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Using plant volatile traps to develop phenology models for natural enemies: An example using *Chrysopa nigricornis* (Burmeister) (Neuroptera: Chrysopidae)

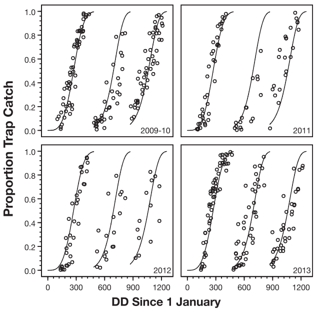
Vincent P. Jones[a,*], David R. Horton[b], Nicholas J. Mills[c], Thomas R. Unruh[b], Eugene Miliczky[b], Peter W. Shearer[d], Kaushalya G. Amarasekare[e,1], Callie C. Baker[a], Tawnee D. Melton[a]

[a] *Department of Entomology, Tree Fruit Research and Extension Center, Washington State University, 1100 N. Western Ave., Wenatchee, WA 98801, USA*
[b] *USDA – ARS, Yakima Agricultural Research Laboratory, 5230 Konnowac Pass Road, Wapato, WA 98951, USA*
[c] *Department of Environmental Science and Policy Management, University of California, Berkeley, CA 94720-3114, USA*
[d] *Mid-Columbia Agricultural Research and Extension Center, Oregon State University, 3005 Experiment Station Drive, Hood River, OR 97031-9512, USA*
[e] *Tennessee State University, Dept. of Agricultural and Environmental Sciences, Room 202 P, Farrell Westbrook Hall, 3500 John A Merritt Blvd, Nashville, TN 37209, USA*

HIGHLIGHTS

- A phenology model for *C. nigricornis* was developed in apple orchards.
- Independent data from apple, pear, cherry and walnut orchards validated the model.
- The results suggest generalist predator models may be useful in multiple systems.

GRAPHICAL ABSTRACT



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ABSTRACT

A model predicting phenology of adult *Chrysopa nigricornis* (Burmeister) (Neuroptera: Chrysopidae) in orchards was developed from field (trapping) data supplemented with development data collected under laboratory conditions. Lower and upper thresholds of 10.1 °C and 29.9 °C, respectively, were estimated from published and unpublished laboratory observations, and were used to develop a phenology model. Season-long field data were collected using white delta traps that had been baited with squalene, a volatile shown previously to be highly attractive to *C. nigricornis*. The model was developed from data collected in three Washington apple orchards, and was validated using independent data sets collected from apple, sweet cherry, pear, and walnut orchards over a 2–4 year period across a much wider geographic region. We found that the mean absolute deviation across all crops and years was 39.7 ± 1.2 day-degrees (DD), or 4.4 ± 0.14 days. Populations of *C. nigricornis* from walnut orchards in California emerged 105 DD later than those in Oregon and Washington, thus requiring correction of average time of first trap catch in California to synchronize models. The ability to use a single model across multiple crops, different prey species and abundances, and different pesticide regimes demonstrates that phenology models for generalist predators may have broader application to IPM programs in other cropping systems.

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[*] Corresponding author.
E-mail addresses: vpjones@wsu.edu (V.P. Jones), kamarase@tnstate.edu (K.G. Amarasekare).

[1] Ph.D. Assistant Professor (Entomology) and IPM Coordinator. Tel.: 615 963 5001; Mobile: 352 281 9591.

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1. Introduction

Phenology models for pests have dramatically changed pest management approaches in a broad range of agricultural systems. Fundamentally, the ability to predict pest phenology allows a shift from a reactive management strategy to one in which management decisions can be planned well ahead of the dates when management activities are actually needed (Croft et al., 1976; Gage et al., 1982; Welch et al., 1978). Phenology models are based on the idea that the duration of various developmental stages of insects and mites (and other poikilothermic organisms) can be predicted by temperature accumulations above some lower temperature at which development rates are zero, and below an upper threshold at which development is prevented because of thermal deactivation of certain physiological processes (Jones, 1991).

One of the first phenology models developed in pest management was for the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). Landmark studies in the mid-to-late 1920's gave detailed information about the developmental of codling moth at various temperatures (Garrett, 1922; Glenn, 1922a,b; Shelford, 1929). This information was used to devise a cumbersome method for calculating heat accumulations, but the method was never widely adopted. Technological and computational improvements in the 1970's allowed scientists to re-visit phenology models for codling moth and a variety of other pest insects (Gage et al., 1982; Riedl and Hoying, 1980; Riedl et al., 1979, 1985; Welch et al., 1978) and helped IPM managers time key management activities (Gage et al., 1982; Welch et al., 1978).

