Pollination Characteristics of Pecan Trees and Orchards

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SUMMARY. There is increasing evidence of substantial pollination related crop losses by pecan [*Carya illinoensis* (Wangenh.) K. Koch] orchards. These most likely occur in block-type orchards consisting of only one or two cultivars, but can also occur at locations with a great number of different genotypes nearby. Main crop cultivars should generally be within about two rows of pollinizers to ensure cross-pollination. Thus, block widths exceeding about four rows between pollinizers are especially likely to exhibit serious pollination problems. Scattered trees of off-type genotypes are potentially of major importance as backup orchard pollinizers. Tree age/size and spring temperatures influence the characteristics of flower maturity windows and are probably primary factors contributing to pollination-related fruit-set losses in many block-type orchards. Flower maturity tends to be earlier in older/larger trees while warmer springs accelerate catkin development relative to that of pistillate flowers. Because of substantial variability in relative differences associated with initiation and duration of flower maturity windows within either protandrous or protogynous flowering types (i.e., Type I or II), selection of complementary pollinizers should be based on the relatively high resolution 30-class flowering classification system rather than the traditional low resolution 2-class system. Other factors sometime causing pollination related crop losses are either abnormally wet weather or strong dry winds during the pollination period or abnormally warm or cool springs. Pollination problems can be visually detected by noting premature non insect related post pollination fruit drop or diminishing fruit set with increasing distance from pollinator trees or off-type genotypes within the orchard.

Pecan is a silvicultural (Fowells, 1965) and horticultural crop (Flack, 1970; Wood et al., 1990). Its native range appears to extend discontinuously from northern Iowa (42° 20' N. Lat.) in the United States to the vicinity of Oaxaca (16° 30' N. Lat.) in southern Mexico (Thompson and Grauke, 1991) where it grows along the floodplain of the Mississippi, Ohio, Arkansas, Illinois, Missouri, Nueces, Colorado, Brazos, Trinity and Red Rivers and their tributaries and in isolated pockets along the small rivers of central and southern Mexico (Fowells, 1965). As a popular horticultural crop, pecan is increasingly planted outside of its native range in the U.S. and is also planted worldwide. Even in the U.S., orchards can be at least 1,000 miles (1,600 km) from the nearest native stands.

Many pecan plantings, both within and outside of the native range, are established in large blocks consisting of only one or two cultivars. This is with the assumption that sufficient cross-pollination for good fruit set is not problematic.

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This is based on the copious production of pollen by trees (Woodroof, 1924), long distance dispersal by wind, likely proximity of trees within the neighborhood, and relatively high viability of pollen grains (Woodroof, 1927). For example, a single 13-year-old 'Mantura' pecan tree was reported to produce pollen sufficient for the production of 29 billion nuts (Woodroof and Woodroof, 1924). Thus, pecan pollination has received little attention since the early 1930s until recently.

Pecan orchards in the U.S. were first established in the late 1800s and early 1900s. The importance of careful selection of cultivars to compensate for dichogamy and climatically induced variations in pollen maturity and dispersal patterns has been repeatedly stressed (Adrian, 1931; Madden and Brown, 1975; Marquard, 1988; Romberg, 1931; Smith and Romberg, 1932, 1940; Stuckey, 1916; Wood 1997; Wood and Marquard 1992; Wood et al., 1997). Many of these original orchards are still cultivated. It was recognized as early as 1916 by Stuckey that orchards should be established using complementary cultivars in close proximity in order to ensure proper fruit set; however, most early orchards were planted in large blocks of only one or two cultivars. The frequency of off-type trees, due to graft failures was usually substantial, thus providing serendipitous and random sources of pollen within orchards. Recent investigations into poor fruit set and filling problems in orchards appearing to receiving near optimal culture found that cross-pollination remains a problem in many orchards (Marquard, 1992; Wood and Marquard, 1992; Wood, 1997). Pecan pollination characteristics and factors affecting pollination are therefore reviewed to provide insight into how to minimize pollination related crop losses.

