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Special Collection: Geospatial Analysis of Invasive Insects
Special Collection

Short-Term Forecasts of Insect Phenology Inform Pest Management

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Abstract

Insect pests cost billions of dollars per year globally, negatively impacting food crops and infrastructure, and contributing to the spread of disease. Timely information regarding developmental stages of pests can facilitate early detection and control, increasing efficiency and effectiveness. In 2018, the U.S. National Phenology Network (USA-NPN) released a suite of 'Pheno Forecast' map products relevant to science and management. The Pheno Forecasts include real-time maps and short-term forecasts of insect pest activity at management-relevant spatial and temporal resolutions and are based on accumulated temperature thresholds associated with critical life-cycle stages of economically important pests. Pheno Forecasts indicate, for a specified day, the status of the insect's target life-cycle stage in real time across the contiguous United States. The maps are available for 12 pest species including the invasive emerald ash borer (*Agrilus planipennis* Fairmaire [Coleoptera: Buprestidae]), hemlock woolly adelgid (*Adelges tsugae* Annand), and gypsy moth (*Lymantria dispar* Linnaeus [Lepidoptera: Erebidae]). Preliminary validation based on in-situ observations for hemlock woolly adelgid egg and nymph stages in 2018 indicated the maps to be ≥93% accurate depending on phenophase. Since their release in early 2018, these maps have been adopted by tree care specialists and foresters across the United States. Using a consultative mode of engagement, USA-NPN staff have continuously sought input and critique of the maps and delivery from end users. Based on feedback received, maps have been expanded and modified to include additional species, improved descriptions of the phenophase event of interest, and e-mail-based notifications to support management decisions.

Key words: forecasting, insect pests, management, phenology

Native and introduced insect pests cost billions of dollars per year globally, with major negative impacts on forest products, food crops and infrastructure, and ecosystem function (Bradshaw et al. 2016). Insects also spread infectious diseases in humans and livestock (Mellor et al. 2000, WHO 2016). The great diversity of woody plants and their associated pests complicates the logistics of scheduling pest management programs in nurseries, ornamental landscapes, and urban forests. Many insect pests of trees are difficult to detect and monitor (e.g., scales and wood-borers), which further complicates timing of pest management tactics, as does year-to-year variation in weather (Herms 2004). Timely information regarding the developmental stage of invasive species across their range can inform pest management decisions, including early detection, eradication and suppression efforts, or management to slow the spread of a species. These efforts have the potential to reduce nontarget impacts to plants, ecosystem processes, and economic productivity. An understanding of when invasive species will transition between various life-cycle stages, or phenological phases, can facilitate

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effective monitoring activities. The use of phenological models for timing control actions to coincide with peak susceptibility of the target organism optimizes effectiveness by capitalizing on susceptible life stages, reducing chemical use, saving time and money, and minimizing effects to nontarget species (Herms 2004, Murray 2008).

Heat accumulation has long been recognized as an efficient heuristic tool for estimating the timing of phenological transitions in plants and animals (Wang 1960, Cross and Zuber 1972, McMaster and Wilhelm 1997). For many insect pest species, the specific amount of accumulated heat (heat units) above a lower temperature threshold required to trigger a life-cycle event, such as adult emergence, has been quantified as a 'thermal constant' (Campbell et al. 1974), or 'Growing Degree Day (GDD) threshold' (e.g., Herms 2004, Murray 2008, Cornell Cooperative Extension 2010), making it possible to anticipate the timing of the event at a location from temporal accumulation of heat based on daily temperature data. Strong potential exists to combine these thresholds with real-time meteorological data and forecasts to create regional or continental-scale maps that predict the timing of developmental transitions in insects at spatial and temporal scales appropriate for management decisions. Such maps can be a valuable tool to support the complex and locally informed decisions that managers make.

Geographical patterns of GDD accumulation have been used to predict pest activity for many decades (Arnold 1959, Croft et al. 1976, Bishop 2017). This functionality has been implemented in online tools such as those found on the University of California Integrated Pest Management website (http://ipm.ucanr.edu/) that leverage weather station data and estimate the timing of pest activity at a specific location. Degree-day maps featuring daily updates have also been available since 1998 for Oregon and since 2006 for the contiguous United States (L. C., unpublished data; Integrated Plant Protection Center 2019). Other state and region-wide integrated pest management programs around the United States have produced state and regional-scale pest-related GDD maps in recent years (Cornell University 2019).

The U.S. National Phenology Network (USA-NPN) is a rapidly growing national-scale monitoring and research initiative that produces and distributes data, information, and forecasts to support natural resource management and decision-making (Schwartz et al. 2012). The USA-NPN also offers national-scale, daily maps of accumulated heat units (Crimmins et al. 2017a). These GDD accumulations have strong potential for predicting the timing of activity in a wide range of individual species (Melaas et al. 2016, Crimmins et al. 2017b) and can, therefore, serve as the basis for generating real-time and forecast maps of the status of insect pest life-cycle stages. The opportunity is ripe to generate user-friendly, continental-scale, real-time maps, and forecasts of life stages in pests and invasive species.