While phenology models for pests have matured and entered the mainstream of IPM tactics, the development of phenology models for natural enemies have not progressed at the same rate. Although there are a number of studies on the temperature dependent development for natural enemies, there are far fewer models than might be expected given the success of degree-day models for pests in IPM programs. Part of the discrepancy is likely the result of the greater difficulty in rearing and performing development rate studies on natural enemies because of the need for rearing prey or host species in addition to the predator or parasitoid species. An additional complication has been the difficulty of sampling natural enemies quickly, and with sufficient precision and numbers for model development and validation studies. Given the diversity of natural enemies that occur in even the simplest agro-ecosystem, and the need for development rate data at multiple temperatures (so that developmental thresholds can be estimated), it is not surprising that only a few natural enemy models have been developed, validated and used for management purposes.

Major advances in the development of phenology models for both pests and natural enemies have come from a series of papers that evaluated development rates and temperature thresholds for a broad range of arthropods. These studies have revealed several key findings that simplify model development: (1) Insects and mites exhibit development rate isomorphy, where the proportion of total development time spent in a particular life stage does not change with temperature (Jarošík et al., 2002). This means that the lower development threshold (LDT) is constant among life stages within a species, which allows the use of a single stage (e.g., eggs or pupae) to estimate the LDT for a species. In addition, this also means that if the development times for all stages for a given temperature are known, comparable development times for other temperatures can be estimated from only a single life stage, which greatly simplifies laboratory studies (Jarošík et al., 2004). (2) The range of temperatures between the upper and lower thresholds for development of 66 species of insects in 8 different orders averaged 19.8 °C ± 0.7 ($\bar{x}$ ± 95% CI) (Dixon et al., 2009). Therefore, once the lower threshold is determined, the upper threshold can be estimated and tested against field data for accuracy.

The final advance that should accelerate the development of phenology models for natural enemies comes from research performed over the past 10–15 years on the use of herbivore-induced plant volatiles (HIPV)/floral volatile dispensers to evaluate whether natural enemy population abundance and spatial distribution can be manipulated to improve biological control (James, 2003a,b, 2005a,b; James and Price, 2004; Kahn et al., 2008; Toth et al., 2006, 2009; Turlings and Ton, 2006; Yu et al., 2008; Zhang et al., 2006). These studies and more recent ones (Jones et al., 2016, 2011; Rodriguez-Saona et al., 2011) have shown that when paired with traps, HIPV/plant volatile lures can be used to monitor a broad range of natural enemies and provide information on their abundance, diversity, and phenology that would be useful for IPM programs.

In this paper, we focus on the use of a volatile HIPV lure to develop a phenology model for adults of the green lacewing *Chrysopa nigricornis* Burmeister (Neuroptera: Chrysopidae). This species has a transcontinental distribution in North America, extending as far south in the U.S. as New Mexico and Texas, and northwards into most of the Canadian provinces (Garland and Kevan, 2007; Penny et al., 1997). *C. nigricornis* has a distinct preference for deciduous trees and shrubs over herbaceous vegetation (Horton et al., 2009; Petersen and Hunter, 2002; Putman, 1932), and is a common predator of aphids and other soft-bodied arthropods in fruit and nut orchards throughout North America (Szentkirályi, 2001). The species has 2–3 generations per year in the western U.S. (Carroll and Hoyt, 1984; Horton et al., 2012; Toschi, 1965), overwintering in diapause as a cocooned last-instar larva (Tauber and Tauber, 1972) in bark crevices or beneath plant litter. The seasonal activity of adults under Pacific Northwest conditions can be quite prolonged, and may extend from early-May well into October (Garland and Kevan, 2007).

The few quantitative studies that address *C. nigricornis* phenology almost exclusively examine the larval stage (Carroll and Hoyt, 1984; Horton et al., 2012). Here, we demonstrate that a volatile attractant (squalene; Jones et al., 2011) can be used under orchard conditions across a broad geographic range to monitor flight phenology of *C. nigricornis*. We used trap catch data in combination with development rate data for this species to develop a temperature-based phenology model for *C. nigricornis* in fruit and nut orchards of Washington, Oregon, and California. Our objective was not only to develop an effective phenology model for this species, but also to evaluate how phenology models for natural enemies in general may highlight areas where additional research is needed in our efforts to maximize conservation biological control.

2. Materials and methods

2.1. Lure construction

Lures were made using 5 cm wide × 7.5 cm long sections of polyethylene tubing (Associated Bag Company, Milwaukee, WI). The tubing was heat sealed at one end and a 3.8 cm long piece of dental wick was placed into the bag, and 1 ml of squalene (Sigma–Aldrich, St. Louis, MO) was applied to the wick before heat-sealing the other end of the bag (Jones et al., 2011).

2.2. Orchards and traps

We sampled apple, pear, cherry, and walnut orchards in California, Oregon and Washington during the growing seasons of 2009–2013. We used four replicate traps in each orchard, spaced >100 m apart. Lures were placed in the large white plastic delta traps that are commonly used for monitoring codling moth in Western Orchards (Suterra LTD, Bend, OR) or above white panel