Received: 6 December 2019 | Accepted: 15 April 2020
DOI: 10.1002/2688-8319.12007

Ecological Solutions and Evidence | BRITISH ECOLOGICAL SOCIETY

FROM PRACTICE AND EDITOR'S CHOICE

Using phenology data to improve control of invasive plant species: A case study on Midway Atoll NWR

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Handling editor: Andrea Thorpe

[Correction added on July 8, 2020, after first online publication: Peer review history statement has been added.]

Abstract

1. Restoration of degraded lands often depends on knowledge of invasive plant species' ecology coupled with well-timed treatments to control them. Little is known about the reproductive phenology of *Verbesina encelioides* (golden crownbeard), which is a highly invasive annual forb species at Midway Atoll National Wildlife Refuge (NWR). Efforts to control *V. encelioides* on Midway Atoll NWR were challenging, especially when targeted plants went to seed before being treated.
2. To obtain this information, we documented the timing of key reproductive life cycle events in cohorts of *V. encelioides* plants on Midway Atoll NWR for 12 months beginning in August 2016; we visited these plants every 3–7 days and noted which phenophases the plants exhibited.
3. We found that it took an average of 76 days for *V. encelioides* to transition from leaves to seed drop, although the time required varied across the year (range: 31–175 days). Accordingly, invasive plant control schedules were adjusted to re-treat infested areas every 30 days.
4. By incorporating phenology information into invasive plant control operations at Midway Atoll NWR, efforts to eradicate *V. encelioides* will have a higher chance of succeeding. Standardized methods, such as those from the USA National Phenology Network, provided useful tools for optimizing the timing of management practices; moreover, these data may help to better inform management of invasive plant species with regard to restoration efforts at a global scale.

KEYWORDS
invasive plant control, invasive species, land management, Nature's Notebook, phenology, restoration, *Verbesina encelioides*

1 | INTRODUCTION

Success in the restoration of degraded lands often hinges on the ability of land managers to successfully control or eradicate certain invasive plant species. Traits correlated with invasiveness—the ability to compete effectively against co-occurring native species and adaptations allowing them to disperse readily to new locations (e.g., seeds that travel by wind, water, or animals) and spread quickly (e.g., high fecundity)—also make these species very difficult to control (e.g., Willis et al., 2010; Wolkovich & Cleland, 2014). Nearly half of invasive plant eradication efforts fail (Pluess et al., 2012) and it is well-recognized that there is great need for improving the effectiveness of invasive species control efforts on a variety of fronts (Kettenring & Adams, 2011). A better understanding of the biology and timing of invasive plant species phenology can improve a land manager's ability to select an appropriate treatment method and implement that treatment in the field. Here, we describe how we used a standardized phenology data collection program, the USA National Phenology Network (USA-NPN)'s *Nature's Notebook*, to inform management of a highly invasive annual forb species, *Verbesina encelioides* (golden crownbeard), at Midway Atoll National Wildlife Refuge (NWR).

Midway Atoll NWR (28.208 °N; –177.379 °W) consists of three small islands (Sand, Eastern, and Spit Islands) with a total area of 6.2 km^2 surrounded by an emergent coral reef in the North Pacific Ocean. Midway's temperate, subtropical climate allows year-round plant growth though rates are affected by interseasonal variation in temperature and precipitation (Duhr et al., 2018). With cooler temperatures and harsher conditions than comparable tropical counterparts, Midway and other Northwestern Hawaiian Islands habitats are dominated by salt-tolerant and drought-resistant species (PMNM, 2008). On Midway, most of the islands are covered with low-growing forbs and grasses enclosed by a perimeter of shrubs and coastal scrub vegetation. The atoll provides nesting habitat to 21 seabird species, including 70% of the global population of Laysan albatross (*Phoebastria immutabilis*). Midway was chosen as the site of a naval air facility in 1940, just prior to WWII. During the war and in the decades that followed, extensive development led to intentional and accidental introduction of plant and animal species. By 1996, when management of the atoll was turned over to the U.S. Fish and Wildlife Service (USFWS), virtually no native vegetation remained at Midway. Today, Midway Atoll NWR is managed for the benefit of wildlife and is part of the Papahānaumokuākea Marine National Monument. Habitat restoration and the control of invasive species are central to ensuring the long-term conservation of Midway Atoll NWR's natural resources.