To support the management of harmful pests, we leveraged our existing accumulated temperature products, combining them with species-specific GDD algorithms, to produce daily national maps that predict the optimal time to take management action. In this paper, we describe the USA-NPN's Pheno Forecast products and our process for generating these maps, including seeking stakeholder input to shape the products, the technical approaches taken to make the maps, and our approach for delivering the maps, evaluating their accuracy, and soliciting feedback. This multifaceted approach provides a bridge between those who develop phenological models and those who use them. We provide a real-world case example to demonstrate how the maps could be used by natural resource managers. By facilitating real-time feedback between data providers and stakeholders, this approach also ensures tools are rigorously developed, up-to-date, and can be applied in real-world conditions.

Methods

Accumulated GDD Map Products

The USA-NPN generates daily accumulated Growing Degree Day (AGDD) products as raster grids for the contiguous United States (CONUS) using a January 1 start date and two base temperatures, 0°C (32°F) and 10°C (50°F) (Crimmins et al. 2017a, www.usanpn.org/data/agdd_maps). These start date and base temperatures are commonly used in agriculture, turf management, and integrated pest management applications (Alessi and Power 1971, Wolfe et al. 1989, Herms 2004, Roby and Matthews 2004, Cardina et al. 2011). The GDD raster data layers are calculated using the NOAA National Centers for Environmental Prediction Real-Time Mesoscale Analysis (RTMA), Unrestricted Mesoscale Analysis (URMA), and National Digital Forecast Database (NDFD) daily minimum and maximum temperature data products (NOAA 2018a–c). This enables us to calculate accumulated growing degree days for every day of the year and 6 days into the future at the native resolution of the temperature products (2.5 km). USA-NPN AGDD products are calculated using a simple average method (GDD = [{minimum temperature + maximum temperature}/2] – base temperature) (Crimmins et al. 2017a). For example, on a hypothetical day when the maximum and minimum temperatures were 25 and 15°C (77 and 59°F), respectively, and using a base temperature of 10°C (50°F), GDD accumulation would be 10 calculated using Celsius values or 18 calculated using Fahrenheit values. These raster GDD layers are available at a daily timestep from 1 January 2016 through 6 days into the future.

The USA-NPN also offers 30-yr average (1981–2010) temperature accumulation raster grids for the contiguous United States using a 1 January start date and two base temperatures, 0°C (32°F) and 10°C (50°F) (Crimmins et al. 2017a), calculated using parameter–elevation relationships on independent slopes model (PRISM) daily minimum and maximum temperature data products (PRISM Climate Group 2019). All USA-NPN GDD products are calculated and offered in °F. In 2019, the USA-NPN expanded capacity to offer accumulated GDDs using any start date after 1 January, any base temperature, and the double sine method for calculating accumulated growing degree days. The double-sine method is an alternative to the simple average method for calculating growing degree days that involves fitting sine curves between daily minimum and maximum temperatures (Allen 1976). These enhancements enable the calculation of Pheno Forecast maps using models with these requirements (Table 1).

Defining Pheno Forecast Map Requirements

The USA-NPN aims to create tools and products that meet the needs of practitioners as well as researchers. This approach is rooted in building and sustaining relationships with partners (Kirchoff et al. 2013, Wall et al. 2017). USA-NPN staff first listen to stakeholders to identify opportunities, where phenological information can enhance planning, decisions, and management actions (Gerst et al., in press). Second, working with stakeholder input, we assess the need for new data products based on the decisions they are trying to make and the suite of products already available. Finally, once products are identified and developed, we freely deliver the information in relevant, user-friendly formats at spatial and temporal scales most appropriate for management applications. This approach of consulting with stakeholders to identify problems and needs, and collectively developing solutions, is recognized as a 'consultative' style of engagement (Meadow et al. 2015) and has the benefit of maximizing the applicability of the product to the end user.

Table 1. Insect pest species and phenological events for which USA-NPN offers Pheno Forecasts.

