

Pests and Agricultural Commodity Losses: Evaluating Alternative Approaches to Damage Function Estimation

Kelly Cobourn¹, Rachael Goodhue¹, Jeffrey Williams¹, and Frank Zalom²

¹ Department of Agricultural and Resource Economics, University of California, Davis

² Department of Entomology, University of California, Davis

Contact author: Kelly Cobourn, cobourn@primal.ucdavis.edu

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Abstract

Estimating the economic impact of a pest requires linking biological and economic systems via a damage function. The most common damage function approach links exogenous pest populations to cumulative commodity yield losses at harvest. This type of representation is a reduced form because it is not pest population levels *per se* that drive damage, but the underlying factors that affect pest populations and the susceptibility of the host. We specify and estimate a structural damage function and compare the results with those of the reduced form. We do so using two alternative models, one that explains the level of crop damage from a pest, and one that explains the timing of that damage during the host's growing season.

We address our objectives within an empirical application to the olive fruit fly in California. In formulating the structural damage function, we draw from current scientific literature on olive fly and olive fruit phenology. The structural damage function takes into account the feedback between climate, host susceptibility, and pest populations. Moreover, the structural approach disaggregates damage rates across space and time, unlike the typical reduced form. The estimation results indicate that endogeneity is a salient concern in both the timing of initial crop damage, and in the levels of damage evidenced in some cultivars. The structural damage function dominates the trapping-based reduced form in terms of explanatory power in every model estimated.

Pests and Agricultural Commodity Losses: Evaluating Alternative Approaches to Damage Function Estimation

Estimating the economic impact of a pest requires linking biological and economic systems via a damage function. The most prevalent damage function approach estimates the percent yield loss at harvest as a function of a pest's population level. This type of damage function, however well it fits the data, is a reduced-form representation. It is not pest population levels *per se* that drive damage, but the underlying factors that affect pest populations and, perhaps simultaneously, the susceptibility of the host. A reduced-form approach may further misrepresent the underlying damage process by assuming an approximately linear damage relationship or by aggregating over space and time. In addition, models that use pest population levels often rely on a proxy for pest populations, such as trapping, which may introduce measurement error and bias into the estimation results. Any of these potential pitfalls associated with a reduced-form damage function may lead to erroneous predictions for biological and economic outcomes under alternative management scenarios.

In this paper, we specify and estimate a structural damage function in the context of the olive fruit fly in California. We use two alternative structural models, one that explains the level of crop damage from the pest and one that explains the timing of that damage during the host's growing season. These models specify fruit damage rates over space and time as a function of fruit characteristics, climatic factors, and management practices. In contrast to a reduced-form approach, which assumes that pest populations are exogenous, these models take into account possible simultaneity in pest populations and crop damage levels. They also disaggregate damage rates across space and time so that they can explain differences in damage rates between cultivars in the same site and

the same cultivar in different sites. The structural models also explain the path of infestation rates over the course of the season rather than total cumulative damage at harvest.

From a practical standpoint, the results of this analysis will aid in targeting the timing of chemical sprays and harvest to minimize production costs and crop losses. Accordingly, the results will augment current Integrated Pest Management (IPM) recommendations for the olive fly. Methodologically, this chapter contributes to the literature on bioeconomic modeling with a novel empirical extension to the field of pest management. A reduced-form pest damage relationship marks a first step towards endogenizing biological responses in an economic modeling framework. However, using a reduced form may limit the value of the resulting estimates. We compare the analytical results under a structural biological modeling approach with those using a reduced-form specification and comment on the relative advantages of the former. We conclude by discussing under what circumstances the reduced-form aptly approximates the structural damage function.

Pest Damage Function Literature

The economic literature regarding pest management issues predominantly utilizes reduced-form damage specifications. The October 2007 *Journal of Agricultural and Applied Economics*, a special issue on the economics of invasive species in tropical and subtropical regions, illustrates this point well. There are a number of studies in the issue that empirically estimate economic damages from various invasive species. Each of these studies assumes a constant rate of economic loss as a function of invasive species populations. Alamo et al. estimate that half of all plantains and bananas produced in

Puerto Rico are infected with black sigatoga, with estimated yield losses of 25 and 40 percent for infested production units. Similarly, Alavalapati et al. assume a constant percentage of cogongrass infestation in slash pine forests and a percentage decrease in timber productivity per acre infested. Several other studies in the issue use complex biological models of the spread of invasive species (Pendell et al.; Lee, Adams, and Rossi; Kim et al.; and Burnett, Kaiser, and Roumasset). However, in each of these, the link between total economic losses and changing pest populations is a single damage parameter. In other words, these studies assume that the economic damages incurred as a species' population spreads are a constant proportion of that spread.

Invasive species studies in the economics literature, such as those discussed above, often focus on modeling the implications of invasive species' spatial and temporal spread. Devoting the analytical focus to this modeling complexity may require simplification of the pest damage function to keep the analysis tractable. Studies of the economic impacts of native or established pests avoid this analytical tradeoff. Therefore, they may be able to devote more resources to detailed damage function modeling. However, analyses in this segment of the literature predominantly use reduced-form damage models as well. For example, Mitchell, Gray, and Steffey (2004) relate corn root ratings (a direct measure of western corn rootworm damage as the larvae are too small to observe directly) to percent crop losses. Some examples of other studies, among many, that use a reduced-form damage specification include Holst, Meikle, and Markham (2000), Smiley et al. (2004), Torres and Hoy (2005), and Wegbe et al. (2003).

An earlier vein of literature builds on the theoretical framework developed by Lichtenberg and Zilberman (1986) to model the productivity of damage control inputs.

These studies begin with a theoretical production function that expresses total output, Q , as a function of inputs, Z , and a damage abatement function, $G(\cdot)$. The damage abatement function depends solely on damage control inputs X (in this case pesticide applications):

$$Q = Q(Z, G(X)).$$

Carrasco-Tauber and Moffit (1992) utilize this framework to estimate pesticide productivity using the exponential, logistic, and Weibull distributions to describe G . Babcock, Lichtenberg, and Zilberman (1992) incorporate the quality effects of damage control measures in addition to the quantity-based production function above. They formulate a damage function where crop loss is a function of damage control actions and a vector of inputs into production that influence the damage rate. Saha, Shumway, and Havenner (1997) allow for interaction between damage control inputs and general production inputs in $G(\cdot)$. This extension allows production practices to influence the marginal productivity of damage control measures. Each of these studies assumes a baseline level of pest damage, implicit in the functional form assumptions or the relationship between productive inputs and the quantity or quality of output.

In contrast, Christiaans, Eichner, and Pethig (2007) derive a crop production function based on micro-level constrained optimizing behavior by pest and host. Their analysis focuses on modeling *how* pests reduce agricultural productivity, rather than simply assuming that they do. Their formulation allows factors to simultaneously affect host susceptibility and pest populations, which allows the optimal approach to reducing pest damage to involve enhancing crop resilience to infestation and/or reducing pest populations. The authors theoretically highlight differences in optimal pest management

when using a structural versus a reduced-form damage specification. Depending upon context-specific biological parameters, they find that the two damage models may generate differing pest management conclusions. This possibility motivates this paper's analysis. Herein, we formulate a structural damage function model that incorporates simultaneity in pest populations and host susceptibility in the context of a current pest management problem. By comparing the empirical results across structural and reduced-form models, the analysis identifies when and how the two approaches differ and the circumstances under which each type of model is preferable.

