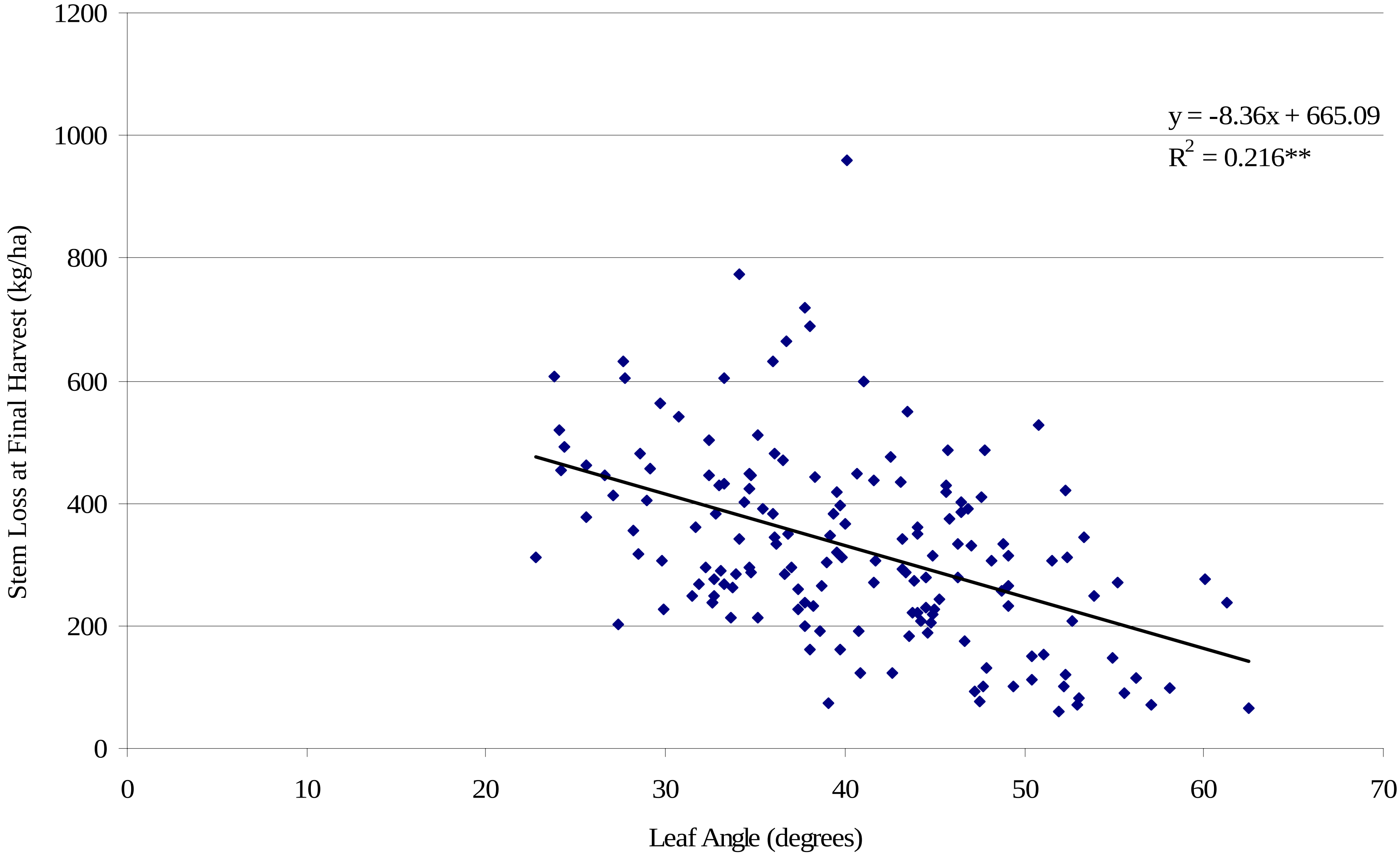

Figure 1. Effect of leaf angle at final harvest on stem loss combined over four locations, 2003-2004.