Species	Life stage predicted	GDD threshold, accumulation method (source)	GDD start date, base temperature
Apple maggot [*Rhagoletis pomonella* Walsh, (Diptera: Tephritidae)][a]	Adult emergence	900 GDD, simple averaging (Wise et al. 2010)	1 Jan., 10°C (50°F)
Asian longhorned beetle [*Anoplophora glabripennis* Motschulsky, (Coleoptera: Cerambycidae)][b]	Adult emergence	689.75 GDD, double sine (Kappel et al. 2017; R. T. T., pers. comm.)	1 Jan., 10°C (50°F)
Bagworm [*Thyridopteryx ephemeraeformis* Haworth, (Lepidoptera: Psychidae)][b]	Caterpillar emergence	600 GDD, simple averaging (Cornell Cooperative Extension 2010)	1 Mar., 0°C (32°F)
Bronze birch borer [*Agrilus anxius* Gory, (Coleoptera: Buprestidae)][b]	Adult emergence	450 GDD, double sine (Herms et al. 2004)	1 Jan., 10°C (50°F)
Eastern tent caterpillar [*Malacosoma americanum* Fabricius, (Lepidoptera: Lasiocampidae)][b]	Caterpillar emergence	90–190 GDD, simple averaging (Cornell Cooperative Extension 2010)	1 Mar., 10°C (50°F)
Emerald ash borer [*Agrilus planipennis* Fairmaire, (Coleoptera: Buprestidae)][a]	Adult emergence	450 GDD, double sine (Herms et al. 2014)	1 Jan., 10°C (50°F)
Gypsy moth [*Lymantria dispar* Linnaeus, (Lepidoptera: Erebidae)][b]	Caterpillar emergence	571 GDD, double sine (Russo et al. 1993)	1 Jan., 3°C (37.5°F)
Hemlock wooly adelgid [*Adelges tsugae* Annand, (Hemiptera: Adelgidae)][a]	Presence of eggs	25 GDD, simple averaging (M. W. and S. L., pers. comm.)	1 Jan., 0°C (32°F)
Hemlock wooly adelgid [*Adelges tsugae* Annand, (Hemiptera: Adelgidae)][a]	Presence of active nymphs	1,000 GDD, simple averaging (M. W. and S. L., pers. comm.)	1 Jan., 0°C (32°F)
Lilac borer [*Podosesia syringae* Harris, (Lepidoptera: Sesiidae)][a]	Adult emergence	330 GDD, double sine (Herms 2004)	1 Jan., 10°C (50°F)
Magnolia scale [*Neolecanium cornuparvum* Thro, (Hemiptera: Coccidae)][b]	Crawler emergence	1938 GDD, double sine (Herms 2004)	1 Jan., 10°C (50°F)
Pine needle scale (*Chionaspis pinifoliae* Fitch, (Hemiptera: Diaspididae)][b]	Crawler emergence	298–448 GDD, simple averaging (Cornell Cooperative Extension 2010)	1 Mar., 10°C (50°F)
Winter moth [*Operophtera brumata* Linnaeus, (Lepidoptera: Geometridae)][a]	Caterpillar emergence	20 GDD, simple averaging (UMass Extension 2017)	1 Jan., 10°C (50°F)

[a] Map released in 2018.
[b] Map released in 2019.

To determine and refine the specifications for our pilot Pheno Forecast maps launched in 2018, we sought input from both existing and new partners. We spoke with over 30 experts and potential data users representing state Cooperative Extension offices, the National Park Service, the U.S. Geological Survey, the USDA Forest Service, the USDA Animal and Plant Inspection Service, state forests, university scientists, and the landscaping and arborist industries between October 2017 and March 2018. Stakeholders advised our selection of species for Pheno Forecasts, focusing on those of strongest management interest and best controlled at specific life-cycle stages. We also sought feedback on preferred map formats, forecast lead times and spatial resolution, and the need for notifications of impending phenological events. The responses to these questions directly shaped the Pheno Forecast maps.

Pheno Forecast Maps

Based on input from experts and the availability of published GDD thresholds for management-relevant life-cycle events in key insect pests, we selected a small group of species and life-cycle events for Pheno Forecasts (Table 1). Pheno Forecast maps depict, on a given day, the status of the insect's life-cycle stage across the contiguous United States. Locations are categorized into one of the four conditions: not yet approaching the life stage of management interest, approaching the stage, experiencing the stage, and past the stage. The status of a location is determined by comparing the local GDD accumulation to a published heat accumulation threshold for the life-cycle stage. The published thresholds implemented to generate the maps are provided in Table 1.

The Pheno Forecast maps are generated by clipping the USA-NPN CONUS AGDD raster layer (Crimmins et al. 2017a) for a single day to the states representing the species' known distribution (approximated from maps found at EDDMapS.org and published sources and updated annually). Next, the layer display is transformed from a continuous accumulation to the four discrete condition categories listed above through a map reclassification operation. Daily maps and 6-d forecast maps for each species are generated and updated each night. All code used to generate the maps is available on the USA-NPN repository at https://github.com/usa-npn.

Pheno Forecast maps are published nightly to the USA-NPN website as.png image files (www.usanpn.org/data/forecasts). The Pheno Forecasts are also available as map layers in the USA-NPN online data visualization tool (www.usanpn.org/data/visualizations). In 2019, we implemented the 'viridis' color ramp on all maps. The 'viridis' color ramp maximizes perception and interpretation by all users, including those with color vision deficiency (Nuñez et al. 2018).

Map Validation

The computational accuracy of the daily accumulated growing degree day maps are assessed by calculating daily GDD accumulations at each of 114 U.S. Climate Reference Network stations and comparing the values for these locations to the accumulated GDD values for the same locations as calculated by USA-NPN using daily URMA gridded products. To estimate the performance of the AGDD maps in 2018, the daily AGDD accumulations calculated using the URMA gridded temperature data were compared with accumulations made at the Climate Reference Network (CRN) locations across the contiguous United States (www.usanpn.org/agdd_uncertainty).