V. encelioides was first observed at Midway Atoll NWR in 1955 (Neff & DuMont, 1955) and remained at fairly low abundance until the late 1990s. At that time, naval operations ceased and land managers switched from a system of intense road and landscape maintenance to a more "naturalistic" approach by which lawns were left un-mowed and herbicide use along roads and runways was drastically reduced. *V. encelioides* thrived in this new environment and quickly came to dominate much of the Refuge (Feenstra & Clements, 2008). Impacts to albatrosses were evident, especially for birds nesting in tall dense stands of this weed (Bakker et al., 2018). Efforts to control *V. encelioides* were initiated by 1997 (Starr & Martz, 1999; R. Shallenberger, 2018, Friends of Hakalau Forest National Wildlife Refuge, personal communication) but the tools available at the time—a combination of hand-pulling, mowing, and the herbicide glyphosate (trade name RoundUp®, Monsanto Chemical Corporation)—were not sufficient to reduce abundance of the weed in the long-term as new plants were recruited through its substantial seed bank. Success in controlling *V. encelioides* came in 2011, when land managers began using the herbicide aminopyralid (trade name Milestone®, Dow Chemical Corporation), which has a residual effect that can suppress seed germination for up to 1 year post-treatment. The abundance of *V. encelioides* plummeted from approximately 50% cover in 2011 to less than 1% in 2015 (Klavitter et al., 2016; USFWS, 2012; Table S1, Figures S1–S4, Appendix S1). Given that long-term suppression of *V. encelioides* would require significant ongoing effort and expense, land managers have been compelled to attempt eradication of this weed from the atoll.

V. encelioides reproduces exclusively by seed, which plants produce after advancing through vegetative and flowering phenophases. In addition, *V. encelioides* is known to exhibit long periods of seed dormancy, and then rapidly respond, grow, and develop as environmental and climatic conditions become favorable (Feenstra & Clements, 2008; Kaul & Mangal, 1987; Shluker, 2002). Eradication of this weed, thus, ultimately requires that no plant be given the opportunity to produce and disperse ripe seeds. From an operational perspective, this requires that weed control technicians return to areas previously treated in less time than it takes for a seedling to grow to maturity and drop its seeds. While these basic facts were well understood, it was not known how many days it took for *V. encelioides* to go to seed. Moreover, it was assumed that the time required for plants to mature would vary across the year but how much it might vary was unknown. In an effort to obtain this information, we studied the phenology of *V. encelioides* for 12 months beginning in August 2016.

2 | MATERIALS AND METHODS

Rather than create our own methods, we adopted the vetted, standardized phenology protocols developed by the USA-NPN (Denny et al., 2014). Over the course of the study, we collected phenology data from 36 *V. encelioides* plants in four cohorts at two similar sites (flat, mostly sunny, with fine sandy soils) on Sand Island, Midway Atoll NWR. Both of these sites were located in areas dominated by a mix of low-growing grasses and forbs, including *Lobularia maritima*, *Cynodon dactylon*, *Solanum americanum*, *Lepidium virginicum*, *Coronopus didymus*, and *Eleusine indica* (USFWS, 2014), which constitute the dominant vegetation type on Midway's Sand Island. *V. encelioides* is more invasive and pervasive throughout this vegetation type than in other vegetation communities, such as forest (i.e., *Casuarina equisetafolia*) or shrub (i.e., *Scaevola taccada*) communities.

As we collected *V. encelioides* phenology data, we uploaded this data to USA-NPN's National Phenology Database, allowing for immediate analysis (USA-NPN, 2019). Each temporal cohort was composed of individuals having the initial growth phenophase at the start of each observation period; A: mid-August 2016 (n = 11); B: mid-November 2016 (n = 9); C: late December 2017 (n = 14); D: late March 2017 (n = 2; Figure 1). We visited each permanently marked plant every 3–7 days and noted which phenophases (initial growth, leaves, flowers or flower buds, open flowers, fruits, ripe fruits, recent fruit or seed drop) the plant exhibited (Figure 1). Only plants that we were able to track to the recent fruit or seed drop phenophase were used in our analysis; for these, we subtracted the date the plant was first observed in the leaves phenophase, thus yielding days to seed drop. The mean, standard

