Predicting Plum Curculio Immigration into Apple Orchards in Massachusetts: Degree Days versus Tree Phenology

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Determining need for and timing of insecticide applications that will protect fruit from injury by plum curculio (PC) based on presence of adults on host trees has been a critical aspect for managing populations. In concept, a reduction in amount of insecticide used against PC, from the current norm in Massachusetts of three spray applications during May and June to an amount that is precise according to need should be accompanied with an effective approach to monitoring the course of PC immigration into apple orchards. Limb jarring, an approach that involves tapping tree limbs using a pole to dislodge PCs onto an underlying ground cloth is one of the methods traditionally used to determine the time of first appearance, location, and relative abundance of PCs within an orchard. However, limb jarring has several shortcomings: (1) it is labor intensive; (2) it is not very accurate (its effectiveness is highly dependent upon tree size, weather, and other factors); (3) it cannot be used to study immigration, because PCs that are able to overwinter beneath perimeter-row trees will be confounded with true immigrants that overwintered in the woods; and (4) it cannot be performed at night, the time of day when PCs are most active on trees.

In the 2000 combined issue of *Fruit Notes* we reported that panel and pyramid traps baited with attractive odor and deployed in close proximity to the forested areas that are the main overwintering sites of adult PCs offered great potential for monitoring the onset and extent of PC immigration into apple orchards. Here, we investigated, over a five-year period, temporal dynamics of PC immigration into an unsprayed section of a commercial apple orchard using odor-baited traps. In particular, our objectives were: (1) characterizing the overall pattern of PC immigration; (2) determining the relationships among trap captures, tree phenology, and weather; (3) estimating thermal constants, expressed in Degree Days, for different stages (onset, 50^{th} and 80^{th} percentiles of cumulative captures) of PC immigration; and (4) determining the relative predictability of different stages of PC immigration by comparing tree phenology versus thermal constants.

Materials & Methods

Study site and trap deployment. We conducted this study over a period of five years (2000-2004) at the University of Massachusetts Cold Spring Orchard Research & Education Center (Belchertown, MA) utilizing a 1.4-acre unsprayed block comprised of a section having 216 small (M.9 rootstock) McIntosh and Delicious trees located on the eastern side, and two smaller sections having 145 medium-sized (M.26 rootstock) trees of various disease-resistant varieties located on the western side (Figure 1). The perimeter of the entire block, bordered almost entirely by mixed deciduous forest, was about 500 yards.

Traps utilized for the study were of two different types: (a) clear sticky Plexiglas panels (2 x 2 feet), which capture PCs in flight, and (b) a trunk-mimicking black pyramid traps, which capture PCs approaching host trees primarily by crawling. The woods-facing side of each panel was coated with Tangletrap glue to capture PCs that were presumably immigrating from the woods into the orchard block.

For each of the five years, traps were deployed in pairs along the periphery of the orchard, in close proximity to the woods. Each pair of traps was spaced 10 yards from other trap pairs on either side except in 2004, when the distance between each trap pair was 35 yards. For each of the five years, trap captures were pooled across all traps of the same type deployed in

