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Pecan Nut and Kernel Characteristics Show Genotype–Environment Interactions

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Abstract. **Results are presented for performance of pecan [*Carya illinoinensis* (Wangenh.) C. Koch] clones at six established National Pecan Advanced Clone Testing System (NPACTS) sites for 16 nut quality factors from 1980 through 1985. Total nut weight and percent kernel were significantly greater at Tulare, Calif. than at any other location, with ≈80% of the clones averaging 6.5 g/nut or more and ≈90% averaging at least 54.5% kernel. Nut weight was smallest at El Paso, Texas. Daily mean temperatures during nut expansion may be a major factor determining nut weight response. Low nut density was characteristic of more clones at Baton Rouge, La. than at any other location. Kernel color was lightest at El Paso and darkest at Baton Rouge, with darker color appearing to be related to high field moisture conditions before harvest. Nut weight was not related to kernel percentage, color, or percent kernel covered with fuzz (packing material); thus, large nuts are not necessarily of lower quality and can be selected in an effective breeding program. Amount of nut "packing material" retained in the sutures of kernel halves after shelling was generally not related to other traits, except that material retained in ventral grooves increased with nut and kernel weight. Depth and width of dorsal grooves were not related to retention of packing material and can be disregarded in future pecan nut evaluation systems. Many other expected character relationships were verified and the overall NPACTS nut evaluation system will be revised based on these results.**

The largest pecan breeding program in the world is located at Brownwood, Texas and is conducted by the USDA/ARS. Selected crosses are made at Brownwood, where initial screening is also made. Subsequently, the superior clones for nut quality, precocity, maturity, and other horticultural characteristics enter the National Pecan Advanced Clone Testing System (NPACTS), in which they are tested in the various U.S. pecan production areas.

Little is known about pecan genetics, environmental influence, or important nut and kernel characteristics (Madden and Malstrom, 1975). An evaluation system for pecan nut samples has been devised; however, the importance of each character and its relationship to other characteristics, especially across grossly different environments, have never been studied. The very nature of NPACTS allows such data to be collected for pecan. Studies with similar data in other crops have improved breeding and selection methods and produced insight into genetic control of important economic characteristics (Byrne et al., 1987; Hansche et al., 1972; Hansche and Brooks, 1965; Poysa et al., 1986; and Thompson, 1977). The purpose of this research was to document environmental influences on pecan nut and kernel characteristics and to study character interrelationships. Such knowledge will allow improvement and refinement of the overall pecan breeding program.

Materials and Methods

Results characterizing clones in this report are summaries of data collected at six locations during 1980 through 1985. The locations summarized are Baton Rouge, LA; Brownwood, (W. R. Poage Pecan Field Station), Goldthwaite, Pecan Bayou (near Brownwood), and El Paso, Texas; and Tulare, Calif. Each clone was grafted onto seedling rootstocks from a locally adapted clone. A different number of trees of each clone were sampled at each location. Some locations had single trees of each clone randomized throughout the test, while others had up to four replicates. Generally, all orchards were well cared for, according to local recommendations. All tests were irrigated as needed.

At harvest, a 50-nut sample was randomly hand-picked from each clone and stored under cool (5C), relatively dry conditions until analyses were made. The analysis consisted of 10 randomly selected nuts from the sample for determining nut characteristics. Width was determined by rolling a nut in the jaws of a micrometer to determine maximum diameter and buoyancy by measuring grams of lift after nuts were submerged in a small container of water. This value was added to nut weight to determine nut volume, since water has a density of 1. Nuts were then dried, cracked, and shelled as would be done in commercial shelling plants.

Kernel weight as a percentage of total nut weight yielded the percentage of the nut that was edible (percent kernel or kernel content). The percentage of kernel surfaces covered with fuzz (packing material) and the amount of packing material retained in dorsal or ventral grooves were estimated. Packing material in the dorsal grooves refers to remnants of sutural bundles from the shell, while that in the ventral grooves is rudimentry secondary septum from the shell. Kernel color ratings were based on a 1–10 scale, where 1–3.5 = lightest (best), 4–5.5 = light brown, 6 = medium brown, and 10 = darkest (worst). Maximum dorsal groove depth and the width of the groove at the top were recorded after cutting the kernel half-way through the center (across grooves).

