A Model for Predicting Pecan Production under Arid Conditions at High Elevations

Darrell Sparks¹

Department of Horticulture, University of Georgia, Athens, GA 30602

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ABSTRACT. A multiple regression model ($R^2 = 0.945$) was developed from historical data, 1971-92, to predict pecan [*Carya illinoensis* (Wangenh.) C. Koch] production in an arid climate at high elevations. Dependent variables were year of production as a measure of production trend, number of degrees below 0.6°C following budbreak as a measure of late spring freeze injury, and number of degrees below 0.6°C preceding nut maturity as a measure of early fall freeze injury. Year of production was the dominant factor influencing production. Freezing temperature following budbreak had about two times more effect on production than freezing temperature preceding nut maturity. Pecan production under arid conditions at high elevations depends on fewer variables (three) than previously shown for humid conditions (eight variables).

A mathematical model was developed recently that predicted pecan nut production under humid conditions with an R^2 equal to 0.908 using a complex of eight variables (Sparks, 1996). Five of the variables were directly or indirectly related to rainfall during critical tree and fruit developmental stages in the current and previous growing season. Rainfall determined production directly by influencing soil moisture for growth and indirectly by creating conducive conditions for scab [*Cladosporium caryigenum* (Ell. & Langl.) Gottwald], the major disease of the foliage and fruit. Production increased with the previous year's heating degree-days. The model revealed alternate bearing to be a relatively minor factor. Major factors controlling nut production in order of importance could be summarized as 1) excessive or deficient soil moisture during fruit elongation and expansion, especially during the previous growing season; 2) high humidities conducive to scab disease; and 3) drought during the period of kernel development in either the previous or current year. Thus, the dominant constituent regulating yield in a humid climate is the rainfall during the years preceding and during production.

Factors controlling pecan production in an arid climate should be independent of the rainfall dominating in a humid climate. Soil moisture in arid areas is regulated primarily by flood irrigation; thus, humid conditions created by rainfall are insufficient for disease development on the foliage and fruit. However, a marginally short growing season characteristic of high-elevation, temperate climates would be detrimental in some years. The objective of this study was to develop a model for predicting nut production under arid conditions at high elevations. A model would have practical applications for processors in estimating the current year's nut supply and would also estimate the relative importance of individual variables on pecan production.

Materials and Methods

Production data used to construct the model were reported by the National Agricultural Statistics Service (1973-96) for the 22-year period of 1971-92 for New Mexico (Fig. 1). New Mexico was selected for determining variables affecting nut production in an arid climate at high elevations for four reasons. First, New Mexico's

geography fits the typical classification of an arid climate with only ≈ 260 mm of rainfall (Las Cruces) per year (National Climatic Data Center, 1971-95). Second, elevation in the pecan growing region of New Mexico ranges from ≈ 914 to 1326 m (Bryant, 1976). Third, New Mexico accounts for $\approx 50\%$ of the total production in the arid pecan growing regions of the United States (Herrera, 1995a). Fourth, New Mexico has produced pecans longer than any other arid region in the United States, thus furnishing an ample historical production record. As mentioned, the model was derived from reported production from 1971-92 and its precision was validated by production in 1993-95 according to the National Agricultural Statistics Service (1973-96). Data before 1971 were not integrated into the model because pecan production was limited primarily to one grower (Sparks, 1997).

Variables (Table 1) analyzed as significant in a model to predict nut production included 1) year of production, 2) previous year's production, 3) previous year's heating degree-days, 4) current year's heating degree-days, 5) freezing temperatures following

Fig. 1. Pecan production in New Mexico, 1971-92. The relationship to time (smooth line) is $Y = 55536 - 3754652(1/X)$, $r^2 = 0.9048$, $SEE \pm 1236$, $P \leq 0.05$.

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¹Professor of horticulture.

Table 1. Variables analyzed for modeling pecan production.

Variable	Mean	±sd
Y = New Mexico's nut production (metric tons)	9185	3820
X ₁ = Previous year's production (metric tons)	8754	3831
X ₂ = Production trend 1971–92 or 71–92 (year)	81.5	6.3
X ₃ = Previous year's heating, April–October (degree-days)	917	80
X ₄ = Current year's heating, June–September (degree-days)	818	63
X ₅ = Degrees below 0.6 °C following budbreak (no.)	1.1	0.9
X ₆ = Degrees below 0.6 °C preceding nut maturity (no.)	1.8	1.3

Table 2. Average minimum temperature (°C) following budbreak and preceding nut maturity in New Mexico.