We evaluate the biological accuracy of the Pheno Forecast maps by comparing reports of insect life-cycle events submitted to *Nature's Notebook* (www.naturesnotebook.org), the USA-NPN's plant, and animal phenology monitoring program (Rosemartin et al. 2014), to Pheno Forecast maps for the days the observations were submitted. *Nature's Notebook* uses 'status' protocols, meaning that on each date an observation of an individual plant or insect is made, the status of a phenophase, or life-cycle stage, is recorded ('yes' if it was occurring and 'no' if it was not [Denny et al. 2014]). Using observations of the species of interest, we can directly compare whether observer reports of phenological status match those predicted by the Pheno Forecast maps. In 2018, only lilac ash borer (*Podosesia syringae* Harris) and hemlock woolly adelgid were available for monitoring within *Nature's Notebook*; in 2019, all species for which Pheno Forecasts are offered were made available for monitoring via *Nature's Notebook*. To encourage the collection of ground observations on these species to support model validation, we launched a campaign—a focused effort to encourage observation of a small group of species—called 'Pest Patrol' (www.usanpn.org/nn/PestPatrol), focused on all 12 insects, in 2019.

Map Dissemination and End-User Engagement

From March to September 2018 and then again starting in March 2019, we e-mailed monthly newsletters to individuals subscribing to our Pheno Forecast mailing list (sign up form at www.usanpn.org/data/forecasts). Newsletters contained 6-d forecast maps and a summary of which locations were not yet approaching, were approaching, had met, or had passed the key life-cycle stage window.

To recruit subscribers to the monthly Pheno Forecast e-mail list and to promote the Pheno Forecast map products, we advertised the maps via the USA-NPN website, USA-NPN newsletters, and social media. We also posted notifications about the maps to topically relevant e-mail listservs and drafted articles for *City Trees*, the online magazine of the Society of Municipal Arborists (Crimmins et al. 2018); *The Forestry Source*, a monthly newspaper from the Society for American Foresters (Crimmins 2018a); *The Leaflet*, a Casey Trees newsletter; the International Society of Arboriculture e-newsletter; and *Journal of Extension* (Crimmins 2018b).

In 2019, we launched location-based notifications. Users that sign up to receive species-specific notifications are sent two e-mails: one when the species is anticipated to transition into the life stage of interest within a 2-wk period at their location, and then again when the transition is anticipated within 6 d. To determine when to send the 2-wk notifications, we established a 'warning' threshold for each species, representing the amount of heat that is typically accumulated 7 days prior to the threshold of interest (Table 1) being met. For example, the threshold for magnolia scale (*Neolecanium cornuparvum* Thro) crawler emergence is 1,938 GDD (calculated using temperatures in °F; Herms 2004). This threshold is typically met on August 6 in central Ohio, on 20 July in central Kentucky, on 12 July in central Tennessee, and 14 June in central Georgia. 2 wk prior to these dates, GDD accumulation is 1,617 (in °F units) in Ohio, 1,568 in Kentucky, 1,569 in Tennessee, 1,553 in Georgia. Therefore, we established 1,577 GDDs—the average of these four values—as the 'warning' threshold for magnolia scale crawler emergence. When this 'warning' threshold is reached for a user's location on the 6-d forecast, the first notification, indicating that the transition is expected within 2 wk, is sent. When the actual threshold of interest is reached for a user's location on the 6-d forecast map, the second notification, indicating that the transition is expected within a week, is sent.

We solicited feedback on the Pheno Forecast maps through a form on the USA-NPN website (www.usanpn.org/data/forecasts) and promoted this request in the Pheno Forecast monthly newsletters. In addition, we contacted subject matter experts and map users directly and asked for input at regional natural resource workshops. Specifically, we asked whether users would like to see the maps offered for additional species and we solicited suggestions for improvements or modifications.

Results

Pheno Forecast Treatment Maps

In 2018, we piloted Pheno Forecast maps for management-relevant life-cycle stages in five insect pest species and, in 2019, released maps for seven additional species (Table 1). Maps are available for each species from 1 January 2016 through the present day, as well as for 6 d into the future. Maps show, on a daily basis at 2.5-km pixel size, locations where a pest species is not yet approaching the life stage of management interest, approaching the stage, experiencing the stage, and past the stage (Fig. 1).

Growing Degree Day and Pheno Forecast Map Validation

Mean absolute error (MAE) for AGDD calculations for all 114 CRN locations over 2018 was 325.1 GDDs (calculated from °F temperature values using 0°C [32°F] base temperature) and 221.2 GDDs (calculated from °F temperature values using 10°C [50°F] base temperature). At individual stations, MAE for the full year varied by 1 to 1,552 GDDs (0.007–11.6%) of the total annual GDD accumulation and from 9 to 1,072 GDDs (0.2–25.8%) of the total annual GDD accumulation for the 0 and 10°C base temperature products, respectively. There was a general bias toward more rapid heat accumulation in the URMA-gridded temperature products at many of the station locations, though there were no clear geographical patterns to this bias (Supp Fig. 1 [online only]). The impact of this bias in the URMA temperature products varies by geography and time of year, as heat accumulates at varying rates over the year and by latitude. However, generally, the differences in heat accumulation rates translate to approximately less than a week in when the thresholds are predicted to be met.