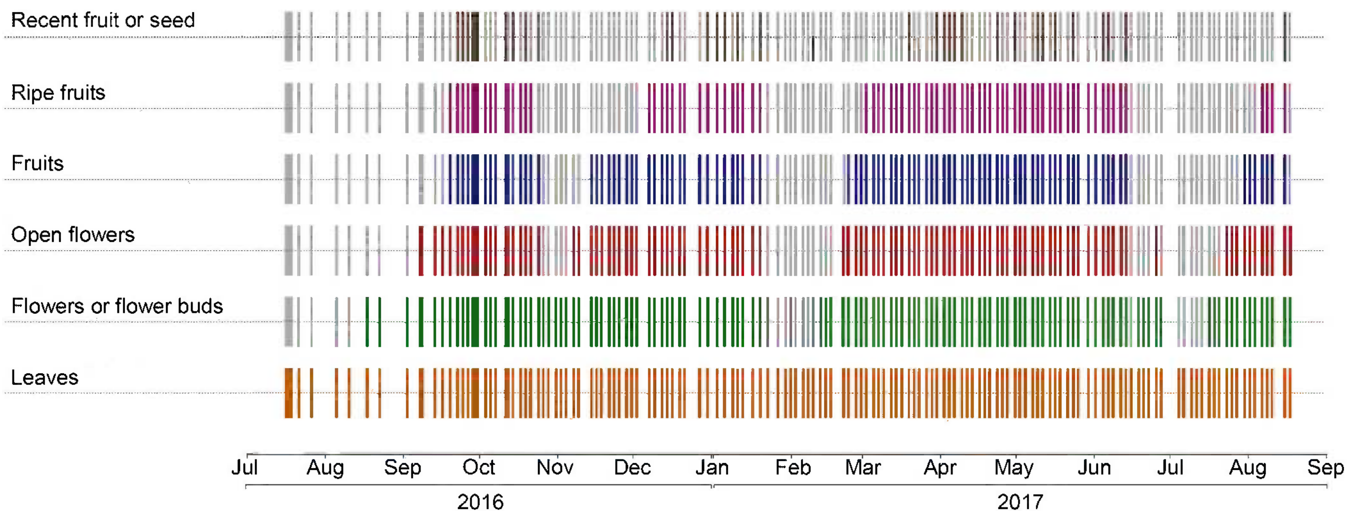

FIGURE 1 Calendar of phenological activity (presence/absence) for *V. encelioides* plants on Midway Atoll NWR, observed from August 2016 to August 2017. Colored bars indicate the presence of a given phenophase, whereas gray bars denote the absence of that particular phenophase. Graphic courtesy of the USA National Phenology Network

deviation, minimum, and maximum days to seed drop was calculated for all plants combined and for each cohort.

3 | RESULTS

We found that it took an average of 76 days (± 39.17 *SD*; min = 30; max = 175, *n* = 36) for *V. encelioides* to transition from leaves to the recent fruit or seed drop phenophase and that the time required varied across the year (Figures 1 and 2). Cohort A, which sprouted in the warm months of late summer, had the lowest number of days to seed drop (44 ± 8.9 *SD*; min = 31; max = 63) while Cohort C, which emerged in late December had the highest (119 ± 8.9 *SD*; min = 89; max = 175). Cohort B, which emerged in late fall, took only slightly more time to go to seed (48 ± 11.6 *SD*; min = 30; max = 67) than did Cohort A. The average of 65 days (± 17.0 *SD*) observed for Cohort D (late March) could reflect a rapid acceleration of growth rates in early spring, but the sample size for this group was very small as most plants in this cohort did not advance to the ripe seed phenophase due to a variety of reasons (e.g., accidental treatment by weed control technicians). Although the data are limited for Cohort D, we did find that the *V. encelioides* plants grew at a rapid pace in comparison to their winter counterparts (Cohort C), which has implications for management and control. All summary statistics were calculated using the statistical software R (R Core Team, 2019).

4 | DISCUSSION

Phenology information gathered from each cohort was used immediately by Refuge land managers on Midway Atoll NWR. When data from the first cohort of plants revealed that *V. encelioides* could go to seed in as little as 31 days, weed control schedules were adjusted such that the time elapsed between treatments was 30 days or less. Previously, control schedules were dictated mainly by external factors such as weather, staffing, and logistics and the time elapsed between control bouts for each of the 59 sectors (i.e., weed management units) could vary from several weeks to several months, without regard to the plant's phenology. During our study, treatment schedules were adjusted as new phenology information became available regarding seasonal changes in *V. encelioides* phenology (i.e., Cohorts A, B, C, and D; Figure 2). Thus, control bouts were more frequent during periods of rapid *V. encelioides* growth in the late summer and less frequent during winter months when *V. encelioides* growth rates declined (Figures 1 and 2).