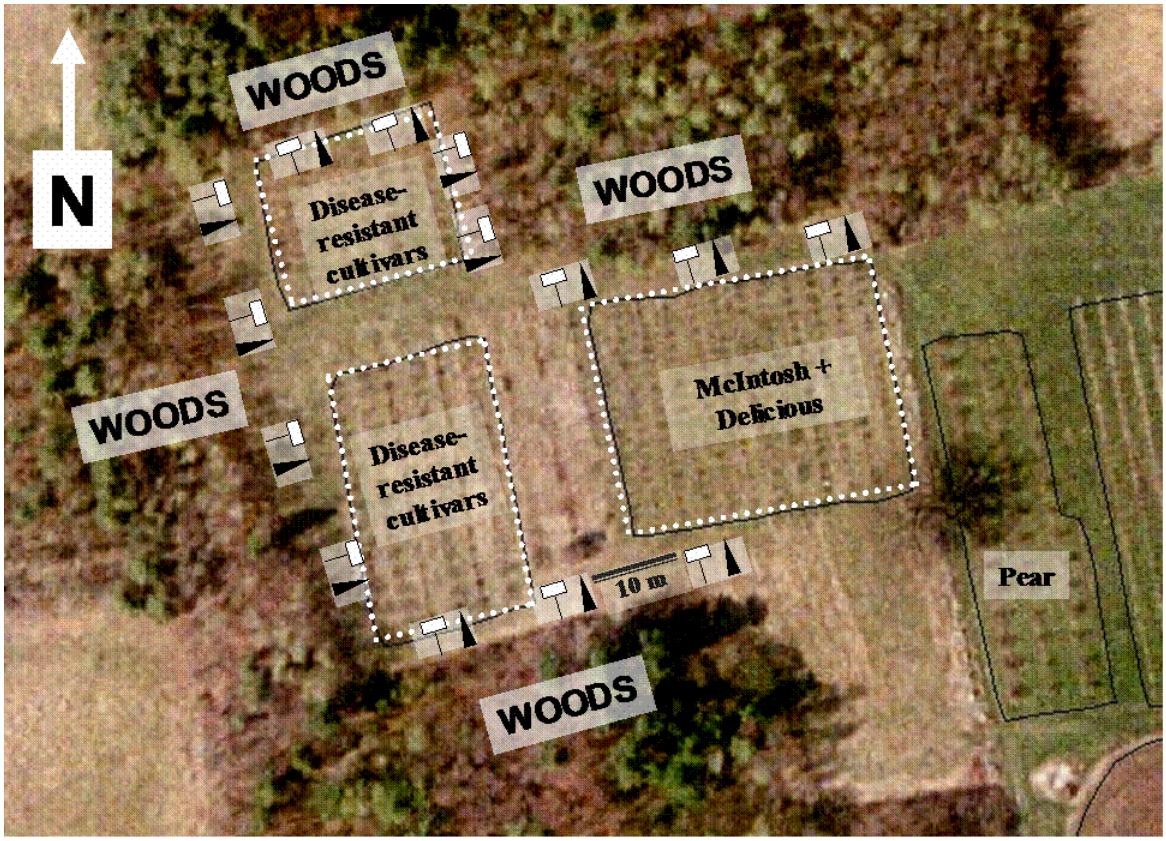

Figure 1. Unsprayed section of the apple orchard used for this study (UMass Cold Spring Orchard; Belchertown, MA). Panel and pyramid traps were deployed in pairs along the periphery of the orchard block, in close proximity to woods, the main overwintering sites of adult PCs. The perimeter of the block was about 500 yards. Picture: courtesy of Jon Clements (UMass Extension).

the orchard. The predominant bait used for luring PCs to traps was composed of benzaldehyde (attractive, synthetic, host-plant odor) in association with and grandisoic acid (PC aggregation pheromone). For each trapping year, trap deployment and baiting took place approximately during the silver-tip stage of bud development. Traps were inspected for PC captures on a daily basis (7:30-10:00 AM) from the moment of trap deployment until fruit reached 1.2 inches in diameter (by late June/early July). All adult PCs captured were brought to the laboratory, where they were sexed. All females captured were dissected under a stereomicroscope to determine the sexual maturity stage (presence of mature eggs) and mating status (presence of sperm in the spermatheca).

Characterizing PC immigration. The process of PC immigration into the apple orchard was characterized beginning with the day of first captures by traps. The next important stages of PC immigration were the 50th and 80th percentiles of cumulative captures. The latter occurred around petal fall, the stage of tree phenology at which PCs have shown the highest activity and dispersal and the time at which the first insecticide is commonly applied against PC. We ended the studies by late June/early July, when no captures occurred for 3-4 consecutive days with relatively high temperatures.

Classification of tree phenology. We monitored and characterized, on a daily basis, the different stages of bud and fruit development on the McIntosh trees using the following numerical code: (1) silver tip, (2) green tip, (3) half-inch tip, (4) tight cluster, (5) first pink, (6) full pink, (7) first bloom, (8) full bloom, (9) petal fall, (10) within a week after petal fall, and (11)

2-6 wks after petal fall (depending on the year). Stages 1-9 were considered as pre-petal fall, whereas stages 10-11 were post-petal fall.

