PECAN PRODUCTION IN NORTH AMERICA

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ABSTRACT

Future arthropod management strategies for pecan, *Carya illinoenensis* (Wangenh.) C. Koch, will likely be increasingly influenced by the cultural strategies of husbandry protocols and how they influence the alternate bearing characteristics of trees and orchards. Commercial North American pecan husbandry involves three distinct generalized commercial production strategies (i.e., native groves, seedling orchards, and improved orchards), four production subsystems (i.e., nonpruned discrete canopies, selectively pruned discrete canopies, hedge pruned discrete canopies, and hedge pruned continuous canopies), and several prominent sub-subsystems relating to water (dry vs. irrigated), nitrogen (moderate vs. high), ground cover (none vs. grasses vs. legumes vs. inter-cropping), livestock (grazing vs. nongrazing), input (organic vs. non-organic), and pest control (biological vs. chemical vs. integrated). Thus, integration of these systems and sub-subsystems yield hundreds of distinct production systems—each of which potentially influences both the nature of arthropod damage and the economic success of husbandry. The large number of native grove operations, plus the trend toward industrialization (i.e., intensively managed improved orchards), low-input management, and organic farming means that husbandry merits a considerable investment in development of commercially acceptable arthropod management strategies. Alternate bearing is a key stress physiology phenomenon to which orchard, or grove, profitability is tightly linked; therefore occupying a pivotal position on which nearly all commercially successful arthropod management practices are likely to be linked.

INTRODUCTION

Pecan, *Carya illinoenensis* (Wangenh.) C. Koch, is one of the few economically important food crops originating from North America (Flack 1970, Wood et al. 1990). It is widely cultivated within its native range and is beginning to be cropped as an exotic throughout much of North America and the world (Wood and Payne 1991). During this time as a horticultural crop, pecan has substantially advanced toward biological domestication; however, in the "evolutionary" sense, pecan remains essentially undomesticated. This is because cultivated cultivars are only slightly diverged from wild types; plus they still possess the necessary genetic fitness for unaided survival and reproduction in their native habitat (Flack 1970). As a relatively new horticultural crop, first receiving serious attention in the early 1900's, husbandry is still evolving, and strategies for arthropod management are also evolving.

Pecan orchards are long-lived (potentially >100 years), with genetic diversity being relatively low and genetic makeup essentially fixed (aside from mutations and transplants to replace missing trees). Conversely, the variety and genetic diversity of arthropod pests are potentially great and is undergoing continuous evolutionary change. Successful husbandry
therefore involves development of effective and profitable management strategies for a multitude of ever changing co-evolved (>180 species; Payne and Johnson 1979) arthropod pests. Thus, most arthropod pest problems are both complex and dynamic (Harris 1991). This means that pecan entomologists face the difficult task of developing superior pest management strategies for a continuously evolving pest in a wide variety of production approaches spanning many different environmental and tree physiological situations.

Harris (1991) reviewed pecan arthropod management approaches and concluded that progress in adapting production methods will benefit from a more integrated holistic approach. He also notes that there is need for careful consideration of each production situation and the development of an arthropod management plan consistent with the production program (Harris 1983, 1985, 1991). The success of arthropod management strategies is tied to constraints by cultural practices adopted by horticulturists and farmers. Thus, an understanding of pecan production systems, and the relative importance they possess in regards to North American production, potentially impacts the development of highly successful arthropod pest management strategies. Efforts to develop these strategies are most likely to be successful if they take into account key crop associated biological factors, such as alternate bearing, that drive cultural strategies devised by horticulturists. This report reviews North American commercial pecan production systems within which entomologists are tasked with devising successful arthropod management strategies.

PECAN PRODUCTION SYSTEMS

North American Production. Commercial nutmeat production within the United States originates from one of four distinct production regions. These regions are the a) southeast (Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Arkansas), b) northern (Tennessee, Kentucky, Indiana, Illinois, Missouri, Iowa, Kansas, and Nebraska), c) south-central (Oklahoma and Texas), and d) western (New Mexico, Arizona, Utah, Nevada, and California) (Wood 2001). The majority of production from improved orchard operations originates from the southeast regions, followed by the southwestern region. Most of the native orchard operations are in the south-central region and in Louisiana.

The 1997 Agricultural Census indicates that pecan production in the United States is currently based on about 10,107,170 managed trees (~15% nonbearing), comprising 199,168 ha (492,137 acres) (Wood 2001). These orchards and groves are dispersed among 19,900 farm operations in 24 states, and roughly produce about 158,757 t (350,000,000 lbs) of in-shell nuts annually. Similar plantings in Mexico comprise about 61,107 ha (150,998 acres) and produce about 54,000 t (120,000,000 lbs) of in-shell nuts (E. Herrera, personal communication). Fifty-six percent of commercial U.S. pecan acreage (199,198 ha) is on farms with ≥ 40.5 ha (100 acres), comprising 5% of U.S. farms. There are 905 farms managing at least 40 ha (100 acres; i.e., 5.4% of the total farms) and 124 farms managing at least 202 ha (500 acres; i.e., 0.7% of the total farms). Thus the vast majority of pecan operations are small, with 62% of U.S. pecan farms managing less than 6.1 ha (15 acres) of trees; although, most of the acreage is associated with large farms.

The skewed distribution of the number of pecan farming operations toward small planting, but concentration of acreage on relatively few farms possessing large orchards, likely has important ramifications for development of optimal pest management strategies. This is partially because the multitude of small holdings are likely to a) be influenced by both beneficials and pests from other crops and forest adjacent to the planting, b) possess low quality or underpowered spray equipment for arthropod control efforts, c) exhibit greater crop vulnerability to pests because of lower tree vigor and poorer health, due to less attention to management of fertilizer and water supplements, and d) be poorly managed from the
standpoint of practices that minimize alternate bearing (i.e., most notable that of maintaining mechanical crop thinning and pruning).