Since the implementation of these optimized control schedules, *V. encelioides* has remained at or below 1% land cover on Midway Atoll NWR (U.S. Fish and Wildlife Service, unpublished data; Table S1, Figures S1–S4, Appendix S1). Based on surveys conducted during 2017, both density and frequency of *V. encelioides* on Sand Island were lower than in 2016 (Taylor, 2017; Figures S5 and S7). Frequency data for Eastern Island indicated a decrease in *V. encelioides* abundance from the 2012–2014 to the 2015–2017 period; however, no difference was found in either frequency or density from 2016 to 2017 (Taylor, 2017; Figures S6 and S8). Whether *V. encelioides* abundance has stabilized on Eastern Island or whether it continues to decline as a result of eradication efforts, remains an important question. Adjusting treatment schedules based on *V. encelioides* phenology data has been an important tool in maintaining low frequency and density of this invasive species across Midway Atoll NWR. However, considering the relatively small sampling period for *V. encelioides* phenology data collection in this study, as well as variation in interannual environmental conditions, further study regarding the rate of phenological development throughout the year (and especially the early spring) is needed to better inform the timing of treatment.

One major challenge in this control effort is ensuring that plants are treated before they can disperse ripe seeds. So far, efforts to

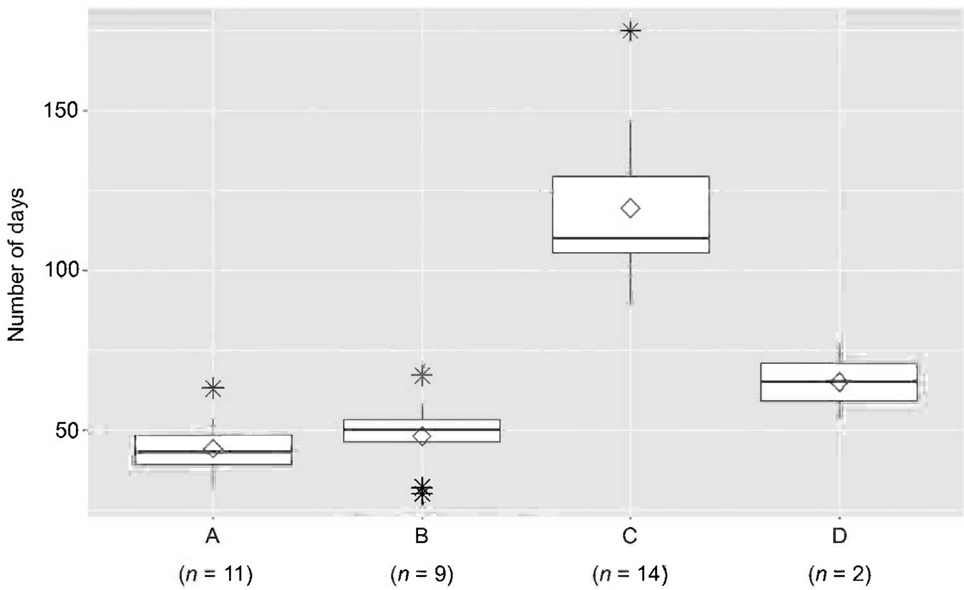

FIGURE 2 Number of days from first observation of leaves phenophase to recent fruit or seed drop for *V. encelioides* plants on Midway Atoll NWR by cohort (A, B, C, D). In the boxplots, diamonds (◇) are the means, bars are the medians, and asterisks (*) are outliers

eradicate *V. encelioides* on Midway Atoll NWR total more than US $2.1 million (USFWS, 2012, 2019). By incorporating phenology information into day-to-day weed management operations at Midway Atoll NWR, control and (ultimately) eradication efforts targeting *V. encelioides* will have a greater chance of succeeding. It will be critical for technicians to continue to locate and treat all plants within a control area, as even letting a single plant develop to seed-drop stage requires that areas be re-visited for months or even years due to multi-year seed viability (Cacho, Spring, Pheloung, & Hester, 2006; Feenstra & Clements, 2008).

Very few studies to date have revealed information pertaining to the phenology of *V. encelioides* (e.g., Kaul & Mangal, 1987). Moreover, *V. encelioides* exhibits high phenotypic plasticity and ecological variability (Kaul & Mangal, 1987); as such, phenological monitoring results from a given season or year may not be necessarily relevant or accurate to inform future treatment schedules. Although our data from 2016 to 2017 was very useful to inform treatment schedules immediately on Midway Atoll NWR, ongoing monitoring is needed to understand the temporal variation of this species' phenology so that it can be integrated into localized, adaptive longer term treatment schedules. Therefore, we encourage regular, ongoing phenological monitoring of *V. encelioides* (and other target invasive species) to further our understanding of seasonal variation in the time required for it to go to seed; moreover, monitoring phenology should occur at multiple sites, among various cover classes, throughout seasons to understand the phenological plasticity of this species. Without taking into account the phenology of *V. encelioides*, complete eradication may remain an elusive goal.