Theoretical Structural Damage Function

In formulating the structural damage function, we draw from current scientific literature on olive fly and olive fruit phenology. Although the fly is relatively new to California, it has a long history in the Mediterranean. Both European and California-based studies posit that fruit characteristics, climate, and management practices influence fly populations and infestation levels. Studies of olive fruit phenology establish the importance of climatic factors to fruit growth and susceptibility to infestation by the fly. The structural damage function takes into account the potential for feedback between climate, fruit size, and fly populations in determining damage rates and timing.

Fruit properties hypothesized to affect infestation levels vary across studies and include size, shape, color, and hardness of the epicarp (Burrack, 2007; Katsoyannos and Pittara, 1983; Katsoyannos and Kouloussis, 2001; Neuenschwander et al., 1985; Rizzo and Caleca, 2006). Although the conclusions of these studies differ and often contradict one another, they widely find that fruit size is strongly correlated with infestation rates. Research to date has not established whether size is a determinant of infestation rates or

whether it captures a correlation that is driven by another characteristic, such as the composition of surface waxes (Burrack, 2007). Though size may be a proxy for other fruit characteristics in terms of fly ovipositional preference, there is no doubt that size is an important determinant in larval success. Thus, size is an important characteristic to consider in formulating the structural damage function model, though the relationship to damage rates should be interpreted as one of correlation, not causation.

While fruit characteristics impact damage rates by cultivar, the presence of an active and reproductively mature fly population is necessary for infestation of olives. As of 2004, the olive fruit fly infested every olive-growing region within California. Once established, a number of factors drive fly population patterns between and within years. In particular, weather conditions and management practices influence the adult fly population level and the number of fly generations realized in the olive growing season. Rice (2000) documents temperature thresholds outside of which fly development ceases. Temperatures below 40 and above 100 degrees Fahrenheit terminate development in all stages: egg, larva, pupa, and adult. Adult flights or reproductive activity occurs between 60 and 100 degrees Fahrenheit. The gradient of temperature change may also affect the fly population. Koveos (2001) finds that flies suffer higher mortality rates from an unexpected decrease in temperature than from an equivalent but gradual decrease. Therefore, greater weather variability may lead to a decrease in fly populations and activity.

Several studies establish the relationship between management practices, such as irrigation, post-harvest sanitization, and pruning, and fly population levels. Irrigation provides a convenient water source for flies and contributes to fruit infestation (Burrack,

2007; Yokoyama, 2007). Between seasons, the fly pupates in fallen olives and in the top four inches of soil. A failure to sanitize after harvest contributes to a greater carry-over population in the following spring. Insecticide treatments, namely the application of GF-120 Naturalyte Bait or Surround WP (kaolin clay), affect fly mortality. Moreover, management practices and chemical applications employed in nearby olive orchards influence fly populations and damage levels at a given site because the fly is highly mobile. Adult olive fruit flies readily migrate long distances to find olives and have been shown to fly as much as 6.5 kilometers without resting.

Based on the conclusions and hypotheses of these scientific studies, we specify a theoretical damage function that varies by olive type and across the growing season. Damage (DG) is a function of fruit characteristics (FC), climatic factors (CM), and management practices (MG):

$$DG_{it} = f_D(\mathbf{FC}_{it}, \mathbf{CM}_{it}, \mathbf{MG}_{it}), \quad i = 1, \dots, N, t = 1, \dots, T. \quad (1)$$

The matrix \mathbf{FC} is of dimension $NT \times k$, where N is the number of individuals for which observations are recorded in each time period, T is the total number of time periods, and k is the number of variables describing fruit properties for each observation. Similarly, \mathbf{CM} is $NT \times l$, and \mathbf{MG} is $NT \times m$, where l and m are the number of variables in the climate and management vectors, respectively. This notation suggests a balanced panel, though that need not be the case; we use this notation for simplicity.

A problem arises in using equation (1) alone to define the structural damage function. Based on the scientific studies discussed, the vector of fruit characteristics must include a measure of olive size. Although fruit size is a driving factor in damage, fruit size is also driven by climatic and management factors, i.e. fruit size is endogenous.

Moreover, the same climate and management variables may differentially drive variation in olive size and fruit damage. Thus, we add a second equation explaining olive size, as measured by volume (VL):

$$VL_{it} = f_V(\mathbf{CM}_{it}^V, \mathbf{MG}_{it}^V), \quad i = 1, \dots, N, t = 1, \dots, T. \quad (2)$$

We allow the vectors of climatic and management variables in equation (2) to differ from those in equation (1), and denote the volume-equation vectors with a superscript V . The theoretical structural damage specification is a system of simultaneous equations composed of a damage function and an olive size function. We hypothesize that this two-equation system is triangular, rather than recursive, and test the validity of this assumption in the empirical analysis.

Empirical Structural Damage Function

The following system of two equations constitutes the empirical counterpart to equations (1) and (2):

$$DG_{it} = \alpha^D + \beta^D FC_{it} + \gamma^D CM_{it}^D + \lambda^D (DD_{it} * MG_{it}^D) + \delta^D (DD_{it} * ST_{it}) + \phi^D (DD_{it} * CV_{it}) + \varepsilon_{it}, \quad i = 1, \dots, N, t = 1, \dots, T \quad (1')$$

$$VL_{it} = \alpha^V + \gamma^V CM_{it}^V + \lambda^V (DD_{it} * HD_{it}) + \delta^V (DD_{it} * ST_{it}) + \phi_k^V (DD_{it} * CV_{ik}) + \nu_{it}, \quad i = 1, \dots, N, t = 1, \dots, T \quad (2')$$

where $FC = (VL, RL, VL * LATE)$, $CM^D = (DD, DD^2, MV)$, $MG^D = (IR, GC, MT)$, $CM^V = (DD, DD^2, HD, PR)$, $ST = (Amador, Butte, Sonoma, Tulare, Ventura, Yolo)$, and $CV = (Arbequina, Frantoio, Koroneiki, Leccino, Mission, Sevillano)$. We exclude the Solano site and the Manzanillo cultivar from the set of site and cultivar indicators. Damage, the dependent variable in equation (1'), is a function of olive volume (VL), the effect of which may differ late in the growing season (indicated by $LATE$), olive shape (RL),

accumulated degree days (DD), and variance of the daily minimum temperature (MV) in any time period t . The relationship between accumulated degree days and damage may be quadratic, i.e. heat may affect fly damage at a decreasing rate. In addition, we include a number of interaction terms to allow the heat-damage relationship to vary across management practices, site, and cultivar. Specifically, the heat-damage relationship may differ in those orchards that have irrigation systems (IR), ground cover (GC), are maintained (MT), and across site (ST) and cultivar (CV). Equation (2') defines the empirical volume function. Olive volume is a function of heat (DD), humidity (HD), and precipitation (PR). The heat slope parameter may differ by humidity level and *vice versa*. The heat-volume relationship may also differ across site and cultivar, as in the damage function.

The interaction terms included in the econometric specification (1') and (2') reflect potential unobserved differences in biological responses to climate and management factors. It may be that heat interacts with different site characteristics or cultivar-specific factors to affect volume or damage in a way that is not described well in a linear-in-parameters econometric framework. For example, even when exposed to the same number of heating degree days, a small Arbequina or Koroneiki olive's volume may not increase in the same way as that of a colossal Manzanillo or Sevillano. The rationale for including heat-irrigation interaction in the damage equation is that irrigation systems may provide a source of water for flies during warm periods, enabling their survival and continued reproductive activity. Thus, a greater rate of damage, holding degree days constant, may occur in those orchards with irrigation.