All data were analyzed to give means, least significant differences, standard deviations, and character correlations. Cu-

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Table 1. Means and least significant differences for 15 nut and kernel quality traits of pecan at six locations.

Variable	Overall	Baton Rouge, La.	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare Calif.	LSD among locations[z]
Nut								
Weight (g)	6.7	6.7	7.4	6.6	6.7	6.0	7.6	0.4
Buoyancy (ml)	2.0	2.6	2.1	1.6	1.9	1.9	2.2	0.2
Volume (ml)	8.8	9.3	9.5	8.2	8.6	8.0	9.8	0.5
Density ($g \cdot ml^{-1}$)	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.0
Length (mm)	39.0	42.0	40.0	37.3	39.5	36.2	40.9	0.9
Diameter (mm)	21.9	21.6	22.5	21.4	21.8	21.5	22.5	0.5
Length:width ratio	1.8	2.0	1.8	1.8	1.8	1.7	1.8	0.1
Kernel								
Weight (g)	3.7	3.7	4.0	3.7	3.6	3.4	4.4	0.2
Content (%)	55.5	55.8	53.7	56.1	53.6	56.2	58.0	1.1
Color (1-10)	2.8	4.0	3.3	2.5	2.8	2.0	2.2	0.2
Fuzz (%)	12.4	28.1	6.5	10.7	15.9	6.4	7.6	4.7
Dorsal groove depth (mm)	3.3	3.5	3.1	3.3	3.6	3.5	3.3	0.2
Dorsal groove width (mm)	1.8	1.8	1.7	2.0	2.0	1.8	1.7	0.1
Dorsal groove packing (%)	6.7	5.1	4.3	8.3	6.9	6.5	10.9	2.8
Ventral groove packing (%)	7.4	8.4	8.6	7.0	7.8	4.2	13.5	2.2

[z]LSD ($P = 0.05$) for comparison among locations.

Table 2. Correlations between nut weight and 14 other pecan characteristics at six NPACTS locations, 1980–1985.

	Nut wt (g)						
Variable	Overall	Baton Rouge, La.	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare, Calif.
Nut							
Buoyancy (ml)	0.585****	0.322**	0.447****	0.402**	0.225NS	0.504****	0.765****
Volume (ml)	0.937****	0.884****	0.940****	0.894****	0.884****	0.910****	0.963****
Density ($g \cdot ml^{-1}$)	−0.116NS	0.271*	0.167NS	−0.060NS	0.231NS	−0.069NS	−0.520**
Length (mm)	0.532****	0.554****	0.579****	0.546****	0.437**	0.559****	0.726****
Diameter (mm)	0.823****	0.637****	0.828****	0.640****	0.650****	0.766****	0.698****
Length : width ratio	−0.165NS	−0.030NS	−0.094NS	0.065NS	−0.128NS	−0.063NS	0.331NS
Kernel							
Weight (g)	0.943****	0.937****	0.953****	0.917****	0.913****	0.927****	0.966****
Content (%)	−0.138NS	−0.002NS	0.142NS	−0.048NS	0.200NS	−0.085NS	−0.088NS
Color (1–10)	0.196NS	−0.068NS	0.098NS	0.218NS	0.053NS	0.011NS	−0.041NS
Fuzz (%)	0.057NS	−0.085NS	−0.141NS	−0.146NS	−0.275NS	0.044NS	0.543**
Dorsal groove depth (mm)	0.471****	0.406***	0.463****	0.427***	0.517***	0.471****	0.096NS
Dorsal groove width (mm)	0.513****	0.269*	0.461****	0.415***	0.205NS	0.352***	0.187NS
Dorsal groove packing (%)	−0.120NS	0.110NS	−0.053NS	−0.297*	−0.007NS	−0.077NS	−0.237NS
Ventral groove packing (%)	0.283**	0.324**	0.223*	0.064NS	0.080NS	0.260*	0.092NS

NS,*,**,***,****Nonsignificant and significant at the 0.05, 0.01, 0.001, and 0.0001 levels, respectively.

mulative clonal distributions were determined to visually characterize location responses for six nut and kernel quality traits. The Kolmogorov–Smirnov (KS) two-sided test critical percentage values ($P = 0.05$) were computed to compare clonal differences in cumulative clonal distributions (Conover, 1971). Location responses were deemed significantly different for a particular characteristic if the differences between any two cumulative percentage curves equaled or exceeded the KS critical percentage value along the location slopes. The KS procedure was used since it gave a more conservative comparison of clonal responses to location differences than did the LSDs.