Flowering types

Pecan is a wind pollinated monoecious crop exhibiting heterodichogamy (Adrian, 1930; Grauke and Thompson, 1996). Flowering is dichogamous within an individual tree or cultivar. Thus, there is a difference in the location and timing of functioning female and male organs. This characteristic encourages out-crossing and ensuring genetic diversity in wild popu-

lations. Individual trees and cultivars are therefore almost always either protogynous (female organ matures first) or protandrous (male organ matures first). Protogyny is dominant, under control of a single major gene, but also with secondary modifier genes likely being involved (Thompson and Romberg, 1985). Synchrony of pollen release and pistillate flower receptivity varies from none to complete and is influenced by genotype and environmental conditions (Wood et al., 1997; Worley et al., 1992). Dichogamy is generally incomplete in most pecan cultivars. Pollination dynamics can therefore cause fruit set problems. Crop losses can be due to poor pollination, excessive self-pollination, or xenia (Romberg and Smith, 1946).

Staminate inflorescence

The staminate inflorescence (i.e., the group of catkins) is produced during the spring that pollen sheds. Two to four groups can be found at each bud site on current season shoots. These groups consist of three catkins joined to a common stalk. Protogynous cultivars produce long, thin catkins possessing long, thin bracts whereas protandrous cultivars produce relatively short, wider catkins and bracts (Woodroof and Woodroof, 1929). The dichogamy type of most cultivars is therefore relatively easily identified from a distance by the general appearance of catkins. Protogynous and protandrous cultivars also differ in that the development of catkins is such that protogynous cultivars initiate anthers on catkins during the spring that pollen is shed whereas protandrous cultivars do so the summer prior to pollen shed (Wetzstein and Sparks, 1984). These catkins are composed of about 100 to 400 individual staminate flowers with each anther possessing four pollen sacs containing about 365 pollen grains each (Woodroof, 1930).

Pollen characteristics

Pecan pollen was studied by Wetzstein and Sparks (1985). They found pollen to be triplicate, paraisopolar, and suboblate, with a tectate and microechinate surface. The pores are located toward one pole and are thus within one hemisphere (i.e., paraisopolar). Grains are circular in polar view and suboblate in equatorial view. Grains exhibit three apertures (triplicate) which are circular and non-

bordered with the exine thickening around these pores. The surface of the pollen grain is tectate and microechinate or spiniferous with surface sculptures being scattered and about 0.2 μ m high. Structurally malformed grains appear to be uncommon, but are enfolded at anthesis. When pollen is placed on a moist stigmatic surface or on germination medium, it hydrates quickly, becomes spherical, and can produce a pollen tube within about 1 h. Observations by Wetzstein and Sparks (1985) suggests that pollen under field conditions is short-lived, because germination percentage decreasing rapidly after storage 5 d at room temperature. Similarly, Woodroof (1930) found that pollen failed to germinate after 72 to 96 h of storage at room temperature. There seems to be insufficient morphological differences among cultivars to allow for identification to the cultivar level based on morphology, although identification is possible by molecular approaches (Wetzstein and Sparks, 1985).

Dispersal strategy

Pollen dispersal within trees varies with tree position. Catkins located in the lower interior of the tree usually shedding first whereas those at the top of the tree shed last. Within a current season shoot, pollen release proceeds from the base of the shoot toward the tip. Because pollen maturity is closely linked with bud break, years experiencing weather conditions leading to uneven bud break will also exhibit uneven pollen shed. Rate of flower development is influenced by temperature, thus abnormally warm or cool springs not only alter the date of pollen shed, but also disrupts the timing of flower maturity between male and female flowers because their relative maturity rates do not respond equally to changes in temperature (Wood, 1997). Thus, unusual spring temperatures can alter pollen shed and stigma maturity windows and lead to insufficient pollination.