Calculating Thermal Constants. Thermal constants for the initiation of PC immigration (START), and the 50th and 80th percentiles of cumulative captures were estimated using a temperature threshold of 43°F for the resumption of adult PC activity after overwintering. On each trapping year, Degree Days started to accumulate on January 1.

Relative Predictability of PC Immigration: Tree Phenology versus Thermal Constants. To determine whether the onset of immigration was better explained by accumulation of Degree Days or by tree phenology, two coefficients of variation (CV) were constructed. A coefficient of variation is a relative measure of variability (it uses the standard deviation [SD]) around a mean value, therefore a low CV (relative to the other CV estimated) suggested greater reliability of the particular method used to predict onset of PC immigration. Our first CV involved mean thermal constants (using the mean DD and SD obtained across the five trapping years), whereas the second CV involved the particular phenological tree stage at which PCs started immigrating into the orchard block (using the mean and SD of the numerical codes used on each year).

Results

Overall pattern of PC immigration. In all, 4,279 PCs were captured by traps across all five trapping years (Table 1). On average, the entire period of PC immigration lasted 63 days, with the shortest and longest periods encompassing 51 days in 2000 and 85 days in 2002, respectively. The earliest start of PC immigration occurred in 2002 (on 14 April), whereas the latest start of immigration took place in 2001 (on 2 May). PCs started immigrating when trees were either at the silver tip stage (stage 1) (in 2004), at the tight cluster tree stage (stage 4) (in 2000, 2002, and 2003) or at the first pink tree stage (stage 5) (in 2001). Fifty percent cumulative captures occurred when trees were either in full bloom (stage 8) in 2000 and 2001, by petal fall (stage 9) in 2003 and 2004, or during the first week of fruit development (stage 10) in 2002. Eighty percent cumulative captures took place during stage 10 (i.e., first week of fruit development) in four of the five years (2000-2003) or during stage 11 (i.e. after one week of fruit development) in 2004.

Table 1 shows that of the total number of PC immigrants captured by traps (potentially colonizing host trees), on average, 59% have already done so by petal fall, with the remaining 41% being captured by traps after petal fall. A statistical test revealed that numbers of PCs being captured by traps before and after petal fall differed significantly across years. The period of time required from the last day of petal fall to achieve 80% cumulative PC captures was one week in 2000 and 2004, two weeks in 2003, and three weeks in 2001 and 2002.

Relationships among trap captures, tree

Table 1. For each of the five trapping years, PC captures (by panel and pyramid traps combined) occurring before petal fall (PF) (phenological tree stages 1-9) and after petal fall (phenological tree stages 10-11).

EVENT	2000	2001	2002	2003	2004	Average
Total PCs captured	430	544	1,354	485	1,366	
Last day PF	05/24	05/16	05/17	05/22	05/14	
Cum. captures last day PF	307	303	575	289	877	
Percent of total	71.4	55.7	42.5	59.6	64.2	58.7 ± 4.8