The same rationale holds for the interactions between ground cover and degree days and maintenance and degree days. In locations with ground cover, a larger fly population may carry over from the previous year, and hence result in a greater level of damage, given temperature. The degree-day-humidity interaction in the volume equation captures the negative effect of humidity on olive growth. Holding temperatures constant, greater humidity tends to reduce olive size (Sibbett and Ferguson 2005). The converse holds as well.

Humidity and precipitation affect olive size but do not affect fruit damage levels directly in this specification. This is the key identifying assumption in this empirical formulation. If the system is recursive, i.e. the correlation between ε and v is non-zero and volume is an endogenous right-hand side variable, humidity and precipitation allow us to consistently estimate the parameters of (1'). This result holds given that humidity and/or precipitation are significantly correlated with fruit volume, but not with damage rates. Research on olive fruit phenology supports a relationship between moisture and fruit size. Sibbett and Ferguson (2005) note that olives prefer dry growing regions and that humidity and precipitation suppress fruit growth. The entomological literature on the olive fly does not support a relationship between humidity and fly activity or reproductive maturity, which justifies excluding humidity and precipitation from the damage function.

There are several different ways to define the dependent variable, damage. A table olive processor may consider an olive with any visible ovipositional stings damaged and unsuitable for canning. One possibility is to define an olive with greater than or equal to one sting or egg as damaged ($DG = 1$) or undamaged ($DG = 0$). Ovipositional

stings constitute aesthetic damage to an olive, but do not necessarily lead to infestation that degrades olive pulp quality. We use this damage definition to estimate a damage timing model. Alternatively, from an oil processor's point of view, a large amount of damage may be tolerable, depending upon how quickly fruit is transported to a crushing facility. However, any olives with secondary rot or fungal infestation due to larva growth are unusable for oil production. We use a continuous measure of damage severity, either mean fruit fly eggs per olive or cumulative larvae at time t , to estimate two damage level models.

Damage Function Data

We estimate damage level and timing models using a data set collected by Hannah Burrack and Frank Zalom of the University of California, Davis, Department of Entomology. Collaborating researchers in California orchards statewide collected field infestation data weekly from May to December of 2005. Field sites are located in Amador, Butte, Solano, Sonoma, Tulare, Ventura, and Yolo counties. Figure 1 demarks each site's specific location and table 1 summarizes the field sites, cultivars, and site characteristics. The chosen sites were untreated for olive fruit fly at the time of data collection, and had a sufficient olive crop to yield a sizeable sample of olives weekly. At each site, a number of trees of different cultivars were chosen.¹ The sample included a total of seven cultivars across the seven test sites, yielding fifteen unique site-cultivar pairings.²

¹ The cultivars sampled included four oil-specific varieties (Arbequina, Frantoio, Koroneiki, and Leccino), one mixed-use variety (Mission), and two table varieties (Manzanillo and Sevillano).

² . For each cultivar at each site, samples of olives were collected from each quadrant of two to four trees weekly. The number of olives collected per tree each week varied depending on olive volume and damage rates. Early in the season, before olives on each tree reached a volume of 10 mm³, 12 olives per tree were

Researchers recorded information on fruit measurements, damage, and infestation data. Damage and infestation data include the number of stings on the outside of each olive, the number of eggs inside each olive, the number of live and dead larvae (of each instar stage), the number of larval exit holes, and the number of pupae. Each of these measures represents a stage in the lifecycle of an olive fruit fly, as illustrated in figure 2. In total, the 2005 dataset contains observations on 81,267 olives. Data for other variables postulated to impact fruit fly cultivar preference (such as surface wax composition or oil/water content) were not collected as part of the caging experiment. However, as previously discussed, the relationship between volume and damage may capture the relationship between other cultivar-specific characteristics and damage.

In addition to fruit characteristics and management practices, estimation of (1') and (2') requires climate data. We collect daily data on minimum and maximum temperatures, relative humidity, and precipitation from each site's nearest weather station. Using minimum and maximum daily temperatures, the UC Davis IPM Degree Day Calculator generates daily and accumulated degree days based on pest or fruit development thresholds. We use three measures of degree days in the empirical analysis. We define growing degree days for olive fruit based on a lower threshold of 50 degrees Fahrenheit and no specific upper threshold, heating degree days for reproductively mature female flies based on activity thresholds of 60 and 100 degrees Fahrenheit, and heating degree days for larval development which halts outside the range of 46-95 degrees Fahrenheit. Table 2 summarizes the empirical data and their sources.

collected. No damage is observed on olives smaller than this volume threshold. Samples collected during this early period were used to monitor olive growth to decide when to begin sampling for infestation levels. After olives reached 10 mm³ in volume, a random sample of 100 olives per tree per week was culled for dissection. Once damage rates exceeded 50 percent of the fruit collected, the number of sampled olives was reduced to 52 per tree in order to preserve olives for later sampling dates.

Figure 3 illustrates accumulated degree days by site using each of the above sets of thresholds. The Ventura County and Sonoma County sites exhibit fewer growing degree days, which is consistent with their cooler coastal climates. Tulare County had the warmest climate, and the most time within fly and olive development temperature bounds, in 2005. The accumulated degree day trends are similar within coastal locations and interior sites, but differ between the two groups. The trends in the former are more linear, which is driven by more constant or gradually changing temperatures. In interior locations, growing degree days follow more of a cubic trajectory. This is driven by greater divergence between summer and spring/fall temperatures and more rapid temperature changes. Figure 3 suggests a possible mean-variance tradeoff: in interior locations, flies may develop more rapidly and prolifically but see a greater mortality risk due to variance in temperatures than flies in coastal sites.

Empirical Damage Level Models

We estimate two damage level specifications, the first of which uses the number of eggs per olive as a measure of damage, and the second of which uses the cumulative number of larvae per olive. The cumulative number of larvae at time t equals the total number of developing larvae inside the olive plus the number of larval exit holes observed. The olive fruit fly has multiple overlapping generations per year, so a single olive may be host to several generations of flies. Exit holes indicate that a surviving larva left the olive to pupate in the soil (or pupated inside the olive and exited) and may later develop into an adult fly that can propagate future generations. The dataset is a panel, with data on olives from a cross-section of trees collected each week during the growing season. Each sampled tree constitutes an “individual,” and we define each calendar week as a time

unit, i.e. $t=1$ for olives collected on any day during the week May 15 – 21, 2005. There are a total of 29 weeks (ending the first week of December, 2005) during which participants collected olives from 48 trees. The panel dataset is unbalanced, though for each tree the caging experiment began prior to any infestation and continued through to the end of the season, i.e. there is no sampling selection issue. The panel dataset includes 1,140 observations.

We disaggregate the stochastic error terms in equations (1') and (2') according to a basic unobserved effects specification. The error terms are given by

$$\varepsilon_{it} = c_i + u_{it}, \text{ and } v_{it} = h_i + v_{it}, \quad (3)$$

where c_i and h_i represent unobserved time-constant heterogeneity among trees sampled. Such heterogeneity may arise if, for example, there are systematic differences in the way in which an individual tree reacts biologically to a particular soil or irrigation method, its sun exposure, amount of pruning, or its age. The u_{it} and the v_{it} are the equations' idiosyncratic errors. We assume that the idiosyncratic error terms are iid with mean zero and constant variance, and that strict exogeneity holds for v_{it} . There may be correlation between the unobserved effects and the explanatory variables, particularly in the damage equation. For example, unobserved heterogeneity in damage due to sun exposure may be correlated with heating degree days. In this case, modeling the unobserved heterogeneity components as fixed effects ensures consistent parameter estimates. To capitalize on this advantage, we sacrifice inclusion of any time-invariant variables, such as site or cultivar indicators. However, we later conduct hypothesis tests to compare the estimated fixed effects across sites and cultivars to determine whether there are systematic unobserved effects in those dimensions.