Pollen is shed when the mature pollen sacs longitudinally split upon drying (Woodroof, 1930). Released pollen grains are flattened or concaved, thus providing greater lift and ability to be dispersed by wind before settling to the ground. A gentle tap or shaking of limbs will release a cloud of pollen when conditions are met for dehiscence.

cence. Timing of this dehiscence is strongly influenced by both temperature and relative humidity of the surrounding air. Dehiscence appears to occur when relative humidity is below about 85% (Woodroof and Woodroof, 1929), thus dehiscence in the humid southeastern U.S. usually does not occur before mid morning whereas shed can begin earlier in the drier southwestern U.S. Dry air at relatively high temperatures, especially with winds to desiccate the anther will hasten pollen dispersal and also shorten duration of release by the tree. These conditions also shorten the pistil's receptivity period. Conversely, moist and cool conditions can lead to a protracted and delayed dispersal of pollen and can extend the period of pistil receptivity. Especially wet conditions can result in an immense release of pollen as soon as lower humidity (i.e., less than about 85%) allow the anthers to split. The period of pollen dispersal can extend from about 3 to 10+ d, depending upon environmental factors. The pattern of release exhibits a normal distribution, but can be skewed due to environmental reasons.

Pistillate inflorescence

To achieve proper fruit set it is important that pistillate flowers receive the proper amount of pollen at the proper time and that environmental conditions are suitable for pollen germination and subsequent fertilization. These pistillate flower targets are produced in a cluster, on a spike, at the tip of current season shoots. These flowers are differentiated in early spring after receiving a requisite exposure to low temperatures (Amling and Amling, 1983) and typically result in 1 to 6 flowers per cluster. Abnormal weather or insect damage can occasionally produce clusters consisting of about 20 to 100 flowers, of which most typically set fruit.

The maturation of pistillate flowers proceeds acropetally, from the base to the tip of the cluster. The bilobed stigma of the developing pistil occurs in a variety of colors, sizes, and shapes, depending upon cultivar. For example, color can range from dark green to light green to yellow to pink to red to purple. Stigma color appears to be unrelated to time of receptivity. The surface of the stigma develops a wet-like appearance at or about the time that they become receptive (Wetzstein

and Sparks, 1983). This appearance is thought to be closely associated with the state of receptivity (Woodroof and Woodroof, 1926; Adriance, 1931). The stigmatic surface has rounded, projecting papillae that give it a rough appearance. These papillae excrete an exudate that secures pollen grains to the stigmatic surface upon contact. This non copious surface exudate forms a pattern of thicker and thinner patches and appears to correspond to the Heslop-Harrison and Shivanna's Group IIBi stigma type (Heslop-Harrison and Shivanna, 1977; Wetzstein and Sparks, 1986). The adherence of pollen dusted onto the stigmatic surface is generally regarded as reflecting the window of receptivity and is therefore used to describe maturity patterns for cultivars in attempts to ensure selection of complementary cultivars in plantings. Individual flowers and the flowers within a single cluster are usually receptive within a about 2 d period (Smith and Romberg, 1941), however a span of about 4 to 10+ d occur for all flowers within a tree to become receptive (Wood et al., 1997). The maturity pattern for pistillate flowers is that of a normal curve, but can be substantially skewed due to temperature, humidity and likely other environmental factors.

Fertilization process

Pollen grains are polarly flattened at anthesis, but become rounded and fully hydrated within about 1 h after exposure to the exudate found on the surface of receptive stigmas (Wetzstein and Sparks, 1989). After pollination, pollen grains appear to germinate within about 3 h (Wetzstein and Sparks, 1989) with pollen tubes growing along the stigmatic cell surfaces and downward toward papilla cell junctions where they enter the stigmatic surface between adjacent stigmatic cells. They then grow rapidly toward the ovule. This growth has been estimated to have been about $150 \mu\text{m}\cdot\text{h}^{-1}$ from 3 to 8 h after pollination (Marquard, 1992). The stigmatic surface begins to degenerate shortly after being pollinized, resulting in a general darkening of the stigmatic surface beginning within about 24 h of pollination (Wetzstein and Sparks, 1989). Stigmatic cells are flattened by about 48 h after pollination. McKay (1947) observed that polar fusion of the nucleus with one of the male gametes occurs about 4 h after

pollination, resulting in the formation of the endosperm nucleus. This nuclear endosperm is recognized in developing fruit as the liquid endosperm (Woodroof, 1928; Yates and Sparks, 1993). The second gamete fuses with the egg about 4 to 7 d post pollination.

