

Ecological Relationship of Medfly and Coffee in Guatemala and Mexico

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ABSTRACT: Coffee is the main host of Medfly (*Ceratitis capitata*) in Mexico and Guatemala; however the medfly-coffee relationship is not well understood. We show that the coffee belt on the slope of the Sierra Madre Mountains exhibits a gradient in the time of fruit maturation and harvest which impacts the growth potential of the medfly population. Information about coffee growth and maturation shows that Medflies could infest the coffee berries at low elevations (~400m) in July, and follow the maturing coffee to final harvest at high elevations (~2100m) in December. Generation times at the extremes vary from 3 weeks to 3 months due to temperature differences, but the total degree-day accumulation and fruit availability allows for an average of 5-6 generations of exponential population increase (based on the average temperature over the last 10 years). Pupation times after coffee harvest in December can exceed 90 days at higher elevations, which would result in the emergence of the highest population of adult flies in March-April. Phenologically, the coffee is in its stress phase at this date and coffee berries are scarce, likely resulting in dispersal of mature adults to search for hosts. Many dispersing flies are captured in detection traps in March-April and can be seen as part of an ecological "shell game": the Medfly population outbreaks appear in one location in March-April (uninfested or host-poor areas west of the leading edge of the eradication program), while the growing population was actually present at another location months earlier (e.g., July-December in untreated coffee areas to the East).

Key Words: *Ceratitis capitata*, *Coffea arabica*, population dynamics

INTRODUCTION

Coffee (*Coffea arabica* L.) is the main host of medfly (*Ceratitis capitata* Wied.) in Mexico and Guatemala. Although commercial and backyard production of other host fruit are infested and cause concern regarding quarantine issues, coffee makes up the vast majority of host biomass available in this region. The highest population densities in the program are detected by traps in coffee, as are the vast majority of larvae. However, the ecological relationship between coffee and medfly is not well understood, nor are the implications for program management.

Advancement of the Moscardem eradication program through Guatemala has been obstructed by the dense belt of coffee production in Southwestern Guatemala, along the southern slope of the Sierra Madre Mountain range. Every year, adult flies are detected in traps placed along the border of South-Western Guatemala and South-Eastern Mexico, mostly during the months of February to May, with a peak in March-April. These detections

result in costly actions directed to prevent the medfly's colonization and establishment in eradicated/low-prevalence areas in the Western region of the coffee belt. Despite the yearly management efforts, little progress has been made in advancing the eradication areas through Guatemala.

This paper compiles information about the biology and production of coffee to look for patterns to explain the observed medfly population dynamics. A better understanding of the prevalence of the resources provided by the key host and its relationship to the population dynamics of the medfly may provide the information to develop new strategies to achieve the objectives of the Medfly Program.

MATERIALS AND METHODS

The medfly data presented in this study were taken directly from the medfly program's GIS database for the year 2005. The information on medfly and coffee was obtained from local growers, faculty from local Universities, coffee institutions (e.g., ANACAFE in Guatemala and Comcafe from Chiapas, Mexico), peer-reviewed publications, and the internet. Infor-

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mation on air temperatures for degree-day analysis was obtained from the Guatemala and Mexican weather service. It represents the current (2006) understanding of the authors about coffee and medfly biology. Maps and GIS analyses were conducted with Arc-Map software from ESRI.

RESULTS

A. The Annual Coffee Cycle

1. Stress period. Coffee is a perennial crop, however the coffee cycle can be said to begin after harvest, during the dry, stress period that is required by the plant for flowering. Theoretically, the stress needed to instigate flowering can be caused by a variety of factors, but an extended dry period is the only real cause reported under natural conditions.

2. Flowering is caused by a consistent rainfall within a short period (1 week-10 days) after a stress phase. The flowering is not related to temperature, degree-day accumulation, or to photoperiod and, for this reason, varies from year to year with the onset of the rainy season. Short rains in isolated areas often provoke some flowering that result in berries that are not harvested; but the generalized "normal" flowering that concludes in the annual harvest is evident, widespread, and nearly simultaneous throughout a wide area over a short period of time regardless of elevation. The normal flowering occurs about 3 days after "substantial rain" (A. Titus and G. Pereira).