Because the damage system is triangular, application of Heckman's (1979) sample selection bias correction method is particularly convenient as it yields an immediate Hausman test for endogeneity. We assume that the requisite conditions hold.³ An additional concern further complicates estimation of the damage system. There is a large probability mass at zero for each measure of damage and infestation (figure 4). This creates a problem in estimation that is technically identical to censoring. We estimate equation (1') as a Tobit model with a lower censoring value of zero and employ the associated standard assumptions on the distribution of the data. As Heckman (1979) points out, the Tobit methodology is a special case of the sample selection methodology. Combining the Tobit and Heckman methodologies conceptually involves adding a third equation (or a second reduced form equation) to the empirical damage system. Smith and Blundell (1986) first combined these two estimation methods. They note that including an estimated regressor in equation (1') results in understated standard errors. They derive a complex analytical expression for the appropriate variance-covariance matrix. We exploit computing power to obtain appropriate standard errors via bootstrapping.

Table 3 reports the estimation results for (1') and (2') using alternative measures of damage. The estimates reported in the first column for each model are the marginal effects on the conditional expectation of the latent dependent variable (which has

³ We assume that $E(u | X, c) = 0$, $E(u | VL) \neq 0$, $E(u | Z, h) = 0$. The first condition requires that the idiosyncratic error term in the damage function is orthogonal to the vector of regressors and individual unobserved heterogeneity. This holds by assumption. The second requires that the white noise error term in the damage function is correlated with olive volume. This holds based on scientific research. As to the third, Z contains many of the same variables as X , but it contains only exogenous elements in the damage equation plus humidity and precipitation, which we assume have no direct impact on damage or infestation rates, conditional on X . Further, we assume that the two error terms are linearly related, or that $u = \varphi v + \zeta$, $Corr(\zeta | v) = 0$, $E(u | v) = \varphi v$. Finally, we assume that no explanatory variables in one equation are perfectly collinear (the usual full rank condition). Throughout the analysis, we assume homoskedastic errors. To determine the validity of this assumption, we examined the relationship between each explanatory variable and the dependent variable. There does not appear to be any systematic relationship between the error terms and the explanatory variables.

probability mass for negative values). The column to the right of these reports the marginal effects of the explanatory variables on the conditional expected value of the observed dependent variable. The reported estimates in the table are very small; the units for each are given in the second row. The predominance of zeros for each of the dependent variables prohibits taking their logs (and the convenience of a double-log interpretation). Further, the absolute number of eggs or larvae in any one olive is small, ranging from 0-34 and 0-11, respectively (table 2). Therefore, the relative, rather than absolute, magnitudes of the coefficients and their signs are the primary focus of the ensuing discussion.

The signs of the coefficient estimates correspond with expectations based on the scientific literature. The results reported for the volume model reveal that accumulated growing degree days have a positive and decreasing effect on olive volume, and that increases in humidity tend to reduce olive size. The humidity-degree day interaction is positive and significant. This indicates that increased growing degree days, dampen the negative effect of humidity on olive volume. The positive sign on the Sevillano-degree day interaction term is reassuring. Sevillanos are the largest of all olive varieties grown in California, and we expect to see greater growth for those than for other cultivars, given the same number of growing degree days. Although we refer to this model as structural, it still contains some reduced-form elements. Specifically, the model does not explain underlying biological processes that drive differences in phenology between cultivars. This level of biological detail is outside of the scope of this study. Overall, the adjusted R-squared for the volume equation suggests a very good fit. The explanatory variables

included (plus the estimated, but not reported, fixed effects) explain 95 percent of the variation in olive volume.

The second column of results suggests that volume positively affects damage levels, as measured by mean number of eggs per olive, but with a tapering effect late in the season. Burrack (2007) documents a reduction in damage rates on large olives, namely Manzanillo and Sevillano fruit. Each time a fly oviposits, they leave behind a chemical that deters oviposition by another on the same site. Despite continuing increases in volume, it may be the case that these large varieties are less attractive for oviposition when they are more saturated with eggs and stings late in the season. This explanation rests on the implicit assumption that damage does not inhibit olive growth. Entomologists have found no evidence to contradict this assumption (*ibid.*). Late in the season, while Manzanillo and Sevillano olives continue to grow but experience less infestation, smaller Mission olives evidence more damage. The negative sign on this coefficient may indicate that the negative size effect swamps the positive effect.

A negative sign on the coefficient for accumulated degree days (for adult flies) indicates that heat in excess of that required to increase olive volume hampers fly damage. None of the degree day-management interaction terms is significant. However, the fixed effects reflect the effect of site-specific time-invariant factors, such as the presence of irrigation, on damage levels. Each of the other degree day-site and degree day-cultivar interaction terms is significant and positive, with the exception of that for Sevillano olives. Thus, the negative heat effect is dampened for these sites relative to the Solano County site. In the case of Amador, the heat effect is completely offset, so that further increases in heat increase damage rates. Amador County is located in the Sierra

Foothills region, and exhibits lower average temperatures than the other sample sites. The result that greater growing degree days increase the damage levels for Arbequina, Frantoio, Koroneiki, Leccino, and Mission olives reflects that these oil cultivars mature later in the growing season than Manzanillos and Sevillanos.

A natural question that arises concerning the fixed effects is whether damage rates differ by factors that are time-invariant and site-specific. For three of the seven sampling sites, hypothesis tests indicate that individual unobserved heterogeneity is significantly different by tree of the same cultivar.⁴ These sites are unirrigated and for the most part, unmanaged. Therefore, there may be greater heterogeneity in damage rates across sites with untended trees. In contrast, all of the sampled trees in Butte, Solano, Tulare, and Ventura counties evidence identical fixed effects across all trees within a site. This is a remarkable result for the Solano County site, in particular, as seven different cultivars, both oil and table varieties, were sampled there. However, the Solano County site is a germplasm administered by the University of California, Davis. The trees are planted in parallel rows, rather than groves, and the numerous cultivars are located in closer proximity to one another than differing cultivars in other sites.

The Tobit model for the mean eggs specification reports a pseudo R-squared of 0.51. The Hausman test of endogeneity cannot reject that the coefficient for the volume equation residuals is significantly different from zero at any conventional level. Therefore, in this specification, there is no evidence that the error terms of equations (1') and (2') are correlated, i.e. there are no underlying factors that simultaneously determine volume and oviposition rates. Burrack (2007) suggests that, beyond a minimum volume

⁴ This result holds for Leccino trees in Amador County, Mission trees in Sonoma County, and Manzanillo and Mission trees in Yolo County.

threshold, flies will sting any available olive without preference for those that happen to be larger. It may be that damage by oviposition is predominantly determined by factors that affect adult fly activity, rather than by changes in fruit size.

In the specification that uses mean cumulative larvae as the dependent variable, the number of eggs observed in an olive positively influences larval performance in that same fruit. Aside from the impact of volume on oviposition and the subsequent increase in larvae, volume does not have a significant effect on larvae except for late in the season, presumably for the same reasons discussed above. Again, the Hausman test suggests that there is no volume-related endogeneity in the damage function. The interaction terms are insignificant: location and cultivar influence larval performance only insofar as they affect the mean number of eggs per olive. The reported pseudo R-squared for this specification is 0.75. The pseudo R-squareds for the eggs and larval specifications are not directly comparable – they are valid only on evaluating different models with the same dependent variable and the same underlying dataset. We use these statistics in the next section as one basis of comparison between the structural and reduced-form models.

