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## Population Ecology

# Seasonal Population Dynamics of Three Potato Pests in Washington State

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## Abstract

Pest phenology models allow producers to anticipate pest outbreaks and deploy integrated pest management (IPM) strategies. Phenology models are particularly useful for cropping systems with multiple economically damaging pests throughout a season. Potato (*Solanum tuberosum* L.) crops of Washington State, USA, are attacked by many insect pests including the potato tuberworm (*Phthorimaea operculella* Zeller), the beet leafhopper (*Circulifer tenellus* Baker), and the green peach aphid (*Myzus persicae* Sulzer). Each of these pests directly damages potato foliage or tubers; *C. tenellus* and *M. persicae* also transmit pathogens that can drastically reduce potato yields. We monitored the seasonal population dynamics of these pests by conducting weekly sampling on a network of commercial farms from 2007 to 2014. Using these data, we developed phenology models to characterize the seasonal population dynamics of each pest based on accumulated degree-days (DD). All three pests exhibited consistent population dynamics across seasons that were mediated by temperature. Of the three pests, *C. tenellus* was generally the first detected in potato crops, with 90% of adults captured by 936 DD. In contrast, populations of *P. operculella* and *M. persicae* built up more slowly over the course of the season, with 90% cumulative catch by 1,590 and 2,634 DD, respectively. Understanding these seasonal patterns could help potato producers plan their IPM strategies while allowing them to move away from calendar-based applications of insecticides. More broadly, our results show how long-term monitoring studies that explore dynamics of multiple pest species can aid in developing IPM strategies in crop systems.

Key words: monitoring, pest complex, phenology model, population dynamics, potato

Understanding the population dynamics of pests is the foundation of integrated pest management (IPM; Dent 2000, Pedigo and Rice 2006). Knowledge of the seasonal dynamics of pests allows crop producers to time sampling to coincide with key pest life stages (Pedigo and Rice 2006). Characterizing seasonal pest dynamics also allows producers to deploy pesticide sprays and other control tactics effectively, increasing their value and decreasing negative impacts on the environment (Welch et al. 1978, Nietschke et al. 2007). Moreover, when IPM tactics are timed properly with key pest development stages, it can minimize the need for subsequent insecticide treatments (Afun et al. 1991, Wilby and Thomas 2002, Herms 2004).

For many crop producers, however, the ability to monitor mobile insect pests is costly, time-consuming, and imprecise. Producers therefore often rely on regional monitoring networks and models to predict pest distributions across landscapes (Marsh et al. 2008). For pests whose development is mediated by temperature, phenology models allow producers to time IPM strategies based on accumulated degree-days (DD) rather than on calendar date (Afun et al. 1991, Herms 2004, Sporleder et al. 2004). Such models are critical due to yearly and regional fluctuations in temperature and other conditions (Choi and Ryoo 2003). However, when growers lack information on pest population dynamics, it can be difficult to predict when pests will exceed economic thresholds that warrant treatment (Mumford and Norton 1984). In such cases growers often rely on calendar-based sprays of pesticides for management (Schreiber 2003, Schreiber et al. 2015, Rondon and Murphy 2016).

Potatoes (*Solanum tuberosum* L.) in Washington State, USA, are one system where IPM has historically been lacking (Waller et al. 1998). Potatoes are the most economically valuable vegetable crop in Washington, with sales valued at US$792 million in 2013 (USDA 2013). To improve soil health and reduce the impact of pests, potatoes are typically grown in 3- to 4-yr rotations with crops such as corn, mint, onion, alfalfa, wheat, and *brassicas* (Honeycutt et al. 1996, Dung et al. 2015). Potatoes anchor these rotations by having greater profit potential than other crops. As the economic viability

of many growers is dependent on producing robust yields of potatoes, growers are often risk-averse when managing pests (Waters and Jensen 2014).

Conventional potato production typically involves applying a systemic neonicotinoid at planting, which protects the crop from numerous foliar feeding pests for several months (Schreiber et al. 2015). Many growers supplement these treatments with calendar-based broad-spectrum pesticide treatments to prevent pests from reaching economic thresholds (Guenthner et al. 1999, Schreiber 2003, Schreiber et al. 2015, Rondon and Murphy 2016). However, end users of potato products have pushed for more sustainable IPM practices. The potato industry has in turn largely shifted toward a more information-intensive approach that considers pest population dynamics and natural enemies in decision-making (Ehler 2006, Rondon 2012). Development of pest phenology models would further aid potato growers in shifting toward these more sustainable growing practices.

In the Columbia River Basin, an area that encompasses 670,000 irrigable acres (Kunkel and Bakes 1965) and the primary region in Washington where potatoes are grown, three key insect pests are the potato tuberworm (*Phthorimaea operculella* Zeller), beet leafhopper (*Circulifer tenellus* Baker), and green peach aphid (*Myzus persicae* Sulzer) (Crosslin et al. 2006, Munyaneza et al. 2006, Rondon 2010). Each of these pests directly damages plants by feeding on leaves or tubers, which decreases yield and quality (Rondon 2010). Furthermore, *M. persicae* and *C. tenellus* can vector devastating pathogens. *Myzus persicae* transmits potato leafroll virus and potato virus Y (Thomas et al. 1997, Crosslin et al. 2006), while *C. tenellus* vectors a phytoplasma known as the beet leafhopper transmitted virescence agent that causes purple top disease (Munyaneza 2006, Murphy 2014).

To aid the potato industry in sustainably managing these pests, an area-wide insect monitoring network was established, whereby weekly sampling of each pest was conducted. We used data from this network from 2007 to 2014 to develop seasonal population dynamics models for each pest based on accumulated temperature units. This information should improve the ability of potato producers to anticipate and manage each of the three pest populations, and facilitate the transition of the potato industry toward more sustainable IPM practices.