The cultivation of pecan at both exotic and indigenous locations potentially influences the nature of pecan pest management. For example, exposure of orchards or groves to a broad spectrum of well-adapted co-evolved arthropod pests and beneficials is likely to produce a pest management situation that could be either more, or possibly less, challenging than an exotic location in which an exotic pest or an introduced co-evolved pest outbreak occurs. Many arthropod pests can be potentially transported via nuts, propagation wood, or nursery trees to orchard sites outside the host native range to attack trees; thus, potentially leaving behind co-evolved beneficials that might otherwise suppress pest populations. Additionally, husbandry outside the native range, can potentially expose trees to exotic pests to which the tree has insufficient natural defenses. An example of this is the destructive impact of an indigenous Australian longhorn borer (i.e., Agriianome spinicollis (Macleay)) on tree health and longevity in certain Australian orchards (Deane Stahmann, personal communication).

The composition of pecan farming units is such that operations tend to be segregated into one of three general types of production systems. These are "native", "seedling", and "improved cultivars" tree populations. In regards to in-shell production, "improved cultivars" have dominated "natives" and "seedlings" in the U.S. since about 1970 (Fig. 1). Salient aspects of each of the three generalized production systems and notable relevance to arthropod pest management are as follows.

Native Groves. Natives are populations of trees left standing from forest that have been appropriately thinned to maximize sunlight exposure while also leaving only the best specimens. "Best" is usually based both on the size of the in-shell nut and tree health. These selected populations are termed "groves" or "native groves". There are 180+ species of arthropods that attack pecan trees (Payne and Johnson 1979), and most of these can be found in native groves. The most important of these are listed in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Scientific name</th>
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<tbody>
<tr>
<td>Pecan weevil</td>
<td>Curculio caryae (Horn)</td>
</tr>
<tr>
<td>Black pecan aphid</td>
<td>Melanocallis caryaefoliae (Davis)</td>
</tr>
<tr>
<td>Pecan nut casebearer</td>
<td>Acrobasia maxvorella Neunzig</td>
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<tr>
<td>Hickory shuckworm</td>
<td>Cydia caryana (Fitch)</td>
</tr>
<tr>
<td>Pecan leaf scorch mite</td>
<td>Eotetranychus hicroiae (McGregor)</td>
</tr>
<tr>
<td>Yellow pecan aphid</td>
<td>Monelliopsis pecanis (Bissel)</td>
</tr>
<tr>
<td>Blackmargined aphid</td>
<td>Monella caryella (Fitch)</td>
</tr>
<tr>
<td>Southern green stink bug</td>
<td>Nezara viridula (Linnaeus)</td>
</tr>
<tr>
<td>Brown stink bug</td>
<td>Euschistus servus (Say)</td>
</tr>
<tr>
<td>Dusty stink bug</td>
<td>Euschistus tristigmus (Say)</td>
</tr>
<tr>
<td>Green stink bug</td>
<td>Acrosternum hilare (Say)</td>
</tr>
<tr>
<td>Leaffooted bug</td>
<td>Leptoglossus phyllopus (Linnaeus)</td>
</tr>
</tbody>
</table>

* List provided by Ted Cottrell

The commercially most important foliar feeding pests are usually aphids [especially Monella caryella (Fitch), Melanocallis caryaefoliae (Davis), Monelliopsis pecanis (Bissel)].
FIG. 1. In-shell production (in metric tons) of "improved cultivars" (A) and "natives and seedling" (B) pecan nuts in the United States since 1930.
and pecan leaf scorch mites, *Eotetranychus hicortae* (McGregor). The most important fruit pests are usually pecan weevil, *Curculio caryae* (Horn), pecan nut casebearer, *Acrobasins nuxvorella* Neunzig, and hickory shuckworm, *Cydia caryana* (Fitch) (Mizzell 2002). Of course, other pests can exceed these in economic importance, depending upon the orchard situation and location.

### TABLE 2. Most Common Minor Arthropod Pests of North American Pecan Groves and Orchards.a

<table>
<thead>
<tr>
<th>Common name</th>
<th>Scientific name</th>
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<tbody>
<tr>
<td>Pecan leaf phylloxera</td>
<td><em>Phylloxera notabilis</em> (Pergande)</td>
</tr>
<tr>
<td>Southern pecan leaf phylloxera</td>
<td><em>Phylloxera russelae</em> (Stoetzel)</td>
</tr>
<tr>
<td>Pecan phylloxera</td>
<td><em>Phylloxera devastatrix</em> (Pergande)</td>
</tr>
<tr>
<td>Pecan spittlebug</td>
<td><em>Clastoptera achatina</em> (Germar)</td>
</tr>
<tr>
<td>Walnut caterpillar</td>
<td><em>Datana integerima</em> (Grote &amp; Robinson)</td>
</tr>
<tr>
<td>Fall webworm</td>
<td><em>Hyphantria cunea</em> (Drury)</td>
</tr>
<tr>
<td>Pecan cigar casebearer</td>
<td><em>Coleophora laticornella</em> (Clemens)</td>
</tr>
<tr>
<td>Pecan serpentine leafminer</td>
<td><em>Stigmella juglandifoliella</em> (Clemens)</td>
</tr>
<tr>
<td>May beetle</td>
<td><em>Phyllophaga</em> spp.</td>
</tr>
<tr>
<td>Pecan leaf roll mite</td>
<td><em>Aceria caryae</em> (Kiefer)</td>
</tr>
<tr>
<td>Alder spittlebug</td>
<td><em>Clastoptera obtuse</em> (Say)</td>
</tr>
<tr>
<td>Pecan catocala</td>
<td><em>Catocala maestosa</em> (Hulst)</td>
</tr>
<tr>
<td>Pecan catocala</td>
<td><em>Catocala viduata</em> (J. E. Smith)</td>
</tr>
<tr>
<td>Pecan budmoth</td>
<td><em>Gretchina bolliana</em> (Slingerland)</td>
</tr>
<tr>
<td>Shoot curculio</td>
<td><em>Conotrachelus pecanae</em> (Nutt.)</td>
</tr>
<tr>
<td>Shoot curculio</td>
<td><em>Conotrachelus aratus</em> (Germar)</td>
</tr>
<tr>
<td>Nut curculio</td>
<td><em>Conotrachelus hicoriae</em> (Schoot)</td>
</tr>
<tr>
<td>Obscure scale</td>
<td><em>Chrysomphalus obscurus</em> (Comstock)</td>
</tr>
<tr>
<td>Potato leafhopper</td>
<td><em>Empoasca fabae</em> (Harris)</td>
</tr>
<tr>
<td>Asian ambrosa beetle</td>
<td><em>Xylosandrus crassusculus</em> (Motschulsky)</td>
</tr>
<tr>
<td>Shothole borer</td>
<td><em>Scolytus rugulosus</em> (Müller)</td>
</tr>
</tbody>
</table>