Results and Discussion

Means and least significant differences (Table 1) are presented to show variability among locations. Generally, no location seemed to be more or less stable as far as increasing or decreasing variability overall.

Nut weight. Based on the nut weight means in Table 1, nut size at El Paso was only 79% of that noted for Tulare (6.0 vs. 7.6 g/nut). Also, highly significant positive correlations indicate that nut volume, nut length, nut diameter, and kernel weight are closely associated with nut weight (Table 2). The associa-

Table 3. Percentage differences for nut weight required between locations for cumulative frequency distributions to be significantly different (P = 0.05).

	Location				
Location	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare, Calif.
Baton Rouge, La.	23	27	28	24	34
Brownwood, Texas		25	26	21	31
Goldthwaite, Texas			30	26	35
Pecan Bayou, Texas				27	36
El Paso, Texas					33

tions between nut weight and each of these traits, plus depth of dorsal grooves, for most locations were significant.

The cumulative percentage frequency distribution of nut weight (Fig. 1A) also shows that Tulare produces a significantly larger nut, whereas El Paso produces a significantly smaller nut, when compared to the other locations. Nut weight was at least 6.5 g (154 nuts/kg) in 80% of the clones at Tulare and in ≈70% of the clones at Brownwood. A difference of 31% between Tulare and Brownwood is required for significance (Table 3); therefore, the nut weight distributions for these two locations are not considered different. About 30% of the clones at El Paso had nuts weighing at least 6.5 g. Differences of 50% and 60% between El Paso and Brownwood, and between El Paso and Tulare, respectively, indicate that the cumulative frequency distributions for these locations differ significantly.

Nut density. The mean density of 0.81 at Goldthwaite was significantly greater than that for all the other locations and was followed by Tulare, with a mean density of 0.79 (Table 1). Nut density was significantly lower for Baton Rouge than for any other location. There were highly significant negative correlations of nut density with buoyancy and percentage of kernel covered by fuzz at all locations, except for percentage of fuzz at Tulare (Table 4). Direction of response varied (plus or minus) among locations for correlations between nut density and nut weight, nut volume, width of dorsal groove, nut length, nut diameter, percentage of nut that is kernel, and kernal weight. Both positive and negative correlations were of significant magnitude for density associations with nut weight and kernal weight. For example, this relationship is illustrated by the positive and negative nut density x nut weight correlations of 0.271 (P=0.05) and −0.520 (P=0.01) for Baton Rouge and Tulare, respectively. Pronounced modifications of genotype responses for these traits, which are related to nut filling in the various location environments, were therefore evident. Evidence of genotype x environment interaction is supported by a significant difference between density cumulative frequency distribution curves for Goldthwaite and Baton Rouge (Fig. 1B), although the distribution differences among the other locations for density were relatively minor.

Nut length : width ratio. The greatest length : width ratio (L:W), 2.0, was expressed at Baton Rouge (Table 1). The least, 1.7, was noted for El Paso. The difference in L:W between the El Paso and Baton Rouge locations resulted primarily from a pronounced restriction of the expression of growth in nut length of most clones at El Paso. Thus, mean nut length at El Paso was ≈14% less than at Baton Rouge, whereas width was only 0.2% less. The L:W means at Goldthwaite and Pecan Bayou were also less than that at Baton Rouge, mainly because of less growth in nut length (−11%, −6%) rather than in width (−3%, +1%). However, the mean L:W of nuts at Brownwood and Tulare differed from that at Baton Rouge, mainly because of

Table 4. Correlations between nut density and 14 other pecan characteristics at six NPACTS locations, 1980–1985.