By combining data from many locations in publicly accessible databases such as the USA-NPN's National Phenology Database, important discoveries could be made about the ecology of this species and how its growth and phenology might differ across the wide variety of environmental conditions and climate regimes where it occurs (Wolkovich etal., 2013). This is especially important as *V. encelioides* continues to expand its geographic range having recently colonized, for example, a 40-km^2 area in eastern Tunisia (Sayari, Mekki, & Taleb, 2016).

Although land managers charged with abating the threat of invasive species have long considered plant growth stage when making decisions regarding treatment, the use of systematic, quantitative data on plant phenology does not appear to be widespread (Table 1; see Wolkovich & Cleland, 2011; Buisson, Alvardo, Le Stradic, & Morellato, 2016). Incorporating plant phenology data into invasive plant treatment plans can make the difference between success and failure. For example, in a study by Wallace et al. (2016), the phenology of *Pennisetum ciliare* (buffelgrass)—an aggressive invasive plant in the Sonoran Desert—was tracked to identify periods of reproduction and green-up when plants were most susceptible to mechanical removal and herbicide application.

One obstacle to collecting relevant plant phenology data as part of an invasive plant management project is the time and expense required. However, the recent availability of simple, standardized methods, data collection tools, and online databases such as those provided by PlantWatch Canada, USA-NPN, the Pan European Phenology Project, and others (Beaubien & Hamann, 2011; Denny et al., 2014; Templ et al., 2018) enable managers to leverage volunteer scientists to support these efforts (Rosemartin et al., 2014; Wallace et al., 2016; e.g., https://fws.usanpn.org/midway-atoll-nwr). Phenology data collected by volunteer scientists can also inform other aspects of ecological restoration, including increasing understanding of competitive advantages of invasive species over natives (Wolkovich & Cleland, 2011). Data collected through *Nature's Notebook* at National Wildlife Refuges other than Midway Atoll NWR have been used to guide the choice of species to plant in restoration sites and plan the timing of seasonal flooding and construction activities to promote native species

TABLE 1 Summary of case studies of invasive species management that has been improved by phenology monitoring

System	Invasive species	Phenological event	Management action	References
United Kingdom	Himalayan balsam (*Impatiens glandulifera*)	Flowering	Mow or trim plants during flowering or prior to flowering	CABI (2019)
South Wales	Japanese knotweed (*Fallopia japonica var. japonica*)	Rhizome source-sink strength	Apply herbicide at appropriate strength to coincide with seasonal changes in rhizome source-sink strength	Jones et al. (2018)
Coachella Valley, Colorado Plateau, USA	Asian mustard (*Brassica tournefortii*), redstem filaree (*Erodium cicutarium*), Mediterranean grass (*Schismus* spp.)	Leaf emergence	Treat early germinating exotics early before native plants emerge	Marushia, Cadotte, and Holt (2010)
Eastern Austria	Common ragweed (*Ambrosia artemisiifolia*)	Production of male inflorescences (allergenic pollen)	Mow plants shortly before male flowering, subsequent cuts on resprouting shoots	Milakovic, Fiedler, and Karrer (2014)
Northeastern Illinois, USA	Miscellaneous invasive plant species	Flowering	Use phenological calendar to determine treatment actions based on phenological event	NIIPP (2013)
Southeast Montana, USA	Green spurge (*Euphorbia esula*)	Pre-flowering	Graze pastures before green spurge plants begin to flower	Rinella and Hileman (2009)
Texas Hill Country, USA	Yellow bluestem (*Bothriochloa ischaemum*)	Stem elongation and flowering	Burn plants before 50% of all tillers are pre-reproductive	Ruckman, Schwinning, and Lyons (2011)
New Jersey, USA	Mile-a-minute (*Polygonum perfoliatium*)	Fruiting	Mow or weedwack prior to fruiting	Snyder and Kaufman (2004)
Wisconsin, USA	Miscellaneous invasive plant species	Dormancy, new growth, flowering, mature fruits or seeds, senescence	Use phenological events to increase invasive plant species detectability	University of Wisconsin (2019)
California grasslands, Santa Rosa Plateau, USA	Wild oat (*Avena fatua*), great brome (*Bromus diandrus*), compact brome (*Bromus rubens*)	Seeds	Mow plants before seed maturation	Valliere, Balch, Bell, Contreras, and Hilbig (2019)
Sonoran Desert. USA	Buffelgrass (*Pennisetum ciliare*)	Leaf green-up and emergence	Apply herbicide 1–2 weeks following precipitation threshold when plants are 50% or more green	Wallace et al. (2016)
California, USA	Miscellaneous invasive plant species	New growth, flowering, fruiting, senescence	Use phenological detectability calendar to map recent plant species invasions	Wrubel, Steers, and Aquila (2014)

and reduce the spread of invasive species (USA-NPN, unpublished data). In addition to contributing to our understanding of ecology and environmental change, data collection programs like *Nature's Notebook* can also engage the public, increase awareness of invasive species, boost scientific literacy, and build constituencies for conservation and restoration.