3. Fruiting occurs soon after pollination and the fruit begin to develop, or "fill" soon afterward. Flowering and maturation of the fruit is temperature-dependent, i.e., the fruit develops faster in warmer temperatures. One study in Chiapas, Mexico (Barrera-Gaytan, 1994) reported a difference of 33 days after flowering to reach the same stage of maturity between 400 and 1000m in altitude. Altitudes above 1000m result in an even greater difference (Figure 1) in maturation.

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Once the coffee berries reach a uniformly deep red color, they are ready to be harvested. It should be noted that the ripening of the fruit is not uniform, and there is variation among plants at the same altitude; indeed, among branches within the same plant. However, any stage of ripeness can be thought of as a wave, moving from low elevation to high elevation over several months. This relationship between geography, temperature, and biology results in a gradient in the availability of host material for the Medfly population.

B. Medfly Life Cycle

The Medfly generation time is determined by degree-day accumulation. A total of 328 C degree days are needed to complete one life-cycle from egg to adult (APHIS Mediterranean Fruit Fly Action Plan 2003). The amount of time needed to complete this cycle varies dramatically with temperature, and therefore with altitude (Figure 1). Within the coffee belt in Guatemala and Mexico, the number of weeks needed to complete one generation can be as few as 3-4 weeks in the hot lowland areas, and more than 16 weeks in the highlands (1800-2200 m). Although coffee is the only host fruit present in sufficient quantity (2,000-5,000 kg/ha) of fruit to result in the high populations detected during the yearly surveillance program, the adult Medflies are not detected until after the coffee is harvested (Figure 2). The peak capture varies from year to year but tends to occur in March or April, some 3 months after the last coffee is harvested in December/January.

C. Degree Day Model

The degree day map layer was developed using weather stations located throughout Guatemala and the State of Chiapas, Mexico. We used regression to determine the linear relationship between elevation and the average temperature recorded by the weather stations for each month over a 10 year period. The equation from this elevation-tem-

perature relationship was applied to the 90m elevation GIS layer (NASA-SRTM), which resulted in a map layer of estimated average daily temperatures. This layer was then used to calculate the average daily degree day accumulation (base threshold 12.2 degrees C) for each month. Figure 1 shows the average degree-day accumulation (expressed in

weeks of generation time) only within the coffee area.

D. GIS Detection Database

Over 30,000 traps are checked on a regular basis throughout the Medfly Program area in Guatemala and Mexico. Each trap is geo-referenced and entered into a Microsoft Access database which for each of the 10 centers

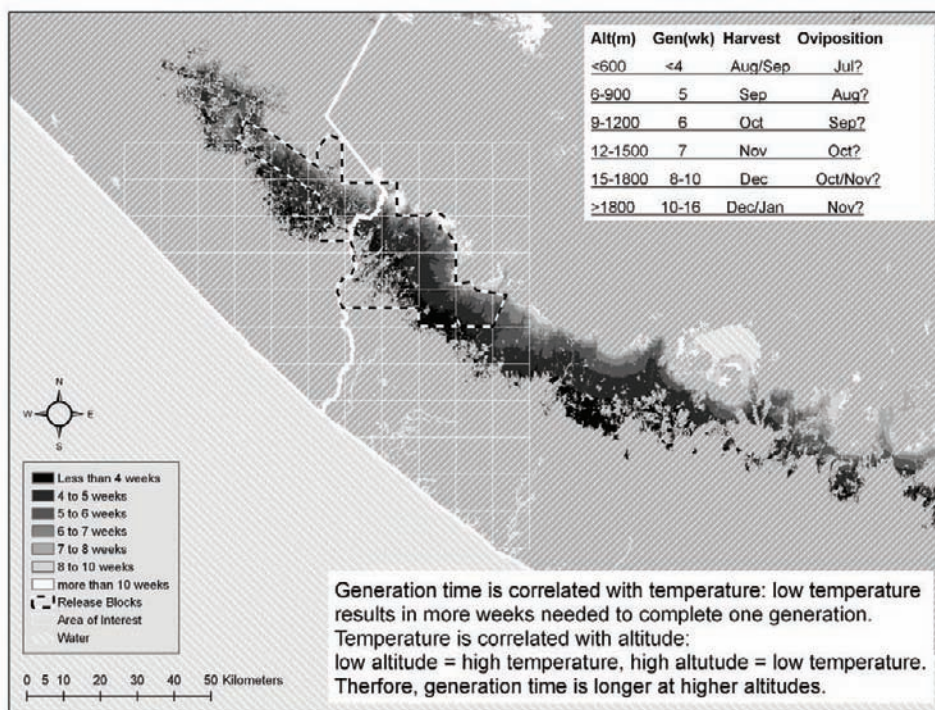


Figure 1. Generation time (in weeks) based on degree-day accumulation in the coffee belt of Guatemala and Mexico. SIT release block for 2004 outlined indicating suppression. 10km grid shows area in which trapping was conducted during 2005. Table shows Relationship among altitude, Medfly generation time in weeks, harvest date, and estimated date that the coffee fruit is available for oviposition (color break).