	Nut density (g·ml⁻¹)						
Variable	Overall	Baton Rouge, La.	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare, Calif.
Nut							
Weight (g)	−0.116NS	0.271*	0.167NS	−0.060NS	0.231NS	−0.069NS	−0.520**
Buoyancy (ml)	−0.854****	−0.801****	−0.789****	−0.914****	−0.872****	−0.876****	−0.933****
Volume (g·ml⁻¹)	−0.441****	−0.199NS	−0.174NS	−0.489***	−0.238NS	−0.426****	−0.727****
Length (mm)	−0.429****	0.017NS	−0.282**	−0.319*	−0.297NS	−0.349***	−0.417*
Diameter (mm)	−0.293***	−0.246*	−0.074NS	−0.135NS	−0.036NS	−0.351***	−0.702****
Length : width ratio	−0.158NS	0.200NS	−0.214NS	−0.157NS	−0.231NS	−0.099NS	−0.017NS
Kernel							
Weight (g)	−0.068NS	0.348**	0.232*	0.089NS	0.300NS	0.071NS	−0.569**
Content (%)	0.208*	0.330**	0.303***	0.345*	0.415**	0.456****	−0.184NS
Color (1–10)	−0.198NS	−0.164NS	−0.123NS	−0.051NS	0.138NS	−0.126NS	−0.084NS
Fuzz (%)	−0.560****	−0.508****	−0.298***	−0.368**	−0.785****	−0.365***	−0.397NS
Dorsal groove depth (mm)	−0.125NS	0.027NS	−0.020NS	0.008NS	−0.351*	0.083NS	−0.094NS
Dorsal groove width (mm)	−0.186NS	−0.102NS	−0.039NS	−0.183NS	−0.211NS	−0.324***	0.180NS
Dorsal groove packing (%)	0.344***	0.080NS	0.302***	0.151NS	0.146NS	0.352***	0.408*
Ventral groove packing (%)	0.364****	0.417***	0.385****	0.255NS	0.364*	0.171NS	0.262NS

NS,*,**,***,****Nonsignificant or significant at the 0.05, 0.01, 0.001, or 0.0001 levels, respectively.

Table 5. Correlations between kernel content and 14 other pecan characteristics at six NPACTS locations, 1980–1985.

	Kernel content (%)						
Variable	Overall	Baton Rouge, La.,	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare, Calif.
Nut							
Weight (g)	−0.138NS	−0.002NS	0.142NS	−0.048NS	0.200NS	−0.085NS	−0.088NS
Buoyancy (ml)	−0.223*	−0.291*	−0.172NS	−0.362**	−0.291NS	−0.386***	0.089NS
Volume (ml)	−0.174NS	−0.145NS	0.043NS	−0.211NS	0.016NS	−0.197NS	−0.020NS
Density ($g \cdot ml^{-1}$)	0.208*	0.330**	0.303***	0.345*	0.415**	0.456****	−0.184NS
Length (mm)	−0.063NS	0.138NS	0.094NS	−0.165NS	0.049NS	−0.210NS	0.193NS
Diameter (mm)	−0.185NS	−0.172NS	−0.044NS	0.096NS	−0.074NS	−0.139NS	0.018NS
Length : width ratio	0.079NS	0.233NS	0.044NS	−0.043NS	0.069NS	−0.083NS	0.179NS
Kernel							
Weight (g)	0.192NS	0.337**	0.429****	0.351**	0.567****	0.285**	0.171NS
Color (1–10)	−0.072NS	−0.010NS	−0.066NS	0.016NS	0.248NS	−0.042NS	0.022NS
Fuzz (%)	−0.361****	−0.251*	−0.359****	−0.268NS	−0.357*	−0.388***	0.087NS
Dorsal groove depth (mm)	0.016NS	−0.036NS	0.141NS	0.119NS	−0.189NS	0.225*	0.537**
Dorsal groove width (mm)	−0.464****	−0.143NS	−0.300***	−0.237NS	−0.226NS	−0.388***	−0.810****
Dorsal groove packing (%)	0.356****	0.101NS	0.333***	0.186NS	0.329*	0.523****	0.275NS
Ventral groove packing (%)	0.190NS	0.117NS	0.387****	0.377**	0.090NS	0.262*	0.146NS

NS,*,**,***,****Nonsignificant or significant at the 0.05, 0.01, 0.001, or 0.0001 levels, respectively.

Table 6. Correlations between kernel color and 14 other pecan characteristics at six NPACTS locations, 1980–1985.