Phenology data collected for use in restoration and invasive plant management at the local scale can also inform other areas of science at the regional or even global scale (Enquist, Kellermann, Gerst, & Miller-Rushing, 2014). National initiatives dedicated to compiling phenology information (such as the Pan European Phenology Project, Swedish Phenology Network, PlantWatch in Canada, and more) provide researchers and resource managers access to standardized protocols and data that can inform management interventions and enhance restoration success (Enquist et al., 2014). The value of crowd-sourced phenological data will likely increase with efforts such as the "Global Alliance of Phenological Observation Networks" (GAPON), an international cooperation with the goal to coordinate, collect, and share phenological data (for a complete list of phenology networks worldwide, see https://www.usanpn.org/partner/gapon).

AUTHOR CONTRIBUTIONS

RVT, WAH, ABH, and EP conceived and designed the research; RVT, WAH, and ABH collected data; RVT and WAH analyzed the data; RVT, WAH, and EP wrote and edited the manuscript.

ACKNOWLEDGMENTS

We thank the USFWS for their support in this project to better understand invasive plant phenology; we also thank USFWS Service staff and volunteers and Chugach DBSI, Inc. contractors for their ongoing efforts in managing *Verbesina encelioides* and other invasive plant species on Midway Atoll NWR. We also acknowledge and thank the USA-NPN for their assistance in implementing phenology monitoring protocols on Midway Atoll NWR and sharing our work with other restoration practitioners and managers.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/2688-8319.12007

DATA AVAILABILITY STATEMENT

Phenological data used in this manuscript are archived online via Nature's Notebook (USA Phenology Network) and are available for download via the Phenology Observation Portal (https://data.usanpn.org/observations/).

DISCLAIMER

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the USFWS.

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REFERENCES

Bakker, V. J., Finkelstein, M. E., Doak, D. F., VanderWerf, E. A., Young, L. C., Arata, J. A., … Vanderlip, C. (2018). The albatross of assessing and managing risk for long-lived pelagic seabirds. *Biological Conservation*, *217*, 83–95. https://doi.org/10.1016/j.biocon.2017.08.022

Beaubien, E. G., & Hamman, A. (2011). Plant phenology networks of citizen scientists: Recommendations from two decades of experience in Canada. *International Journal of Biometerology*, *55*(6), 833–841. https://doi.org/10.1007/s00484-011-0457-y

Buisson, E., Alvardo, S. T., Le Stradic, S., & Morellato, L. P. C. (2016). Plant phenological research enhances ecological restoration. *Restoration Ecology*, *25*(2), 164–171. https://doi.org/10.1111/rec.12471

CABI. (2019). Impatiens glandulifera (Himalayan balsam) [original text by Tanner, R., updated by Pollard, K.]. In *Invasive species compendium*. Wallingford: CAB International. Retrieved from https://www.cabi.org/isc/datasheet/28766.

Cacho, J. O., Spring, D., Pheloung, P., & Hester, S. (2006). Evaluating the feasibility of eradicating an invasion. *Biological Invasions*, *8*, 903–917. https://doi.org/10.1007/s10530-005-4733-9

Denny, E. G., Gerst, K. L., Miller-Rushing, A. J., Tierney, G. L., Crimmins, T. M., Enquist, C. A. F., … Weltzin, J. F. (2014). Standardized phenology monitoring methods to track plant and animal activity for science and resource management applications. *International Journal of Biometeorology*, *58*, 591–601. https://doi.org/10.1007/s00484-014-0789-5

Duhr, M., Flint, E. N., Hunter, S. A., Taylor, R. V., Flanders, B., Howald, G. R., & Norwood, D. (2018). Control of house mice preying on adult albatrosses at Midway Atoll National Wildlife Refuge. In C. R.Veitch, M. N.Clout, A. R.Martin, J. C.Russell, & C. J.West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 21–25). Gland, Switzerland: International Union for Conservation of Nature.