If stigmatic surfaces receive excessive pollen, such as in controlled crosses, proper fertilization does not occur, causing fruit to abort within a few weeks after being pollinized (Romberg and Smith, 1950). There is circumstantial evidence in english walnut (*Juglans regia* L.) that the temperature at which pollen develops can influence its germination characteristics when exposed to higher or lower temperatures (Polito et al., 1991). If such a temperature adaptation response occurs in pecan then a substantial rise or fall in temperatures during the pollination period might result in poor germination of pollen on the stigmatic surface and subsequently reduced fruit set. It is also observed in walnut that orchard trees of certain cultivars often experience yield losses due to exposure to excessive amounts of pollen (McGraham et al., 1994). This trait appears to occur for only a few walnut varieties (G.S. Sibbett, personal communication) and is not presently known to occur in pecan cultivars in orchards.

Pollination related fruit drop

Developing pecan fruit can abort during the time prior to pollination to many months afterwards. Pollination appears to play a role in fruit drop, with pollination problems potentially being recognized by the degree and pattern of fruit drop. Four categories of fruit drop have been described that covers the entire fruit development period (Sparks and Madden, 1985). It was long recognized that pistillate flowers abscising at the time of full bloom are weak and underdeveloped (Woodroof, 1928). The occurrence of such flowers and the associated drop is inversely related to shoot vigor (Isbell, 1928). The second drop, occurs just after pollination, begins about 14 d after pollination and continuing up to about 45 d post pollination (Smith and Romberg, 1941). This drop coincides with non pollinated controls, therefore being thought to be due to lack of fertilization (Sparks and Madden, 1985). This drop also occurs when trees are self-pollinated. Thus fruit drop

from about 14 to 45 d after pollination is likely due to problems with pollen availability or to self-pollination. A third drop occurs about 54 to 90 d post pollination and corresponds with the first and subsequent divisions of the zygote (McKay, 1947). This drop is thought to be due to failure of the zygote to divide, resulting in abortion of the embryo shortly thereafter. This drop appears to be enhanced by self-pollination (Sparks and Madden, 1985). The fourth drop tends to be more subtle than the previous three drops, is associated with apparent embryo abortion where the embryo shrivels with no discoloration of the seed coat or accompanying tissues. This drop may also be associated with self-pollination or incompatible parentage.

Incompatibilities

It appears that viable pollen from any pecan source can successfully fertilize pistillate flowers. However, circumstantial evidence indicates the existence of incompatibilities to such a degree that certain cultivars appear to tolerate self-pollination much better than do others and that certain pollen parents produce greater fruit sets than others (personal observations). Pecan also exhibits a xenia effect in that pollen source affects kernel filling and perhaps other nut characteristics (Romberg and Smith, 1946).

Pollination problems

A rapid increase in establishment of pecan orchards in the southwestern U.S., far outside of the native range, led to a renewal of interest in pollination related concerns in commercial orchards. Investigation of these orchards by Marquard (1988) revealed that pollination problems were more common and severe than commonly supposed. Most southwestern orchards consist of 'Wichita' and 'Western Schley', both generally regarded as mutually complementary. It was discovered in these orchards that yield losses occur when pollinizers are two or more rows away from the main crop. Much of this loss was associated with reduced kernel quality due to self-pollination. The further trees were from the pollinizer, the greater was the percentage of self-pollination.