a List provided by Ted Cottrell

Relevance to Total Production. About 1/3 of the yield of in-shell nuts marketed in the U.S. is from native groves (Thompson 1984, Wood 2001). Although data are unavailable, production from native groves in Mexico is only a small percentage (<5%) of that nation's pecan production (A. Bejar, personal communication). In the U.S. industry, production from native groves typically comprises most of the crop originating from Oklahoma, Louisiana, Kansas, Missouri, and Illinois and much of it from Texas and significant amounts from Arkansas, Mississippi, and Tennessee. Because the farm-gate wholesale price received for natives is usually substantially less than that of improved trees, and because such groves typically produce only 1/3 to 1/2 (typically 560 to 1120 kg/ha in-shell nuts) the yield of improved orchards, native groves rarely benefit from intense husbandry efforts. Thus, trees are potentially under greater water, nutritional, or shade stress, plus cost of management inputs becomes a critically important factor in the development of arthropod management strategies for native groves (Reid and Eikenberry 1990).
Native groves have long occupied a prominent position in the U.S. pecan industry and will continue to do so for decades to come. In terms of number of farm operations, there are likely more farms managing native trees than those of seedling or improved trees. Additionally, the enhanced profit potential for cultivation of native groves, coupled with relatively low prices for agronomic crops in the 1980's and 1990's, has led to a substantial increase in the acreage of native trees being farmed. This effect is especially prominent in Oklahoma where a 26% increase in the number of pecan farms and an 87% increase in the number of acres of trees occurred from 1987 until 1997 (Wood 2001). Most of this increase was due to either native groves being carved from riparian forest or to renewed interest by farmers in harvesting previously abandoned native groves (M. W. Smith, personal communication).

Relevance to Arthropod Management Strategies. Native groves naturally possess relatively high genetic variability and grow on riparian sites characteristic to those in which the species evolved. Of the three distinct population classes under husbandry, natives are genetically, and also likely ecologically, most diverse; therefore, most resembling wild pecan populations. This population structure, site, and usual close proximity to forest confers substantial uniqueness regarding both pest and beneficial arthropod populations. With the exception of an occasional individual tree, populations of certain pests only occasionally reach the destructive levels commonly encountered in seedling or improved orchards. This is partially due to the relatively minor disruption of the arthropod ecosystem and high genetic diversity of host trees.

Native groves possess a distinct advantage over seedling or improved orchards, from the standpoint of control of fruit feeding arthropods, in that they possess key natural defense factors that tend to be absent, or much reduced, in the seedling or improved orchards. These factors are: a) genetic diversity of host genotypes, b) diversity of natural enemies, c) an extreme irregular bearing of individual trees (i.e., high alternate bearing index or high amplitude bearing cycles), and d) synchronized cropping (i.e., masting). For example, pecan weevil populations in native groves are partially checked via periodic masting associated with satiation and starvation. Additionally, the genetic diversity of the host population means that while individual trees may succumb, the grove population is protected from an epidemic (Browning 1980, Harris 1980).

Cultural strategies in native groves vary substantially, partly depending upon the geographical location of the grove and the importance of the grove to the overall farming operation. Management of groves of pecan is often ancillary to other crops, with cattle often being the commodity of focus, and thus being allowed to graze among the trees. In fact, many of these groves primarily function as pasture and shelter for cattle. Such groves typically support native grasses, and improved grasses or legumes. Many of these farming operations view an occasional crop of pecan nuts as a free gift from nature and thus do relatively little in way of management of cultural inputs or pests. Conversely, other operations impose a high level of management in efforts to maximize grove profitability.

The nature of management received in native groves is partially dependent upon the geographical location, or environment, of the grove. For example, groves in Texas are typically sprayed with zinc due to the influence of relatively high soil pH on suppression of root uptake and soil availability; whereas, those in Louisiana are often sprayed for pecan scab due to the influence of high humidity on susceptibility, and those in the northern part of the range in Kansas and Missouri rarely require spraying for either.

Because of the relative low price of nuts from native groves, trees usually receive relatively little regarding orchard inputs (e.g., irrigation, nutrients, pruning) and are therefore likely to experience greater physiological stress than trees of the other two orchard types. For example, native trees are usually fairly well fertilized with nitrogen, but they are rarely
irrigated. This exposure to dry soil during nut filling, and also during the time when trees are
restoring storage pools of photoassimilate and nitrogenous compounds, is likely a key
contributor to severe alternate bearing of trees in native groves.

Alternate bearing is typically biennial cycling of flowering and fruit-set, but "on" years
can also occur only every 3-5 years. Large crops ("on") of relatively poor quality nuts are
usually followed by years of little or no flowering and fruit-set ("off") with high nut quality.

Thus stress factors that trigger, or enhance the magnitude of, alternate bearing have potential
great impact on arthropod management strategies. For example, large populations of foliar
feeding arthropods, such as aphids and mites, may be a greater threat to quality nutmeat yields
from highly stressed trees in native groves than to better managed and potentially lower
stressed trees in seedling or improved orchards.

Seedling Orchards. Seedling and improved populations are planted by man and are
termed "orchards" rather than "groves." Seedling trees comprise several subclasses, based on
origin. These subclasses are: a) open-pollinated progeny of cultivars or favored natives, b) the
rootstock of transplanted trees in which the scion died, and c) outdated or archaic cultivars.

Because of usually lower wholesale prices for seedling nuts, seedling orchards typically
receive less cultural and pest management inputs than do improved orchards. They also
typically receive greater inputs than do native groves, yet there are notable exceptions.