	Kernel color rating (1–10)						
Variable	Overall	Baton Rouge, La.	Brownwood, Texas	Goldthwaite, Texas	Pecan Bayou, Texas	El Paso, Texas	Tulare, Calif.
Nut							
Weight (g)	0.196NS	−0.068NS	0.098NS	0.218NS	0.053NS	0.011NS	−0.041NS
Buoyancy (ml)	0.225*	0.106NS	0.184NS	0.040NS	−0.080NS	0.075NS	0.059NS
Volume (ml)	0.215*	0.003NS	0.144NS	0.172NS	−0.000NS	−0.021NS	−0.006NS
Density ($g \cdot ml^{-1}$)	−0.198NS	−0.164NS	−0.123NS	−0.051NS	0.138NS	−0.126NS	−0.084NS
Length (mm)	0.146NS	0.006NS	0.155NS	0.131NS	−0.118NS	−0.244*	−0.237NS
Diameter (mm)	0.187NS	0.031NS	0.010NS	0.202NS	0.129NS	0.128NS	0.264NS
Length : width ratio	−0.017NS	−0.072NS	0.136NS	−0.010NS	−0.188NS	−0.318**	−0.391*
Kernel							
Weight (g)	0.158NS	−0.070NS	0.089NS	0.218NS	0.176NS	−0.028NS	−0.029NS
Content (%)	−0.072NS	−0.010NS	−0.066NS	0.016NS	0.248NS	−0.042NS	0.022NS
Fuzz (%)	0.147NS	0.087NS	0.067NS	−0.049NS	−0.045NS	−0.227*	−0.145NS
Dorsal groove depth (mm)	0.129NS	−0.115NS	0.058NS	0.023NS	0.147NS	0.045NS	−0.107NS
Dorsal groove width (mm)	0.282**	0.299*	0.135NS	0.148NS	0.083NS	0.175NS	−0.148NS
Dorsal groove packing (%)	−0.033NS	0.049NS	0.222*	−0.230NS	0.206NS	−0.011NS	−0.125NS
Ventral groove packing (%)	−0.098NS	0.007NS	−0.004NS	−0.221NS	0.109NS	0.063NS	−0.040NS

NS,*,**Nonsignificant or significant at the 0.05 or 0.01 levels, respectively.

less growth in nut length (−11%, −6%) rather than in width (−3%, +1%). Only ≈10% of the clones at El Paso had a L:W >1.8, whereas nearly 60% of the clones had a L:W >1.8 at Baton Rouge (Fig. 1C).

Nut L:W was positively correlated with nut length and leaf color, and the correlations with nut length were highly significant at all locations, as expected. Nut L:W was negatively associated with nut width, depth, and width of dorsal grooves, and kernel color for all locations except Brownwood. The correlations with nut width were highly significant at all locations except Tulare, where it was nonsignificant. Nut L:W correlations with all other traits were positive at one or more locations, and negative at the other locations.