In 2018, observers submitted to *Nature's Notebook* 60 unique records of the 'eggs' phenophase and 59 unique records for the 'active nymphs' phenophase for hemlock woolly adelgid. Confusion matrices—tables that indicate the rate of true versus false positives and true versus false negatives—revealed 87% accuracy for the 'eggs' phenophase (Table 2) and 92% accuracy for 'active nymphs' (Table 3). In the case of 'eggs', 13 records were reported as 'no' when the model predicted that eggs would be present; however, adelgid eggs are contained within the woolly mass around the adult, and when few eggs are present, they can be difficult to detect. In the case of 'active nymphs', all eight 'yes' reports were submitted at greater growing degree day accumulations than the model indicates active nymphs would be present; this suggests that the GDD window for 'active nymphs' may be broader than is currently reflected in the Pheno Forecast model for this species and phenophase. This information will be used to modify the GDD threshold used to predict the window of activity for this phenophase.

Pheno Forecast Feedback and Usage

In 2018, 65 individuals subscribed to the monthly Pheno Forecast e-newsletters, and e-mail open rates averaged 50% over the year. Of the eight responses via the online feedback form in 2018, four expressed positive support for the utility of the maps, and six contained requests for additional species. None of the responses yielded negative feedback. Individual species Pheno Forecast maps received ~400 views per month over the period March to November 2018, totaling over 18,000 page views of the Pheno Forecast maps in 2018.

Discussion

Pheno Forecast Use

The Pheno Forecast maps are designed to support existing tools and resources already used by tree care specialists, arborists, foresters,

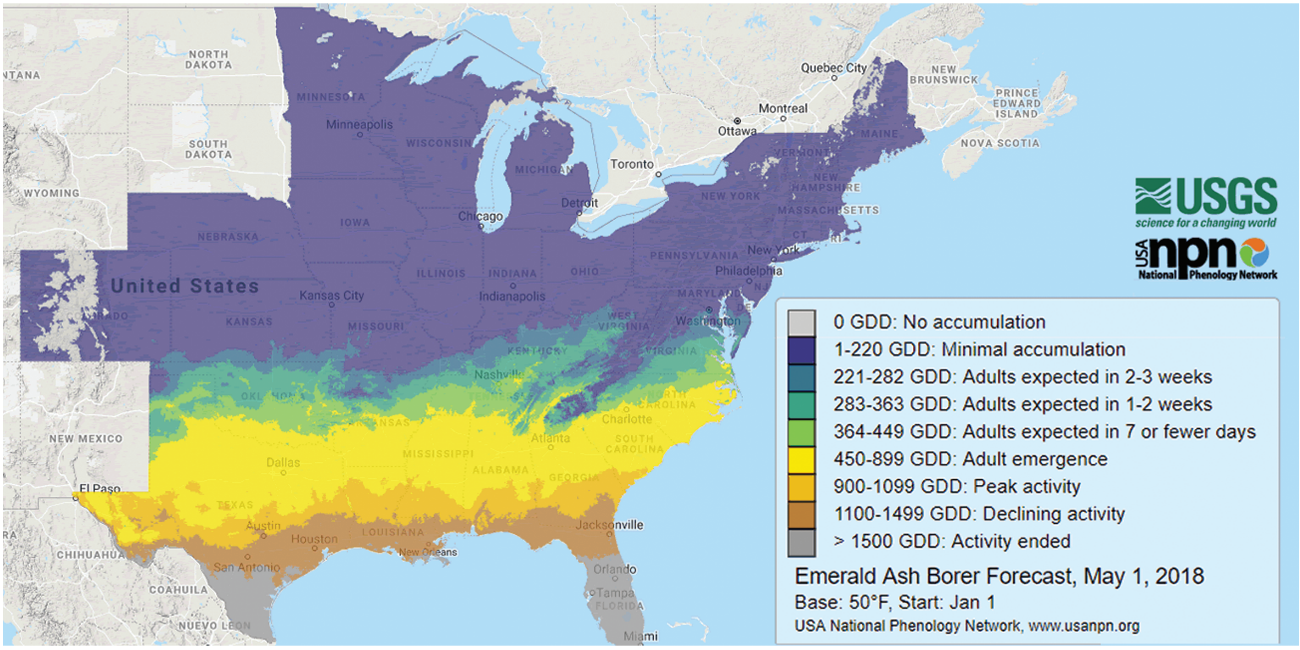

Fig. 1. Pheno Forecast map for emerald ash borer for 1 May 2018. Colors indicate the status of adult emergence. The status of a location is determined by comparing the local GDD accumulation to a published heat accumulation threshold for the life-cycle stage.

Table 2. Hemlock woolly adelgid 'eggs' Pheno Forecast confusion matrix

n = 98	Predicted No	Predicted Yes	Total
Actual No	68	13	81
Actual Yes	0	17	17
Total	68	30	98

Accuracy, calculated as (True Positives + True Negatives)/(Total Positives + Total Negatives), for this map is (17 + 68) / (30 + 68) = 87%.