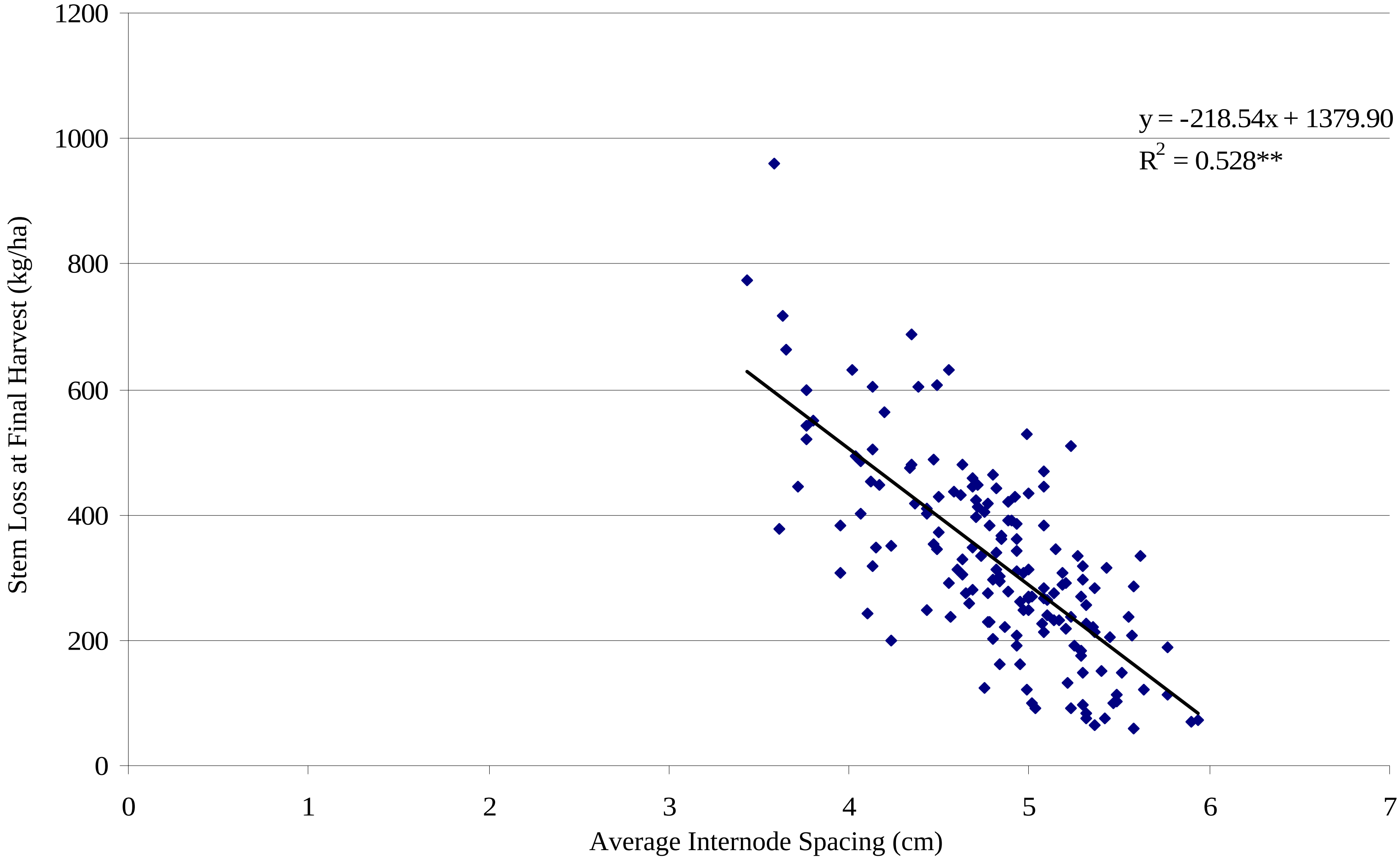

Figure 2. Effect of average internode spacing on stem loss combined over four locations, 2003-2004.

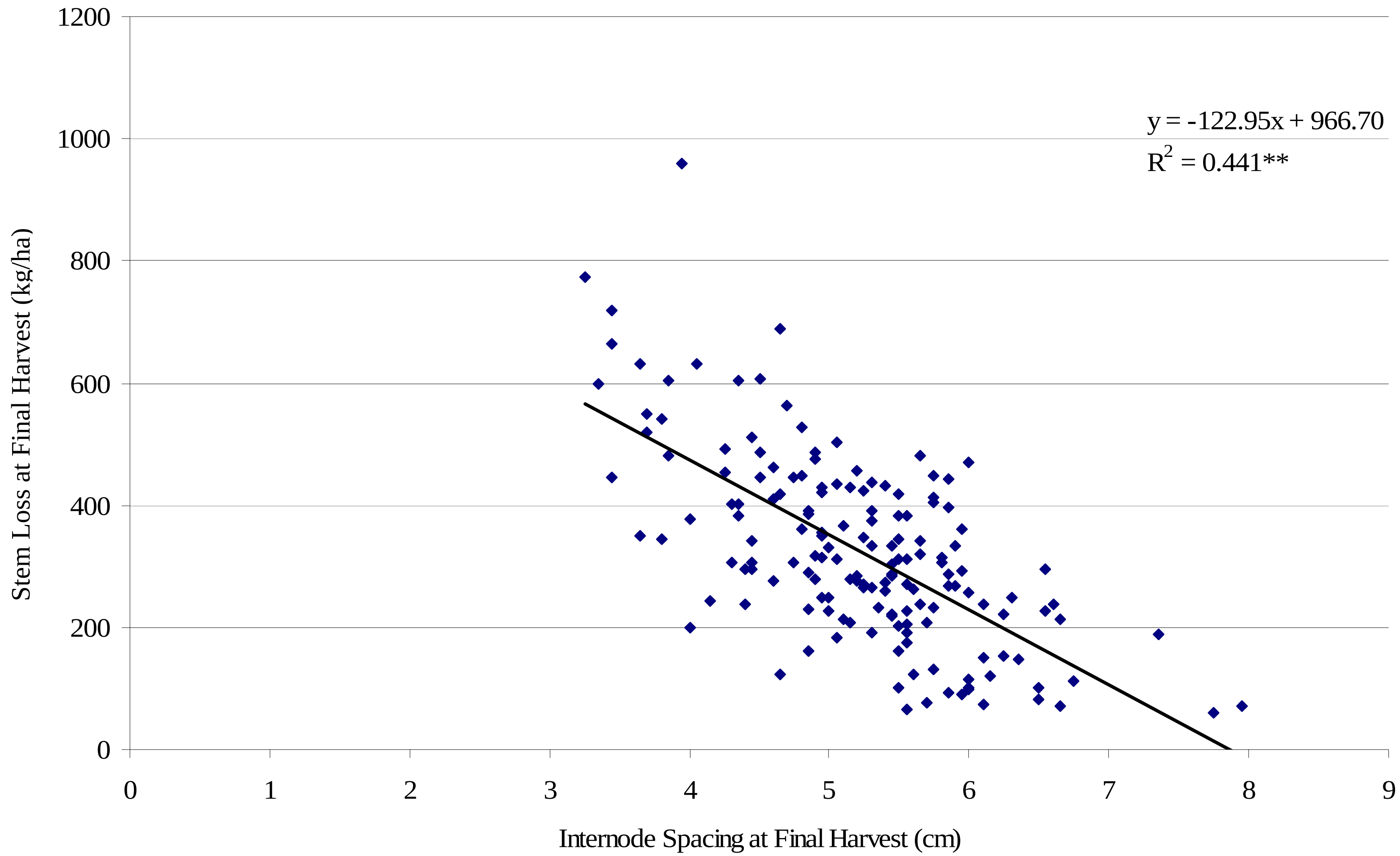

Figure 3. Effect of internode spacing at final harvest on stem loss combined over four locations, 2003-2004.