The results of the structural damage function estimation differ when performed on table and oil cultivars separately. Table 4 presents the estimated parameters for each group.⁵ The Hausman test for endogeneity finds evidence that the structural damage function for the table olive group is triangular, or that volume is endogenous in (1'). The estimated coefficient on volume residuals in the oil olive regression is close in magnitude to that for table olives, but is not significantly different from zero. The opposite result holds when using larvae as the dependent variable. The volume residuals are significant in explaining variation in the number of larvae observed in oil olives, but not in table

⁵ Here, we exclude the set of degree day interaction terms due to collinearity.

olives. It may be that larger table olive varieties are more attractive to flies for ovipositional purposes, but they are already large enough to accommodate larval development so further increases in volume have little effect on larvae observed. Conversely, for oil olives, oviposition may have more to do with the presence of an adult fly population than with size. However, because oil olives are so small, increases in size are correlated with increases in larval incidence. In the combined analysis, forcing identical parameters on table and oil cultivars despite substantial differences in olive size and infestation rates, appear to have obscured some group-specific simultaneity in olive size and damage.

Empirical Reduced Form Damage Function

A reduced form counterpart to the damage system in (1') and (2') expresses damage as a function of pest populations, as measured by trapping alone. Specifically,

$$DG_{it} = \alpha + \eta TR_{it} + m_i + \mu_{it}, \quad i = 1, \dots, N, t = 1, \dots, T \quad (4)$$

where TR is the average number of total flies trapped per site during week t , DG is as discussed above, m represents unobserved individual heterogeneity, and μ is the idiosyncratic error term. As in the structural estimation, we use fixed effects and Tobit estimation. Table 5 reports the reduced-form results.

The reduced form model estimates indicate that trap numbers are an insignificant determinant of infestation rates. Many of the fixed effects coefficients in these specifications are significant, which suggests that a constant by location better predicts infestation rates across space than fly population numbers. Burrack (2007) notes that fly population peaks are often followed by a lagged increase in infestation rates. Table 5 reports a second specification for each model that includes trapping numbers lagged up to

five weeks. The coefficients on trapping numbers lagged two, three, four, and five weeks are significant and positive. With lagged terms, the model pseudo R-squared terms range from 0.25 to 0.31, or about half of the pseudo R-squareds for the structural models.

There are several explanations for why trapping may be a poor measure of the population of reproductively mature females in the case of olive fruit fly. For example, there are two types of lures used at present, neither of which accurately gauges the reproductively mature female fly population (which causes damage). Moreover, bait efficacy fluctuates with temperatures over the course of the season and declines over time. If bait is less attractive during periods of high female flights or larval development, trapping numbers may move counter to damage or infestation levels. Measurement error threatens the consistency of the parameter estimates in equation (4). However, trapping levels and damage are both affected by temperatures, so the consistency of the parameter estimates for equation (4) are compromised even without considering measurement error.

The reduced-form damage function in expression (4) is more detailed than many of the reduced-form damage functions in the literature. By estimating unobserved heterogeneity across trees, we allow this function to differentiate damage rates at a much more disaggregated spatial level than studies that specify damage rates by region or by country. In addition, (4) disaggregates damage rates across time by estimating the trajectory of damage rates over the growing season. We estimate the mean damage rate at harvest by cultivar. The results indicate that, left untreated, oil varieties Arbequina, Frantoio, and Koroneiki suffered no damage in 2005. In contrast, Leccino olives, another oil variety, and mixed-use Mission olives experienced losses on the order of 30 to 33 percent. Table varieties Manzanillo and Sevillano were 100 and 80 percent damaged, on

average, by typical harvest dates in 2005. These averages correspond roughly with estimates from Burrack (2007) based on data for individual olives across several growing seasons. She estimates 1-15 percent crop loss for Arbequina, Frantoio, and Koroneiki olives, 1-30 percent loss for the Leccino cultivar, 8-80 percent loss of Mission olives, 18-70 percent loss for Manzanillos, and 80-100 percent loss for Sevillano olives.

Comparison of Structural and Reduced-Form Models

Based on a comparison of the pseudo R-squared values from the structural and reduced-form estimations, the structural models explain twice the variation in the dependent variables as the reduced-form models. Results using Akaike's information criterion (AIC), which takes into account both the maximized value of the likelihood function and the number of parameters estimated in both models, also indicate that the structural models better fit the damage data.

To test the validity of the structural model as a predictive tool, we withhold observations on four trees from estimation.⁶ Figure 5 illustrates predicted damage and observed damage for each tree over the growing season.⁷ The structural model approximates the data series well for the trees in Amador and Butte County. It overstates infestation in Sevillano olives in Solano County, and understates levels for Mission olives in Ventura County. Across the four predictions, the structural model slightly understates infestation in October and November (during the harvest period) and overstates infestation in late November and early December. A striking result from these figures is

⁶ I exclude 2005 season observations on a Leccino tree in Amador Counties, a Manzanillo tree in Butte County, a Sevillano tree in Solano County, and a Mission tree in Ventura County.

⁷ Note that the scale of the vertical axis differs between panels. Butte County trees exhibit a high level of infestation in 2005, with up to 16 eggs per olive on average. Amador County, on the other hand, has a maximum of about 1.2 average eggs per olive. Infestation in Solano and Ventura lies between these two extremes.

that the structural model predictions reflect differences in infestation during the growing season, while the reduced form specified in (4) estimates a relatively constant infestation trajectory. This result suggests that the reduced form may predict damage rates more accurately for locations that exhibit constant, low level fly infestation. Orchards that display highly variable infestation levels correspond to those locations with cubic growing degree day trajectories. In sites with greater seasonal temperature fluctuations, the structural damage function will likely generate substantially different estimates of the economic impacts of the fly than the reduced form.

Damage Timing Model

The damage timing model augments the levels analyses in two formidable ways. First, for trees with very low levels of infestation the levels models predict zero damage for the entire growing season.⁸ The timing model may help pin down a predicted time of infestation when the levels model fails to predict damage. Secondly, because table olive processors are extremely sensitive to any positive level of damage, growers of table olives may benefit from more precisely targeting their initial date of chemical pesticide treatment. At present, the Integrated Pest Management (IPM) program recommendation is to begin biweekly spraying upon olive flowering early in the season and to continue through harvest. Early season spraying may be redundant and costly in terms of grower costs of production and environmental degradation resulting from pesticide use. This section examines in greater detail factors that affect the initial date of fly infestation in an effort to further refine fly treatment recommendations.

⁸ No trees in the dataset exhibit zero damage for the entire growing season.

For the timing analysis, we define damage as a binary transition variable and estimate the structural damage function using a duration modeling approach.⁹ The duration of interest is the length of time in the season that a tree's olives remain undamaged. We proceed using the Weibull distribution to model the length of time until infestation. It is likely that, holding all of the damage function covariates constant, as the season progresses the likelihood of fly damage on any one tree increases (as olive oviposition sites are exhausted). The Weibull distribution is the simplest means of incorporating the possibility of duration dependence. Table 6 reports the estimated parameters of the damage timing function.

The Weibull hazard function for each specification is monotonically increasing, as indicated by the positive estimated values for p . This result supports the hypothesis of positive duration dependence. The median amount of time before a tree exhibits infestation through oviposition is 13 weeks into the growing season, which runs from August 7th through the 13th. The median amount of time before larval development is one week longer. Table 7 reports median survival times specific to each site-cultivar combination. In each case, the median survival time occurs within the growing season, which reflects that all cultivars experience fly damage at some point.