Relative abundance of diverse cultivars and feral germplasm proximate to most orchards in the central and southeastern U.S. has contributed to the commonly accepted belief that pollina-

tion is not a problem in this region where most of the U.S. pecan production originates (Wood et al., 1990). This was partially based on observations of the great abundance (Woodroof, 1924, 1930) and mobility (Woodroof and Woodroof, 1927) of pollen produced by trees and its potential availability to regional orchards. Nevertheless, the detection of extensive self-pollination in many southeastern block-type orchards by Wood and Marquard (1992) using isozyme techniques suggests that pollinizer-related crop losses are far more likely than commonly supposed and is especially likely to occur in block-type orchards. Thus, for the first time since the first half of the 20th century (Stuckey, 1916; Adriance, 1931; Romberg, 1931; Smith and Romberg, 1946) these findings not only raise the question of serious pollination problems in areas where pecan is commonly cultivated, but also quantified severity of problem in orchards typical of many within the region.

An intensification of efforts to study pollination in block-type planting in Georgia demonstrated pollination problems in a 'Desirable'/'Stuart' (i.e., 20 rows 'Desirable' and 4 rows of 'Stuart' in a repeating pattern) orchard (Wood, 1997). 'Desirable' was grown as the main crop and 'Stuart' as the pollinizer. This combination has historically been regarded as mutually complementary in regards to flower maturity. The investigation revealed serious pollination related fruit set problems in certain years and with a sigmoidal decline in fruit set in 'Desirable' trees as distance from the 'Stuart' pollinator increased. It was also evident in such orchards that off-genotypes (i.e., other cultivars or seedling trees) in the central region of these blocks were usually surrounded by 'Desirable' trees with heavy fruit set, but with declining fruit set with increasing distance from the off-type genotypes. Thus, off-genotypes are potentially of substantial importance as backup pollinizers and therefore ensure against crop losses due to poor pollination. This study showed that maximum fruit set occurs on rows immediately adjacent to the pollinizer and that crop trees should not be more than two trees from the pollinizer if pollen related crop loss is to be avoided. Thus, blocks should probably not consist of more than four rows of a single cultivar before joining a pollinizer row. It appears that proper pollination is more closely linked to the

amount of canopy between the pollinizer and the target tree than to the distance the target tree is separated from the pollinizer. This study suggests that greatest cross-pollination is achieved when trees are adjacent to pollinizers and that the amount of canopy pollen must penetrate to reach target trees is more important than is the distance that pollen travels.

Experiences related by orchard managers in areas outside the native range of pecan indicate that highest kernel quality occurs when trees are adjacent to pollinizers and that quality declines with increasing row distance from the pollinizer. This likely reflects a self-pollination problem, although reduced fruit-set may also be involved. Similarly, highest fruit quality and yields are reported on trees in plantings consisting of alternating rows of two complementary varieties (such as 'Wichita' and 'Western Schley'). Trees in many southeastern U.S. orchards typically exhibit greatest fruit-set when either downwind from wild or feral trees or on the windward margins of orchards.

Pollination related problems can also occur in orchards located in regions where wild pecan trees are abundant. The potential for a population of wild trees to produce a great abundance of pollen dispersed over a long period of time is suggestive that cross-pollination is unlikely to be a problem in block-type planting near wild trees. However, this does not always appear to be the case. For example, a large 'Wichita' orchard along the Colorado River in Texas exhibited near total crop failure—in a season following an abnormally dry autumn, winter, and spring—except for trees along the edge of the orchard facing the river where canopies were exposed to pollen from wild trees. Fruit-set in this orchard declined from the perimeter to the interior with fruit-set decreasing sharply after 4 rows into the orchard (personal observation). Thus, crop losses due to poor cross-pollination can also occur at locations with abundant wild trees.