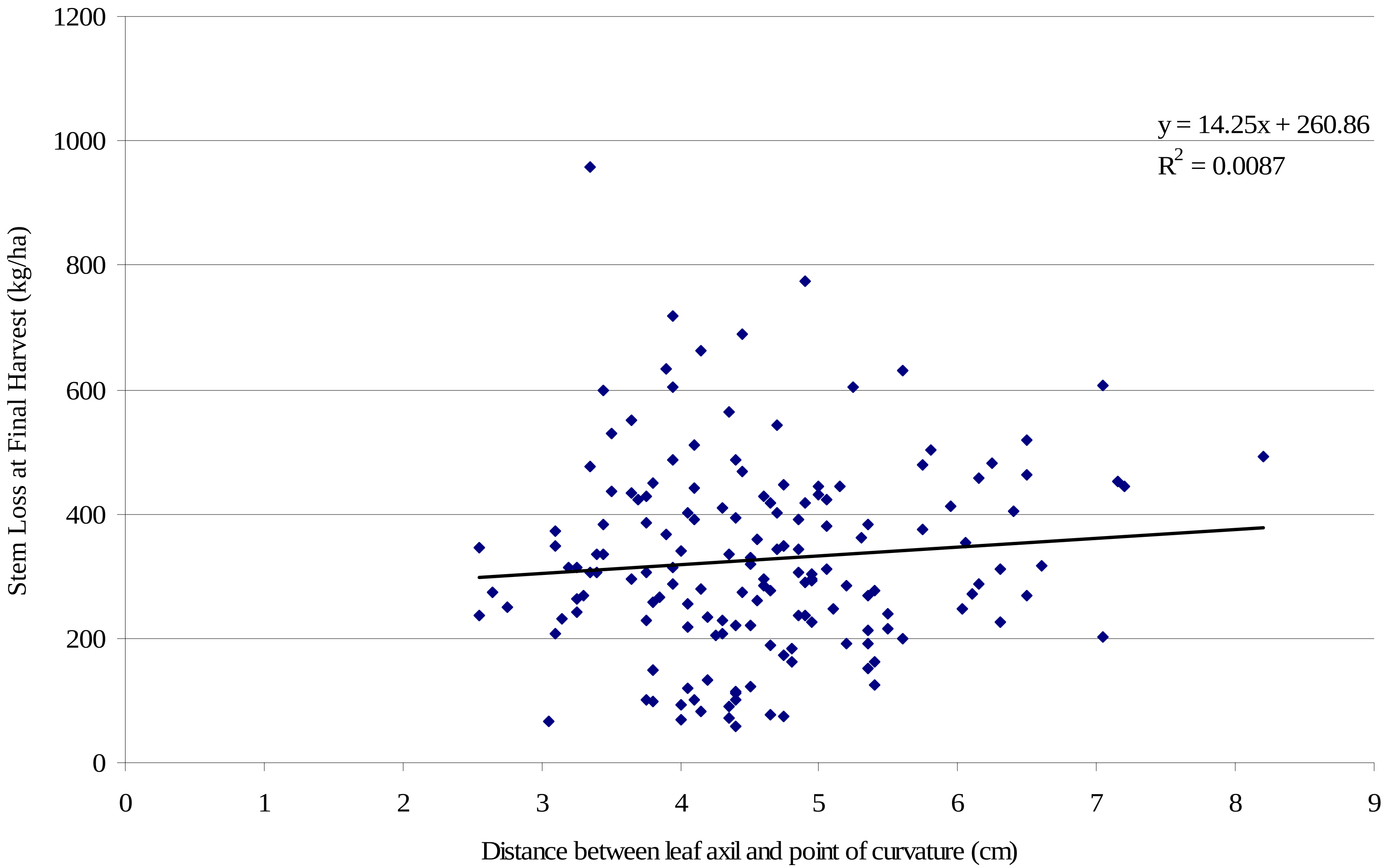

Figure 4. Effect of leaf curvature at final harvest on stem loss combined over four locations, 2003-2004.