Enquist, C. A. F., Kellermann, J. L., Gerst, K. L., & Miller-Rushing, A. J. (2014). Phenology research for natural resource management in the United States. *International Journal of Biometeorology*, *58*, 579–589. https://doi.org/10.1007/s00484-013-0772-6

Feenstra, K. R., & Clements, D. R. (2008). Biology and impacts of Pacific island invasive species. 4. *Verbesina encelioides*, golden crownbeard (Magnoliopsida: Asteraceae). *Pacific Science*, *62*(2), 161–176. https://doi.org/10.2984/1534-6188(2008)62[161:BAIOPI]2.0.CO;2

Jones, D., Bruce, G., Fowler, M. S., Law-Cooper, R., Graham, I., Abel, A., … Eastwood, D. (2018). Optimizing physiochemical control of invasive Japanese knotweed. *Biological Invasions*, *20*, 2091–2105. https://doi.org/10.1007/s10530-018-1684-5

Kaul, M. L. H., & Mangal, P. D. (1987). Phenology and germination of crownbeard (*Verbesina encelioides*). *Weed Science*, *35*(4), 513–518. https://doi.org/10.1017/S0043174500060471

Kettenring, K. M., & Adams, C. R. (2011). Lessons learned from invasive plant control experiments: A systematic review and meta-analysis. *Journal of Applied Ecology*, *48*(4), 970–979.

Klavitter, J., Schubert, G., Leary, P., Hall, S., Schulmeister, S., Duhr-Schulz, M., … Moore, E. (2016). Invasive plant *Verbesina encelioides* management at Midway Atoll National Wildlife Refuge: Advancing toward eradication. Presentation at the 43rd Annual Pacific Seabird Group, Turtle Bay, Hawaii.

Marushia, R. G., Cadotte, M. W., & Holt, J. S. (2010). Phenology as a basis for management of exotic annual plants in desert invasions. *Journal of Applied Ecology*, *47*(6), 1290–1299. https://doi.org/10.1111/j.1365-2664.2010.01881.x

Milakovic, I., Fiedler, K., & Karrer, G. (2014). Management of roadside populations of invasive *Ambrosia artemisiifolia* by mowing. *Weed Research*, *54*(3), 256–264. https://doi.org/10.1111/wre.12074

Neff, J. A., & DuMont, P. A. (1955). A partial list of the plants of the Midway Islands. *Atoll Research Bulletin*, *45*, 3–11.

Northeastern Illinois Invasive Plant Partnership (NIIPP). (2013). *Northeastern Illinois regional phenology and treatment calendar*. Retrieved from http://niipp.net/files/niipp/files/2011/01/Phenology-Calendar-Final_October-18-2013-1.pdf.

Papahānaumokuākea Marine National Monument (PMNM). (2008). Papahānaumokuākea Marine National Monument Management Plan, Honolulu, Hawaii.

Pluess, T., Jarošík, V., Pyšek, P., Cannon, R., Pergl, J., Breukers, A., & Bacher, S. (2012). Which factors affect the success or failure of eradication campaigns against alien species?*PLoS ONE*, *7*(10), e48157. https://doi.org/10.1371/journal.pone.0048157

R Core Team. (2019). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Rinella, M. J., & Hileman, B. J. (2009). Efficacy of prescribed grazing depends on timing intensity and frequency. *Journal of Applied Ecology*, *46*(4), 796–803. https://doi.org/10.1111/j.1365-2664.2009.01676.x

Rosemartin, A. H., Crimmins, T. M., Enquist, C. A. F., Gerst, K. L., Kellermann, J. L., Posthumus, E. E., … Weltzin, J. F. (2014). Organizing phenological data resources to inform natural resource conservation. *Biological Conservation*, *173*, 90–97. https://doi.org/10.1016/j.biocon.2013.07.003

Ruckman, E. M., Schwinning, S., & Lyons, K. G. (2011). Effects of phenology at burn time on post-fire recovery in an invasive C_4 grass. *Restoration Ecology*, *20*(6), 756–763. https://doi.org/10.1111/j.1526-100X.2011.00830.x

Sayari, N., Mekki, M., & Taleb, A. (2016). Golden crownbeard (*Verbesina encelioides*, Asteraceae), first record for the Tunisian flora. *Flora Mediterranea*, *26*, 19–24. https://doi.org/10.7320/FlMedit26.019

Shluker, A. (2002). Harmful non-indigenous species (HNIS) report for *Verbesina encelioides*. Puunene, HI: Hawaiian Ecosystems at Risk. Retrieved from http://www.hear.org/hnis/reports/verbesina_encelioides_hnis.pdf.