Influence of spraying during pollination periods

The influence of foliar sprays of trace elements or pesticides on fertilization of pistillate flowers, when applied at or about the time of stigma receptivity, have been of concern as factors potentially contributing to pollination related crop losses. Research

by He and Wetzstein (1994) indicated that certain fungicides applied during microspore development may potentially influence fertilization. Subse-

quent field studies by Reilly and Wood (1996) evaluated the impact of standard foliar zinc and fungicide sprays (i.e., propiconazole, fentin hydroxide,

or fenbuconazole) found no detectable influence on fertilization or fruit-set of either 'Cheyenne' or 'Desirable' trees in orchards. However, the effect

Table 1. Flowering classification of pecan cultivars at different ages. Classes reflect pollination and receptivity periods for ensuring cross-pollination. Type I = protandrous (pollen releasing first), Type II = protogynous (pistillate flowers receptive first); VE = very early, E = early, M = mid, L = late, VL = very late maturity of the respective flower type.^z

Type I				Type II			
Tree age (years)							
Cultivar	<10	10-20	>20	Cultivar	<10	10-20	>20
Dependable	I-E/L	I-E/M	I-E/M	Frotscher	II-VE/E	II-E/M	II-E/M
Cheyenne	I-E/M	I-E/M	I-M/M	Elliott	II-VE/M	II-E/M	II-E/M
Pawnee	I-E/M	I-E/M	I-M/L	San Saba	II-E/M	II-E/L	II-M/M
Centennial	I-E/M	I-E/M	I-E/M	Schley	II-E/M	II-E/M	II-E/M
Cherokee	I-E/M	I-E/M	I-M/M	Shawnee	II-E/M	II-E/M	II-L/VL
Cape Fear	I-E/M	I-E/M	I-E/M	Gloria Grande	II-E/M	II-E/M	II-M/L
Evers	I-E/M	I-E/M	I-E/M	Delmas	II-E/M	II-E/M	II-M/L
Owens	I-E/M	I-E/M	I-M/L	Candy	II-E/M	II-E/M	II-M/L
Desirable	I-E/L	I-E/M	I-E/M	Podsednik	-	II-E/M	II-E/M
Woodard	I-M/L	I-E/M	I-E/M	Teche	II-E/M	II-E/M	II-E/M
Alley	I-E/L	I-E/M	I-E/M	Wichita	II-E/M	II-E/L	II-M/L
Moore	I-E/L	I-E/M	I-E/M	Chickasaw	II-E/M	II-E/M	II-E/M
Caddo	I-E/L	I-E/M	I-M/L	Kernoodle	II-E/M	II-E/M	II-M/L
San Saba Imp.	I-E/L	I-E/M	I-E/M	Waukeenah	II-E/M	II-E/M	II-E/M
Jackson	I-E/L	I-E/M	I-M/M	Hirschi	II-E/M	II-E/M	-
Mobile	I-E/L	I-E/M	I-M/M	Cowley	II-E/L	II-E/L	II-E/L
Harris Super	I-E/VL	I-E/M	I-M/M	Mahan	II-M/M	II-E/L	II-M/L
Barton	I-M/M	I-M/M	I-M/M	Forkert	-	II-M/M	II-L/VL
Kiowa	I-M/M	-	- ^x	Odom	II-M/M	II-E/M	II-E/M
Forkert	I-M/M	-	-	Shoshoni	II-M/M	II-E/M	II-M/L
Western Schley	I-M/M	I-E/M	I-M/M	Sioux	II-M/M	II-E/M	II-L/VL
Riverside	I-M/L	I-E/M	I-E/M	Apache	II-M/M	II-E/M	II-E/M
GraCross	I-M/L	I-M/L	I-M/L	Van Deman	II-M/M	II-E/M	II-M/L
Pabst	I-M/L	I-E/L	I-M/M	Mohawk	II-M/M	II-M/M	II-M/M
Success	I-M/L	I-E/M	I-E/M	GraBohls	II-M/M	II-E/M	II-M/L
Podsednik	I-M/L	-	-	Stuart	II-M/LH	II-E/L	II-M/L
Squirrel's Del.	I-M/L	I-E/M	-	Comanche	II-M/L	II-M/L	II-M/L
Nelson	I-M/L	I-M/L	-	Kiowa	-	II-M/L	II-M/L
Starkings H.G.	I-M/L	I-M/L	I-M/M	Choctaw	II-M/L	II-M/L	II-E/M
Major	I-M/L	I-M/L	I-M/L	Burkett	II-M/L	II-E/L	II-E/M
Dooley	I-M/VL	I-M/L	-	Moreland	II-M/L	II-E/L	II-L/L
Giles	I-M/L	I-M/L	-	Melrose	II-M/L	II-M/M	II-L/L
Farley	I-L/L	I-M/L	I-M/L	Moneymaker	II-M/L	II-E/M	II-E/M
Peruque	I-L/L	I-L/L	-	Pensacola Clu.	II-M/L	II-M/M	II-M/L
Russell	I-L/VL	I-L/L	-	Sumner	II-M/L	II-E/M	II-M/L
				Ideal	II-M/L	II-M/L	II-E/M
				Colby	II-M/L	II-M/L	-
				Green River	II-M/L	II-M/L	-
				Norton	II-M/L	II-M/L	-
				Posey	II-M/L	II-M/L	-
				Maramec	II-M/L	II-M/L	II-L/VL
				GraTex	II-L/L	II-M/L	-