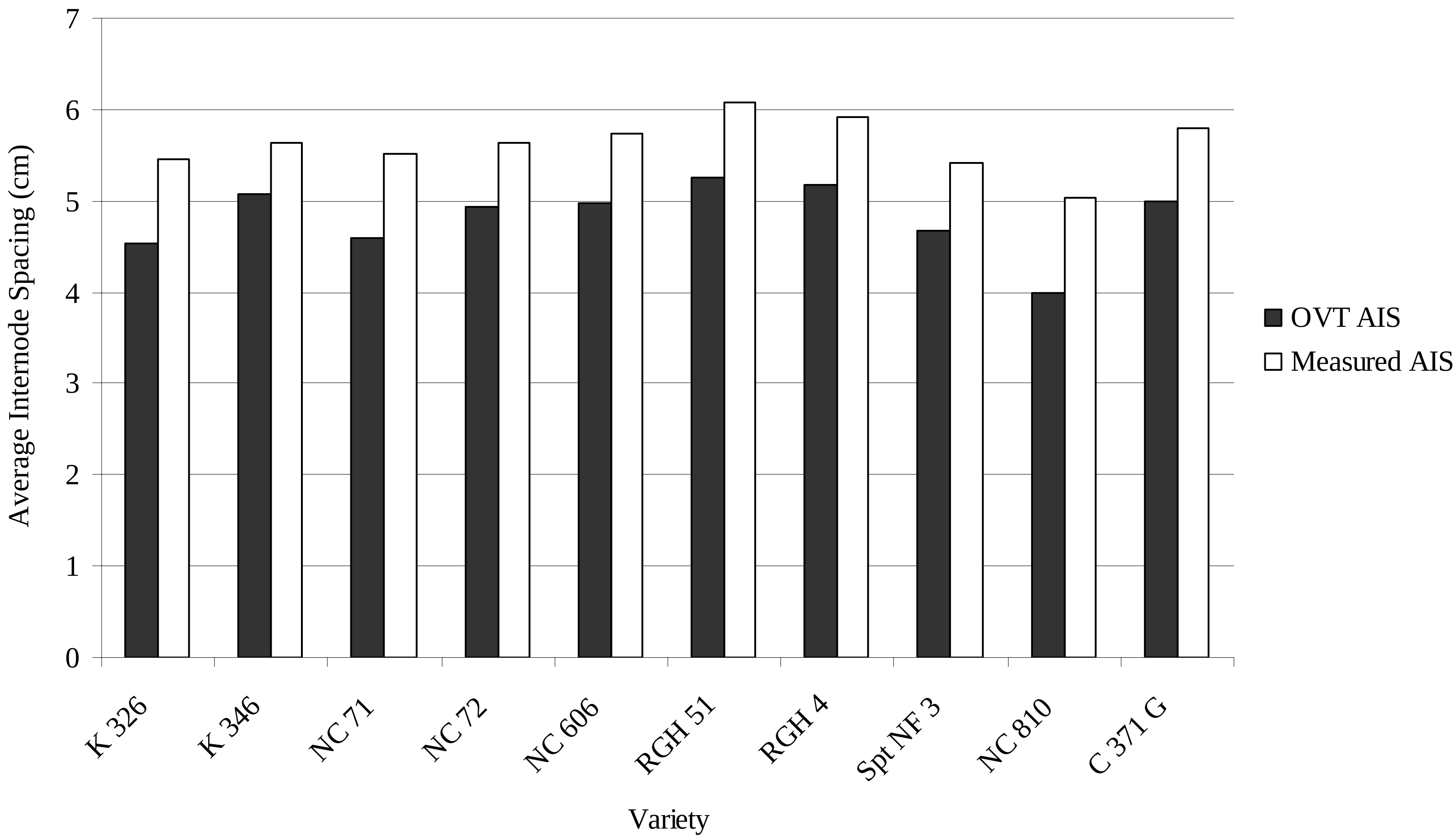

Figure 5. NC Tobacco OVT average internode spacing data (3 year average, 2001-2003) compared to measured average internode spacing data combined over four locations, 2003-2004.