In the eggs model, an increase in volume of ten percent leads to a 10.05 percent increase in the hazard rate. This translates into a reduction in median duration of about

⁹ Consistent with the scientific literature and the assumptions of the previous section, we assume that the length of the duration of non-infestation does not affect the future values of the explanatory variables (specifically, infestation has no effect on an olive's growth trajectory). This is Lancaster's definition of "strict exogeneity" in the context of duration modeling with time-varying covariates. Similarly, we assume that the explanatory variables are external covariates, i.e. whether or not a tree is not infested or infested has no effect on the time path of any of the covariates. To incorporate fixed effects into the model, we include site and cultivar indicator variables, but do not distinguish between trees. Reducing the number of fixed effects relative to the damage level model was necessary because including an indicator for each tree in the sample prevented model convergence.

10.2 percent, or a little more than one week. In other words, the model predicts that an olive that is ten percent larger than the median olive will become infested in late July/early August. The same interpretation holds for accumulated degree days. In both specifications, the coefficient on the volume residuals is statistically significant at either the one or ten percent level. The Hausman test cannot reject the presence of volume-driven endogeneity for damage timing. Burrack and Zalom are currently working on a statistical model that determines the minimum volume threshold under which olives are not susceptible to fly damage. The result that volume and damage timing, by either measure, are determined simultaneously is not surprising given their working hypothesis. The analysis herein adds that, past that threshold, increases in volume and adult fly degree days push the timing of olive damage forward in the growing season.

Conclusion

The structural damage function formulated and estimated in this analysis highlights the importance of underlying climatic factors and host characteristics in driving pest infestation. Moreover, the model results indicate that, for table olives in particular, climatic factors drive fruit growth and damage rates simultaneously. Failing to account for endogeneity when estimating a damage function results in inconsistent parameter estimates and will ultimately skew estimates of the economic impact of the pest. Further, simultaneity in fruit size and damage is particularly important with respect to the timing of initial fly damage during the growing season. Entomologists working on questions related to the olive fruit fly hypothesize the existence of, and are working on estimating, minimum fruit volume thresholds for infestation by cultivar. Ultimately, their volume threshold work, taken in tandem with our results on the role of changes in volume and

degree days on damage rates, will aid in refining Integrated Pest Management recommendations. Doing so will enhance the cost-effectiveness of chemical treatments, and defray increases in production costs resulting from fly infestation. Our finding that some cultivars do not widely exhibit damage until August or September indicates that spraying beginning in May is unnecessary in some cases, and that producers will benefit from treatment recommendations that differ by location and cultivar.

The predictions generated by the structural and reduced-form damage level models suggest that the former better fits damage processes in regions with greater variance in temperature. The reduced form appears to more accurately predict the infestation trajectory over a growing season for those sites with less variable climatic conditions. The reduced form estimated in this analysis constitutes an intermediate approach between the structural damage function and the highly-reduced damage functions that estimate cumulative damage at harvest. Our reduced form relies on trapping data but disaggregates damage rates across the growing season. This temporal differentiation is particularly important to endogenizing harvest timing in an economic analysis. In the future, we plan to incorporate these damage functions into an economic optimization framework to evaluate biological and economic outcomes under differing management institutions.

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Tables and Figures

Table 1. Caging Data Site Descriptions

Site	County	Cultivars	Irrigation	Management Strategy	Number of Trees	Ground Cover	Geographic Region
Oneto	Amador	Leccino	Unirrigated	Unmanaged	50-100	Grass	North/Inland
Oroville	Butte	Manzanillo Mission	Irrigated Unirrigated	Moderate Unmanaged	>100	Grass	North/Inland
Petaluma	Sonoma	Mission	Unirrigated	Unmanaged	<10	Grass	North/Coastal
Exeter	Tulare	Manzanillo	Irrigated	Managed	50-100	None	South/Inland
Ojai	Ventura	Mission	Unirrigated	Unmanaged	<10	Grass	South/Coastal
Davis	Yolo	Manzanillo Mission	Unirrigated	Moderate Unmanaged	10-50	None Grass	North/Inland

Source: Burrack and Zalom, 2005 Fruit Development & Infestation Data

Table 2. Description of Empirical Variables

Variable	Measure	Unit	Range	Source
Damage	Number stings	Olive	{0,...,34}	Burrack and Zalom, 2005 Fruit Development & Infestation Data
Damage	Total cumulative larvae	Olive	{0,...,11}	
Volume	Height, width, length	Olive	[0.3,13708.0]	
Roundness at Length	Height, width, length	Olive	[0.5,1.4]	
Irrigation	Non-irrigated/Irrigated	Site	{0,1}	
Management	Unmanaged/Moderate/ Commercial	Site	{0,1,2}	
Ground Cover	None/Grass	Site	{0,1}	
Trapped Flies	Total Trapped	Site	[0,129.6]	
Olive Degree Days	Min/Max Daily Temperatures	Site	[863.0,5220.7]	California Irrigation Mgmt. Information System (CIMIS), UC IPM Online Weather Database
Adult Fly Degree Days	Min/Max Daily Temperatures	Site	[258.7,2712.4]	
Fly Larvae Degree Days	Min/Max Daily Temperatures	Site	[1213.2,5565.4]	
Variance in Min Temperature	Min Daily Temperatures	Site	[0.6, 72.3]	
Humidity	Relative Humidity (%)	Site	[23.2,90.4]	California Climate Data Archive
Precipitation	Total Inches	Site	[0,1.8]	

Table 3. Results of Structural Damage Function Estimation for the Volume, Mean Eggs, and Mean Cumulative Larvae Specifications

Variable	Volume	Mean Eggs		Mean Larvae	
	dy/dx	dy*/dx (x10 ⁻²)	dy/dx (x10 ⁻⁶)	dy*/dx (x10 ⁻²)	dy/dx (x10 ⁻⁴)
Constant	283.13	-733.15 ^a		-338.51 ^a	
Mean Number of Eggs				23.71 ^a	295.29
Volume		0.17 ^a	0.46	-0.01	-0.19
Volume*Late Season		-0.03 ^a	-0.07	-0.01 ^a	-0.17
Roundness-at-Length		-25.43	-68.10	26.09	324.9
Accumulated Degree Days	1.37 ^a	-7.16 ^a	-1.92	0.01	0.15
Accumulated Degree Days ²	-0.00 ^a	0.00 ^c	0.00	0.00	0.00
Var in Min Temperature		-0.07	-0.18	-0.00	-0.00
Humidity	-18.40 ^a				
Precipitation	-0.00				
Estimated Volume Residuals		-0.12	-0.03	0.03	0.35
<i>Interactions with Accumulated Degree Days</i>					
	Humidity	0.01 ^a			
	Irrigation		0.57	1.52	0.07
	Ground Cover		-2.43	-0.65	-0.06
	Maintenance		0.17	0.46	0.05
<i>Sites</i>	Amador	-0.26 ^a	0.78 ^a	2.10	0.04
	Butte	-0.75 ^a	0.58 ^a	1.56	-0.02
	Sonoma	-0.55 ^a	0.67 ^a	1.81	0.02
	Tulare	-0.76 ^a			
	Ventura	-0.83 ^a	0.68 ^a	1.82	0.02
	Yolo	-0.83 ^a	0.54 ^a	1.44	-0.01
<i>Cultivars</i>	Arbequina	-1.20 ^a	5.78 ^c	15.50	0.27
	Frantoio	-0.99 ^a	0.31 ^c	0.84	-0.01
	Koroneiki	-1.34 ^a	10.73 ^b	28.80	-0.04 ^c
	Leccino	-0.89 ^a	0.27 ^a	0.74	0.01
	Mission	-0.45 ^a	0.10 ^b	0.28	0.00
	Sevillano	1.40 ^a	-0.38 ^a	-1.03	0.04
Estimation Method	OLS		Tobit		Tobit
Adj or pseudo R-squared	0.95		0.51		0.75
Log Likelihood Value			-886.27		-253.22
AIC			1898.54		634.44

^a, ^b, ^c denote significance at the one, five, and ten percent levels.