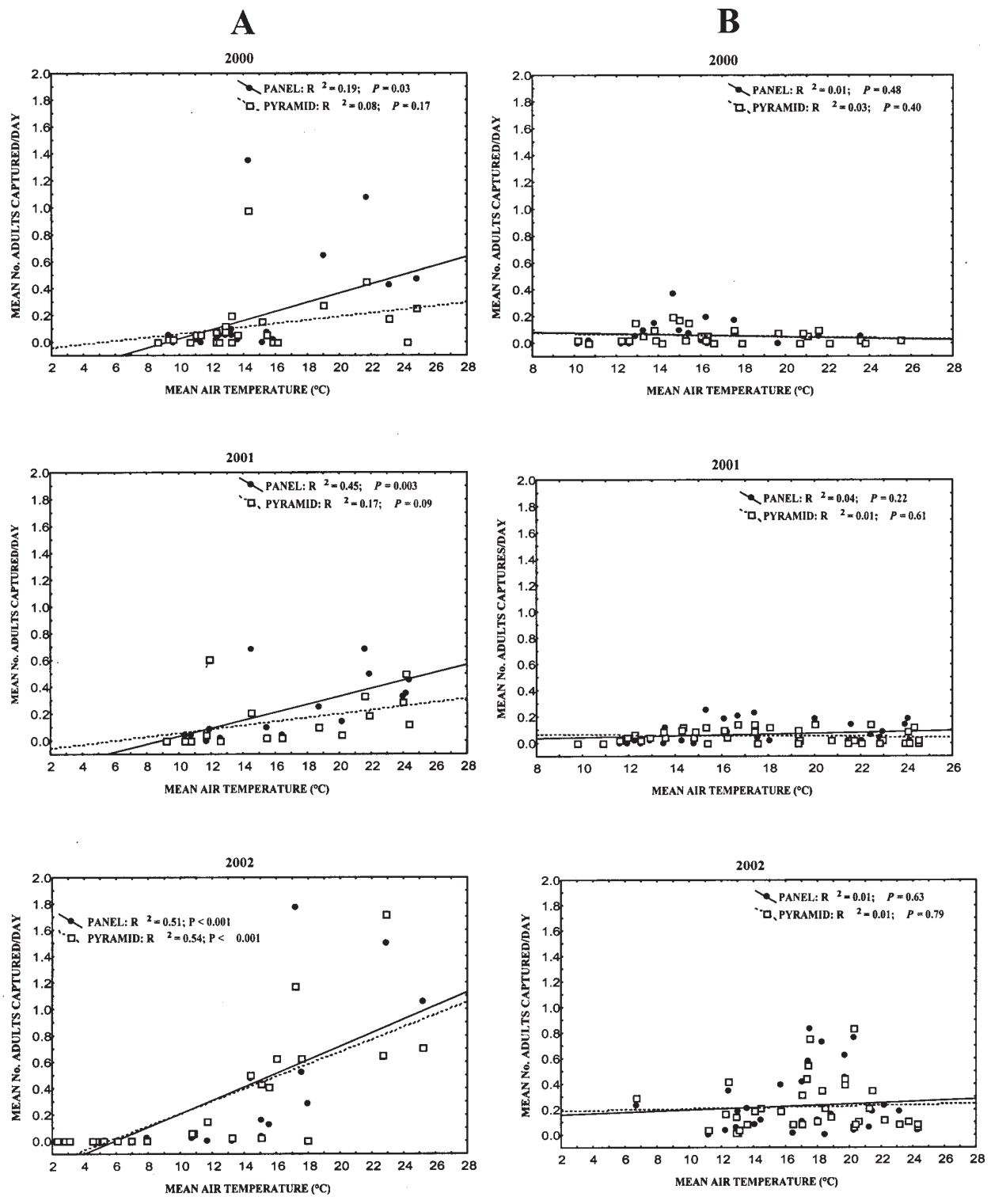

Figure 2. For each of the five trapping years, relationships between daily PC captures by panel and pyramid traps and mean air temperature either (A) before or (B) after petal fall. The number of days before/after petal fall was 23/52 in 2000, 17/43 in 2001, 33/51 in 2002, 24/30 in 2003, and 29/37 in 2004, respectively. R^2 values denote, on a scale of 0 to 1, the amount of common variation between the two variables. An $R^2 = 1$ indicates a perfect correlation.