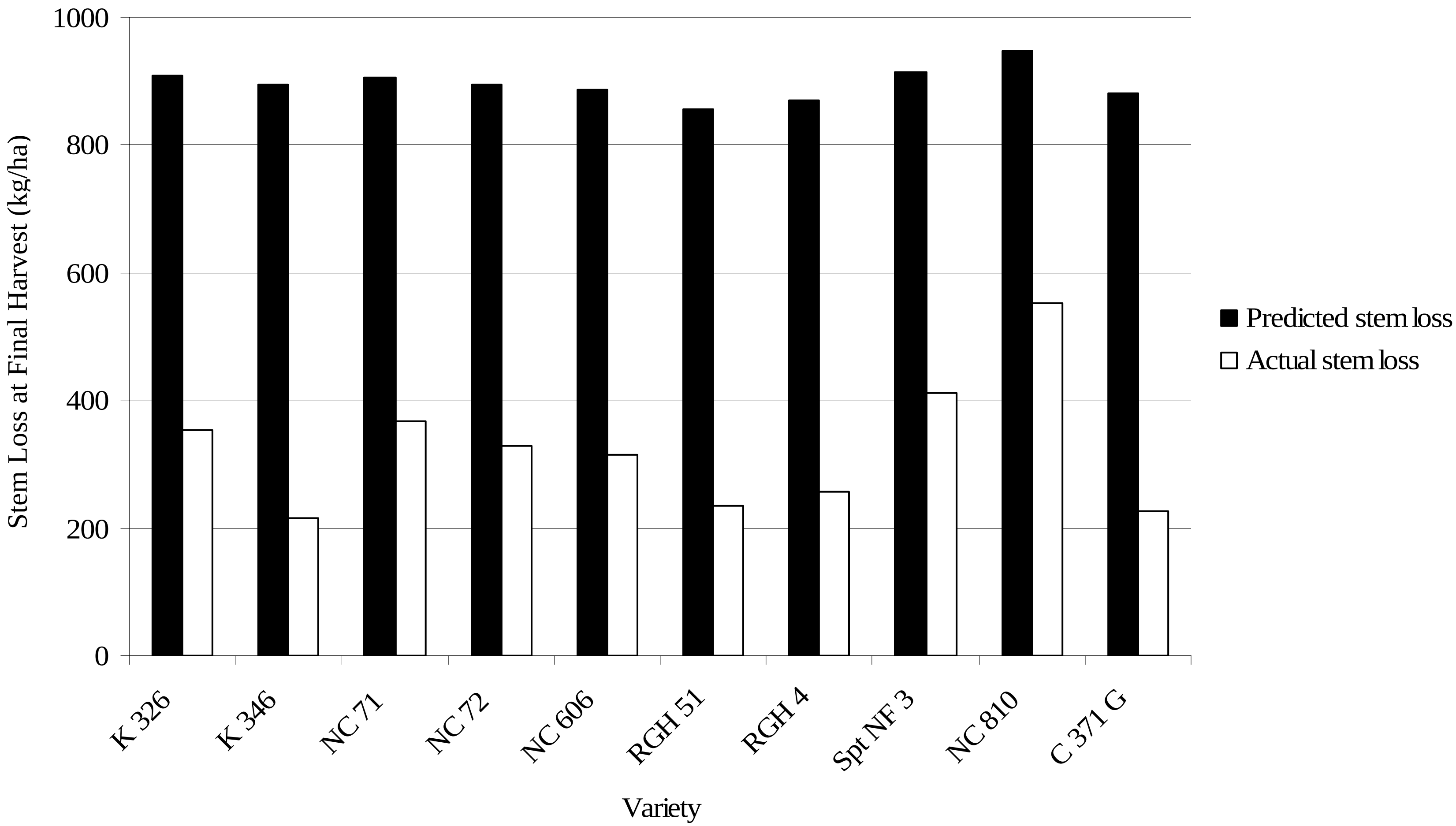

Figure 6. Predicted stem loss computed from model using average internode spacing compared to actual stem loss at final harvest combined over four locations, 2003-2004.

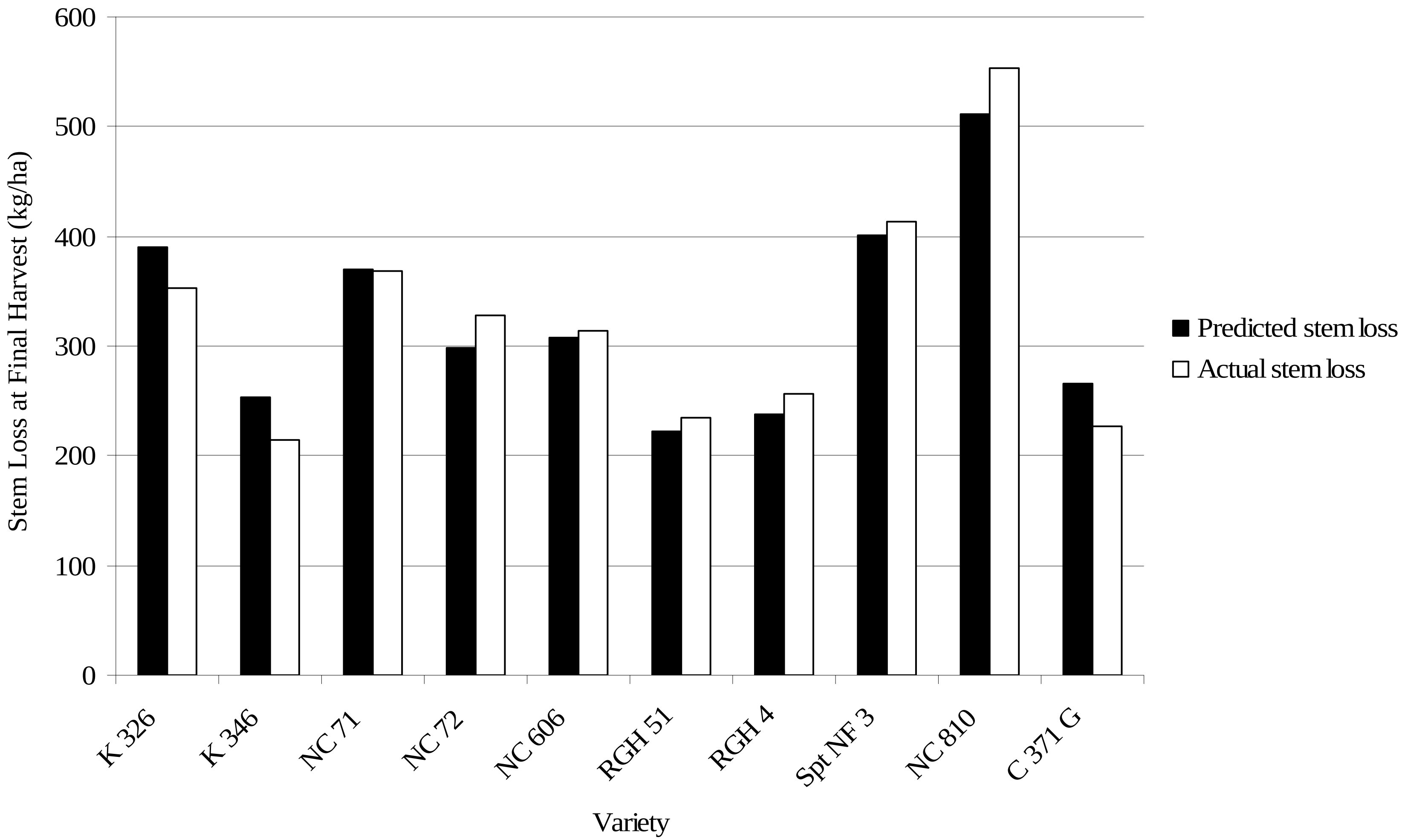

Figure 7. Predicted stem loss computed from model using leaf angle, average internode spacing, and leaf curvature compared to actual stem loss at final harvest combined over four locations, 2003-2004.