## Materials and Methods

### Pest Monitoring Network

In 2007, a monitoring network for key insect pests of potato crops in Washington State was developed. The monitoring network consisted of weekly sampling of between 24 and 80 commercial potato fields dispersed throughout six counties in the Columbia River Basin during the potato-growing season (April through October; Table 1). Each year, all but one or two fields in the network were managed conventionally, with the others managed organically. All fields produced russet cultivars of potatoes, and management was performed by the growers who owned each field. Within this network, monitoring of *P. operculella* and *C. tenellus* began in 2007, and monitoring of *M. persicae* began in 2009.

### Pest Sampling Protocols

In each sampled field, *C. tenellus* was monitored using double-sided 13.33- by 9.5-cm yellow sticky cards (AlphaScents, Portland, OR). Sticky cards were mounted on wooden stakes 7.62 cm above the ground. In each field, we used two sticky traps for *C. tenellus*

**Table 1.** Details of the regional pest monitoring network over time

| Year | Pests | Sampled fields | First sample | Last sample | # samples/ pest |
|------|-------|----------------|--------------|-------------|-----------------|
| 2007 | Ct, Po | 68 | 2-April | 31-Oct. | 2,097 |
| 2008 | Ct, Po | 80 | 7-April | 26-Oct | 2,222 |
| 2009 | Ct, Mp, Po | 25 | 11-May | 12-Oct | 513 |
| 2010 | Ct, Mp, Po | 36 | 28-April | 22-Oct | 932 |
| 2011 | Ct, Mp, Po | 37 | 26-April | 14-Sep | 851 |
| 2012 | Ct, Mp, Po | 39 | 2-May | 2-Oct | 897 |
| 2013 | Ct, Mp, Po | 38 | 30-April | 27-Aug | 675 |
| 2014 | Ct, Mp, Po | 43 | 2-May | 26-Sep | 945 |

Shown are the pests sampled (Ct = *C. tenellus*; Mp = *M. persicae*; Po = *P. operculella*), the number of fields sampled weekly in each year, the date of the first and last sample each year, and the total number of samples per pest in each year (note not all fields were sampled over the entire date range due to variation in planting date and vine kill).

sampling; the traps were located along field edges at locations with low weedy vegetation and spaced at least 300 m apart. Adult males of *P. operculella* were monitored using one Pherocon VI Delta Trap with a pheromone lure (TRÉCÉ Inc, Adair, OK) per field, suspended 30.5 cm from the ground with PVC pipes. The traps were checked weekly, and lures were replaced every 3 wk. *Myzus persicae* were sampled by vigorously shaking five potato plants, five times over a 4.75-liter, 20.3-cm-diameter collection bucket. This was repeated four times for a total of 20 plants sampled per field. Alate and apterous aphids were pooled in these samples; over 99% of collected aphids were wingless. All sampled plants were at least 15 m from the field edge or the outermost tracks of irrigation equipment. Monitoring of each insect was conducted weekly throughout the growing season until vine kill in each field. The density of each pest in a given week was calculated per trap (for *C. tenellus* and *P. operculella*) or per plant (for *M. persicae*) by taking the average number caught in all traps, or the average number sampled per plant, in each field each week.

### Collection of Temperature Data

Data on temperature for each field site in each week in each year were obtained by the National Climate Data Center (NCDC). Daily temperatures were obtained from NCDC weather stations nearest to each sample site (weather stations averaged ~22 km from each field, with a range from 5 to 47 km). To calculate accumulated degree-days for each field site in each week, we used the rectangular method (Herms 2004):

$$DD = \frac{T_{max} + T_{min}}{2} - T_{base}$$

Where $DD$ is the measure of daily heat accumulation, $T_{max}$ is the average daily maximum temperature, $T_{min}$ is the average daily minimum temperature, and $T_{base}$ is the lower developmental threshold of the insect. The lower developmental threshold values used for *P. operculella*, *C. tenellus*, and *M. persicae* were 11, 14.4, and 4°C, respectively (Harries et al. 1948, Ro et al. 1998a, Sporleder et al. 2004). Accumulated degree days, the total heat accumulated from $T_0$, were calculated in each year using a biofix date of 1st January.

### Development of Seasonal Dynamics Models

Data on the cumulative abundance (% of total insects caught over the season) of each pest was regressed against accumulated degree-days to assess the seasonal population dynamics of each pest.

We modeled cumulative abundance, also known as population emergence, as a function of temperature to identify key periods of growth for populations of each pest. Data used to construct these models were based on the cumulative emergence of each insect in each field where sampling was conducted in each year, and the corresponding degree day accumulation in that field. Thus, each field in each week in each year served as one data point in the regression models. Table 1 shows the total number of sample points used to construct the models for each pest ($n = 9,132$ for *C. tenellus* and *P. operculella* and $n = 4,813$ for *M. persicae*). The relationship between degree-days and cumulative abundance of each pest was modeled using a four-parameter Weibull distribution:

$$y = a\left[1 - e^{-\left|\frac{x-x_0+b\ln(2)^{\frac{1}{c}}}{b}\right|^c}\right]$$

where $y$ is percent cumulative abundance, $x$ is time, in cumulative degree-days, $x_0$ is the time in degree days required to reach 50% emergence, and $a$, $b$, and $c$ are empirically derived constants. The parameter $a$ is the theoretical maximum percent cumulative abundance, $b$ is the rate of increase, and $c$ is a shape parameter (Royo-Esnal et al. 2015). Fitting of the four-parameter Weibull function for cumulative abundance was performed using SigmaPlot 10.0 (Systat Software, Inc, San José, CA). This distribution is commonly used in models of pest population dynamics (Wagner et al. 1984) and provided the best fit to our observed data.