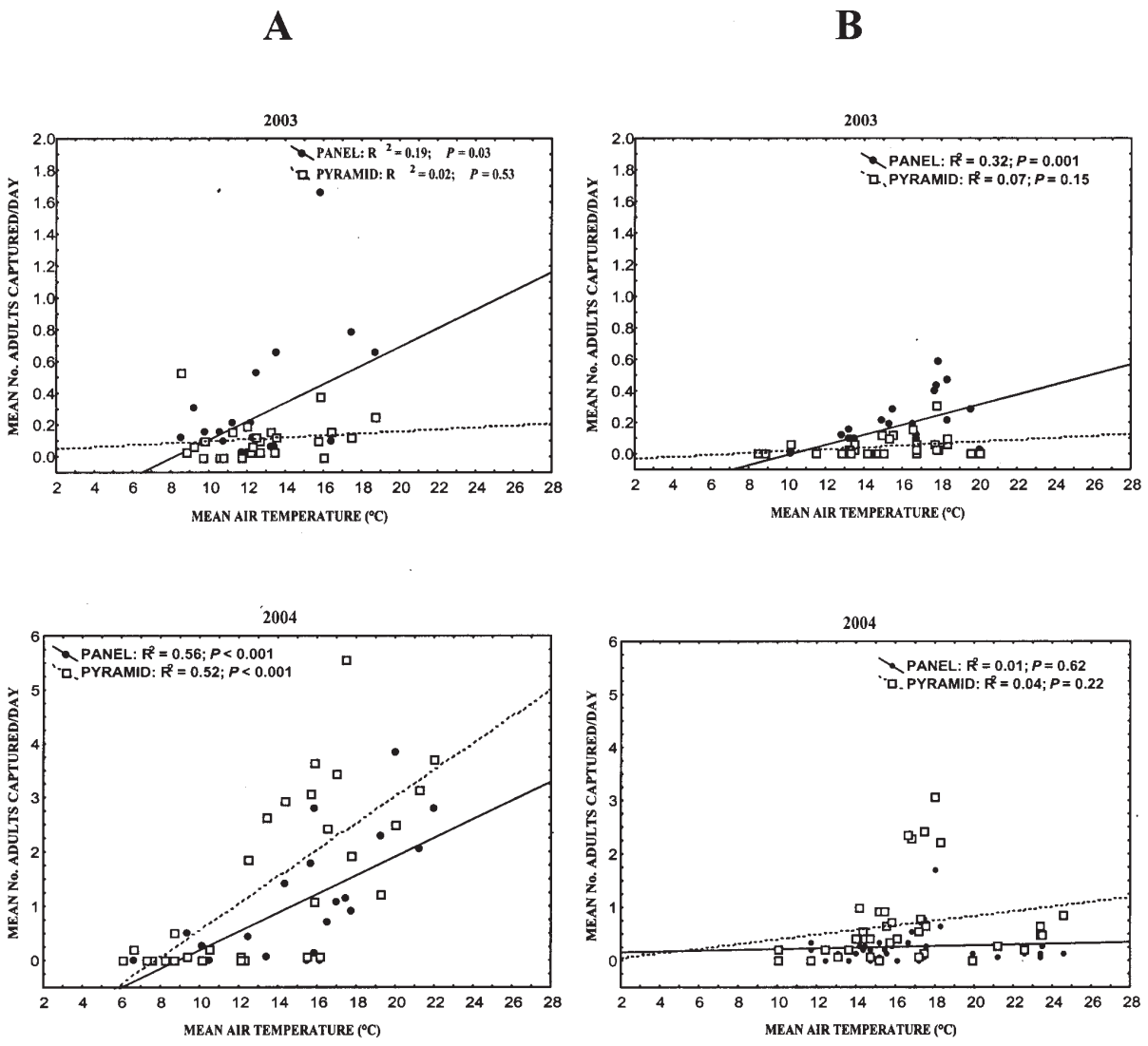

Figure 2. Continued.

phenology, and weather. Correlation analyses revealed a strong positive influence of mean daily air temperature on PC captures by panel traps before petal fall for each of the five trapping years. Captures by pyramid traps were less influenced by temperature than panel traps (Figure 2A). In contrast, the relationship between mean air temperature and captures by either panel or pyramid traps after petal fall was rather weak, except in 2003 for panel traps (Figure 2B). The proclivity of adults to either fly or crawl was independent of sex.

Thermal constants for different stages of PC immigration. Table 2 shows the thermal constants (base 43°F) for different stages of PC immigration. On average, PC immigration started when 235 DD had accumulated since January 1. The number of DD accumulated since January 1 to attain 50% and 80% cumulative captures was 480 and 775, respectively.