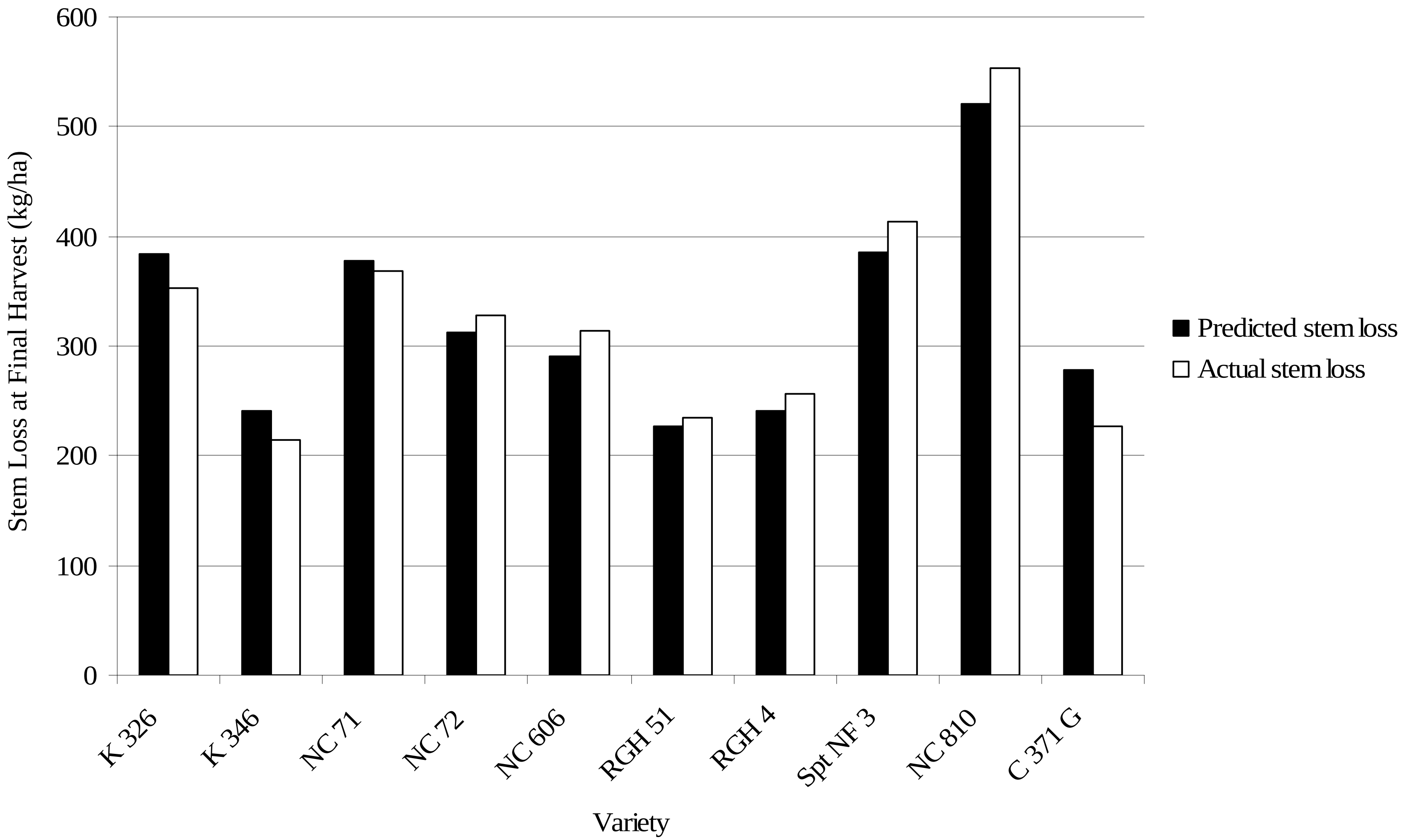

Figure 8. Predicted stem loss computed from model using leaf angle and average internode spacing compared to actual stem loss at final harvest combined over four locations, 2003-2004.

APPENDIX

Table A-1. 2nd Harvest: Effect of variety on leaf angle at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	----------------------	----------degrees	----------	----------------------
K326	34 bc	33 abc	28 abc	27 abc
K346	33 bcd	34 ab	28 ab	27 abc
NC 71	27 e	30 bcd	24 de	24 e
NC 72	29 e	29 cd	27 bcd	25 de
NC 606	29 de	29 cd	24 d	26 cde
RGH 51	30 cde	32 abc	25 cd	27 bcd
RGH 4	40 a	36 a	29 ab	29 a
Spt NF 3	37 ab	33 ab	30 a	29 ab
NC 810	27 e	27 d	21 ef	26 cde
C 371 G	31 cde	33 abc	28 abc	29 ab
NC 297			24 d	24 de
Spt 168			20 f	25 de

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-2. 3rd Harvest: Effect of variety on leaf angle at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	---	--------------degrees-----------	---	
K326	34 a	35 bc	30 bc	32 a
K346	33 ab	38 ab	31 bc	31 a
NC 71	30 b	30 e	27 de	30 a
NC 72	31 ab	35 bc	27 d	26 a
NC 606	31 ab	34 cd	29 cd	30 a
RGH 51	33 ab	40 a	32 b	31 a
RGH 4	34 ab	37 abc	35 a	31 a
Spt NF 3	34 a	36 bc	33 ab	30 a
NC 810	25 c	28 e	24 ef	30 a
C 371 G	33 ab	30 de	33 ab	34 a
NC 297			27 d	29 a
Spt 168			22 f	29 a