## Results

### Seasonal Pest Dynamics
The weekly average densities of each of the three monitored insect pests over the course of the 2007 to 2014 potato-growing seasons are shown in Figs. 1–3. Populations of *P. operculella* (Fig. 1) were initially detected in late May or June across all years. Densities of this pest typically increased as the growing season progressed and reached a peak in September or October just prior to the season's end (Fig. 1). The numbers of *P. operculella* collected was fairly consistent across years, except in 2013 and 2014 when the maximum population size was 3 to 12 times greater than peaks observed in 2007 to 2012. Unlike *P. operculella*, populations of *C. tenellus* were typically detected earlier in the season, with the first observations in April or early May (Fig. 2). Populations of *C. tenellus* typically had 1 to 3 peaks per year in the early season, although in two years (2007 and 2008) populations peaked immediately before the end of the growing season (Fig. 2). In contrast to *P. operculella*, densities of *C. tenellus* varied widely from year to year, with the maximum density in a year ranging from as low as two insects per trap (averaged across all sites in a year) to as high as 25 insects per trap (Fig. 2). Of the three pests, *M. persicae* was detected latest in potato fields, with initial observations occurring in June or July (Fig. 3). Similar to *P. operculella*, populations of *M. persicae* increased during the potato-growing season, with maximum densities observed immediately preceding the end of the season (Fig. 3).

### Phenology Models
The relationship between cumulative abundance of each pest and accumulated degree-days (DD) is shown in Fig. 4. The seasonal dynamics of each pest were consistently mediated by temperature, with the Weibull model explaining 90, 89, and 94% of the variation in cumulative abundance for *P. operculella*, *C. tenellus*, and *M. persicae*, respectively (Table 2). The abundances of *P. operculella* and *M. persicae* were relatively low early in the season, and did not

dramatically increase until 800 and 1,000 DD, respectively (Fig. 4). However, populations of *P. operculella* increased over a relatively short window, with 10% of the population collected by 808 DD, 50% by 1,058 DD, and 90% by 1,590 DD (Fig. 4). In contrast, populations of *M. persicae* increased more gradually, with 10% of the population collected by 1,051 DD, 50% by 2,001 DD, and 90% by 2,634 DD (Fig. 4). Unlike the other pests, the first *C. tenellus* captured always occurred early in the growing season between 0 and 21 accumulated DD, with the last *C. tenellus* captured occurring no later than 996 DD in any year. Populations of *C. tenellus* had a steep phenology curve, with 10% of the population collected by 77 DD, 50% by 327 DD, and 90% by 936 DD (Fig. 4).

## Discussion

The proper timing of IPM strategies is critical for successful pest control, allowing producers to minimize insecticide applications and maximize their economic and environmental sustainability. Pest phenology models provide producers with a precise method for predicting the most effective time to take action against pests (Ascerno 1991). One of the key components of any IPM plan is to detect initial pest infestations so that management actions can be deployed before pests reach economic thresholds. When phenology models are not available, pest monitoring often involves dispatching monitoring teams or crop consultants to sample fields on preplanned calendar days. However, due to yearly variations in weather, calendar-based planning is not reliable and leads to imprecise treatments (Rondon and Murray 2016). A more accurate way to determine when to sample for pests, and make subsequent management decisions, is to measure the amount of heat accumulated over time, providing a physiological based time scale (Masetti et al. 2015).

Here, we examined the relationship between weekly trap catch data and cumulative degree-days in an effort to provide an accurate tool for management of three key potato pests. We found that simple phenology models explained over 90% of the variation in emergence of each pest. This suggests that our models could greatly improve the precision of IPM in potatoes, and provide the foundation for a web-based decision-support system for potato growers in the Columbia Basin. For example, the Washington State Decision Aid System (DAS) uses pest phenology models to enhance the effectiveness of IPM programs in the tree fruit industry (Jones 2010). In DAS, crop producers receive targeted predictions of pests based on their geographic location and phenology models; producers also receive forecasts of how pest populations might change over a 4 wk window based on phenology models and weather predictions. This allows producers to anticipate mobile pest populations and apply appropriate management (Jones 2010). A similar approach could be implemented in potatoes based on models developed here.

Our phenology models should allow potato producers to anticipate when populations of three key pests are likely to occur. Our results show that environmental conditions early in the growing season are most important for *C. tenellus*, given that this pest occurs in high abundance with relatively few degree days accumulated. Early migrations of this pest into potato crops could bring diseases such as purple top (Munyaneza et al. 2006, 2010), making early season monitoring critical. Population densities of *C. tenellus* typically remained low throughout May, and increased sharply early in the season as temperatures became favorable. Sudden increases in densities of this pest typically coincided with the peak density for any given year, indicating that early-season migration of adults from wild host plants into potatoes is a critical time for management.
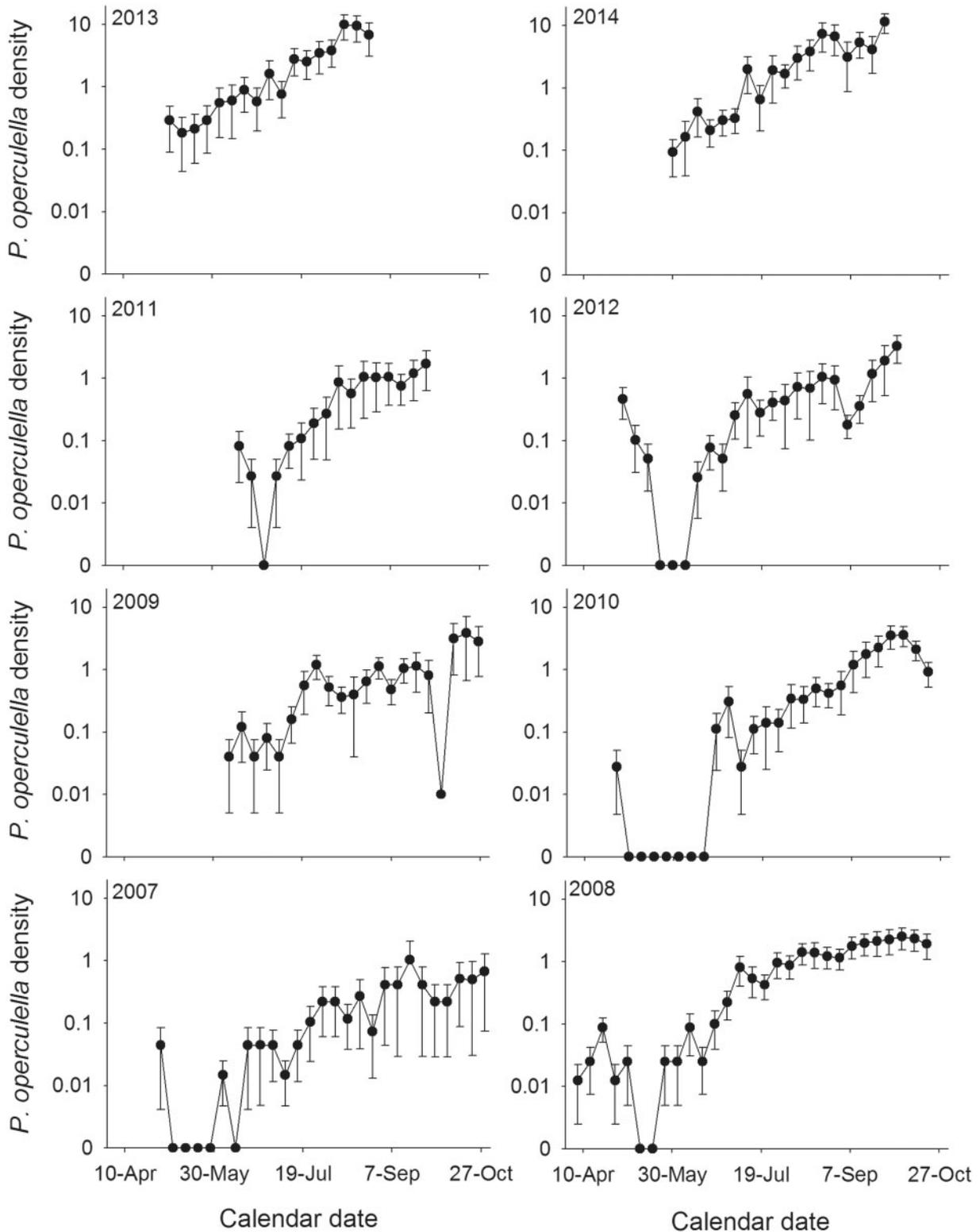
**Fig. 1.** The weekly trap catch of *P. operculella* (average density per trap) in potato fields from 2007 to 2014. Shown are the weekly means averaged across sampling locations in each week each year (±SE).