throughout the region. The information from each center is sent to the regional program in Guatemala City for processing and results in an integrated file of information that is common to all of the centers, including, among many other parameters, the capture of fertile flies per trap per day. The data displayed here in Figure 2 include both the posting (location) of each trap capture as well as the accumulated number of flies within a 10 by 10 kilometer

grid inside a defined area of interest. We selected the area of interest based on the presence of traps, fertile detections, and the proximity to the coffee along the coastal area. There are other coffee regions in Guatemala and Mexico, but this paper addresses only the coffee belt of South-Western Mexico and South-Eastern Guatemala. The area south and east of the area of interest did not have traps and can be considered to have been highly infested.

DISCUSSION

Medfly and the Coffee Cycle

At some point during the coffee maturation process, the fruit is sufficiently ripe to serve as a host for Medfly oviposition. Detailed studies on the exact stage of coffee that is susceptible to attack by Medfly in Mexico and Guatemala have not been published, though data from Hawaii and Kenya (Harris and Carey 1989 and Agasa 1971) suggest that coffee berries are available for oviposition at or near color break, when the fruit changes from green to orange/red. Color-break is not of importance to producers and so records are not kept about when this stage is reached in coffee plantations; however it seems reasonable to estimate that it is approximately 1-1.5 months prior to harvest (depending on temperatures).

The coffee fruit matures more rapidly at warmer temperatures and therefore the coffee berries are available for oviposition earlier in the annual cycle at lower altitudes. In infested areas (e.g., to the east of the area of interest in Figure 3) medflies are able to invade this newly available resource from alternate hosts nearby, or may already be present in the coffee plantations at low densities supported by the few off-season coffee fruit. Once the generalized annual cycle of coffee production is available for oviposition (up to 3,000 kg of coffee berries per hectare can be harvested according to Anacafe in Guatemala), resources for population increase are unlimited and exponential population growth can occur. As the population increases with each generation, the flies can follow the ripening coffee up the elevation/temperature gradient, potentially continuing the exponential increase until the final harvest at the highest elevations is complete and the last generation pupates.

The number of eggs produced by an average female varies with many factors, but a good host and conditions should result in 500-800 eggs. Papadopoulos et al (2002) found an average of 562 eggs per female and a 33% survival

rate of egg to adult in apples. A hypothetical population increase based on conservative estimates of medfly demographic parameters (50 eggs, or perhaps only 10%, surviving to adult) after the calculated 5.68 generations permitted by the temperatures at various elevations from June to December is shown in Figure 4. This simple figure shows the tremendous potential of the medfly population to change from undetectable to outbreak levels of density in a short period of time.

Enormous numbers of Medflies would then emerge in the highly infested coffee plantations at high elevations after harvest (pupation time of 3 or more months or 249 degree-days), the result of potentially more than 5 generations of exponential population growth. The coffee plants are in the stress/rejuvenating phase of their cycle at the dates that the mass emergence takes place. During this time of the year, the vast majority of coffee plants are defoliating or regenerating leaves (depending on elevation) and coffee berries are infrequent. The adult medflies should be able to find protein, mature, and mate, but would then be resource-limited in finding host sites for oviposition.

Adult Medflies are generally thought to remain near to where they emerge and not to disperse long distances (Plant & Cunningham 1991). This generalization, however, assumes that the area in which the flies emerge is host rich and under conditions similar to those present when the eggs were laid. In the situation described here, the Medflies emerge into the coffee plantations at a time in which they are resource limited and dispersal would be a likely response. Under this assumption, an unknown proportion (but large number) of flies would begin undirected dispersal in search of suitable hosts. The adult Medflies would likely move in all cardinal directions, or perhaps be influenced by the prevailing wind direction or other environmental factors. Recent studies have shown that Medfly adults do move 50km or more under certain conditions (Israely et al. 2005). Given the enormous densities of source

populations emerging from the coffee belt, even a very small percentage of flies dispersing 50 or more km would be a large number of flies, some of which would be captured in traps.