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-3. 4th Harvest: Effect of variety on leaf angle at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--	---------------------------degrees---------------------------	--	
K326	33 bcd	41 e	43 ab	43 cd
K346	39 a	56 a	47 a	57 a
NC 71	30 cde	41 e	37 cde	45 bcd
NC 72	28 de	47 cd	36 cde	41 de
NC 606	34 abc	46 de	38 cde	49 bc
RGH 51	34 a-d	54 ab	40 bc	50 b
RGH 4	36 ab	49 bcd	46 a	49 bc
Spt NF 3	26 e	34 f	33 ef	35 e
NC 810	25 e	34 f	30 f	37 e
C 371 G	36 ab	52 abc	43 ab	45 bcd
NC 297			39 bcd	44 bcd
Spt 168			35 de	45 bcd

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-4. 1st Harvest: Effect of variety on leaf loss at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--# leaves lost per hectare---			
K326	10356 a	3990 a	1479 a	628 a
K346	12373 a	3497 a	1838 a	269 bc
NC 71	15108 a	2959 a	2735 a	224 bc
NC 72	9908 a	3138 a	2779 a	359 abc
NC 606	11252 a	2690 a	1793 a	179 bc
RGH 51	9594 a	3228 a	1659 a	134 c
RGH 4	9504 a	2914 a	2421 a	403 abc
Spt NF 3	7621 a	1928 a	897 a	134 c
NC 810	11163 a	2511 a	1704 a	179 bc
C 371 G	11521 a	2824 a	2037 a	269 bc
NC 297			2511 a	448 ab
Spt 168			2779 a	269 bc

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher’s protected LSD at p=0.05.

Table A-5. 2nd Harvest: Effect of variety on leaf loss at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--	---------# leaves lost per hectare---------	--	-----------------------
K326	4842 a	2197 a	2376 bcd	2107 a
K346	5828 a	2555 a	2824 bcd	1793 a
NC 71	5469 a	2062 a	3676 abc	2286 a
NC 72	4618 a	2914 a	3945 ab	2017 a
NC 606	5021 a	2600 a	2511 bcd	1838 a
RGH 51	4842 a	3317 a	3004 bcd	1524 a
RGH 4	6052 a	3093 a	2466 bcd	2107 a
Spt NF 3	3855 a	2600 a	2197 cd	1524 a
NC 810	4035 a	2466 a	1928 d	1255 a
C 371 G	6321 a	2600 a	3586 abc	1928 a
NC 297			2735 bcd	2376 a
Spt 168			4752 a	1883 a

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-6. 3rd Harvest: Effect of variety on leaf loss at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--# leaves lost per hectare--			
K326	2600 ab	3093 a	1076 a	3228 a
K346	2152 bc	3004 a	1435 a	2914 a
NC 71	2645 ab	3990 a	1166 a	3183 a
NC 72	2555 ab	3497 a	1614 a	2914 a
NC 606	2286 bc	3317 a	2017 a	2242 a
RGH 51	1614 c	4008 a	1748 a	2376 a
RGH 4	2062 bc	2959 a	1255 a	2869 a
Spt NF 3	2511 ab	2286 a	1255 a	2107 a
NC 810	3183 a	2062 a	2511 a	2914 a
C 371 G	1435 c	2242 a	1569 a	2152 a
NC 297			1748 a	3228 a
Spt 168			2152 a	2735 a

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-7. 4th Harvest: Effect of variety on leaf loss at three locations, 2003-2004.

Variety	Wake 03	Wilson 03	Wilson 04
	----------------------------------# leaves lost per hectare	--	
K326	1345 bc	941 b	403 a
K346	1748 bc	852 b	897 a
NC 71	1659 bc	1793 a	941 a
NC 72	2331 b	986 b	1345 a
NC 606	2376 b	986 b	1435 a
RGH 51	986 c	583 b	986 a
RGH 4	2242 b	762 b	1255 a
Spt NF 3	3676 a	1748 a	1300 a
NC 810	2331 b	1838 a	1121 a
C 371 G	1300 bc	807 b	897 a
NC 297			852 a
Spt 168			1076 a

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-8. 2nd Harvest: Effect of variety on leaf curvature at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	----------------------------	----------cm----------	----------------------------	
K326	4.5 cd	4.5 ef	6.0 cd	5.5 cde
K346	5.5 abc	5.0 c-f	6.5 ab	6.0 ab
NC 71	5.5 bc	5.0 b-e	6.5 abc	6.0 b
NC 72	5.0 cd	5.0 c-f	6.0 abc	5.5 b-e
NC 606	6.5 a	5.5 abc	7.0 a	6.0 bcd
RGH 51	5.5 bcd	4.5 def	6.0 abc	5.5 b-e
RGH 4	4.5 d	4.5 f	5.5 d	5.5 e
Spt NF 3	6.5 ab	5.5 a	6.0 abc	6.5 a
NC 810	5.0 cd	5.5 a-d	6.0 bcd	5.5 de
C 371 G	5.5 bc	5.5 ab	6.0 bc	6.0 b-e
NC 297			6.0 bcd	6.0 bc
Spt 168			6.5 abc	5.5 b-e

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-9. 3rd Harvest: Effect of variety on leaf curvature at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--	----------------cm----------------	--	
K326	4.5 cd	4.0 cd	4.5 b-e	4.5 e
K346	5.0 bcd	5.0 ab	5.5 a	5.0 bc
NC 71	4.5 cd	5.0 ab	5.0 abc	5.0 b-e
NC 72	5.0 cd	4.5 bcd	5.0 abc	5.0 bcd
NC 606	5.5 ab	5.0 a	5.0 ab	5.5 b
RGH 51	5.0 cd	4.5 bcd	5.0 bcd	4.5 de
RGH 4	4.5 d	4.0 d	4.5 e	4.5 de
Spt NF 3	6.0 a	5.0 a	5.0 ab	6.0 a
NC 810	5.0 bc	5.0 a	5.5 a	4.5 cde
C 371 G	5.0 cd	4.5 abc	4.5 de	4.5 b-e
NC 297			4.5 cde	4.5 cde
Spt 168			5.0 abc	4.5 cde