Therefore, it would be advantageous to manage this pest with seed treatments or early-season application of pesticides to control migratory populations moving into potatoes; such applications are likely to prevent populations from reaching economic thresholds throughout the growing season. Indeed, once populations peak in

the mid-summer they typically decline rapidly and late-season treatments are not warranted.

Our phenology models for *C. tenellus* are also important given that their ability to transmit the pathogen that causes purple top disease is largely dependent on potato phenology. This species is most
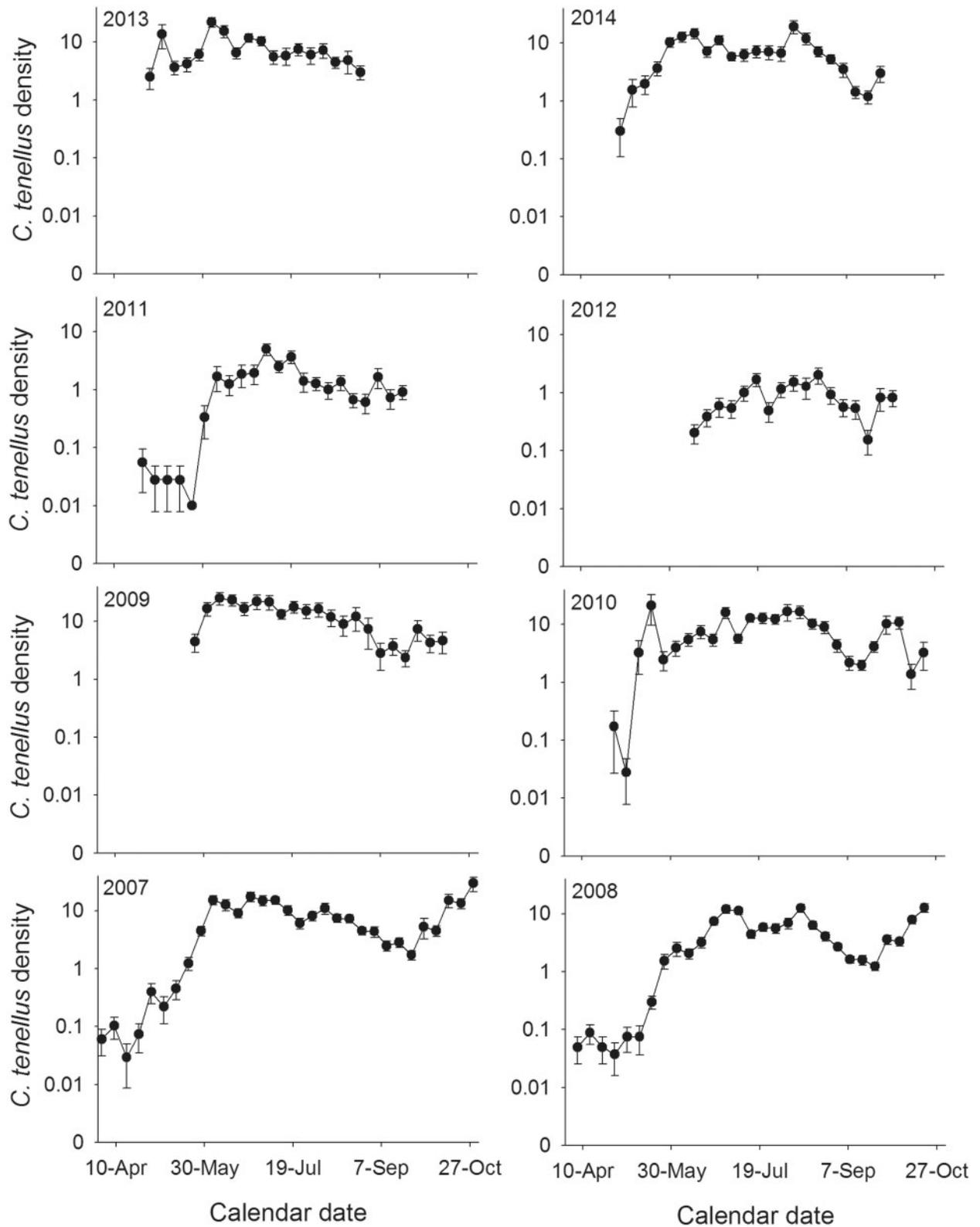
**Fig. 2.** The weekly trap catch of *C. tenellus* (average density per trap) in potato fields from 2007 to 2014. Shown are the weekly means averaged across sampling locations in each week each year (±SE).