Table 3. Hemlock woolly adelgid 'active nymphs' Pheno Forecast confusion matrix

n = 59	Predicted No	Predicted Yes	Total
Actual No	89	0	89
Actual Yes	8	0	8
Total	97	0	97

Accuracy, calculated as (True Positives + True Negatives)/(Total Positives + Total Negatives), for this map is (0 + 89)/(8 + 89) = 92%.

and natural resource managers. Though we do not yet have specific examples of how our map products have been used in the field, we provide the following case study as an example of how a resource manager could apply the products to inform species- and location-based pest management.

Case Example: Planning for Emerald Ash Borer Treatment in Arkansas

Emerald ash borer (*Agrilus planipennis*) is non-native beetle from Asia, which has spread across the eastern United States since 2002. In their larval stage, the beetles destroy the heartwood of ash trees, killing them within a few years. The pest is responsible for the death of hundreds of millions of ash trees (Herms and McCullough 2014).

Ideally, treatments should be undertaken prior to egg-laying, which occurs ~14 d after adults emerge. Adult emergence begins around 450 GDD (calculated from °F temperature values using 10°C [50°F] base temperature) and continues until ~1,000 GDD (Herms et al. 2014).

Based on the emerald ash borer Pheno Forecast map, on the arbitrary date of 15 April 2018, the region where adults were expected to be emerging encompassed Texas, Louisiana, Mississippi, Alabama, Georgia, and South Carolina (Fig. 2a). A swath to the north was approaching the time when adults would be emerging.

Accessing the Pheno Forecasts through the USA-NPN visualization tool offers the added benefit of allowing the user to explore the seasonal pattern of heat accumulation at a site. This information can be used to evaluate whether the time to treat might occur earlier or later than average. For example, as of 15 April 2018, Little Rock, Arkansas fell within the 'adults expected in 1–2 wk' category (Fig. 2a). Clicking on northwest Little Rock on the map revealed that 352 GDD had accumulated by 15 April at this location. Further, by clicking the 'Show Accumulation' link, the pattern of heat accumulation at the site to-date and based on the 30-yr average is provided (Fig. 2b). This plot indicates that the 450 GDD threshold at which management should commence is normally reached in Little Rock, Arkansas, on 20 April. However, the region experienced a cooling trend starting around 1 April, and as of 15 April, heat accumulation for this location was 2 d behind schedule (blue text in legend of Fig. 2b). A pest manager in the region might use this information to anticipate a later start to emerald ash borer emergence and might adjust the timing of treatments accordingly.

Pheno Forecast User Feedback

Generally, feedback from end users on the Pheno Forecast maps was positive. Comments received through the Pheno Forecast feedback form included 'Terrific and super useful!' 'So glad these are being implemented on a greater scale', and 'These are really useful models'. Furthermore, the average open rate for the Pheno Forecast newsletters of 50% is greater than the industry standard of about 20% (Constant Contact 2018). Finally, dozens of individuals requested that we expand the maps to include more pest species, indicating a demand for expanded services. The Pheno Forecasts appear to fill an open niche, offering real-time and forecasted, dynamic, freely available maps of insect status across the United States—something that previously was not readily available to natural resource managers, municipal arborists, and backyard gardeners, or was only available for small regions, for particular species, or on an ad-hoc basis. Providing the maps in tandem with local daily heat accumulation information offers the additional advantage to users to place current conditions within a richer context.

Interactions with end users after the pilot maps were released revealed several opportunities for improvement to better meet stakeholder needs. First, the version of the maps that were released in 2018 were focused on the 'timing of treatment'—that is, map categories portrayed locations as 'not yet approaching treatment window', 'approaching treatment window', 'actively in treatment window', and 'past treatment window'. Stakeholders suggested that we instead display the legend as status relative to a life stage rather than status relative to a treatment window, offering the end user the opportunity to determine at what stage to implement treatment. Second, some end users indicated that for several species, our legend categories were too broad to accurately represent the period when the species would be in the life stage of interest. Furthermore, some stakeholders requested addition of smaller temperature accumulation bins prior to the onset of the life stage of interest, thereby providing users more nuanced information regarding the imminence of the event of interest occurring. We modified the maps released in 2019 to feature a greater number of legend categories that encompassed smaller GDD accumulations and focused on the status of the insect life stage. In addition, the Pheno Forecast maps released in 2019 featured several additional enhancements over the pilot maps released in 2018. First, we expanded the suite of Pheno Forecasts to include seven species requested by end users (Table 1). Second, we implemented the double-sine method for calculating GDDs for Asian longhorned beetle, gypsy moth, bronze birch borer (*Agrilus anxius* Gory), emerald ash borer, and magnolia scale, where this approach has demonstrated superior performance to the simple average method (Allen 1976, Russo et al. 1993, Herms 2004, Kappel et al. 2017). Third, we implemented start dates other than 1 January and a base temperature other than 0°C (32°F) or 10°C (50°F) for three species (Table 1).