Thus, environmental influences of different locations greatly

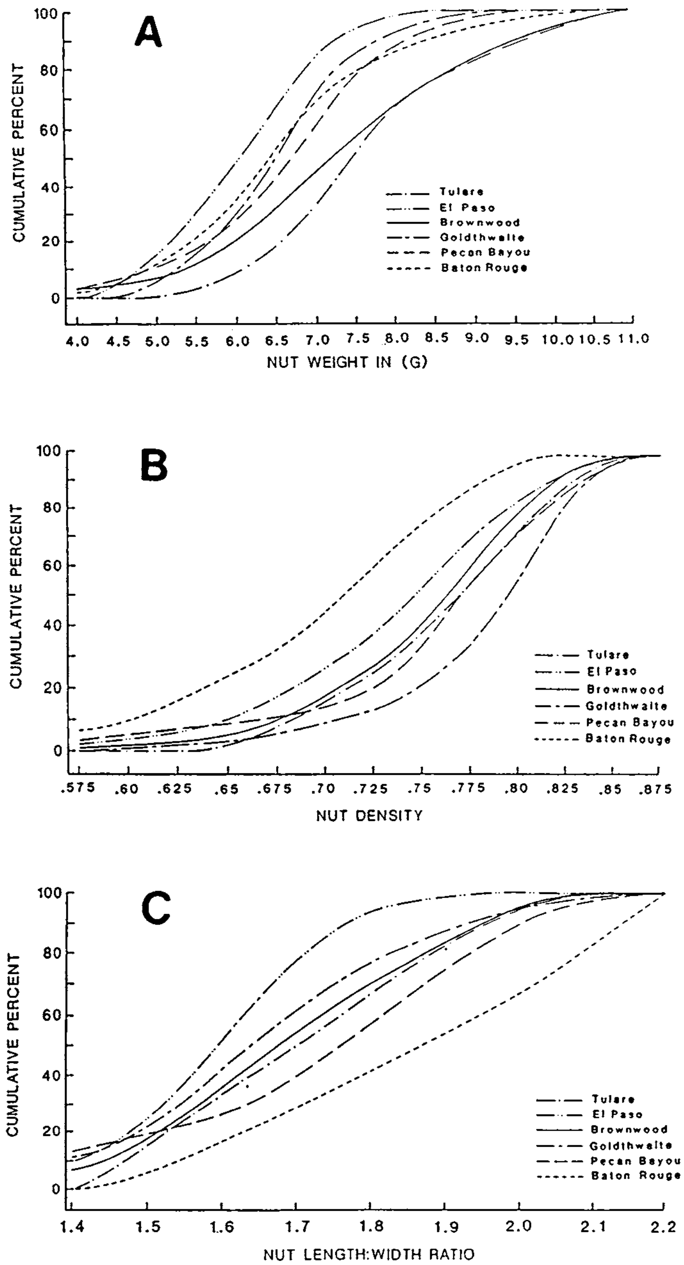

Fig. 1. The cumulative frequency distributions for nut weight (**A**), nut density (**B**), and nut length: width ratio (**C**) at six locations.

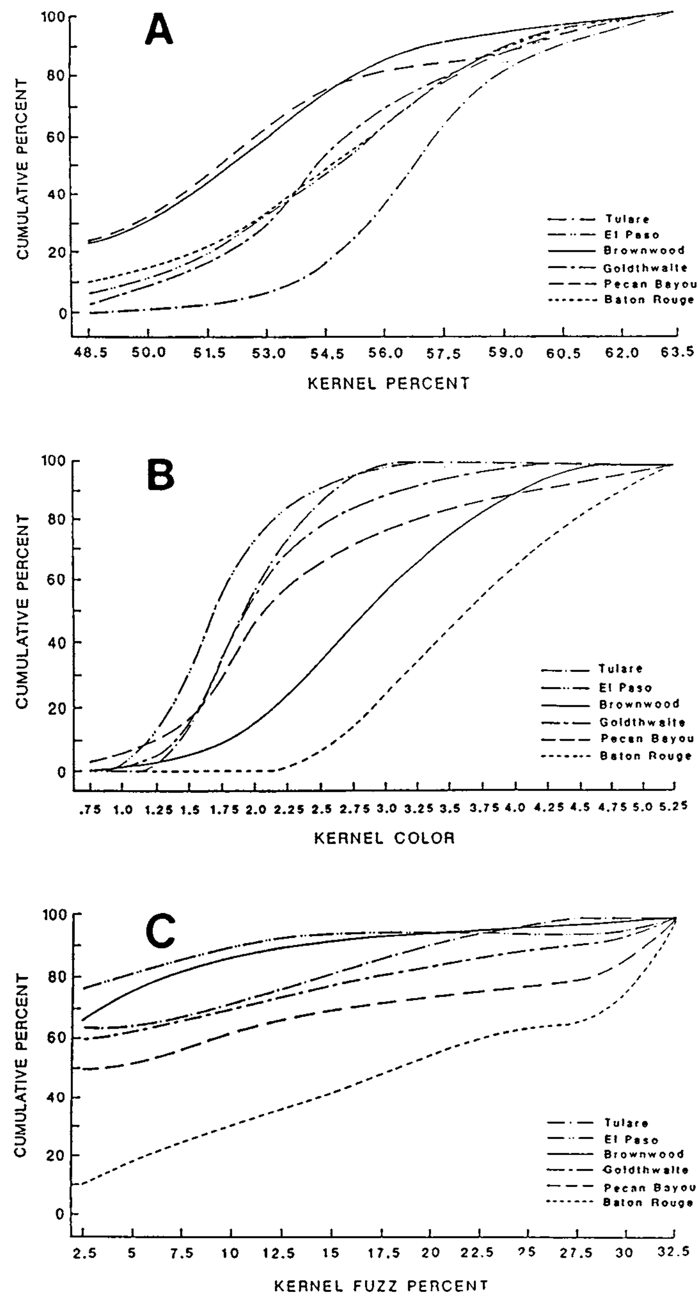

Fig. 2. The cumulative frequency distributions for percentage of kernel (**A**), kernel color (**B**), and percentage of kernel covered by fuzz (**C**) of pecans at six locations.

altered clonal distributions for nut dimensions, mainly by enhancing or restricting growth in length. Positive, highly significant associations of L:W with nut length were observed regardless of location, although dimension differences between Brownwood and Baton Rouge, and between Tulare and Baton Rouge, were partly due to effects on nut width as well. L:W was greatest at Baton Rouge and least at El Paso.