effective in vectoring purple top to young potatoes, with transmissibility of the phytoplasma decreasing significantly 6 wk after the emergence of potato plants (Munyaneza et al. 2010). Potatoes older than 6 wk are considerably less susceptible to purple top, likely due to increased constitutive and induced plant defenses. Thus, growers should target their sampling and monitoring efforts for *C. tenellus* from potato emergence until 1,000 DD, as this period reflects the susceptible stage of potatoes and coincides with increasing densities
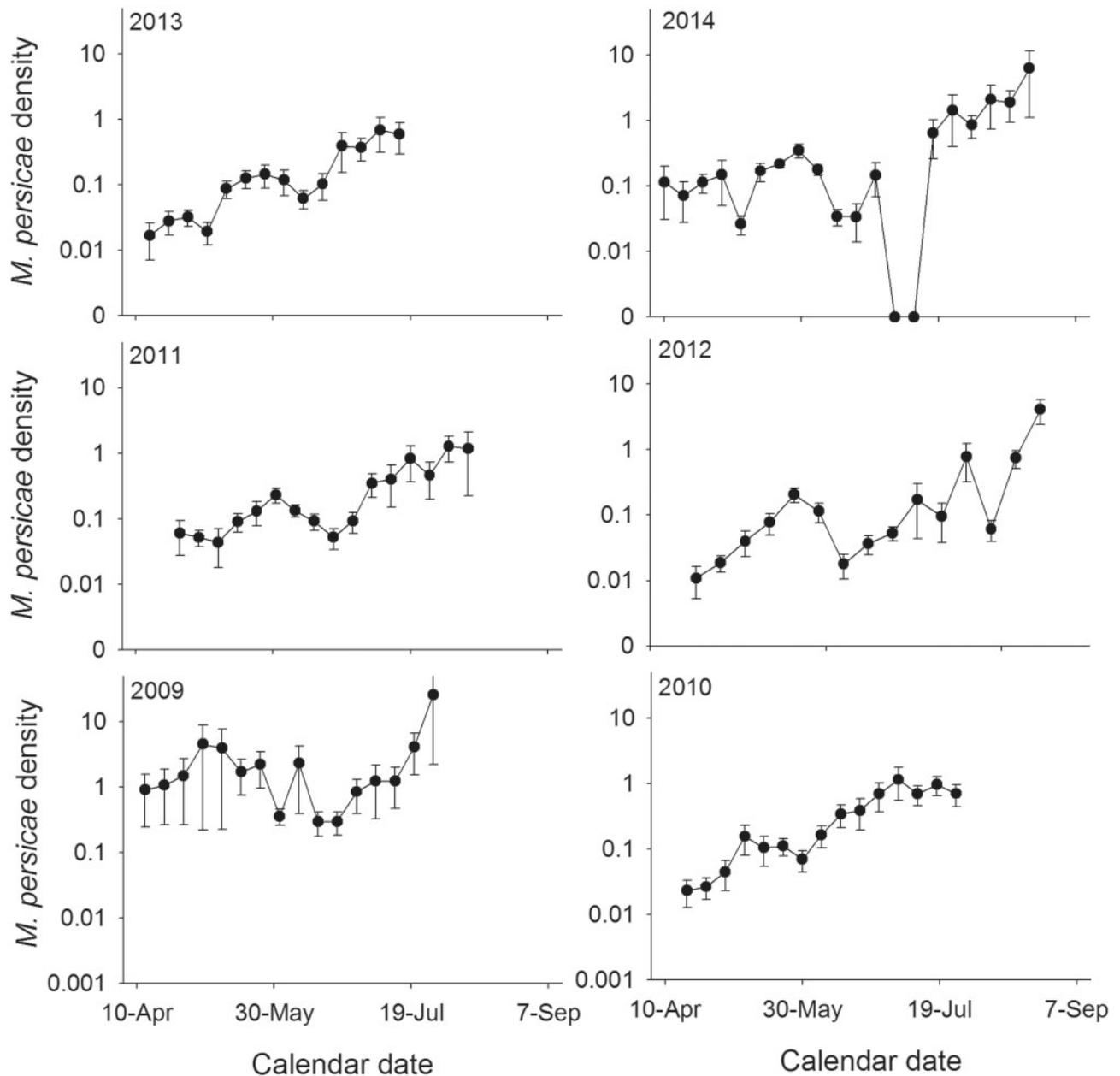
**Fig. 3.** The weekly trap catch of *M. persicae* (average density per plant) in potato fields from 2009 to 2014. Shown are the weekly means averaged across sampling locations in each week each year (± SE).

of the pest. After this period, potatoes are likely to be resistant to purple top, and *C. tenellus* populations rapidly decline, such that continued monitoring would be unnecessary.

*Myzus persicae* is a broad generalist that can transmit over 100 diseases to 30 plant families including potatoes, beans, and *brassicas* (van Emden et al. 1969). In addition to crops, weeds such as lambs-quarter (*Chenopodium album* L.) and pigweed (*Amaranthus retro-flexus* L.) are suitable hosts for *M. persicae* in the Columbia Basin (Tamaki 1975, Tamaki and Olsen 1979, Horn 1981). Our observation that weekly densities of *M. persicae* remained low until late summer suggests that aphids may not move into potatoes until the middle of the season when these alternative hosts become limiting. However, the vast majority (>99%) of *M. persicae* collected in our study were apterous (i.e., wingless). Monitoring populations of alate aphids to determine when they arrive in potato fields, and

correlating this information with populations of nonwinged aphids would aid in clarifying migratory patterns from alternative hosts to potatoes.