Limitations of Pheno Forecasts

For several species, we used GDD thresholds that were developed using data collected at one or a few locations across the species' range. The risk of taking this approach is that thresholds developed in one location may not work well in other locations, especially if local adaptation is at play. Across geography, a species' sensitivity to particular environmental cues to phenology can vary (Akers et al. 1984, Savolainen et al. 2007, Leimu and Fischer 2008, Liang 2016).

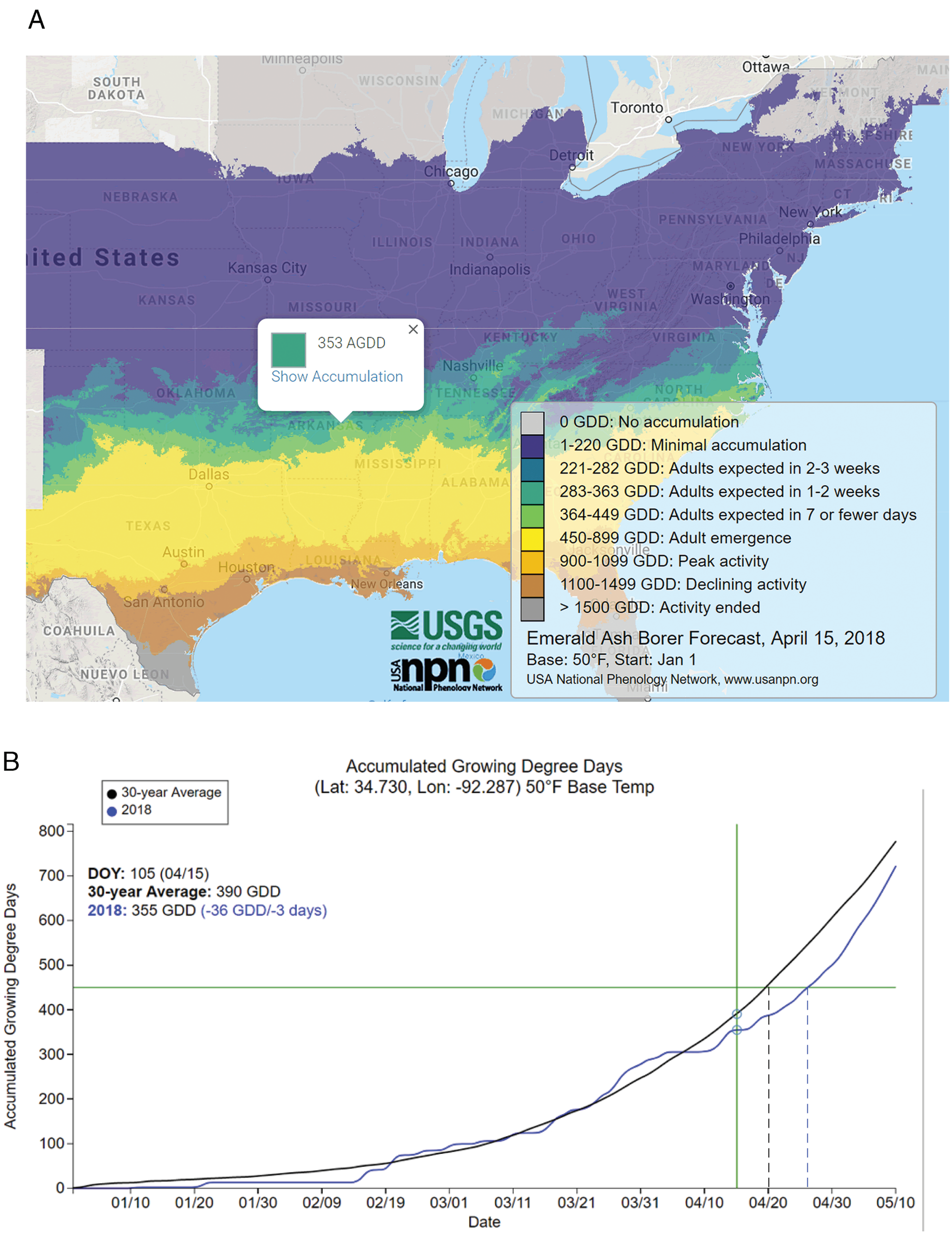

Fig. 2. (a) Emerald ash borer Pheno Forecast for the representative date of 15 April 2018. (b) Pattern of heat accumulation for northwest Little Rock, Arkansas through April of 2018 (blue line) relative to the 30-yr average (black line). The 450 GDD threshold at which management should commence is typically reached at this location on 20 April (black dashed vertical line). As of 15 April, heat accumulation for this location was 28 GDD less than average for the date, the equivalent of about 2 d behind the long-term average for the date (difference from normal shown in blue text in upper left corner).

In cases where this is pronounced, a universal accumulated GDD threshold, as implemented in the Pheno Forecast maps, will not perform well at predicting the timing of transition, even if accumulated heat is the primary forcing variable.