Figure 2 shows that, in 2005, the majority of flies were captured from March to May, with a peak in April. The map of these captures (Figure 3) demonstrates that the majority of the flies were detected near the border of the treated (fly release) area and the infested coffee. There is a clear gradient of captures (shown in the quadrants in Figure 3) from the highest (4,317 captures) in the border quadrant, with lower captures the further away a quadrant is regardless of direction. This pattern is consistent with adult flies dispersing from the infested coffee areas from the east into the trapping grid. Note that flies were captured throughout the trapped area regardless of presence of coffee. In the most western captures (the furthest from infested areas), an equal number were found in coffee as in the host-poor coastal areas. This pattern is consistent with what would be expected from dispersing flies searching for hosts. The alternate hypothesis that the captured flies are due to the resurgence of very low populations throughout the area is less compelling, given the pattern of captures. Inconsistencies include the presence of fertiles at the same time, in such different ecological

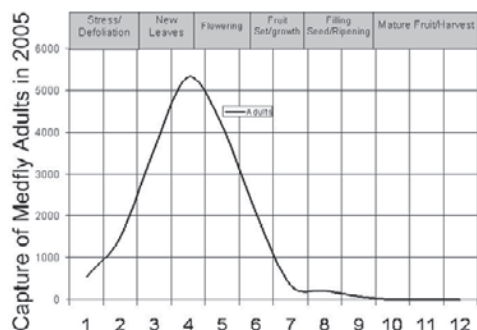


Figure 2. Total number of adult *C. capitata* captured per month in 2005 in the ~5,000 traps located within the 10km grid shown in Figure 1. General phenology of coffee is summarized along the top.

areas so distant from one another, and the apparent increase of medfly population density in coffee at the same time of year that berries are the least frequent.

Another way that coffee could be important to the dispersal of the medfly is through the movement of infested coffee berries after harvest from the infested area to uninfested area for sale or processing. This would result in the larvae leaving the fruit, pupating, and emerging as adults in the uninfested areas.

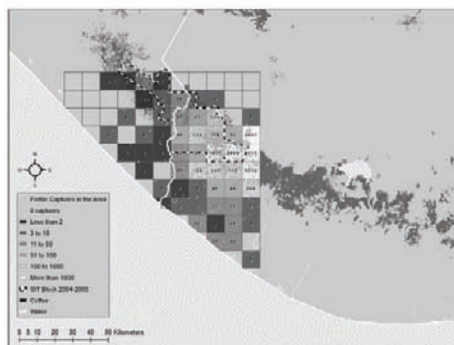


Figure 3. Location of fertile captures and the total adult captures per 10 km grid cell in 2005.

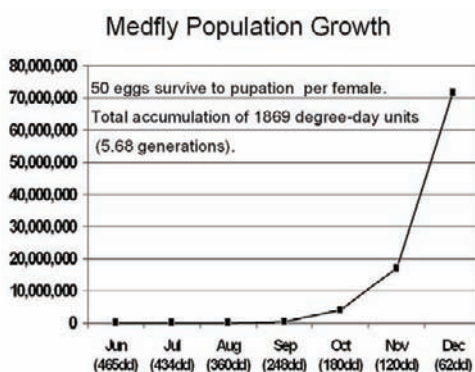


Figure 4. This potential *C. capitata* population growth is based on the degree day accumulation over the gradient of altitudes and dates of fruit availability oviposition. In this hypothetical example, one female begins oviposition in July, with 50 adults (25 female) surviving to reproduce. The December value can represent the number of pupae.

REACTION TO DISPERSING FLIES

Historically, expensive control measures, including bait sprays, have been used to prevent the establishment of infestations by flies captured in Feb-May. However, when fertile flies are detected again in the same area the following year, it appears as if the control measures were not effective. This interpretation of failed control results in a repeat of the previous year's control measures, often in the same location, stagnating the program's progress. However, it may be that expensive control measures applied over a large area (aerial application of insecticide), are not always necessary to protect coffee at this stage of its cycle (Stress or Flowering). If the fertile flies are detected in an area under constant release of sterile males, then the sparse availability of oviposition sites would allow the population to remain at levels that could effectively be controlled by the consistent release of sterile male flies: thus preventing permanent establishment. This scenario could dramatically change the timing and locations of management strategies that have been in use over the 25 years of the medfly eradication program.