Other phenology models of *M. persicae* that included alate aphids in the Columbia Basin have shown that peak migration into potatoes occurs before 1,300 DD (Ro 1998a, b). However, our phenology models showed that populations of nonwinged aphids did not typically peak until past 2,000 DD. Therefore, it is possible that migratory individuals moving into potatoes take at least 700 DD to establish and begin to reproduce. This delay in population growth may be due to the effectiveness of early-season treatments of neoni-cotinoids, which kill early-season migrants and prevent populations from growing rapidly. In turn, populations do not increase rapidly until insecticides decay within the plant tissue later in the season. The method we used to monitor *M. persicae* was aimed at
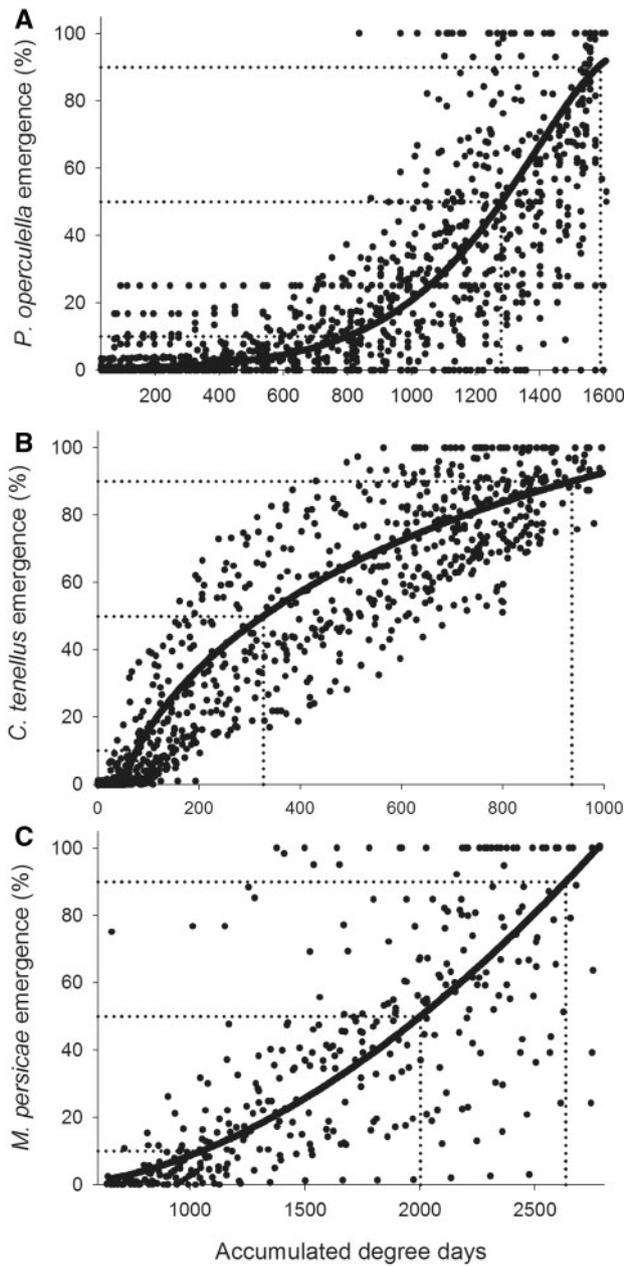
**Fig. 4.** The cumulative population emergence of (**A**) *P. operculella*, (**B**) *C. tenellus*, and (**C**) *M. persicae* in relation to accumulated degree-days. The circles represent the data, and the curves show the Weibull model for each species. The data shown were averaged by weather station (i.e., the cumulative emergence across all sites nearest a given weather station in a given week in a given year were averaged); the Weibull model was developed using the entire dataset (Table 1). The dotted lines indicate the number of cumulative degree-days where 10, 50, and 90% of the total population was collected.

**Table 2.** The best-fit parameters of the Weibull model for each pest (Ct = *C. tenellus*; Mp = *M. persicae*; Po = *P. operculella*)

| Insect | a | b | c | $x_0$ | $R^2$ |
|---|---|---|---|---|---|
| Ct | 1.39 | 839.4 | 0.72 | 558.7 | 0.90 |
| Po | 0.98 | 1,809,904 | 7,232.3 | 1273.2 | 0.89 |
| Mp | 1,407.9 | 150,542.7 | 1.74 | 122,406.6 | 0.94 |

quantifying wingless morphs rather than migrants. Future monitoring might focus on methods to collect migratory adults early, while sampling of potato vegetation to collect resident populations in fields should be performed after 1,500 DD.

Despite the observation that the potato tuberworm is one of the most economically important pests of potatoes, no economic thresholds levels have been determined for this pest (Clough et al. 2010). The first recorded outbreak of major economic significance of this pest in the Columbia Basin occurred in 2004, and early studies showed that increased pest densities were associated with higher spring, summer, or fall temperatures (DeBano et al. 2010). Our study confirms that this pest occurs throughout the growing season, with development throughout the year. Other studies have found that populations increase at an optimal temperature of 28 to 30°C which, unsurprisingly, aligns with average high temperatures in the early summer months across the Columbia Basin. While Masetti et al. (2015) showed that rainfall also affects potato tuberworm, precipitation may not be a limiting factor in our region as all potatoes are irrigated.

One key difference between our models and other phenology models is that we did not track discrete generations or discrete developmental stages of each insect. We started monitoring the fields early enough to catch the first flight of adult insects and then tracked only adults. Because these three insects are multivoltine species with overlapping generations, a phenology model specific to each generation could further improve forecasting accuracy. However, our models provide a foundational framework that can be built upon.