Location	Avg min temp ²		Elevation (m)
	Following budbreak	Preceding nut maturity	
Carlsbad	3.9	2.6	951
Artesia	0.3	0.4	1012
Hobbs	4.2	2.3	1102
Roswell	3.6	2.3	1112
Las Cruces	3.2	3.2	1183
Hatch	0.3	0.0	1235
Deming	0.5	1.5	1311
Tularosa	1.8	1.9	1350

²Temperature data assumes the same dates of budbreak and nut maturity as in the Las Cruces area. Data are averages for the 22-year period, 1971–1992.

budbreak, and 6) freezing temperatures preceding fruit maturity. Because of the desert climate, soil moisture is maintained by flood irrigation. Thus, the rationale was that rainfall would be inconsequential to production in arid climates and was not included as one of the variables tested in the model.

Numerical expression for year of production was the two-digit calendar year. The rationale was that the production year would be a measure of the change or trend in production with time. New Mexico's production increased 3-fold from 1971–81 but only ≈1.5-fold from 1981–91. Thus, the rate of increase decreased with time (Fig. 1). The rationale for including the previous year's production was that it would be a measure of alternate bearing (Sparks, 1996).

Heating degree-days were calculated from the daily mean temperature determined by averaging the maximum and minimum for the day. Calculation of the heating degree-days was the sum of the degrees over the growing season that the daily mean temperature was above base 18.3 °C, a base temperature suitable for pecan growth and development (Sparks, 1989, 1996). The previous year's heating degree-days were accumulated daily from 1 Apr. to 31 Oct. and the current year's heating degree-days were accumulated daily from 1 June to 30 Sept. The interval from 1 Apr. to 31 Oct. is the period of photosynthetic activity for the pecan tree (Mielke, 1981), and 1 June to 30 Sept. encompasses most of the fruit growth (Davis and Sparks, 1974). The rationale for analyzing these variables was to account for temperature conditions favorable or unfavorable to photosynthetic activity in the tree.

Freezing temperatures were calculated from the lowest temperature recorded within the time frame appropriate to encompass "after budbreak" and before "fruit maturity." Critical temperature for assessing freeze damage was number of degrees below 0.6 °C. Dates of budbreak were calculated by a chill-heat model (Sparks, 1993). Dates of nut maturity were determined by assuming days from budbreak to nut maturity is constant at 195 d for 'Western

Schley' (Sparks, 1992), the predominant cultivar (≈90%) in New Mexico (Herrera, 1995a). Thus, for a given year, nut maturity date was date of budbreak plus 195 d. Times of budbreak and nut maturity were for the Las Cruces area, which accounts for ≈70% of the New Mexico production (Herrera, 1995a). Temperatures after budbreak and preceding nut maturity vary geographically within the pecan growing region of New Mexico (Table 2), resulting in differences in the frequency and severity of freeze damage. For example, in 1979 an early fall freeze reduced the crop in the Roswell area (Wheeler, 1983) but New Mexico as a whole had a substantial production of 6700 t (Fig. 1). Generally, freeze damage in Las Cruces has been relatively minor. Selecting locations for freeze damage assessment is further complicated by the inconsistent temperature variations among locations from year to year. For example, the maximum and minimum r^2 was 0.615 and 0.021, respectively for low temperature following budbreak at Las Cruces from year to year with individual locations in Table 2. Freeze injury was assessed using the average of only freezing temperatures in a given year for the locations (Table 2). For instance, if a freeze occurred only for Hatch and Deming, the average temperature for these two locations was used to assess freeze damage for the entire New Mexico crop for that year. If a freeze did not occur at any location, the number of degrees below 0.6 °C was 0. The rationale for including freezing temperature before budbreak and preceding nut maturity was indirectly related to the fact that New Mexico's pecan production is situated at high elevations of ≈914 to 1326 m (Bryant, 1976), resulting in a marginal growing season for pecans from the perennial threat of late spring and early fall freezes.

Temperatures, recorded as maximum and minimum per 24 h, were taken as recorded by the National Climatic Data Center. Heating degree-days were calculated for the Las Cruces station only. Minimum temperatures after budbreak and preceding nut maturity were for all stations in Table 2.

The relationship of nut production to the variables was delineated by multiple regression analyses (Ezekiel and Fox, 1959). The equation producing the lowest standard error of the estimate (SEE) and with all partial regression coefficients statistically different from 0 was used as the final model. During the development of the model, minimization of the SEE was also used to confirm days from budbreak to nut maturity (i.e., 195 d) and to confirm number of degrees below 0.6 °C as the critical temperature for indexing freeze damage.