Relative predictability of PC immigration: Tree phenology versus thermal constants. Using CV's, we determined that initiation of PC immigration was better explained by accumulation of Degree Days (CV= 13.2) than by tree phenology (CV= 42.2).

Female sexual maturity stage and mating status.

Table 2. For each of the five trapping years, date and stage of tree phenology for the first captures, and thermal constants (expressed in Degree Days [DD]) estimated for different stages of PC immigration (START, 50th and 80th percentiles of cumulative captures). See Materials and Methods for a description of numerical ranks used to characterize phenological tree stage.

EVENT	2000	2001	2002	2003	2004	Mean ± SE
START (date)	05/02	04/30	04/15	04/29	04/17	
START (rank of tree phenology)	(4)	(5)	(4)	(4)	(1)	3.6 ± 0.7
START ($DD_{43°F}$)	283	212	209	248	222	235 ± 14
50th percentile (date)	05/07	05/11	05/24	05/19	05/12	
50th percentile ($DD_{43°F}$)	404	450	556	462	526	480 ± 27
80th percentile (date)	06/01	06/08	06/05	06/08	05/21	
80th percentile ($DD_{43°F}$)	785	853	789	732	713	775 ± 25

Figure 3 (A-E) reveals that, except for 2003, all females captured by traps were already sexually mature and/or had been mated by the end of the petal-fall period. These findings will be discussed in the next article of *Fruit Notes*.

Conclusions

In this study we focused on the relative importance of weather factors and tree phenology on the timing of PC immigration into an apple orchard as determined by trap captures. Because odor-baited traps were deployed along the periphery of the orchard block and inspected on a daily basis for the entire period of PC immigration, we believe this study examined timing and extent of PC immigration from overwintering sites (which primarily are woods) more accurately than previous studies that have relied on branch-tapping.

Based on our combined data, we propose the occurrence of a pre- and a post-petal-fall period of PC immigration, each of which is influenced to a different extent by temperatures prevailing in spring. The relative influence of temperature on patterns of PC immigration was very strong during the pre-petal-fall period of immigration, whereas immigration taking place during the post-petal-fall period depended to a lesser extent on temperature. In almost all cases, captures by panel traps were more strongly influenced by air temperature than captures by pyramid traps.

Historically, the timing of PC immigration was related to either soil and air temperatures or to host-plant phenology, but the relative influence of these two environmental factors had not been quantified in detail before. Here, we determined that the onset of immigration was better explained by accumulation of DD (base 43°C) than by tree phenology. This finding means that examination of the stages of bud development in spring is a poor tool for forecasting onset of PC immigration.

Our trap-capture patterns obtained over a five-year period allow us to characterize PC immigration as follows. First, stretches of hot weather occurring during the pre-petal-fall period (as in our 2000 season) are conducive to concentrated PC emergence and immigration. Under these conditions, most adults may be present within orchards before the end of the pre-petal-fall period and thus a petal-fall spray covering the entire orchard block is recommended and should yield excellent control of the majority of the population. Second, during the post-petal-fall period, PC immigration continues but with a lesser influence of weather, unless cool temperatures (such as in our 2002 season) have prevailed during the pre-petal-fall period, which would lead to an extended period of PC emergence and immigration.

We recommend that, depending on the type of weather (primarily temperature) prevalent during the pre-petal-fall period of PC immigration, the first spray