Impact of knowledge about Medfly-Coffee relationship on program management.

One key change that this information might bring to the way the program is managed is the way the data is interpreted. For example, SIT has been thought to be ineffective in some areas of the program due to continued detections of Medfly adults and larvae on an annual basis. The failures in detection have been assumed to be caused by refugia where localized populations might be too high for SIT to work, uneven application of SIT or bait spray, or other failure in how the technical aspect of the program is conducted. If our hypothesis is correct, it suggests a scenario in which SIT works well in areas where it is applied consistently. Detections are not caused by a resurgence of local populations that were undetected but not controlled by SIT, but due to influx of fer-

tile adults (possibly in combination with movement of infested coffee berries) from outside the treated area. The sterile release blocks do not prevent movement of fertile flies and subsequent oviposition, but they should prevent establishment.

Thus one implication of this hypothesis may be that sterile flies should be released preventively during the emergence and dispersal period (Feb-May). The preventive block should cover the areas within the dispersal range of the flies during this period. Although the detection system is weak it appears to be sufficient to see the pattern of movement of the fertile flies and could be used to guide the design of the preventive release blocks. The preventive blocks could be removed after dispersal has stopped and after any outbreaks have been eradicated.

The routine aerial application of expensive insecticidal bait to control the dispersing adults may not be warranted. If the adults entering the SIT blocks are prevented from establishing populations by the sterile flies, then the insecticidal treatments, though they may kill many of the dispersing flies, are unnecessary as no populations will be established either with or without sprays. In any case, applying bait spray during the emergence may not be the best way to break the annual coffee-medfly cycle.

For the program to advance, eradication methods need to prevent/reduce the population growth from June to Dec in infested areas adjacent to controlled areas at the leading edge of the program (SIT blocks). It might be possible that SIT alone could eliminate the population growth. If the blocks are moved forward of the leading edge (into infested coffee) when the fertile population density is naturally at its lowest and before the coffee berries are ripe enough for oviposition (say June or July), then the control brought by SIT might be enough to prevent or drastically reduce the population buildup. SIT alone might not be sufficient, however, at least not consistently from year to year. The control could be improved by applying bait sprays just prior to beginning SIT

to eliminate surviving adults. These bait applications might reduce the fertile population density to levels that SIT could effectively prevent population growth.

Although it would seem more efficient to concentrate resources to prevent population build up forward of the leading edge of the program, other tactics could be developed from the same basic medfly-coffee relationship. Another possible strategy might be to apply bait spray to the infested areas adjacent to the leading edge later in the year, before the population builds up to its highest density (say Oct-Nov). This would cut the out the last generation where exponential growth yields the largest increase in population and, if timed correctly could dramatically reduce the number of dispersing adults. However, timing the applications would be difficult and the rainy season is unpredictable and may last too long some years to allow timely application.

Uninfested areas (i.e., to the West/NW of SIT blocks) that are not protected by SIT are susceptible to infestation and establishment from the dispersing adults. These areas would need to be closely monitored by a reliable detection system. Higher density eradication blocks (and/or other control methods) could be implemented when fertile Medflies are detected in unprotected areas.

Medfly detections and threat of introduction by dispersal are to be expected as part of the ecological relationship between coffee and the pest. If this expectation can be built into the program planning, yearly detections during the dispersal phase can be treated as an expected occurrence with a solution, and not an emergency situation that requires that planning be changed, funding redirected, and advances abandoned.

Note from 2008. Since this paper was written, experiments by Rendon and Villatoro with ground release of flies have shown movement of sterile medflies up to 60KM. Flies were released in the coffee area and detected to the west. The pattern

of captures was similar to those shown in Figure 3. Most were found near the release site, but some were captured on the coast and others in coffee to the west. This shows both that medflies do disperse, and that the trap grid currently in place is sensitive enough to capture this movement.

On the other hand, careful analysis of the fly emergence over several years shows that, while there may be some movement of the flies from lower to higher altitudes, the majority of flies emerge from between 1000 and 1400 meters in altitude. In this paper, we hypothesized that there would be a maximum emergence above this altitude (above 1800m), but it does not appear to be the case. This data seems to indicate that there is an additional generation at this altitude during and after harvest (Jan-Feb) from which the maximum fly population density emerges in March-April.

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