^zClassification is based on flowering data from Wood et al. (1997) and Worley et al. (1992) for tree growing in Georgia (U.S.). Cultivars may interact with environmental conditions to produce flower classes if grown at locations outside the southeastern U.S.

^xClassification is as follows: 'Desirable' is classified as I-E/L as a young tree (i.e. less than 10 years old) and I-E/M as an old tree (i.e., greater than 20 years old) because of relative changes in flower development with tree age or size. Thus, 'Desirable' is a Type I, or protandrous cultivar, as a young tree it typically disperses pollen during the early (E) portion of the pollination season and displays receptive flowers during the late (L) phase of the pollination season. Therefore, as I-E/L, 'Desirable' requires a complementary cultivar, one that is classified as II-E/L for pollination (meaning that both cultivars cross-pollinate each other). Thus, as a young tree, only 'Tejas' and 'Cowley' are highly complementary with 'Desirable', however, 'Desirable' can be pollinated by any cultivar possessing a II-?/L classification (where ? = VE, E, M, L, VL). This means that 'Curtis', 'Cowley', and 'Stuart', etc. are noncomplementary pollinators of young 'Desirable' trees. As a relatively old tree 'Desirable' changes flowering characteristics from I-E/L to that of I-E/M, where the receptivity period shifts from late (L) to mid (M) season. Thus, a mature 'Desirable' tree requires a II-E/M cultivar in order to be fully complementary (i.e., 'Elliott', 'Gloria Grande', and 'Sumner') whereas II-?/M and II-E/? cultivars would be only partially complementary.

*Data not available.

of these chemicals at high rates is unknown.

Boron is a nutritional amendment potentially sprayed onto foliage during pollination to enhance fruit-set. It is important in a multitude of physiological processes, including pollen germination and germ tube growth (Tisdale et al., 1993). While plum and apple orchards [*Prunus domestica* L. and *Malus sylvestris* (L.) Mill. *domestica* (Borkh.) Mansf.] sometime receive foliar B sprays to enhance fruit-set, it is presently unknown if fruit-set of pecan can be increased by B applications. Unpublished observations by the author indicate that if supplemental fertilization with B enhances fruit-set for pecan, then it probably only does so when foliar B concentration is less than 20 ppm. The effect of B nutrition and sprays to canopies likely merits further investigation.