Relevance to Total Production. It is in the southeastern U.S. that seedling orchards are
most prominent (Wood 2001). They decline in both frequency and commercial significance,
from east to west, across the U.S. pecan belt. There is little or no nut production originating
from seedling orchards west of central Texas. The most prominent states with seedling
orchards are Georgia, Alabama, and Mississippi. There is also substantial production in
Texas, Louisiana, Florida, South Carolina and North Carolina. The total contribution of
seedling derived-nuts to the annual U.S. production of pecan nuts is usually not as great as that
from native groves, yet they account for a substantial percentage of production in Georgia
 (~18%), Alabama (~62%), Florida (~62%), Mississippi (~41%) and the Carolinas (~25%).

Relevance to Arthropod Management Strategies. A usual characteristic of seedling
orchards is that there is substantial variability in nut size and shape characteristics, shelling
characteristics, nut quality, and time of fruit ripening. Thus, the resulting nut crop is usually
nonuniform and often of reduced value, at the wholesale level, than nuts from improved
orchards. This relatively low profitability of many seedling orchards means that expenditures
on pest management programs are likely to be less than that in either improved orchards or
certain native groves. Additionally, the amount of genetic diversity among trees in seedling
orchards is usually intermediate to that of native or improved orchards. This reduced
genotypic diversity and reduced economic incentive of state-of-art management often increase
the severity of problems attributable to key arthropod pests.

The tendency for less than state-of-art management means that alternate bearing intensity
is typically greater in seedling orchards than in improved orchards. For example, the level of
"I" [an index of bienniality ranging from 0-1; where 0 equals no change in production from
year to year and 1 reflects an absence of production in alternate years (Pearce and Dobersek-
Urbanc 1967)] in Georgia for seedling derived nuts is about 0.34 vs. 0.27 for nuts from
improved orchards (Wood 2001). The difference is even more dramatic for Alabama where
"I" = 0.64 for seedling nuts and 0.45 for improved nuts.

Improved Orchards. Improved orchards are clonal populations of usually one to three
cultivars. One of these cultivars typically serves as the main cultivar and the others as
pollinators. Thus, genetic variation among trees is almost always lowest in improved orchards
-some of which consist of a single cultivar. These orchards typically receive a high level of
cultural and pest management inputs.
Relevance to Total Production. Nuts from improved orchards usually are of greatest overall value to commerce. The majority of improved orchards in North America include some combination of the following cultivars: ‘Stuart’, ‘Desirable’, ‘Wichita’, ‘Western Schley’, ‘Schley’, ‘Pawnee’, ‘Cape Fear’ and ‘Sumner’. About 70% of the nuts produced within the U.S., and about 95% of those in Mexico, originate from improved orchards (Wood 2001). Within the U.S., about 40% of these originate from Georgia, 21% from Texas, and 19% from New Mexico. Almost all of the production west of central Texas is from improved orchards and about 72% of that outside of the native range within the southeastern U.S. is from improved orchards.

Relevance to Arthropod Management Strategies. Production systems associated with improved orchard operations are highly relevant to pecan pest management strategies. This is for the following reasons: a) the vast majority of in-shell pecan production in North America originates from improved orchards, and this dominance is likely to substantially increase over time, b) these orchards are often monoclonal, or nearly so, and thus the near absence of genetic diversity in the host population results in arthropod populations being of a greater potential threat to profitability, c) these orchards usually receive intense cultural management; therefore, the high investment in orchard inputs makes it critical that the investment is substantially protected from arthropod related losses, d) because trees are often managed to maximize cropping, trees are subjected to physiological conditions where foliar damage by arthropods, or damage by other arthropods to tree organs, can have great impact on both current and future yields and profits via effects on alternate bearing related physiological and developmental processes (Wood and Reilly 2000), and e) the high level of nitrogen received by these trees can have significant impact on populations of certain arthropods and subsequent damage (Wood and Reilly 2000).

The "production" related dominance of improved orchards and the increasing cost-price squeeze felt by all types of pecan farm operations, means that there is pressure on pest managers to devise strategies to reduce control costs. Because prophylactic usage of pesticides is usually impractical, and because of the potential for chemicals to reduce canopy photo assimilation (Wood and Payne 1984), and the side-effects of increasing damage due to suppression of non-target beneficials, there has been considerable progress toward the development of biorational insecticidal control and biological control strategies. The importance of the contribution of biorationals and biologicals to intensive pecan husbandry is likely to substantially increase.

PRIMARY PRODUCTION SUBSYSTEMS

Canopy Management Subsystems. Husbandry strategies in improved orchard operations are evolving such that there are four distinct cultural strategies dealing with canopy management. Each of these confers subtle side-effects on arthropod management. These four are orchards with canopies consisting of: a) hedge pruned continuous canopies, b) hedged discrete canopies, c) selectively pruned discrete canopies, and d) nonpruned discrete canopies. These cultural strategies confer substantial differences in canopy environment, tree physiological stresses, and crop loads; thus, potentially impacting certain arthropod management strategies and the degree of arthropod related stress trees can tolerate.

The increasing economic importance of a stable supply of high quality nuts by the North American pecan industry is a major contributor to considerable industry activity focusing on the control of alternate bearing by using either selective limb pruning or hedge pruning strategies. Such strategies typically increase the amount of foliage per unit of fruit crop, thus enabling trees to better tolerate certain biotic and abiotic stresses. This strategy is already becoming common practice in the southwestern U.S. and is beginning to be used in the
southeastern U.S. and Mexico. The hedge-pruning systems are especially relevant to arthropod management in that not only do trees possess a favorable leaf area to fruit ratio, but tree canopies are not as deep and are nearer to the ground. Thus, the nature of the spray application equipment, and ability to ensure good coverage of the canopy, and ability of trees to tolerate higher populations of foliar pests, potentially has great effect on future pest management strategies. These effects are both positive and negative and merit further investigation. Some potentially negative effects of these canopy management trends relate to the potential need for greater attention regarding management of insects attacking trees through cuts on limbs resulting from pruning activities. For example, hedged pruned trees in Australia suffer considerable damage from an indigenous Australian longhorn borer (i.e., *Agriamone spinicollis*), that takes advantage of cuts in large limbs to colonize trees (Deane Stahmann, personal communication). Additionally, foliar damage by potato leafhoppers, *Empoasca fabae* (Harris), greatly increases as the amount and duration of young succulent foliage within the canopy increases due to pruning. Thus, these management practices can potentially require development of new or better arthropod management strategies for these pests.