Table 4. Structural Model Estimation Results for Table and Oil Cultivars, for the Mean Eggs and Mean Cumulative Larvae Specifications

Variable	Table Olives		Oil Olives	
	Mean Eggs (x10 ⁻²)	Mean Larvae (x10 ⁻²)	Mean Eggs (x10 ⁻²)	Mean Larvae (x10 ⁻²)
Constant	-316.60 ^b	-97.23	-624.46 ^c	-106.18
Mean Number of Eggs		21.71 ^a		61.96 ^a
Volume	0.37 ^a	-0.04	0.15	-0.09
Volume*Late Season	-0.02 ^a	-0.01 ^b	0.01	0.01
Roundness-at-Length	349.45 ^b	51.84	-189.61	-2.43 ^c
Accumulated Degree Days	-0.41	0.03	0.41 ^b	0.11 ^c
Accumulated Degree Days ²	0.00 ^c	0.00	-0.00	-0.00
Var in Min Temperature	-1.63 ^b	-0.31	-0.03	-0.10
Estimated Volume Residuals	-0.16 ^b	0.04	-0.15	0.07 ^c
N	413	413	294	294
Pseudo R-squared	0.45	0.63	0.92	
Log Likelihood Value	-480.65	-179.92	-13.40	30.72

^{a, b, c} denote significance at the one, five, and ten percent levels.

Table 5. Results of Reduced Form Model Estimation, for the Mean Eggs and Mean Cumulative Larvae Specifications

Variable	Mean Eggs			Mean Larvae		
	dy*/dx (x10 ⁻⁴)	dy*/dx (x10 ⁻⁴)	dy/dx (x10 ⁻⁴)	dy*/dx (x10 ⁻⁴)	dy*/dx (x10 ⁻⁴)	dy/dx (x10 ⁻⁴)
Constant	-8798 ^b	-7845 ^c		-2441	-1876	
Trapped Flies	-0.64	1.59	0.80	-1.55	-0.73	-0.26
Trapped Flies, t-1		2.20	1.10		-0.45	-0.16
Trapped Flies, t-2		25.96 ^a	13.06		9.91 ^a	3.49
Trapped Flies, t-3		22.26 ^a	11.20		7.55 ^a	2.66
Trapped Flies, t-4		17.59 ^a	8.84		8.67 ^a	3.05
Trapped Flies, t-5		16.43 ^a	8.27		6.97 ^a	2.45
Estimation Method	Tobit		Tobit	Tobit		Tobit
Pseudo-R2	0.23		0.25	0.31		0.35
Log Likelihood Value	-1391.22		-1356.06	-687.62		-652.47
AIC	2868.44		2808.12	1461.24		1400.94

^{a, b, c} denote significance at the one, five, and ten percent levels.

Table 6. Results of Damage Timing Model Estimation, for the Mean Eggs and Mean Cumulative Larvae Specifications

Variable	Mean Eggs Hazard Ratio	Mean Larvae Hazard Ratio
Mean Number of Eggs		10.7638
Volume	1.0054 ^a	1.0020
Volume*Late Season	0.9997	0.9998
Estimated Volume Residuals	0.9965 ^a	0.9973 ^c
Roundness-at-Length	0.0195	1.3761
Accumulated Degree Days	0.9869 ^b	0.9912
Var in Min Temperature	0.9966	1.0155
N	392	454
p	14.87	11.04
Median Duration	13.27	14.25
Log Likelihood Value	33.35	13.92

^a, ^b, ^c denote significance at the one, five, and ten percent levels.

Table 7. Median Time until Initial Fly Infestation, by Site and Cultivar

Site	Cultivar	Use	Median Survival Time	Date Range
Amador	Leccino	Oil	13.97	August 7-14
Butte	Manzanillo	Table	6.40	June 19-26
	Mission	Mixed	6.81	June 19-26
Solano	Arbequina	Oil	18.58	September 11-18
	Frantoio	Oil	11.50	July 24-31
	Koroneiki	Oil	19.53	September 18-25
	Leccino	Oil	8.25	July 3-10
	Manzanillo	Table	6.20	June 19-26
Sonoma	Mission	Mixed	6.95	June 19-26
	Sevillano	Table	4.82	June 5-12
	Mission	Mixed	9.88	July 10-17
Tulare	Manzanillo	Table	12.70	July 31-August 7
Ventura	Mission	Mixed	6.99	June 19-26
Yolo	Manzanillo	Table	6.10	June 19-26
	Mission	Mixed	6.38	June 19-26



Figure 1. Field Data Collection Sites

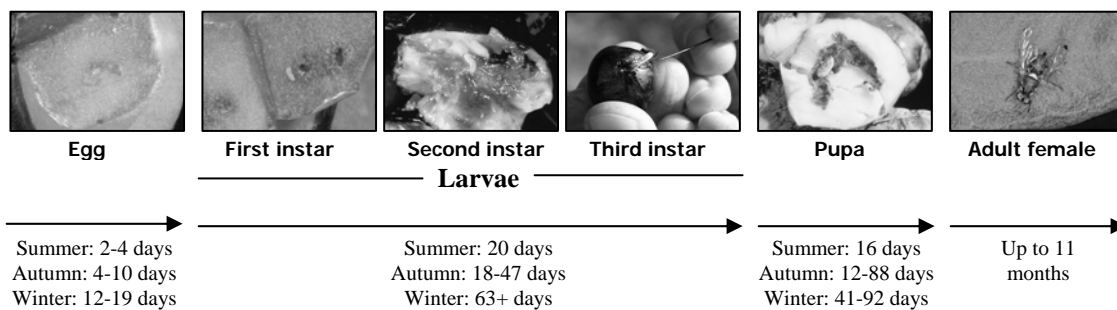


Figure 2. Stages of Olive Fruit Fly Development

Source: Zalom (2003)