In contrast, allowing the threshold to vary based on geography may result in a better-performing model (Liang 2019). For example, Liang and Schwartz (2014) demonstrated that red maple trees in northern locations required less thermal forcing to trigger budbreak than trees in southern locations, bearing out patterns of local adaptation documented for many species via common garden experiments (Kriebel and Wang 1962, Vitasse et al. 2009). Our validation efforts, comparing observations submitted to *Nature's Notebook* to the Pheno Forecast maps, will help us ascertain the extent to which single thresholds perform across species ranges and whether adjustments may be needed to the thresholds. Currently, our Pheno Forecasts provide a broad-scale prediction regarding when management action may be necessary and are intended to supplement the knowledge of local users. By combining the Pheno Forecast maps and tools with in-situ data collection using *Nature's Notebook*, the phenology models can be iteratively improved. Furthermore, future work could incorporate more rigorous validation and error estimates into Pheno Forecasts by showing the degree of agreement between phenology observations submitted to *Nature's Notebook* and the forecast maps geographically.

Another challenge of implementing GDD threshold models developed from one location to other portions of the species range pertains to the start date for heat accumulation. Three of the species models that we have implemented utilize a March 1 start date for heat accumulation (Table 1). The more northerly locations where these models were developed generally do not accumulate substantial heat units prior to March 1. However, these species—bagworm (*Thyridopteryx ephemeraeformis* Haworth), pine needle scale (*Chionaspis pinifoliae* Fitch), and eastern tent caterpillar (*Malacosoma americanum* Fabricius)—exhibit broad distributions across the United States, including southern states where heat units accumulate prior to 1 March. To minimize error in our maps for these species, we excluded Florida, Texas, and Louisiana states where heat accumulation prior to 1 March can be substantial. Observations submitted to *Nature's Notebook* have the potential to further improve the models across species ranges.

Gridded temperature data products, which serve as the basis for derived products like accumulated growing degree days, can also be a source of prediction error. Several factors—including elevation, coastal effects, slope and aspect, riparian zones, and land use/land cover—complicate temperature estimates across space (Daly 2006, Daly et al. 2008). In addition, the RTMA/URMA product is sometimes subject to quality assurance problems inherent in the processing of real-time weather observations, such as errors due to out-of-calibration weather sensors which may not be evident until the errors accumulate as with degree-day calculations (Pruess 1983, Daly et al. 2008, Pondeca et al. 2016). Furthermore, the error associated with the temperature model outputs is not uniform across space or time (Pielke et al. 2002, Daly 2006); temperatures may be less reliable near urban areas, in coastal areas, in topographically complex regions, and near riparian areas. To minimize this source of error, the USA-NPN uses products that are well-regarded, widely applied, and are formally evaluated in peer-reviewed studies (e.g., Myrick and Horel 2006). In the future, we hope to offer USA-NPN accumulated GDD products and Pheno Forecasts based on additional gridded temperature products, such as Parameter-elevation Regressions on Independent Slopes Model (PRISM) products (PRISM Climate Group, Oregon State University 2019), to enable further comparisons and identification of regional biases.

Pheno Forecast Sustainability

Pheno Forecast maps are generated, maintained, and delivered by the USA-NPN, in collaboration with stakeholders and experts in the field. The USA-NPN is funded primarily by the U.S. Geological Survey, rather than through short-term grants. Accordingly, the infrastructure supporting these maps has increased permanence over projects funded for shorter durations.

Future Directions

We will continue to make adjustments and improvements to our technical approach and methods for information delivery based on user feedback in 2019 and further into the future. We anticipate continuing to expand the suite of species and life-cycle events included in Pheno Forecasts, based on user requests. We also anticipate improving the sophistication of modeling approaches used, incorporating additional driving variables such as chilling, day length, and water availability, which are known to play a role in insect development (Wolda 1988). Finally, in the coming years, we expect to leverage longer-term weather forecasts like the 16-d Global Ensemble Forecast System and the 7-mo North American Multi-Model Ensemble to deliver longer-lead Pheno Forecasts, predicting insect pest activity weeks to months into the future.

Conclusions

Over the course of 2018 and 2019, we developed and released a suite of real-time and short-term forecast maps of insect pest life-cycle stages intended to support management actions. We created these maps based on input received from experts in the field as well as end users. Based on feedback received from maps piloted in 2018, we made substantial enhancements for maps released in 2019.

The results of this effort suggest that the USA-NPN is filling an open niche with the Pheno Forecast maps—that is, by operationalizing models and making continental-scale, fine resolution, daily maps, and short-term forecasts freely available in user-friendly formats. The Pheno Forecast maps as described here are unique in having the infrastructure and features that will promote more widespread adoption and acceptance of phenology mapping products for a wider audience. Whereas many online degree-day maps are static images or limited in some way, Pheno Forecast maps have excellent cartography, were designed via stakeholder consultation, are well-documented, have the facility for citizen scientists to submit corroborative observations, and include interactive features, such as zoom and query of data. Other online mapping systems have some of these attributes, but none exhibit the current level of refinement of this system.

We intend to continue to enhance these products based on user needs and input and to continue to identify additional ways we can serve this and expand to a broader stakeholder audience.

Supplementary Data

Supplementary data are available at *Annals of the Entomological Society of America* online.

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