The selective limb pruning discrete canopy system also reduces tree size and opens the canopy for better penetration of insecticidal sprays, but has the side-effect of leaving behind major limbs that have been dehorned. Such practices may prove to produce infection sites for certain wood-boring pests and may merit research to assess potential threat and to devise protective strategies.

The characteristics of North American pecan orchards are likely to change slowly over the coming decades. This is largely due to the long-lived nature of pecan trees and orchards, and to the fact that many orchards can be abandoned, or receive minimal orchard management, during times of low nut prices and can be returned to intensive management during times of high nut prices. Thus, until recently, orchards or groves were rarely replaced. However, there is now a trend toward orchard renovation in which the least profitable trees are being removed and replaced with new cultivars (Goff et al. 1998).

**PRODUCTION TRENDS**

There are several production associated trends occurring in the North American pecan industry. These are partially driven by: a) the fact that pecan is a relatively new crop and is still being domesticated, b) market forces providing economic incentives to farmers able to provide a stable supply of high quality nuts, and c) the need by many farmers to maximize production and/or profits. Certain of these trends are briefly noted as follows.

**Industrialization.** The North American pecan industry is slowly evolving toward industrialization, just as has most other agricultural crops (Wood 2001). There is also a gradually increasing "cost-price" squeeze for most pecan farming operations. These two forces act to increase pressure on farmers to enhance orchard profitability. Thus husbandry practices are slowly evolving toward intensive horticultural practices that tend to focus on maximizing profit per unit of production. Thus, the relative importance of improved orchard operations is expected to substantially outpace that of seedling orchards or native groves.

If industrialization in pecan evolves according to that of many other fruit and tree nut crops, then there is the likelihood of increasingly intensive husbandry practices. These practices are likely to be imposed on orchards containing a single main crop cultivar with a couple of interspersed pollinators. In many cases this monoculture-like system will be located near other *Carya* species that share common pests. Thus the ecological events that occur inside orchards will be influenced by plants outside the orchard that support common pests. This situation—superimposed on a monoculture-like system where nutritive value, extension
of susceptibility windows, etc. - potentially affects host defense mechanisms (i.e., biological associations, confrontation, accommodation, and escapes in time and space; Grant 1977, Harris 1980) and will likely have great influence on future pest management (Mizzell 2002).

Hedge-type pruning strategies are likely to be central to many future intensive husbandry strategies. Because hedging greatly increases the amount and duration of shoots and foliage in the elongation phase of vegetative growth, a key defense mechanism is being altered, and there is likely to be much more feeding by leafhoppers. This has already been observed in hedge-pruned orchards in Australia and Georgia where feeding damaged foliage can mimic certain aspects of Zn deficiency (personal observation). Leafhoppers, especially the glassy-winged sharpshooter, can spread the Xylella fastidiosa bacterium that is implicated as a key causal factor in pecan leafscorch disease (Stevenson and Chang 2000, Sanderlin 2001). Development of a particularly virulent strain of this pathogen could create a crisis in a monoculture-like intensively managed hedge-pruned form of pecan husbandry; thus, placing a great deal of pressure on entomologists to quickly find acceptable solutions.

**Low Input Management.** The profit margin of many seedling and improved orchard units is little or none. Thus, farmers are beginning to explore the concept of low input management, especially in "off" cropping years. This low input approach involves reductions in fertilization, irrigation, and pest control (diseases, arthropods, and weeds) during the "off" year, with the expectation that profits will be greater when viewed within the context of a biennial time frame. This approach appears to be far more attractive to farmers cropping pecan in desert-like regions outside of the native range of pecan than to farm operations in indigenous production zones possessing a vast array of co-evolved indigenous pests. This approach appears to possess substantial merit in certain orchard situations; hence, there may need to be increased attention given to refinements in arthropod management strategies and spray thresholds in such orchards. This exciting aspect of husbandry merits further investigation.

The market niche of organic nuts has recently interested several farmers in developing orchards that meet organic certification requirements. The exclusion of chemical pesticides from such orchards largely limits serious organic farming to geographical locations outside of the native range of pecan, and even then they are likely to be substantially distanced from other pecan operations. The desert climates and wide open spaces of portions of western Texas, Arizona and New Mexico, and certain areas of Mexico, appear to present opportunities for this form of husbandry. As market competition stiffens for pecan nuts, it is likely that this market niche will expand. Thus, presenting entomologists with some potentially challenging opportunities that is likely to involve novel approaches to pest management.

**Increased Genetic Variability.** The concept of a polygenetic host-plant situation in orchards is beginning to attract interest among certain farmers in the southeastern U.S. (Goff et al. 1998). This approach is intended to take advantage of the benefits associated with substantial genetic variation, as is typified by native groves. It involves planting of orchards utilizing as many improved cultivars as possible that also possess resistance or tolerance to key pests such as pecan scab, black aphids, yellow aphids, and scorch mites. Because there is substantial cultivar associated variability in the amount of damage by different specific arthropod pests, such as black aphids, there is the possibility that plantings of cultivars possessing resistance or tolerance might increase profitability due to a reduction in pest control costs. It appears that a key postulate is that the strategy will slow the adaptation of pests to the host genotypes in the orchard, thus extending the potential utility of pesticides and the need for spraying. While the system possesses merit in certain respects, it suffers from a problem cultivars not possessing uniform fruit ripening date and nut characteristics. Thus, the approach possesses serious limitations for industrial level farmers, but may work well for certain small-farm operations.
Nitrogen Management. Fertilization with nitrogen is usually the most expensive nutritional supplement applied to orchards. Because of its relatively low cost compared to most other cultural inputs, it tends to be used in excess. Additionally, lack of good information about nitrogen uptake demand periods and movement through the soil profile under specific orchard situations has likely reduced the effectiveness of nitrogen added to orchards. The realization by horticulturists that N nutrition probably plays more prominent role in alternate bearing physiology than previously thought, and the realization that trees likely need relatively high late-season levels of nitrogen for good return cropping, is propelling activities to enhance late-season nitrogen levels in foliage and in the dormant season storage pool. Such practices potentially influence foliar feeding arthropod populations via the nutritive quality of foliage. Thus, the effect of high foliar nitrogen levels on foliar feeding pest populations merits investigation. Observations by Wood and Reilly (2000) on 'Cheyenne' trees indicated that higher leaf nitrogen reduced damage by the black pecan aphid, *Melanocallis caryaefoliae* (Davis), but increased damage by the pecan leaf scorch mite, *Eotetranychus hicoriae* (McGregor). Thus, the interactions between higher leaf nitrogen levels and damage by late-season arthropods could potentially alter pest management recommendations.