Once the model was finalized, the graphical relationship of nut production to late spring and early fall freezes was calculated as follows. Production trend was arbitrarily set at 88, for year 1988, and was held constant. The average value for freezing temperatures following budbreak was used while calculating the variable effect of freezing temperatures preceding nut maturity. Similarly, the average value of freezing temperatures preceding nut maturity was used when calculating the effect of freezing temperatures following budbreak. Relative importance of the individual vari-

ables on nut production was evaluated by partial r^2 . The graphical relationship illustrates the degree to which nut production can be affected by freezing temperatures in a given year, whereas, the partial r^2 s indicates the relative importance over years.

Results and Discussion

The best equation for modeling nut production was $Y = 56487 - 3702992(1/X_1) - 799X_2 - 545X_3$, where X_1 = production trend or year, 71–92 (year), X_2 = number of degrees below 0.6°C following budbreak, and X_3 = number of degrees below 0.6°C preceding nut maturity. All partial regression coefficients were significantly different from 0, ≤ 0.05 . The R^2 was 0.945 and the SEE was ± 991 t. The equation predicted production with an error ≤ 1 SE of the model or ± 991 t, in 15 of the 22 years (Table 3). The 7 years outside the SEE of 991 varied from 1110 to 1712 t and occurred for 1975, 1978, 1980, 1982, 1983, 1986, and 1987. Regardless, the extremes were within the error of the model. Thus, the relationship of nut production predicted from the model to New Mexico's pecan production was acceptable (Fig. 2). Yield residuals were randomly distributed over years (Fig. 3), indicating the model was not appreciably biased with time.

Change in production has been dominated by trend or time. Trend has had ≈ 22.5 times more effect on production than the combined effects of damage from late spring and early fall freezes. Freezing temperatures following budbreak had about two times more effect on production than freezing temperature preceding nut maturity (Table 4).

As indicated by the modeling equation, nut production increased at a decreasing rate with production trend. Increase in

Table 3. Accuracy of pecan nut production predicted from the climatic model.

Year	t $\times$ 1000		
	Observed production	Predicted production	Observed – predicted
1971	1.9	2.0	-0.1
1972	3.7	3.7	0.0
1973	3.9	4.6	-0.7
1974	6.0	5.6	0.4
1975	5.9	4.8	1.1
1976	5.2	5.4	-0.2
1977	7.0	7.1	-0.1
1978	6.8	8.0	-1.2
1979	6.7	7.5	-0.8
1980	6.7	7.8	-1.1
1981	9.1	8.3	0.8
1982	11.3	10.0	1.3
1983	13.2	11.9	1.3
1984	10.9	10.6	0.3
1985	13.2	12.5	0.7
1986	12.2	10.6	1.6
1987	11.3	13.1	-1.8
1988	11.8	12.6	-0.8
1989	13.2	13.6	-0.4
1990	15.4	14.7	0.7
1991	13.2	13.2	0.0
1992	13.6	14.4	-0.8
1993 ^z	16.3	14.9	1.4
1994 ^z	10.9	12.2	-1.3
1995 ^z	20.4	14.7	-5.7

^zYears used for model validation.

production at a decreasing rate with time suggests a sigmoidal response. A sigmoidal response is supported by the fact that production increased proportionally with production level during the previous year (Fig. 4). The sigmoidal response is apparently due to the massive planting of pecan from 1965 to about 1975 (Stahmann, 1975) followed by plantings that increased at a decreasing rate (Pena, 1995).

The positive relationship of current production to the previous year's production (Fig. 4) contrasts with the negative relationship

Fig. 2. Relationship of predicted vs. New Mexico's nut production, 1971–92. The relationship is described by $Y = 505.4 + 0.9450X$, $r^2 = 0.945$, SEE ± 914 , $P \leq 0.05$.

Fig. 3. Distribution of yield residuals with time resulting from the model used to predict New Mexico's pecan production.

Table 4. Importance of dependent variables on pecan production.

Dependent variable	Partial r^2
Production trend 1971–92 or 71–92 (year)	0.9048
Degrees below 0.6 °C following budbreak (no.)	0.0268
Degrees below 0.6 °C preceding nut maturity (no.)	0.0133
Total	0.9449

in the model for humid conditions (Sparks, 1996). This implies that alternate bearing is not a factor in New Mexico's pecan production. Tree hedging, which is widely used, apparently controls alternate bearing. Also, alternate bearing, which may occur on an individual orchard basis, is masked by the increasing growth of the industry as a whole (Sparks, 1997). Similarly, alternate bearing is not strongly supported by variation in production over time (Fig. 1). Production for 1983–85 might suggest alternate bearing. If so, the effect is minor. However, during this interval, the model predicted production with good precision (Table 3), suggesting that production variation was due to damaging freezes and not to alternate bearing.