Snyder, D., & Kaufman, S. R. (2004). *An overview of nonindigenous plant species in New Jersey*. Trenton, NJ: New Jersey Department of Environmental Protection, Division of Parks and Forestry, Office of Natural Lands Management, Natural Heritage Program. Retrieved from https://www.nrc.gov/docs/ML0719/ML071980094.pdf.

Starr, F., & Martz, K. (1999). Botanical survey of Midway Atoll 1999 update. Report submitted to the U.S. Fish and Wildlife Service, Honolulu, HI.

Taylor, R. V. (2017). Findings from a Survey of Native and Exotic Species on Midway Atoll National Wildlife Refuge. Technical report prepared for the U.S. Fish and Wildlife Service, Honolulu, HI.

Templ, B., Koch, E., Bolmgren, K., Ungersböck, M., Paul, A., Scheifinger, H., … Zust, A. (2018). Pan European phenological database (PEP725): A single point of access for European data. *International Journal of Biometeorology*, *62*, 1109–1113. https://doi.org/10.1007/s00484-018-1512-8

University of Wisconsin. (2019). *Wisconsin invasive species calendar*. Madison, WI: Wisconsin First Detector Network, Division of Extension. Retrieved from https://public.tableau.com/profile/wi.first.detector.network#!/vizhome/InvasiveSpeciesCalendar/WisconsinInvasiveSpeciesCalendar.

USA National Phenology Network (USA-NPN). (2019). Plant and Animal Phenology Data. Data type: Individual Phenometrics. 08/17/2016-08/18/2017 for Region: 28.205467°, 177.38829° (LL). USA-NPN, Tucson, AZ. Retrieved from http://doi.org/10.5066/F78S4N1V.

U.S. Fish and Wildlife Service (USFWS). (2012). Eastern Island, Midway Atoll National Wildlife Refuge *Verbesina* eradication update: November 26, 2012. Honolulu, HI.

U.S. Fish and Wildlife Service (USFWS). (2014). Draft Midway Atoll NWR Terrestrial Habitat Management Plan. Unpublished technical report. Honolulu, HI.

U.S. Fish and Wildlife Service (USFWS). (2019) Interim Programmatic Report for the Midway Atoll NWR *Verbesina* Eradication Project: 10/01/2018-9/30/2019. Honolulu, HI.

Valliere, J. M., Balch, S., Bell, C., Contreras, C., & Hilbig, B. E. (2019). Repeated mowing to restore remnant native grasslands invaded by nonnative annual grasses: Upsides and downsides above and below ground. *Restoration Ecology*, *27*(2), 261–268. https://doi.org/10.1111/rec.12873

Wallace, C. S. A., Walker, J. J., Skirvin, S. M., Patrick-Birdwell, C., Weltzin, J. F., & Raichle, H. (2016). Mapping presence and predicting phenological status of invasive buffelgrass in southern Arizona using MODIS, climate and citizen science observation data. *Remote Sensing*, *8*(7), 524. https://doi.org/10.3390/rs8070524

Willis, C. G., Ruhfel, B., Primack, R. B., Miller-Rushing, A. J., Losos, J. B., & Davis, C. C. (2010). Favorable climate change response explains non-native species' success in Thoreau's woods. *PloS ONE*, *5*(1), e8878. https://doi.org/10.1371/journal.pone.0008878

Wolkovich, E. M., & Cleland, E. E. (2011). The phenology of plant invasions: A community ecology perspective. *Frontiers in Ecology and the Environment*, *9*(5), 287–294. https://doi.org/10.1890/100033

Wolkovich, E. M., & Cleland, E. E. (2014). Phenological niches and the future of invaded ecosystems with climate change. *AoB Plants*, *6*, plu013. https://doi.org/10.1093/aobpla/plu013

Wolkovich, E. M., Davies, T. J., Schaefer, H., Cleland, E. E., Cook, B. I., Travers, S. E., … Davis, C. C. (2013). Temperature-dependent shifts in phenology contribute to the success of exotic species with climate change. *American Journal of Botany*, *100*(7), 1047–1421. https://doi.org/10.3732/ajb.1200478

Wrubel, E., Steers, R., & Aquila, J. (2014). A phenological detectability calendar for invasive plant species. Presentation at the Cal-IPC Symposium, University of California, Chico, CA. Retrieved from https://www.cal-ipc.org/docs/symposia/archive/pdf/2014/Poster2014_Wrubel.pdf.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Taylor RV, Holthuijzen W, Humphrey A, Posthumus E. Using phenology data to improve control of invasive plant species: A case study on Midway Atoll NWR. *Ecol Solut Evidence*. 2020;1:e12007. https://doi.org/10.1002/eso3.12007