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-10. 4th Harvest: Effect of variety on leaf curvature at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	cm			
K326	5.5 bc	5.0 abc	3.5 ef	3.5 de
K346	4.5 d	3.5 e	3.5 f	2.5 f
NC 71	6.0 abc	5.0 ab	5.0 ab	3.5 cde
NC 72	6.5 ab	5.0 bc	5.0 ab	4.5 ab
NC 606	5.0 cd	4.5 cd	4.0 def	3.5 de
RGH 51	5.5 c	4.0 de	4.0 cd	4.0 bcd
RGH 4	5.5 bc	4.5 cd	4.0 de	3.5 e
Spt NF 3	6.5 a	5.0 ab	4.5 abc	4.0 b-e
NC 810	7.0 a	5.5 a	5.0 a	4.0 abc
C 371 G	5.0 cd	4.0 d	4.5 bcd	4.5 ab
NC 297			4.5 ab	3.5 cde
Spt 168			5.0 ab	4.5 a

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-11. 2nd Harvest: Effect of variety on internode spacing at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	-----------------------------	-----cm-----	-----------------------------	
K326	4.0 de	4.5 a	4.0 f	4.0 de
K346	5.0 ab	5.0 a	5.0 bc	4.5 ab
NC 71	4.5 cde	4.5 a	4.5 ef	4.0 ef
NC 72	4.5 abc	4.5 a	4.5 de	4.5 bcd
NC 606	4.5 bcd	4.5 a	5.5 a	4.5 ab
RGH 51	5.0 abc	4.5 a	5.0 ab	4.5 ab
RGH 4	5.0 a	4.5 a	5.5 a	4.5 bc
Spt NF 3	5.0 abc	4.5 a	5.0 ab	5.0 a
NC 810	4.0 e	4.0 a	4.0 f	3.5 f
C 371 G	5.0 a	4.5 a	4.5 cd	4.5 bcd
NC 297			4.0 f	4.0 ef
Spt 168			4.5 cd	4.0 cd

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-12. 3rd Harvest: Effect of variety on internode spacing at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	-----------------------cm-----------------------			
K326	3.5 c	5.0 b	4.5 de	4.0 de
K346	4.5 ab	5.5 ab	5.0 bc	5.0 a
NC 71	4.0 b	5.5 ab	4.5 cde	4.0 ef
NC 72	4.5 ab	5.5 ab	5.0 bc	4.5 d
NC 606	4.0 ab	5.5 ab	5.0 bcd	4.5 bcd
RGH 51	4.5 ab	5.5 ab	5.5 ab	5.0 ab
RGH 4	4.5 a	5.5 a	5.5 a	5.0 abc
Spt NF 3	4.5 ab	5.0 b	5.0 bc	5.0 a
NC 810	3.5 c	4.5 c	4.0 e	3.5 f
C 371 G	4.5 ab	5.0 ab	5.0 bcd	4.5 bcd
NC 297			4.0 e	4.0 d
Spt 168			5.0 bcd	4.5 cd

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-13. 4th Harvest: Effect of variety on internode spacing at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	----------cm----------			
K326	5.0 c	5.5 cde	5.5 ab	4.5 bcd
K346	5.5 ab	6.0 b	5.5 ab	4.5 bcd
NC 71	5.5 bc	5.0 de	5.0 b	4.5 bcd
NC 72	5.5 abc	6.0 bc	5.5 ab	5.0 a
NC 606	6.0 a	6.0 bcd	5.5 ab	5.0 ab
RGH 51	6.0 a	7.0 a	5.5 ab	5.5 a
RGH 4	5.5 ab	6.0 b	5.5 ab	4.5 bcd
Spt NF 3	4.5 d	4.5 f	4.5 c	4.0 de
NC 810	4.0 d	5.0 ef	4.5 c	3.5 e
C 371 G	6.0 a	6.5 b	5.5 b	5.0 ab
NC 297			5.5 ab	4.5 cd
Spt 168			6.0 a	5.0 abc

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.

Table A-14. 4th Harvest: Effect of variety on stem weights at four locations, 2003-2004.

Variety	Wake 03	Wilson 03	Duplin 04	Wilson 04
	--------------------------------	-----------kg/ha-----------	--------------------------------	
K326	408.63 abc	209.41 bc	367.58 bc	426.79 bcd
K346	259.87 ef	89.29 d	234.10 e	276.91 e
NC 71	372.69 bcd	220.45 bc	429.62 ab	448.20 bc
NC 72	257.84 ef	155.65 cd	390.49 b	508.99 b
NC 606	321.30 cde	158.47 cd	342.02 bcd	435.12 bc
RGH 51	237.91 ef	94.67 d	271.98 cde	331.23 cde
RGH 4	292.62 def	126.12 cd	265.94 cde	338.16 cde
Spt NF 3	500.52 a	280.39 b	360.38 bcd	510.30 b
NC 810	458.09 ab	469.94 a	506.89 a	778.46 a
C 371 G	210.34 f	94.92 d	279.86 cde	325.30 cde
NC 297			422.65 ab	442.53 bc
Spt 168			253.61 de	310.30 de

[a]Treatments followed by the same letter within a column are not significantly different as computed by Fisher's protected LSD at p=0.05.