Although spring and fall freezes have a minor effect on production compared with the long-term trend (Table 4), damage within a given year can be substantial (Fig. 5) and can greatly surpass the trend effect. For example, the increase in production due to trend was 450 t from 1991 to 1992, whereas the decrease in production could have been ≥ 3000 t depending on the intensity of a spring freeze (Fig. 5). A fall freeze could further reduce production. Thus, within a year, realization of production potential depends far more on occurrence of freezes than on trend. Within a given year, spring freezes will decrease production ≈ 1.5 times more than fall freezes (quotient of partial regression coefficients in equation and Fig. 5). Spring freezes would be expected to have more impact on production, as the developing bud, shoot, or both may be killed, whereas early fall freezes may inflict less severe damage to the fruit. A fruit close to maturity may have little or no damage, but, 10 d before shuck dehiscence, damage to the fruit may be more severe. Even then, the

damage will vary in proportion to the severity of the freeze. Furthermore, shucks that were frozen can be removed mechanically and a marketable kernel may be retrieved.

Nut production was not related to heating degree-days accumulated during the current or previous year. The previous year's heating degree-days were a factor influencing production under humid conditions (Sparks, 1996). In the model for humid conditions, heating degree-days was used as an estimate of the effect of variation in sunlight and temperature from intermittent, variable cloud cover characteristic of humid climates. On this basis, pecan production in clear-sky, arid climates would not be expected to be related to heating degree-days. The lack of a correlation also suggests that variation in heating degree-days, as such, either in the previous or current year, do not affect pecan production. Bryant (1976) similarly concluded the lack of a positive correlation between nut production and the current season's heat accumulation. The lack of a correlation (linear or curvilinear) with production does not support the contention (Bryant, 1976) that high temperatures adversely affect pecan production. The contention that high temperatures adversely affect production may have been prompted by the assumption that, if pecans are grown under arid conditions, excessively warm temperatures are inherent. If so, the premise is not valid, as heat accumulation in the humid climate of Georgia is much higher than in Las Cruces (Sparks, 1996, 1997).

Compared to growing pecans in a humid climate (Sparks, 1996), predicting pecan production in an arid climate is relatively simple. In the arid area studied, production variation mainly depends on trend, with variation in climate (freeze dates) accounting for only $\approx 4\%$ of total fluctuations in production (Table 4). In contrast, variation in climate accounts for $\approx 50\%$ of production fluctuations under humid conditions (Sparks, 1996). Thus, climate in a humid region complicates predicting pecan production.

Production for the years used for model validation, 1993 and 1994, was predicted within the error of the model (Table 3).

Fig. 4. Relationship of current year's production to previous year's production. The relationship follows $Y = 1151.6 + 0.9177X$, $r^2 = 0.847$, $SEE \pm 1568$, $P \leq 0.05$.

Fig. 5. Pecan production as a function of freezing temperature following budbreak and preceding nut maturity.

However, this was not true for 1995, when the official crop estimate was ≈ 6 SE above the estimate predicted from the model. The initial official estimate for the 1995 crop was 13,600 t (National Agricultural Statistics Service, 1996), which is close to the 14,700 t estimated by the model (Table 3). The National Pecan Shellers Association rejected the initial estimate and maintained that the estimate should be 19,000 t (Davenport, 1996). Eventually, the National Agricultural Statistics Service adjusted its original estimate from 13,600 to 20,400 t. Based on the model, the final official estimate, as well as the estimate of the National Pecan Shellers Association, was unrealistic, and the initial official estimate of 13,600 t was closer to actual production.

With time, the model may require revision. The curve in Fig. 1 suggests that production will eventually approach a maximum as trees mature and few new orchards are planted. Once production maximization occurs, alternate bearing may become a problem. If so, an index of alternate bearing will have to be included in the model. However, the shape of the curve may be contingent on production derived from the ongoing practice of removing mature trees from crowded orchards and transplanting them to new orchard sites (Herrera, 1995b). The model assumes that crop loss is directly proportional to the severity of the freeze. That is, the lower the temperature is below freezing, the greater the percentage of the pecan producing area damaged. The model is developed from data within a time interval in which freezes have generally not occurred in Las Cruces. For this reason, the model will not accurately detect production lost if the entire pecan producing area is frozen following budbreak or preceding nut maturity. The effect of freezes on production could be better estimated if the percentage of total production associated with the weather stations used in developing the model was known. Regardless, the model predicted production with acceptable precision; indicates that late spring and early fall freezes are perennial threats in arid, high-elevation areas; and shows that production in an arid climate can be predicted based on fewer variables than needed to predict production in a humid climate.

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