Our research shows how potato producers should structure their IPM strategies to deal with a complex of pests across the potato-growing season. Producers rarely have to deal with a single pest, and management of any single pest can influence subsequent management of others. Our results indicate that *C. tenellus*, *M. persicae*, and *P. operculella* can be present in the field at the same time, but management could be structured in conjunction with the pests' life cycles. Producers are likely to have to manage *C. tenellus* first because high densities of early-season migrants combined with the susceptibility of potatoes soon after emergence make this pest an early-season priority. In contrast, the most important time to sample *P. operculella* is mid-season, right before tubers form (Bacon 1960). Densities at this time are predictive of their potential impact later in the season. Because foliar feeding is not as economically important as tuber damage, currently this pest is not managed until 2 to 3 wk before harvest when larvae move off of depleted foliage and onto tubers. Lastly, monitoring for *M. persicae* should be conducted in mid- to late-season when populations of the other pests are declining, alternative hosts become rare, and when seed-applied neonicotinoids have decayed. Importantly, within the context of an IPM program, broad-spectrum foliar treatments used on *C. tenellus* will also likely kill aphid natural enemies, and this could have late-season IPM implications.

While understanding pest phenology is important for optimizing the timing of management decisions, the magnitude of pest populations is also critical in IPM. We observed wide variation in the density of each pest across seasons. The three years with the warmest springs in our study were 2014, 2013, and 2009, and these years had the greatest overall pest densities; the coldest years were 2011 and 2012, and these years had the lowest pest densities. Previous studies have shown that the densities of potato pests are strongly affected by spring and summer temperatures (Schreiber et al. 2015, Rondon and Murphy 2016). Our observations show pest densities can vary by several orders of magnitude early in the season (April or

May), and populations exceeding economic thresholds (Schreiber et al. 2015) early in the year tend to stay high through a season. Variation in precipitation, insecticide use, and other farm practices can also influence the density of pest populations from year to year. While our study did not investigate these factors due to our focus on phenology, understanding both phenology and magnitude is crucial for potato IPM. Growers can optimize their IPM by using phenology models to time their scouting and control efforts, but treatment decisions should factor in pest density as well (Schreiber et al. 2015).

Decision-support tools to aid in the implementation of IPM have become more common as technology and farmer education has changed. The first online decision-support systems were developed for agricultural systems in the late 1980s (Jones 2010), but were largely ineffective because the transferability of data to users was restricted to a limited number of computer-savvy individuals (Cox 1996). However, as more producers transition toward more information-intensive IPM, decision-support tools have become increasingly important. A primary challenge in developing such tools is to create targeted models of pest dynamics so that crop producers receive timely, appropriate, and validated information that can be used in IPM decision-making (Cox 1996, Ehler 2006). Here we provide phenology models for three common insect pests of potato. In the future, these models can be applied to improve pest management with the creation of pest-specific decision-support tools.

## Acknowledgments

## References Cited

Ascerno, M. E. 1991. Insect phenology and integrated pest management. J. Arboric. 17: 13–15.

Bacon, O. G. 1960. Systemic insecticides applied to cut seed pieces and to soil at planting time to control potato insects. J. Econ. Entomol. 53: 835–839.

Choi, W. I., and M. I. Ryoo. 2003. A matrix model for predicting seasonal fluctuations in field populations of *Paronychiurus kimi* (Collembola: Onychiuridae). Ecol. Model. 162: 259–265.

Clough, G. H., S. I. Rondon, S. J. DeBano, N. David, and P. B. Hamm. 2010. Reducing tuber damage by potato tuberworm (Lepidoptera: Gelechiidae) with cultural practices and insecticides. J. Econ. Entomol. 103: 1306–1311.

Cox, P. G. 1996. Some issues in the design of agricultural decision support systems. Agric. Syst. 52: 355–381.

Crosslin, J. M., P. B. Hamm, D. C. Hane, J. Jaeger, C. R. Brown, P. J. Shiel, and R. E. Thornton. 2006. The occurrence of PVYO, PVYN, and PVYN:O strains of Potato virus Y in certified potato seed lot trials in Washington and Oregon. Plant. Dis. 90: 1102–1105.

DeBano, S. J., P. B. Hamm, A. Jensen, S. I. Rondon, and P. J. Landolt. 2010. Spatial and temporal dynamics of potato tuberworm (Lepidoptera: Gelechiidae) in the Columbia Basin of the Pacific Northwest. Environ. Entomol. 39: 1–14.

Dent, D. 2000. Insect pest management. CABI Publishing, Wallingford, Oxfordshire, UK.

Dung, J. S., G. Harris, A. Haguewood, and P. Hamm. 2015. Effect of mint, potato and other previous rotational crops on potato yields in the Columbia Basin of Oregon. Am. J. Potato Res. 92: 1–5.

Ehler, L. E. 2006. Perspective: Integrated pest management (IPM): Definition, historical development and implementation, and the other IPM. Pest Manag. Sci. 62: 787–789.

Guenthner, J., M. Wiese, A. Pavlista, J. Sieczka, and J. Wyman. 1999. Assessment of pesticide use in the U.S. potato industry. Am. J. Potato Res. 76: 25–29.

Harries, F. H., and J. R. Douglass. 1948. Bionomic studies on the beet leafhopper. Ecol. Monogr. 18: 47–79.

Herms, D. A. 2004. Using degree-days and plant phenology to predict pest activity, pp 49–59. *In* V. Krischik and J. Davidson (eds), IPM (Integrated pest management) of Midwest landscapes, Minnesota Agricultural Experiment Station Publications, Minneapolis, MN.

Honeycutt, C. W., W. M. Clapham, and S. S. Leach. 1996. Crop rotation and N fertilization effects on growth, yield, and disease incidence in potato. Am. Potato J. 73: 45–61.

Horn, D. J. 1981. Effect of weedy backgrounds on colonization of collards by green peach aphid, *Myzus persicae*, and its major predators. Environ. Entomol. 10: 285–289.