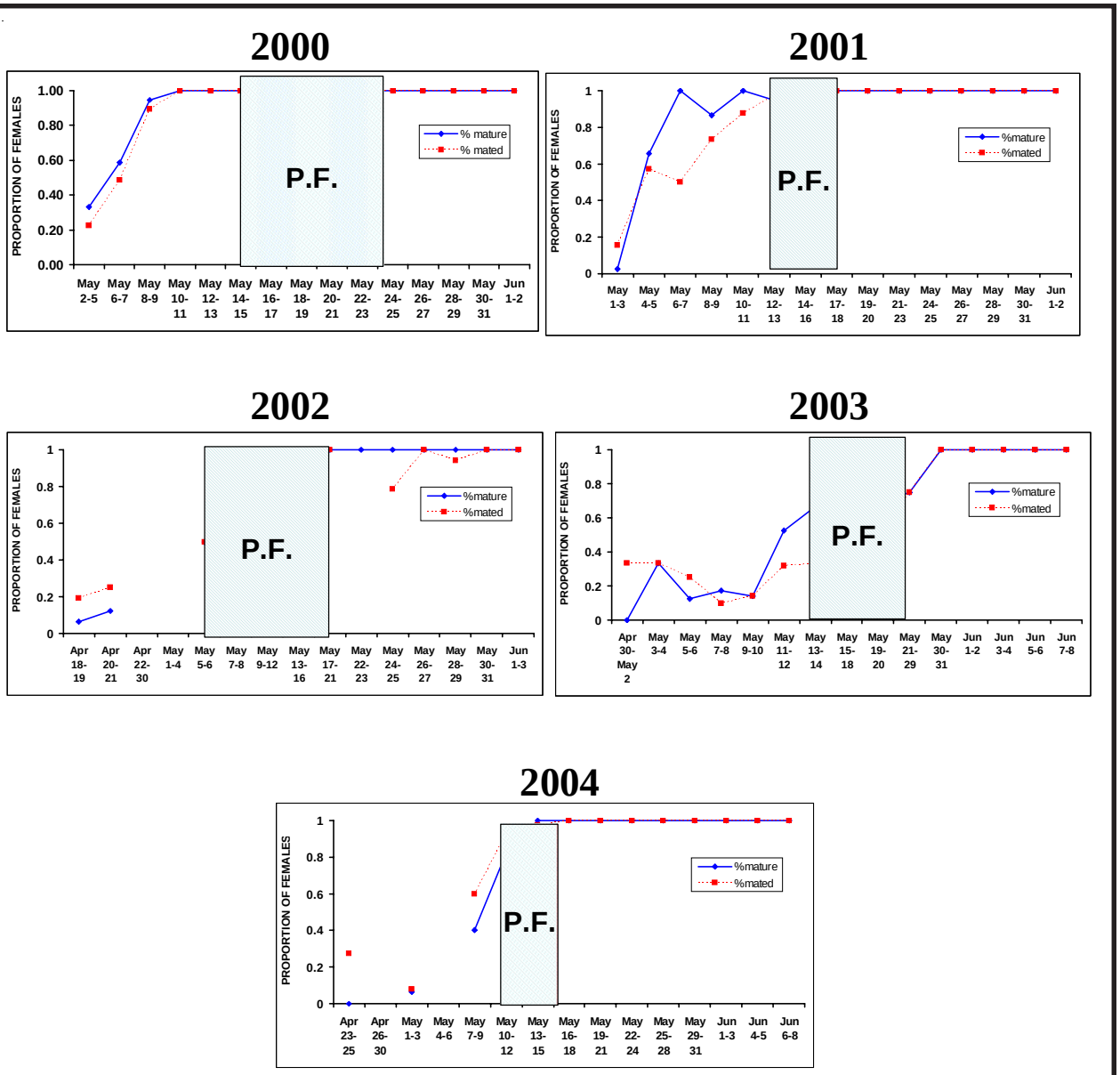

Figure 3. For each of the five trapping years, proportions of PC females captured by traps that were either sexually mature or mated, according to date. For each year, a box with diagonal lines indicates the petal-fall period.

of insecticide (commonly applied by the time of petal fall) be delayed either (1) by one week if the pre-petal-fall period is characterized by high temperatures (as in our 2002 season), or (2) by 10-14 days if cool, rainy weather prevails during the pre-petal-fall period. By doing this, a grower can maximize PC control as a higher proportion of immigrants may be killed, while costs and exposure to insecticide would be minimized given the fewer applications that might be needed. This is analogous to the temperature model developed at Cornell University by Reissig et al. (1998) to control PC, which involves use of cumulative heat unit models to predict, in particular, termination of PC oviposition activity.

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