Zinc Management. Discovery of the ability of foliar applied zinc to correct rosette, and associated low yields, in the 1930's has led to widespread and multiple applications of zinc to orchards. This practice occurs throughout the pecan-belt and typically results in four to seven applications per growing season. The correction of rosette is considered to be one of the key factors that have propelled the growth of the North American pecan industry (Sparks 1987).

A side-effect of zinc spray applications is that orchard managers typically take advantage of the need for application of foliar zinc sprays to also add fungicides and insecticides to the spray mix, thus reducing application costs. However, a disadvantage is that managers often add chemicals to the mix that are not needed and are thus wasting money or inducing pest related problems. Thus tank mixing in association with zinc sprays has been reported to be the greatest single threat to sound arthropod management (Harris 1991). Foliar zinc sprays have been noted as being a major barrier to substantially reducing management costs (Harris et al. 1998). This is an excellent example where horticulturists can potentially modify a key cultural practice for the benefit of IPM.

There are currently research efforts underway to develop better methods of controlling zinc deficiency via small amounts of zinc applied to orchard soils. While this is most promising for acidic soils, there is a possibility that methods could also be adapted for alkaline soils. If successful, then this could have a profound effect on pest management in that foliar spraying zinc will no longer offer managers a "free ride" regarding sprayer operation costs of applying early-season pesticides to canopies. Such a revised cultural practice for zinc nutritional control is likely to cause growers to give greater consideration regarding application of insecticides and miticides. Thus, potentially improving the wise usage of pesticides, but also potentially increasing application costs.

Water Management. Most pecan farmers now have a good understanding of the critical role that water plays in alternate bearing physiology and the influence on subsequent season cropping. This results in the development of water management strategies designed to minimize stress to trees, especially during the time from kernel filling until leaf-drop. The result is that most improved orchards will be better managed in regards to water status. Thus, these orchards are likely to possess less vulnerability to significant crop damage by populations of foliar feeding pests, such as aphids and mites if tree water relations are such that trees and orchards experience minimal stress (Wood and Reilly 2000). Conversely, better water relations could potentially extend the window of susceptibility to pests that could otherwise be avoided, confronted or accommodated (Harris 1991). Thus the increasingly
popular practice of irrigation may potentially influence arthropod management strategies.

ARTHROPOD PESTS OF NORTH AMERICAN PECAN PRODUCTION SYSTEMS

There are many co-evolved and a few exotic pests of North American pecan groves and orchards that are potentially influenced by pecan production systems, subsystems, and sub-subsystems. The relatively major arthropod pests are listed in Table 1. While the identity of the most important pests vary with orchard location, the most notable pests are usually pecan weevil, Curculio caryae (Horn); pecan nut casebearer, Acrobasid nuevorella Neunzig; black aphid, Melanocallis caryaefoliae (Davis); hickory shuckworm, Cydia caryana (Fitch); and pecan leaf scorch mite, Eotetranychus hicoiae (McGregor). However, in certain cases any of the other pests listed in Table 1 can potentially be the most important pest.

The most common relatively minor pests of North American pecan groves and orchards are noted in Table 2. While this listing is not a comprehensive list of relatively minor pests, it does note many of the most common minor pests. The spittlebugs, caterpillars, scale, curculio, leafminers, twig girdlers, and root borers can cause severe, but usually spotty damage to trees and orchards.

LINKAGE OF PEST MANAGEMENT STRATEGIES TO ALTERNATE BEARING

An understanding of the nature of the nexus between successful arthropod pest management and alternate bearing is potentially of fundamental importance if useful pest management strategies are to be developed for certain arthropod pests. When alternate bearing is synchronized to produce masting, it functions in a positive fashion to reduce certain negative aspects of pests and also reduce the populations of certain arthropods (e.g., pecan weevils) (Chung et al. 1995). However, because most farmers need stable year-to-year income, the positive effects of alternate bearing and masting are greatly outweighed by the negative effects on nutmeat yield and revenue. This need for revenue therefore neutralizes a key natural defensive mechanism (i.e., escape in time via masting).

The economically single most important biological problem in pecan husbandry is the innate nature of the tree to alternately bear crops (Amling et al. 1975). The cropping pattern of individual trees is such that relatively large crops are associated with poor nut quality (i.e., "on" year), whereas, small crops exhibit high nut quality ("off" year). This biennial tendency, a highly predictable and common form of alternate bearing, is especially pronounced in commercial improved-type pecan operations (Gemoets et al. 1976; Wood 1993, 1995) and causes major revenue and marketing problems, especially if the cyclic amplitude is great.

Alternate Bearing Theory of Pecan. The fundamental physiology of alternate bearing in pecan is largely unknown. However, its study has led to the synthesis of the two salient theories, the "Carbohydrate Theory" and the "Phytohormone Theory" (Barnet and Mielke 1981), into a new theory—the "Phytohormone-Carbohydrate Theory" (Wood et al. 2003). This theory is similar to the alternate bearing theories hypothesized for several other tree-fruit crops (Greene 2000). It purports that flowering, and subsequent cropping, is fundamentally controlled at two levels. The first level is the regulatory role of flowering inhibitors and promotors (produced by developing fruit and foliage) on floral evocation and development during the previous growing season. The second level is the regulatory role on the tree's dormant season carbohydrate pool on floral development at and soon after bud break of the subsequent cropping season. The former Carbohydrate Theory functioned as a "conceptual tool" on which essentially all husbandry strategies of pecan were linked (Wood 1991). Thus, this Phytohormone-Carbohydrate Theory also possesses merit as a more refined conceptual tool that potentially enables better decision making regarding development or application of...
either cultural or pest management strategies.