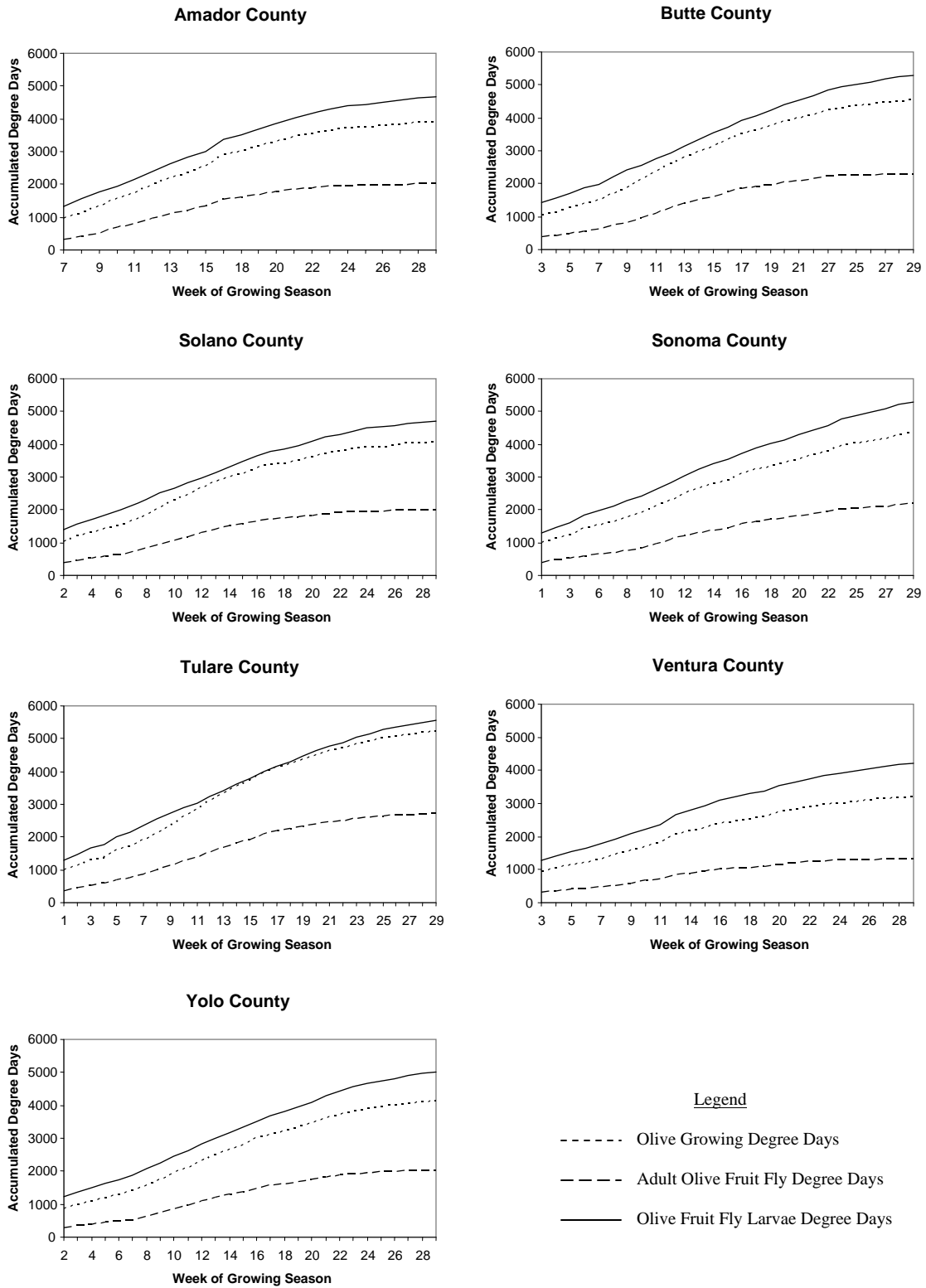


Figure 3. Accumulated Degree Days for Olive Fruit, Adult Olive Fruit Flies, and Fruit Fly Larvae over the 2005 Growing Season, by Data Collection Site

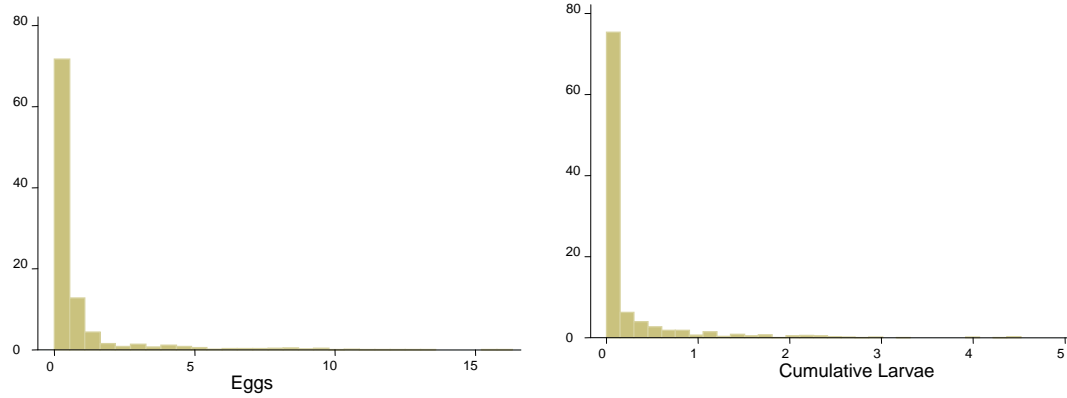


Figure 4. Percent of total observations versus number of olive fruit fly eggs and total cumulative larvae

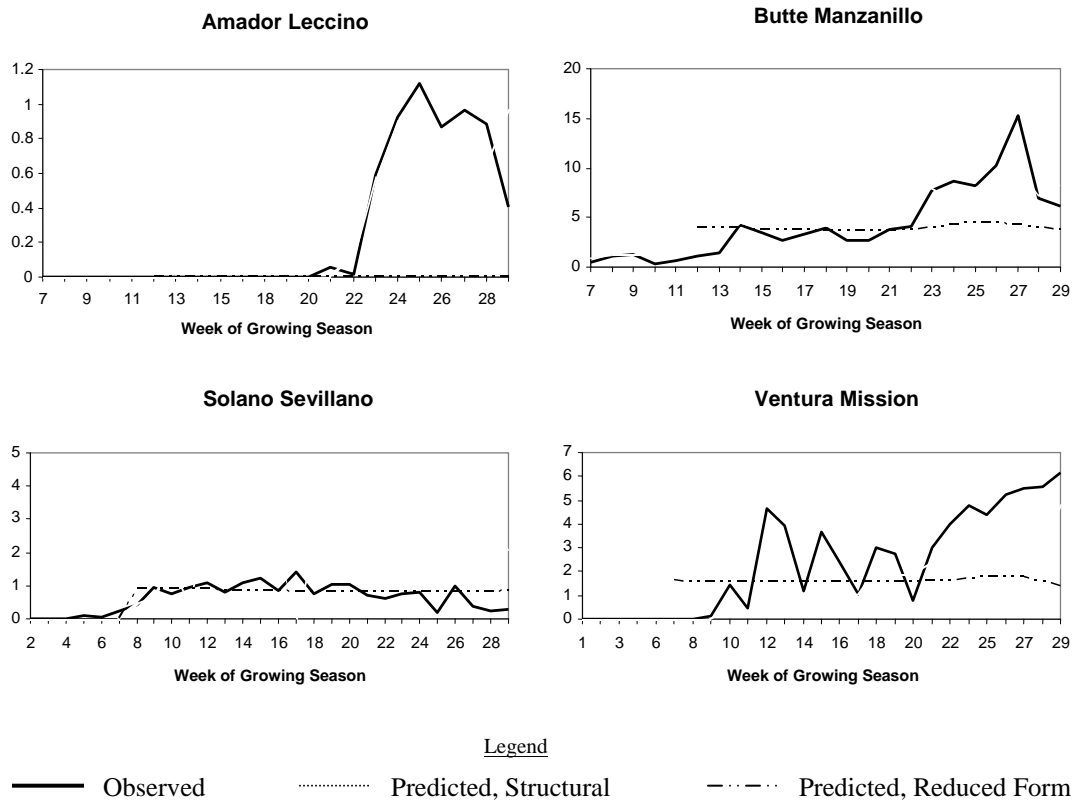


Figure 5. Mean Number of Eggs per Olive over the Growing Season, Observed, Predicted by the Structural Damage Function, and Predicted by the Reduced Form Damage Function, for Four Trees in Four Sites