Jones, V. P., J. F. Brunner, G. G. Grove, B. Petit, G. V. Tangren, and W. E. Jones. 2010. A web-based decision support system to enhance IPM programs in Washington tree fruit. Pest Manag. Sci. 66: 587–595.

Kunkel, R., and D. B. Bakes. 1965. Potatoes in the Columbia basin of Washington. Am. Potato J. 42: 369–376.

Masetti, A., A. Butturini, A. Lanzoni, V. De Luigi, and G. Burgio. 2015. Area-wide monitoring of potato tuberworm (*Phthorimaea operculella*) by pheromone trapping in Northern Italy: phenology, spatial distribution and relationships between catches and tuber damage. Agric. Forest Entomol. 17: 138–145.

Marsh, D. M., and P. C. Trenham. 2008. Current trends in plant and animal population monitoring. Conserv. Biol. 22: 647–655.

Mumford, J. D., and G. A. Norton. 1984. Economics of decision making in pest management. Ann. Rev. Entomol. 29: 157–174.

Munyaneza, J. E., J. M. Crosslin, and J. E. Upton. 2006. Beet leafhopper (Hemiptera: Cicadellidae) transmits the Columbia Basin potato purple top phytoplasma to potatoes, beets, and weeds. J. Econ. Entomol. 99: 268–272.

Munyaneza, J. E., J. M. Crosslin, J. L. Buchman and V. G. Sengoda. 2010. Susceptibility of different potato plant growth stages to purple top disease. Am. J. Potato Res. 87: 60–66.

Murphy, A. F., S. I. Rondon, R. Marchosky, J. Buchman, and J. Munyaneza. 2014. Evaluation of beet leafhopper transmitted virescence agent damage in the Columbia Basin. Am. J. Potato Res. 91: 101–108.

Nietschke, B. S., R. D. Magarey, D. M. Borchert, D. D. Calvin and E. Jones. 2007. A developmental database to support insect phenology models. Crop. Prot. 26: 1444–1448.

Pedigo, L. P., and M. E. Rice. 2016. Entomology and pest management. Pearson Education Inc, Upper Saddle River, NJ.

Ro, T. H., G. E. Long, and H. H. Toba. 1998a. Predicting phenology of green peach aphid (Homoptera: Aphididae) using degree-days. Environ. Entomol. 27: 337–343.

Ro, T. H. and G. E., Long 1998b. Population dynamics pattern of green peach aphid (Homoptera: Aphididae) and its predator complex in a potato system. Korean J. Biol. Sci. 2: 217–222.

Rondon, S. I. 2010. The potato tuberworm: a literature review of its biology, ecology, and control. Am. J. Potato Res. 87: 149–166.

Rondon, S. I. 2012. Building and integrated pest management for potatoes in North America: Where to start? Acta. Hortic. 960: 371–384.

Rondon, S. I., and A. F. Murphy. 2016. Monitoring and controlling the beet leafhopper *Circulifer tenellus* in the Columbia basin. Am. J. Potato Res. 93: 80–85.

Royo-Esnal, A., A. L. García, J. Torra, F. Forcella, and J. Recasens. 2015. Describing *Polygonum aviculare* emergence in different tillage systems. Weed Res. 55: 387–395.

Schreiber, A. 2003. Ramifications of multiple insecticide applications to potatoes for control of leafhoppers. Potato Progress 3: 4.

Schreiber, A., A. Jensen, S. I. Rondon, K. Pike, E. Wenninger, and M. Thornton. 2015. 2015 Integrated pest management guidelines for insects and mites in Idaho, Oregon, and Washington potatoes. Northwest Potato Research Consortium, Eagle, ID. (http://www.nwpotatoresearch.com/IPMStuff/PDFs/NorthwestInsectGuidelines.pdf) (Accessed 31 March 2016).

Sporleder, M., J. Kroschel, M.R.G. Quispe, and A. Lagnaoui. 2004. A temperature-based simulation model for the potato tuberworm, *Phthorimaea*

*operculella* Zeller (Lepidoptera; Gelechiidae). Environ. Entomol. 33: 477–486.

Tamaki, G. 1975. Weeds in orchards as important alternate sources of green peach aphids in late spring. Environ. Entomol. 4: 958–960.

Tamaki, G., and D. Olsen. 1979. Evaluation of orchard weed hosts of green peach aphid and the production of winged migrants. Environ. Entomol. 8: 314–317.

Thomas, P. E., K. S. Pike, and G. L. Reed. 1997. Role of green peach aphid flights in the epidemiology of potato leaf roll disease in the Columbia Basin. Plant. Dis. 81: 1311–1316.

USDA, National Agricultural Statistics Service. 2013. The Idaho, Washington, and Oregon Combined Potato Crop Valued at $1.98 Billion for 2013. (http://www.nass.usda.gov/)

van Emden, H. F., V. F. Eastop, R. D. Hughes, M. J. Way. 1969. The ecology of *Myzus persicae*. Annu. Rev. Entomol. 14: 197–270.

Wagner, T. L., H. I. Wu, P.J.H. Sharpe, and R. N. Coulson. 1984. Modeling distributions of insect development time: a literature review and application of the Weibull function. Ann. Entomol. Soc. Am. 77: 475–483.

Waller, B. E., C. W. Hoy, J. L. Henderson, B. Stinner, and C. Welty. 1998. Matching innovations with potential users, a case study of potato IPM practices. Agr. Ecosyst. Environ. 70: 203–215.

Waters, T. D., and A. S. Jensen. 2014. Insect pests of potatoes, pp 133–147. *In* R. Navarre and M. J. Pavek (eds), The potato: botany, production and uses, CABI, Oxfordshire, United Kingdom.

Welch, S. M., B. A. Croft, J. F. Brunner, and M. F. Michels. 1978. Pete: An extension phenology modeling system for management of multi-species pest complex. Environ. Entomol. 7: 487–494.

Wilby, A., and M. B. Thomas. 2002. Natural enemy diversity and pest control: Patterns of pest emergence with agricultural intensification. Ecol. Lett. 5: 353–360.