Key evidence supporting this Phytohormone-Carbohydrate Theory is reported by Wood et al. (2003). Certain aspects of pecan fruiting are reviewed as follows: a) return bloom is related to date of fruit removal from the tree, with return flowering being greatest when fruit are removed early in the season, even substantially before the initiation of kernel filling (Worley 1978, Sparks and Brack 1972, Wood 1989); b) the removal of fruit during the "late water stage" (immediately prior to the initiation of kernel filling) of development has an overwhelming positive impact on return bloom before there is significant deposition of kernel dry weight (Wood 1989, Smith and Gallot 1990, Reid et al. 1993); c) water stage fruit contains high levels of gibberellin-like substances (Wood 1982), a phytohormone known to have a powerful regulatory influence on flowering in other tree species (Greene 2000) [Thus, contributing to the management practice of mechanically reducing crop loads while kernels exhibit little or no development (Smith and Gallot 1990, Smith et al. 1986, Reid et al. 1993)]; d) shoots, branches, and limbs can be bearing on a cycle opposite to that of other portions of the same tree (Wood 1991); e) there is little or no gross difference in concentration of total carbohydrates in one-year-shoots, where flowers are produced for the following crop season (Smith et al. 1986, Wood and McMeans 1982); f) cropping is closely linked to dormant season assimilate reserves, especially those in roots (Smith and Waugh 1938; Wood 1989; Worley 1979a, 1979b); g) reductions in canopy health, or longevity, enhances alternate bearing; whereas, long-lived and healthy canopies result in greater return fruit-set (Worley 1979a, 1979b); h) crop-set by certain early ripening cultivars is greater than that of certain late ripening cultivars when crop load is thinned in the previous year (Smith et al. 1986); i) trees and limbs possessing a certain source:sink (leaf:fruit) equilibrium that exhibits a relatively low alternate bearing intensity (Wood 1991); j) there is a high positive correlation between fruit-set and growth of shoots and leaves (Gossard 1933); k) return bloom is only mildly reduced in crop years following a large nut crop largely devoid of kernels (Sparks 1974); and l) that alternate bearing intensity is unrelated to date of fruit ripening or and nut size, but has a strong inverse relationship to duration of the post-ripening foliation period, especially in large fruit-size cultivars (Wood et al. 2003). Thus cultural and pest management practices enhancing canopy health and retention usually reduce alternate bearing intensity, but do not eliminate the cycling phenomena (Conner and Worley 2000).

Relevance of Arthropod Management to Alternate Bearing. The above mentioned observations regarding alternate bearing, and implications of the associated Phytohormone-Carbohydrate Theory, indicate that tree stress should be minimal if nutmeat yield is to be stabilized at the individual tree level. Thus the potential for impact on alternate bearing is a basic factor by which all cultural or pest management practices must be tested. This is why pecan husbandry strategies typically strive for an integrated holistic approach aimed at optimizing management of biotic and abiotic factors such as water, nutrient elements, light, diseases, and arthropods via minimizing tree stress. Over 18 species of arthropods have been noted to utilize pecan leaves for feeding (Ring et al. 1985), thus the influence of foliar feeding arthropods on pecan yields can be significant. Additionally, there are many factors that act to cause fruit loss during the growing season (Harris et al. 1986). One of these is the pecan nut casebearer. Nut casebearer related fruit abortions is not all bad. For example, in heavy "on" years fruit production can potentially be beneficial in that they thin an otherwise excessively large crop. In certain cases there might not be a need for insecticidal control of this pest in large crop seasons (Harris et al. 1986). Thus, linkage of arthropod management strategies to alternate bearing can potentially yield direct cost savings as well as help to reduce alternate bearing related yield losses.

Unless breeding efforts can break the linkage between alternate bearing and environmental stresses affecting carbohydrate accumulation, it appears likely that development
of successful arthropod pest management strategies will need to take into consideration how they might contribute to tree stress and affect subsequent cropping. Because of the importance of relatively high inputs of water, light, and nitrogen into most orchard environments, pest management strategies will potentially be influenced by these inputs. Because of the importance of canopy photo assimilation capacity to the moderation of alternate bearing, management strategies that substantially reduce assimilation are unlikely to be acceptable unless the cultural strategy can compensate via increased canopy. Because of the usually near state-of-art management of improved orchards, there is the possibility that native groves and seedling orchards may merit lower pest management spray thresholds than improved orchards. For example, cultural practices employing selective limb pruning or hedge pruning techniques typically produce an excess of foliar canopy. Such orchards might therefore potentially tolerate greater populations of certain foliar feeding arthropods than non-pruned orchards. This possibility merits investigation.

There have been two especially notable examples in which deficiencies in pest management strategies have interacted with alternate bearing physiology to cause major problems in husbandry of improved orchards. These have been associated with the control of aphids and pecan weevil. In the case of aphids, there are three species of pecan aphids that can be especially detrimental to pecan yields under certain circumstances, but are typically only secondary pests (i.e., the yellow pecan aphid, blackmargined aphid, and black pecan aphid are considered by most to be the primary aphid pests). It was reported in the mid 1980's that one or more of these aphid species can potentially reduce the photosynthetic activity (Wood et al. 1985, Wood and Tedders 1986) and chlorophyll concentration of foliage (Tedders et al. 1982), clog the phloem (Wood et al. 1985), induce reduced photo assimilation due to sooty mold and dust accumulation (Wood et al. 1988), remove large amounts of energy via sugars (Tedders and Wood 1987, Wood et al. 1987), reduce starch levels in shoots (Wood and Tedders 1982), reduce vegetative growth and plant dry weight (Tedders et al. 1982), and reduce crop yields (Wood et al. 1987). Additionally, it was also reported that most foliar chemical pesticides being used to control aphids were themselves damaging to trees in that they reduced net photo assimilation by up to about 10-20% for periods up to several days post-treatment, depending upon the chemical and formulation (Wood and Payne 1984, 1986). Thus, aphids and their control tools were discovered to confer many negative effects on the physiology and growth and developmental processes that were unrecognized. It is also noteworthy that during this era it was discovered that in the case of Monellia caryella, population growth was potentially checked by conditioning by previous feeding, thus potentially influencing subsequent damage to the tree (Liao and Harris 1985) and that natural enemies, especially spiders and lacewings, played a key role in reducing aphid populations (Liao et al. 1984).