Percent kernel. Tulare-grown pecans had a significantly higher average percentage of kernel (58.0%) than any other location (Table 1). Nuts from Pecan Bayou and Brownwood had significantly lower percentages of kernel values (≈54%) than the other locations.

Significant associations of percentage of kernel, nut density, percentage of kernel covered with fuzz, and depth and width of dorsal grooves were observed for one or more locations (Table 5). The correlations were highly significant at some locations, nonsignificant at other locations, and changed sign for some characteristics, depending on location. For example, the correlation with nut density was 0.456 ($P = 0.0001$) at El Paso, but was −0.18NS at Tulare. None of the correlations with percentage of kernel were significant at all locations. Associations between percentage of kernel and kernel weight, and between percentage of kernel and density, were positive and significant for all locations except Tulare. Nearly 90% of the clones at Tulare exhibited kernel percentages of 54.5 or greater, whereas only ≈25% of the clones at Brownwood and Pecan Bayou, and ≈50% of the clones at the other locations, exceeded this value (Fig. 2A). The reasons for these differences are not fully understood.

Kernel color. Location means for kernel color differed significantly regardless of locations compared (Table 1). Baton

Rouge nut samples were darker than those from the other locations, with an average rating of 4.0, followed by 3.3 for Brownwood. The very dark color ratings for Baton Rouge samples may reflect weathering under high moisture conditions before sample collection.

Figure 2B shows that ≈60% of the clones at El Paso had kernel color ratings of <2.0. About 30% to 40% of the clones at Tulare, Goldthwaite, and Pecan Bayou were rated <2.0. Only ≈20% of the clones at Brownwood were rated ≤2.0, and no clone at Baton Rouge was rated ≤ 2.0.

Correlations involving kernel color were generally weak, with most being nonsignificant (Table 6). For example, kernel color was positively, but not significantly, associated with nut diameter at all locations.

Kernel fuzz percentage. Location means for percentage of fuzz at El Paso, Brownwood, and Tulare (6.4, 6.5, and 7.6) did not differ significantly from each other (Table 1). The Baton Rouge, Goldthwaite, and Pecan Bayou means differed significantly from any other location mean. Thus, percentage of fuzz was surprisingly similar for El Paso, Brownwood, and Tulare, even though environments at these locations could be expected to differ considerably, while a marked contrast was observed between the Brownwood and Pecan Bayou fuzz percentages, even though these locations are only ≈8 km apart.

The greatest amount of fuzz was observed for the Baton Rouge location, where nut buoyancy was highest and density lowest (Table 1). However, nut buoyancy was also relatively high at Brownwood and Tulare. While percentage of fuzz increased or decreased in environments that tended to elevate buoyancy, the environments in which the greatest buoyancy values were obtained were diverse, considering that these included Baton Rouge, Brownwood, and Tulare. Also, comparison of associations between percentage of fuzz and nut weight and between percentage of fuzz and buoyancy for Brownwood and Pecan Bayou, shows that fuzz expression was significantly influenced (increased or decreased) under conditions causing higher buoyancy, whether percentage of fuzz was closely associated with buoyancy and nut size or not. Fuzz percentage was in fact significantly correlated with buoyancy at all locations except Brownwood, but significant fuzz associations with nut weight were observed for Pecan Bayou and Tulare only, and these associations differed in sign.

Comparison of clonal frequencies shows that 50% to 75% of the clones were included in the 5% of less kernel fuzz interval for all locations, except Baton Rouge (Fig. 2C). Only 10% of the clones included in the test at Baton Rouge occurred in this interval. Fifty percent of the clones at Baton Rouge fell above the 22.5% kernel fuzz interval, while 30% or fewer were above this range at the other locations.

Thus, no specific environmental factor was identified as the underlying cause of increased percentage of fuzz. However, the results show that significant alterations in clonal distributions for percentage of fuzz occurred at different locations, possibly in response to modifications to expression of other quality factors such as density, nut size, and percentage of kernel. Generally the concept that percentage of fuzz is related to other undesirable traits is reinforced by these data.

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