Revised classification of flowering types

The abundance of evidence for pollination problems in commercial orchards led to reevaluation of the traditional Type I/II flowering evaluation system long used by pecan growers and extension specialists to select complementary cultivars. Type I cultivars referred to those maturing pollen first (i.e., protandrous) whereas Type II referred to those maturing the pistillate flower first (i.e., protogynous). Because most orchards have been established with the premise that pollinators were only necessary in locations without orchards within the general vicinity, many orchard exists in which there is poor cross-pollination. Additionally, if pollinators were thought to be needed, then inclusion of a single cultivar from the opposing flowering type was assumed to be adequate. Yet block-type plantings consisting of both a Type I and a Type II cultivar often exhibit pollination related yield losses. Thus, about 80 of the primary cultivars received intensive study regarding staminate and pistillate flower maturity characteristics over five years to study flowering phenograms (Worley et al., 1992; Wood et al., 1997).

The resulting flowering phenograms revealed great variability in degree of dichogamy and length of maturity windows within each dichogamy class. Thus, clearly indicating that Type I and Type II cultivars were often non complementary between classes. These results indicated that the

traditional Type I/II system is a relatively crude, low resolution, means of identifying cultivars that ensure cross-pollination. The resulting high resolution phenograms showed that pollination and receptivity windows throughout the flowering season could be logically divided into very early, early, mid, late, and very late season protandrous (Type I) and protogynous (Type II) types. Thus, allowing for the development of a relatively high 30-class Type I and Type II alternative to the standard two-class Type I/II system for selecting cultivars to ensure cross-pollination of yard and orchard trees (Table 1). The potential importance of this enhanced system becomes increasingly apparent when temperature and age/size related shifts in flower maturity windows are considered. The duration of pollinating and receptivity windows and time interval between these windows shorten as trees age (Wood, 1997). Thus, cross-pollination problems are most likely to occur in relatively young orchards (Wood, 1997). Because environmental conditions influence flower maturity, characteristics and flowering classification may vary depending upon location of cultivation.

Another factor influencing selection of complementary cultivars is the apparent importance of pollen reaching the surface of the stigmatic surface soon after becoming receptive. For 'Cheyenne', maximum fruit set occurred when pistillate flowers received pollen less than about 1 d after becoming receptive, whereas no fruit set occurred when they were pollinated greater than about 4+ d after initial receptivity (Wood, 1997). Thus, the longer receptive pistillate flowers go without pollination, the less chance for fruit set. This may be especially important in environments where stigmas are exposed to strong dry winds such as in arid environments. Orchards in Egypt exposed to strong dry winds during pollination season often display poor fruit set attributed to desiccation of the stigmatic surface of pistillate flowers whereas those protected by wind breaks exhibit normal fruit set (personal observation).

Conclusions

Pollination related problems in commercial U.S. pecan orchards are not only common but can also be severe, even in orchards near large numbers of wild trees. Losses occur as

a result of abortion of non fertilized flowers, or due to diminished fruit quality due to self-pollination. This is most likely to occur in block-type plantings composed of only one or two cultivars. Problems can be identified by pronounced non insect related post pollination fruit drop, decreasing frequency of fruit set with increasing distance from the pollinator row or from off-type genotypes.

Any one of a diverse variety of factors can contribute to cross-pollination problems, but the most likely appears to be failure to include complementary pollinizers in orchards at an appropriate row frequency from the main crop cultivar. A second factor is selection of pollinators based on the relatively low resolution 2-class Type I/II system traditionally used for selecting complementary cultivars. Use of the relatively high resolution 30-class flower maturity classification system to identify pollinators should reduce pollination related losses. Losses can also be reduced by structuring orchards such that the main crop cultivar does not occur in blocks more than four rows across while incorporating two or more complementary pollinizers to ensure cross-pollination when weather or age related factors alter flower maturity windows. The presence of off-type genotypes within orchards can potentially play a major role in ensuring cross-pollination. Such trees should receive serious consideration prior to removal or top-working. Orchards growing in regions where pistillate flowers are exposed to hot, dry winds during the time of stigma receptivity may benefit from the presence of a windrow on the windward side of the orchard so as to reduce potential losses due to drying of the stigmatic surface.

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