These aphid related findings coincided with an era in which managers of most seedling and improved type commercial orchards operated with the mind-set that any damage to the tree's canopy would potentially reduce profits. The new information on potentially harmful aspects of aphid populations was interpreted by many extension specialists and orchard managers to mean that the yellow aphid complex should be kept at very low population levels throughout the growing season. Chemical pesticides were the weapons of choice, with both extensive and intensive usage eventually resulting in certain aphid populations rapidly becoming resistant to pesticides (reducing populations of beneficial arthropods that formally played an important role in keeping aphid populations in check) (Dutcher and Htay 1985). Chemical pesticides were heavily utilized, even though research had indicated that they too conferred negative effects on canopy photo assimilation that might, in many cases, be as great as the negative impact of the aphid population (Wood and Payne 1984, 1986). The result was somewhat of a catastrophic experience for certain farming operations (especially many of those in arid regions), yielding complex problems far exceeding that which they formally
experienced, thus further harming crop yields via the influence of aphids on alternate bearing physiology and nut production characteristics. This dark cloud in aphid management had a silver lining in that it undoubtedly played a key role in convincing orchard managers to embrace integrated pest management strategies (Harris 1991) that later resulted in substantial fiscal savings (Harris et al. 1998). This conversion was also undoubtedly aided by the appearance of the exotic multicolored Asian ladybird beetle, *Harmonia axyridi* (Pallas), in southeastern orchards where this predator greatly reduced damage by yellow-type aphid populations (Mizzell 2002).

Experiences associated with the control of pecan weevil have also served to encourage adoption of IPM approaches. It also illustrates the linkage between pest control and alternate bearing. Carbaryl proved to be an excellent control agent for pecan weevil; thus two to three applications were made to tree canopies from mid August to mid-late September when kernel filling of developing fruit was taking place. Unfortunately, carbaryl was also deadly to many beneficial arthropod species in the orchard ecosystem. The loss of beneficial populations typically led to an explosion in the aphid complex and/or an explosion in scorch mites. The result was often severe damage to the foliar canopy at a critical time (i.e., when developing kernels were needing photo assimilates and tree carbohydrate storage pool was unable to be replenished due to a devastated canopy during the post-ripening period). Thus, misuse of carbaryl not only tended to reduce kernel quality in the year of usage, but also reduced crops the following year via the adverse influence of a depleted carbohydrate pool on the amplitude of alternate bearing. Orchard profitability plummeted for years afterward due to the entraining effect carbaryl had on the biennial bearing cycle. These two above mentioned examples with aphids and pecan weevil illustrate the importance of ensuring that the subtle ramifications of pest control strategies are taken into consideration before they are recommended to orchard managers.

The potential direct and indirect negative side-effects of pesticide spray applications to canopy photo assimilation rates and subsequent alternate bearing related yield characteristics, as described above, illustrates a need for the development of control strategies that minimize exposure of the foliar canopy to chemical pesticides. A search for alternatives for aphid control using surfactants or potassium nitrate in air-blast sprays yielded limited success, but at a level below that which is needed in commercial orchard operations (Wood et al. 1995, 1997; Wood 1997). Alternatives might include biological agents (e.g., nematodes, fungi, bacteria, parasites, and predators), pheromones (e.g., mating disruptors), or application of chemicals to trunks and/or soils. Effective monitoring tools have been developed for most major pecan pests, thus providing a key component of effective IPM strategies (Mizzell 2002).

**SUMMARY**

The development of successful pecan arthropod management strategies for North American pecan operations is challenged with satisfying the needs of many potentially diverse production systems. When the generalized commercial production systems (i.e., native groves, seedling orchards, and improved orchards) are interfaced with the four orchard canopy subsystems (i.e., nonplused discrete, selective limb pruned discrete, hedge pruned discrete, and hedge pruned continuous) and a multitude of sub-systems (e.g., water, nitrogen, orchard floor cover, pest management, livestock, polygenetic, and organic), then there are thousands of distinctly different husbandry systems that potentially merit slightly different approaches to arthropod management. These differences in approach are driven by both economic, biological, and ecological constraints. Thus, no single system of arthropod management will likely accommodate the needs of this diverse array of production situations.
The evolution of cultural practices toward improving canopy, nitrogen, crop load and water management, and toward reducing management in "off" years has great potential impact on the efficacy of certain arthropod control strategies and upon the development of future strategies. Thus, future success will be partially linked to the successful integration of compatible cultural and arthropod management approaches. The wide variety of production systems, plus the continuation of a variety of both large and small changes in husbandry practices, presents an evolving situation that potentially influences the defense mechanisms (i.e., biological associations, confrontation, accommodation, and escapes in time or space; Harris 1980) that enable pecan to successfully cope with pest populations. Thus, husbandry evolution in cultural practices, and the cultivars in which they are imposed, potentially affects key defensive factors (e.g., nutritive quality, tree stress, duration of availability of succulent foliage, alternate bearing, masting, and ripening dates) that present a host of challenges to efforts to develop arthropod management strategies.

The great number of farm operations producing native groves (especially in Texas, Oklahoma, and Louisiana), their longevity, and their profit margins means that there remains considerable need for developing arthropod control strategies relevant to this quasi-natural low input system. Conversely, the great amount of acreage and production associated with improved orchard operations indicates that much effort is likely to be justified regarding the development of strategies for increasingly intensified cultural systems, many of which reflect substantial industrialization.

Pecan arthropod pest management has progressed over the last three decades from unilateral dependency on chemical pesticides toward greater usage of biologically based strategies. Recognition of the role of pecan tree physiology, especially that of alternate bearing physiology, has contributed to this progress. Alternate bearing continues to be a pivotal biological factor potentially regulating the commercial success of arthropod management strategies, especially those for foliar-feeding pests. Thus, familiarity with the Phytohormone-Carbohydrate Theory of alternate bearing, and an understanding of its potential as a conceptual tool, is likely a key factor influencing the commercial success of arthropod management strategies by entomologists.

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